SAE NAPLES
An SAE International Section

ICE2017

13th International Conference on Engines & Vehicles

September 10 - 14, 2017 @ Capri, Napoli

abstracts

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The conference has been sponsored by:

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Silvana Di Iorio, Ezio Mancaruso, Bianca Maria Vaglieco e Robert M. Wagner.

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Engine Combustion

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Oak Ridge National Laboratory, Tennessee (USA)
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Combustion in Spark Ignition Engines	**Christine Mounaime Rousselle** *University of Orleans (France)* **Jamie Turner** *University of Bath (UK)* **Simona Silvia Merola** *Istituto Motori-CNR (Italy)*
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Abnormal Combustion and Cyclic Dispersion	**Tommaso Lucchini** *Politecnico di Milano, (Italy)* **Brian Kaul** *Oak Ridge National Laboratories (USA)* **Paolo Sementa** *Istituto Motori-CNR (Italy)*

Fuels and Lubricant Technologies

Jim Szybist
Oak Ridge National Laboratory, Tennessee (USA)
Sebastian Verhelst
Ghent University (Belgium)

Fuel Injection and Sprays: Modeling	**Michele Battistoni** *University of Perugia (Italy)* **Mario Trujllo** *ERC University of Wisconsin-Madison (USA)*
Fuel Injection and Sprays: Experiments	**Louis-Marie Malbec** *IFPN (France)* **Alessandro Montanaro** *Istituto Motori (Italy)* **Josè V. Pastor** *CMT - Universitat Politècnica de Valencia (Spain)*
Alternative and Advanced Fuels	**Vincenzo Mulone** *University of Rome Tor Vergata (Italy)* **Paolo Carlucci** *University of Salento (Italy)* **Arvind Thiruvengadam** *West Virginia University (USA)*
Automotive Lubricants	**Richard Pearson** *BP (UK)*

Emissions and Emissions Controls

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Imad A. Khalek
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Exhaust Emission Control Systems	**Cary Henry** *Southwest Research Institute (USA)*
Emission Control Modeling	**Mike Smith** *General Motors (USA)*
Emissions Measurement and Testing	**John Storey** *Oak Ridge National Lab (USA)*
Particle Emissions from Combustion Sources	**Silvana Di Iorio** *Istituto Motori (Italy)* **Imad Khalek** *Southwest Research Institute (USA)*
Low Temperature Catalysis	**Panayotis Dimopoulos Eggenschwiler** *EMPA (Swiss)* **Todd Toops** *Oak Ridge National Laboratory (USA)*

New Engines, Components, Actuators, & Sensors

Michael Bargende
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Enabling Technologies	**Thomas Wallner** *Argonne National Lab (USA)*

Hybrid and Electric Powertrains, including Range Extending Engines

Scott Curran
Oak Ridge National Laboratory, Tennessee (USA)
Mike Bassett
MAHLE Powertrain Ltd (UK)

Advanced Hybrid and Electric Vehicle Powertrains	**Burak Ozpineci** *Oak Ridge National Laboratory (USA)*
Controls for Hybrids and Electric Powertrains	**Marcello Canova** *CAR The Ohio State University (USA)* **Paul Chambon** *Oak Ridge National Laboratory (USA)*
Advanced Fuel Cell Vehicle Applications	**Ivan Arsie** *University of Salerno (Italy)* **David Wood** *Oak Ridge National Laboratory (USA)*
Range Extending Engines	**Mike Basset** *MAHLE Powetrain Ltd (UK)*
Powertrain Systems	**Scott Curran** *Oak Ridge National Laboratory (USA)*

Preface

Welcome to the SAE 13th International Conference on Engines and Vehicles in Capri, Napoli (Italy). This conference brings together researchers from more than 30 countries providing an exciting international forum to share and discuss new research results focused on improving the efficiency and emissions of engines and vehicles. The 2017 conference has been organized by Istituto Motori – National Research Council of Italy (CNR), Oak Ridge National Laboratory, and SAENA, an Italian Section of SAE International. The final program includes 170 publications that have undergone a rigorous review based on the SAE International standards. These publications cover a broad range of topics including advanced internal combustion engine concepts, conventional and alternative non-conventional fuel technologies, innovative experimental diagnostics, numerical simulation, advanced controls, and the integration of internal combustion engines with electrified hybrid powertrains. In addition, nine international experts on many of these topics have been invited to deliver plenary lectures on the state-of-the-art and future development trends.

We are grateful for the participation of the many volunteers whose contributions have made for an exciting and high quality technical program. A special thank you to Brandi Schandelmeier for her strong support of all aspects of this conference. This meeting would not have been possible without the tireless contributions of our session and sub-session organizers, authors, and reviewers. We are also thankful to our invited speakers for agreeing to share their expertise and knowledge. Finally, a special thank to all of our sponsors whose financial support and enthusiasm makes this meeting possible.

Robert M. Wagner and Bianca M. Vaglieco

Plenary Lectures

Evolution of Engine Lubricants Technologies Enabling Improved Systems' Efficiency and Extended Durability

Ewa Bardasz
Technical Fellow at Lubrizol (USA)

Crankcase lubricants have been undergoing major changes over recent years in response to societal pressures and global governments' regulations addressing needs to improve fuel consumption and lower the levels of exhaust emissions. Over the last decade global transportation industries have been facing numerous technical challenges and fast moving transformations in the areas of novel combustion processes, sophisticated hardware materials, changes in metal surface topologies, introduction of various types of alternative fuels, more severe operating conditions, launching of low viscosity lubricants, and introduction of ash-free additives.This presentation will offer a journey from the past through the future of crankcase lubricants technologies innovations. It should be recognized that future modern lubricants can provide significant performance benefits by offering improved fuel economy retention, long-term protection of novel combustion systems' hardware, as well as minimizing interactions with critical exhaust catalytic systems. The audience will gain actionable insights what critical performance benefits and challenges they might encounter. At the same time, it is important to recognize that introducing novel base oils and additive lubricant technologies have the potential to offer even further advantages in key performance characteristics, as long as the technical communities within the transportation industry recognize the need for early stage technical collaborations. Challenges that technical teams currently face are complex and need to be resolved quickly. No single technical organization can create the best possible solutions while working in isolation with a limited ideas, short time span and restricted financial resources. It is critical to work together so we can enable progress and innovation for everybody.

Co-Optimization of Fuels and Engines (Co-Optima)

John Farrell
National Renewable Energy Laboratory, (USA)

The Co-Optimization of Fuels and Engines (Co-Optima) initiative is a U.S. Department of Energy (DOE) effort funded by both the Vehicle and Bioenergy Technology Offices. The overall goal of the effort is to identify the combinations of fuel properties and engine characteristics that maximize efficiency, independent of production pathway or fuel composition, and accelerate commercialization of these technologies. Multiple research efforts are underway focused on both spark-ignition and compression-ignition strategies applicable across the entire light, medium, and heavy-duty fleet. The fuel property focus of the R&D includes efforts directed towards characterizing and exploiting the beneficial properties available from biomass-derived fuel blendstocks. In addition to fuels and engines R&D, the initiative is guided by analyses assessing the near-term commercial feasibility of new blendstocks based on economics, environmental performance, compatibility, and large-scale production viability. This talk will provide an overview of the Co-Optima effort and present select technical and analysis highlights, with an emphasis on results from R&D focused on spark-ignition fuels and engines.

Investigation Real World Fuel Consumption Reduction Potential of Hybrid Electric and Conventional Powertrain and Vehicles Using a Dedicated Simulation Platform

Damien Maroteaux
RENAULT Engineering Alliance (France)

The worldwide trends for future CO2 regulation standards are a tremendous challenge for car manufacturers. So-called conventional powertrains and vehicles require the implementation of new control strategies for fuel consumption reduction, like sailing & coasting strategies, electric energy management, or thermal management. Conventional Powertrains are following the path of electrification, using for example separated starter generator (SSG) including in some cases brake and boost functions. A widespread application of both Electric and Hybrid Electric Vehicles is also foreseen for the near future. The application of Advanced Driver Assistance Systems, as well as the ability to connect the vehicle to infrastructure or traffic will also be used to optimize energy consumption. These new technologies will all have to be developed and validated in a very constrained development time schedule. In order to address these challenges, the use of simulation is mandatory. This plenary lecture describes the application of simulation tools and methodologies for fuel consumption in the context of new powertrains and vehicles developed by RENAULT Engineering Alliance. Simulation is used at different stages of the development. In the upstream phase of projects, simulation is used to help decision making to select technical definition, architecture, new control strategies in view of fuel consumption targets. In later phases of project, not only official fuel consumption figures but also real world fuel consumption are estimated and monitored by simulation, as well as vehicle Dynamic Performance. A general view of existing tools and methods is given, together with the requirements for a simulation platform addressing these new challenges. Then the dedicated simulation platform developed for this purpose for Renault-Nissan Alliance, and having a high degree of flexibility, is described. Several application cases are taken as example, ranging from conventional powertrains with new engine and vehicle management strategies, to mild hybrid and plug-in hybrid applications, and up to potential application of driver assistance systems to optimize fuel consumption. An outlook to future applications of this simulation platform will also be given.

Death of IC Engine Again?

Doug Patton
SAE International President (USA)

If you read everything coming from automakers and end users, one would think the ICE is dead. Over the years there have been several challengers to the ICE; steam, electrification and the gas turbine. However, today the ICE remains the mainstay of automotive propulsion systems. The ICE was thought to have reached its limits several times, but it continues to become cleaner and more efficient. Will it continue to evolve or is it about to die?

Carbon Neutral Fuels for efficient ICE: an alternative towards Green Mobility

Dario Sacco
Centro Ricerche Fiat (Italy)

The evolution of the economic, social and energetic context of the coming years is creating ambitious, but exciting, challenges:

- global warming drives the new legislation for CO2 emissions reduction
- energy security puts the attention on oil reserves decrease and new oil fields
- increased urbanization and air quality issues lead to predicted Internal Combustion Engines bans in cities
- cultural and demographic changes are forcing consumer shifts and attitudes

Country pledges for 2030 exceed the warming limit of the Paris Agreement. In other terms, there are just over four years' worth of current emissions left before it becomes unlikely that we'll meet the 1.5°C target without overshooting.
Current global transportation sector is based for more than 95% on oil derived fuels. The long term objective of the de-carbonization of the transport sector is driving the current transition period where a deeply rooted oil-based system is asked to move towards new energy carriers. Electrification doesn't reduce green house gas emission as long as the necessary electricity is generated by conventional power stations. A radical change of feedstock to produce electricity, based on renewables sources, must be implemented to clean-up this kind of energy. When referring to de-carbonisation, it is fundamental to consider the entire fuel chain (from extraction to its end usage, meaning from Well to Wheel) to have a proper comparison among different solutions. In this way technology neutrality is guaranteed. In conclusion, the way to a Green Mobility is based on two parallel paths. Electric vehicles will have a fundamental role in the future fleet because of their CO2-free exhaust emissions but electrification will become the real green solution only when electricity will be generated from renewable sources. New technologies will support the efficiency increase of the Internal Combustion Engines but the development of carbon-neutral fuels will be needed to complete the de-carbonization process.

From Tank-to-Wheel (T2W) to Life Cycle Assessment (LCA) - Zero-CO2 Mobility Concepts and their Different Shades of Green

Christof Schernus and Thorsten Schnorbus
FEV Europe GmbH (Germany)

Whilst the public audience often recognises only battery-electric vehicles (BEV) as the essential pathway to CO2-free mobility, the potential of regenerative fuels for achieving an overall decrease of CO2 emissions is significantly underestimated. This holds true for their use as hydrogen in fuel cells as well as e-fuels or fuels from biomass in internal combustion engines. When it comes to reducing the well-to-wheel based CO2 emission, it is the usage of regenerative energy for propulsion that matters. With the current and near future mix of primary energy used for electricity generation in the grid, also BEVs do not achieve a zero carbon footprint, yet. The powertrain concept analysis in this article considers the CO2 balance relative to the in-vehicle energy storage (tank-to-wheel). This is compared to the balance relative to the sourcing of that stored energy. Thirdly, some light is shed on the use of energy and resources involved in production and disposal of a vehicle (life cycle assessment).

Current state-of-the-art in fuel injection and spray modeling for internal combustion engine simulations

Kelly P. Senecal
Convergent Science (USA)

Simulations of diesel and gasoline engines require accurate representation of the fuel injection and spray processes for reliable predictions of performance and emissions. When simulating fuel sprays, many choices must be made by the user, including turbulence model (RANS vs LES), spray methodology (Eulerian vs Lagrangian), mesh resolution, and various sub-model options. This presentation reviews state-of-the-art techniques for modeling sprays, from everyday production-type simulations to cutting edge research.

Insights into GDI Engine Combustion from an Optical Access Engine

Richard Stone
Oxford University (United Kingdom)

The increased efficiency and specific output with Gasoline Direct Injection (GDI) engines are well known, but so too are the higher levels of Particulate Matter emissions compared with Port Fuel Injection (PFI) engines. To minimise Particulate Matter emissions, then it is necessary to understand and control the mixture preparation process, and important insights into GDI engine combustion can be obtained from optical access engines. Such data is crucial for validating models that predict flows, sprays and air fuel ratio distributions. Mie scattering can be used for semi-quantitative measurements of the fuel spray and this can be followed with Planar Laser Induced Fluorescence (PLIF) for determining the air fuel ratio and temperature distributions. With PLIF, very careful in-situ calibration is needed, and for temperature this can be provided by Laser Induced Thermal Grating Spectroscopy (LITGS). LITGS temperature measurements can also be used to quantify the differences in evaporative cooling with different fuels, thereby explaining observed changes in the volumetric efficiency. Natural light photography can be used for tracking flame fronts, and with suitable calibration of the colour filter array in a high speed colour video camera, then soot pyrometry can be employed to estimate the temperature and soot loading.

Pressure-Temperature Domain Analysis to Provide Insight into Autoignition Processes in SI Engines at High Operating Load

Jim Szybist
Oak Ridge National Laboratory, (USA)

Knock phenomena limit compression ratio and combustion phasing in spark-ignited engines, ultimately limiting engine efficiency. As the industry trends towards downsized engines that require boost to reduce fuel consumption, developing a better understanding of knock phenomena is of increased importance because engines are knock-limited conditions for more of the operating map. To understand these phenomena better, ORNL has adapted and improve an analysis technique focused on the trajectory of the unburned gas through the pressure-temperature domain, an approach conducive to relating the engine phenomena to chemical kinetics. The application of this analysis is demonstrated in three applications. In the first application, experimental combustion analysis showed that pre-spark heat release (PSHR) was present for some fuels under boosted operating condition, but not present for other fuels even though all fuels had the same research octane number (RON = 100). Chemical kinetic modeling of ignition delay throughout the pressure-temperature domain was used to identify a kinetic basis for the PSHR and correctly predicted the trends of the behavior. In the second application, an increase in the combustion duration was identified in the turbulent flame propagation when PSHR was present. This highlights that when PSHR occurs, the flame propagates through partially-oxidized products, a phenomenon that is currently well captured in many models and is also important to capturing the boundary conditions for knock and other abnormal combustion events. The third application focused on the reduced effectiveness of exhaust gas recirculation (EGR) to mitigate knock as load increases, where pressure-temperature domain analysis is used to demonstrate the fundamental reason for reduced EGR effectiveness.

Engine Modeling and Controls

Engine Combustion

Fuels and Lubricants Technologies

Emissions and Emissions Controls

New Engines, Components, Actuators, & Sensors

Hybrid and Electric Powertrains, including Range Extending Engines

Two-Stage Ignition Occurrence in the End Gas and Modeling Its Influence on Engine Knock

Alexander Fandakov, Michael Bargende
IVK, University of Stuttgart
Michael Grill
FKFS
Andre Casal Kulzer
Porsche AG

The most significant operation limit prohibiting the further reduction of the CO_2 emissions of gasoline engines is the occurrence of knock. Thus, being able to predict the incidence of this phenomenon is of vital importance for the engine process simulation - a tool widely used in the engine development. Common knock models in the 0D/1D simulation are based on the calculation of a pre-reaction state of the unburnt mixture (also called knock integral), which is a simplified approach for modeling the progress of the chemical reactions in the end gas where knock occurs. Simulations of thousands of knocking single working cycles with a model representing the Entrainment model's unburnt zone were performed using a detailed chemical reaction mechanism. The investigations showed that, at specific boundary conditions, the auto-ignition of the unburnt mixture resulting in knock happens in two stages. It is demonstrated that the commonly used knock integral is not capable of representing this behavior of the detailed chemical mechanism, meaning an improved approach for modeling the progress of the chemical reactions is needed for the calculation of the knock boundary. Based on these findings, a new two-stage knock integral approach capable of reproducing the auto-ignition behavior of the detailed chemical mechanism was developed. For this purpose, an enhanced three zone approach for modeling the influence of various parameters (pressure, temperature, exhaust gas fraction, air-fuel ratio, ethanol content and surrogate composition) on the ignition delay times of the mixture is proposed. Furthermore, a newly developed model for the ignition delay of the low-temperature ignition as a function of the boundary conditions is presented. Finally, the performance of the new two-stage approach is demonstrated and compared with the results achieved by the commonly used single-stage knock integral.

On the Entrainment Velocity and Characteristic Length Scales Used for Quasi-Dimensional Turbulent Combustion Modeling in Spark Ignition Engines

Adrian Irimescu, Silvana Di Iorio, Simona Merola, Paolo Sementa, and Bianca Maria Vaglieco
Istituto Motori CNR

Quasi-dimensional modeling is used on a wide scale in engine development, given its potential for saving time and resources compared to experimental investigations. Often it is preferred to more complex CFD codes that are much more computationally intensive. Accuracy is one major issue of quasi-dimensional simulations and for this reason sub-models are continuously developed for improving predictive capabilities. This study considers the use of equivalent fluid velocity and characteristic length scales for simulating the processes of fresh charge entrainment and oxidation behind the flame front. Rather than dividing combustion into three different phases (i.e. laminar kernel, turbulent flame propagation and oxidation near the walls), the concept of turbulent heat and mass transfer is imposed throughout the entire process. Within this framework, the calibration of the two coefficients for fresh charge entrainment and oxidation behind the flame front was investigated, based on in-cylinder pressure and flame imaging recorded in a spark ignition (SI) engine fueled with gasoline, ethanol, methane and hydrogen. After the procedure of identifying the pairs of coefficients that ensured good accuracy during flame propagation, a more detailed analysis was performed with respect to the three combustion phases. These findings constitute the basis for developing mass transfer sub-models that ensure improved accuracy for multi-fuel operation of SI engines.

Physical Modeling of a Turbocharger Electric Waste-Gate Actuator for Control Purpose

Andreas Sidorow
BorgWarner Turbo Systems
Vincent Berger and Ghita Elouazzani
PSA Groupe

Gasoline engines have typically a waste gate actuator to control the boost pressure. The electrification of the vehicle and combustion engine components leads to new challenges of application of electric actuators in engine components, like turbochargers, which are faced with relatively high ambient temperatures. Another challenge is a simulation and prediction of the mechanical load on the actuator and kinematic components at different application scenarios, which can help to find the optimal solution which fulfills the durability, controllability, etc. targets. This paper deals with a physical dynamic model of an electric waste-gate actuator and kinematic components. The modeling includes a thermal, electrical and mechanical parts of the turbocharger control system and is validated on test-bench and engine measurements including pulsation effects. The measurements are accomplished on an modern turbocharged gasoline 4 cylinder engine EP gen2 Euro6.2 - China6 from PSA with the displacement volume of 1.6 liters.

Experimental Study of Centrifugal Compressor Speed Lines Extrapolation for Automotive Turbochargers

Guillaume Goumy, Pascal Chesse, Nicolas Perrot, and Rémi Dubouil
Ecole Centrale De Nantes

Downsizing has nowadays become the more widespread solution to achieve the quest for reaching the fuel consumption incentive. This size reduction goes with turbocharging in order to keep the engine power constant. To reduce the development costs and to meet the ever tightening regulations, car manufacturers rely more and more on computer simulations. Thus developing accurate and predictable turbocharger models functioning on a wide range of engine life cases became a major requirement in industrial projects. In the current models, compressors and turbines are represented by look-up tables, experimentally measured on a turbocharger test bench, at steady point and high inlet turbine temperature. This method results in limited maps : on the one hand the compressor surge line and on the other hand the flow resistance curve behind the compressor. Mounted on an engine, the turbocharger encounters a wider scale of functioning points. Using only the actual compressor and turbine maps in an engine simulation is sometimes a limiting factor. For this paper a specific experimental campaign has been performed with different automotive turbochargers on a test bench in order to expand the measured iso-speed lines. On the compressor side, new measurements methodologies are described

- into the choke area, up until a ratio of 0.8,
- beyond the surge line, into the negative mass flow rate.

The results are used to establish semi empirical models of the compressor power in these areas and to study the surge loop amplitude.

Comparison of Eulerian and Lagrangian 1D Models of Diesel Fuel Injection and Combustion

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Diesel engines are being more commonly used for light automotive applications, due to their higher efficiency, despite the difficulty of depollution and extra associated costs. They require more accessories to function properly, such as turbocharging and post-treatment systems. The most important pollutants emitted from diesel engines are NOx and particles (in conventional engines), being difficult to reduce and control because reducing one increases the other. Low temperature combustion (LTC) diesel engines are able to reduce both pollutants, but increase emissions of CO and HC. Besides HCCI and EGR systems, one method that could achieve LTC conditions is by using multiple injections (pilot/main, split injection, etc.). However, understanding multiple diesel injection is no easy task, so far done by trial and error and complex 3D CFD models, or too simplified by 0D models. Therefore, a numerical 1D model is to be adapted to simulate multiple injection situations in a diesel engine. In this paper, existing models are compared to determine the necessary conditions to adapt the model to handle multiple diesel injections. The base model used is that of Ma et al, which is based on the eulerian model of Musculus and Kattke for inert diesel jets. One limitation found on this model was the simplification of the radial distribution of fuel/air mixture, which alters the values obtained from it. This model is compared with a lagrangian model (Hiroyasu, Poetsch), which has an inherent 2D treatment of the diesel jet. A pseudo 2D radial distribution is calculated from the 1D model to create a 2D image of the jet, to be able to compare it to the 2D image obtained from the lagrangian model. Important differences are noted from both models, especially in the thermal dilatation due to the burning of fuel. Since the eulerian model has a fixed spreading angle for the jet, the thermal dilatation is only axial (such as described in Desantes et al.); while in the lagrangian model, since the penetration is fixed, the dilatation is only radial. This difference modifies the fuel/air mixture within the jet, resulting in different heat release traces for both models. To reconcile this difference, a thermal dilatation model is introduced to consider both radial and axial dilatations, to approach a more appropriate fuel/air mixture that properly models the diesel combustion. This lays a first step to arrive to a properly adapted 1D model for multiple diesel injection.

Assessment of the Approximation Formula for the Calculation of Methane/Air Laminar Burning Velocities Used in Engine Combustion Models

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Especially for internal combustion engine simulations, various combustion models rely on the laminar burning velocity. With respect to computational time needed for CFD, the calculation of laminar burning velocities using a detailed chemical mechanism can be replaced by incorporation of approximation formulas, based on rate-ratio asymptotics. This study revisits an existing analytical approximation formula. It investigates applicable temperature, pressure, and equivalence ratio ranges with special focus on engine combustion conditions. The fuel chosen here is methane and mixtures are composed of methane and air. The model performance to calculate the laminar burning velocity are compared with calculated laminar burning velocities using existing state of the art detailed chemical mechanisms, the GRI Mech 3.0, the ITV RWTH, and the Aramco mechanism. The Aramco mechanism was chosen for further investigations, because it predicts very well new experimental data for ambient conditions presented in this work. Significant differences are observed between laminar burning velocities calculated with the original set of coefficients presented by Goettgens et al. for the approximation formula and the Aramco mechanism. Hence, updated parameters for the approximation formulation are presented. The impact of the laminar burning velocity results on the combustion models is discussed.

Numerical Simulation of the Combustion Process of a High EGR, High Injection Pressure, Heavy Duty Diesel Engine

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To comply with Stage IV emission standard for off-road engines, Kohler Engines has developed the 100kW rated KDI 3.4 liters diesel engine, equipped with DOC and SCR. Based on this engine, a research project in collaboration between Kohler Engines, Ricardo, Denso and Politecnico di Torino was carried out to exploit the potential of new technologies to meet the Stage IV and beyond emission standards. The prototype engine was equipped with a low pressure cooled EGR system, two stage turbocharger, high pressure fuel injection system capable of very high injection pressure and DOC+DPF aftertreatment system. Since the Stage IV emission standard sets a 0.4 g/kWh NOx limit for the steady state test cycle (NRSC), that includes full load operating conditions, the engine must be operated with very high EGR rates (above 30%) at very high load. As a consequence, the low air to fuel ratio and the risk of high soot emissions must be handled by means of high fuel injection pressure and proper injection patterns. In this context, the DIPulse multizone predictive combustion model developed by Gamma Technologies was extensively employed to support the engine calibration and the hardware selection processes. After populating the injection rate map starting from a limited set of measurements, the model was then calibrated to simulate the combustion process with extremely high injection pressures and EGR rates, achieving a very good correlation with the experimental data in terms of burn rates, engine performance parameters and NOx emissions. In this way a kind of "virtual test rig" was obtained, on which the effects of different injection patterns and hardware components could be analyzed, thus significantly shortening the hardware selection and calibration activities on the test bench to achieve the project targets.

A Methodology for Modeling the Cat-Heating Transient Phase in a Turbocharged Direct Injection Spark Ignition Engine

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This paper presents the modeling of the transient phase of catalyst heating on a high-performance turbocharged spark ignition engine with the aim to accurately predict the exhaust thermal energy available at the catalyst inlet and to provide a "virtual test rig" to assess different design and calibration options. The entire transient phase, starting from the engine cranking until the catalyst warm-up is completed, was taken into account in the simulation, and the model was validated using a wide data-set of experimental tests. The first step of the modeling activity was the combustion analysis during the transient phase: the burn rate was evaluated on the basis of experimental in-cylinder pressure data, considering both cycle-to- cycle and cylinder-to-cylinder variations. Then, as far as the exhaust temperatures are concerned, a detailed model of the thermocouples was implemented to replicate the physical behavior of the sensors during the warm-up and to compare the simulated temperatures with the measured ones. Finally, a complete analysis of the energy balance during the transient was carried out: the thermal power available to the catalyst inlet was obtained from a complete analysis of power losses (i.e. friction and pumping losses, in-cylinder heat transfer, engine block and engine coolant heating, exhaust manifold heat transfer, etc.). In conclusion, the proposed methodology allows to reliably simulate in details the Cat-Heating transient, showing a valuable potential in driving the main design and calibration choices during the engine development process.

A Fully Physical Correlation for Low Pressure EGR Control Linearization

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Nowadays stringent emission regulations are pushing towards new air management strategies like LP-EGR and HP/LP mix both for passenger car and heavy duty applications, increasing the engine control complexity. Within a project in collaboration between Kohler Engines EMEA, Politecnico di Torino, Ricardo and Denso to exploit the potential of EGR-Only technologies, a 3.4 liters KDI 3404 was equipped with a two stage turbocharging system, an extremely high pressure FIS and a low pressure EGR system. The LP-EGR system works in a closed loop control with an intake oxygen sensor actuating two valves: an EGR valve placed downstream of the EGR cooler that regulates the flow area of the bypass between the exhaust line and the intake line, and an exhaust flap to generate enough backpressure to recirculate the needed EGR rate to cut the NOx emission without a specific aftertreatment device. In this paper it will be demonstrated how, using a 1D-CFD code to characterize the flow in the exhaust line and in the EGR pathway, together with simple physical correlations, it is possible to define the opening laws of the two valves in order to both obtain a linear response of the EGR control and minimize the fuel consumption increase due to the backpressure valve.

Experimental and Numerical Assessment of Multi-Event Injection Strategies in a Solenoid Common-Rail Injector

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Nowadays, injection rate shaping and multi-pilot events can help to improve fuel efficiency, combustion noise and pollutant emissions in diesel engine, providing high exibility in the shape of the injection that allows combustion process control. Different strategies can be used in order to obtain the required flexibility in the rate, such as very close pilot injections with almost zero Dwell Time or boot shaped injections with optional pilot injections. Modern Common-Rail Fuel Injection Systems (FIS) should be able to provide these innovative patterns to control the combustion phases intensity for optimal tradeoff between fuel consumption and emission levels. In this work, a 1D-CFD model in GT-SUITE of a solenoid ballistic Common-Rail injector was firstly refined respect to the previous work and then it was validated against an extensive experimental dataset of single injections, standard double pilot and multi-pilot injection patterns (up to 4 pilot events) with almost zero dwell time between two consecutive injection events. The experimental hydraulic test data used to validate the one-dimensional model were obtained by means of the UniPG Injection Analyzer based on the Zeuch's method. The comparison between the experimental and simulated volumetric injection rates showed a more than satisfactory accuracy of the model in predicting the actual behavior of the ballistic injector for all the injection patterns tested, even for relatively complex injector command strategies, characterized by reduced Dwell Time values between consecutive injection events.

Experimental Characterization for Modelling of Turbocharger Friction Losses

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Today turbochargers are used by car manufacturers on Diesel engines and on an increasing number of gasoline engines, especially in the scope of downsizing. This component has to be well understood and modeled as simulation is widely used at every step of the development. Indeed development cost and time have to be reduced to fulfill both customers' wishes and more stringent emissions standards. Current turbocharger simulation codes are mostly based on look-up tables (air mass flow and efficiency) given by manufacturers. This raises two points. Firstly, the characteristics are known only in the same conditions as manufacturers' tests. Secondly, the turbine efficiency given by turbochargers manufacturers is the product of the isentropic efficiency and the turbocharger mechanical efficiency. This global efficiency is suitable for the calculation of the power transferred to the compressor. But the isentropic efficiency has to be determined to calculate the turbine outlet temperature, in parallel with heat transfers consideration. This implies to evaluate the mechanical efficiency. Most of the time, although experiments show this is not true, users make the hypothesis of a constant value. This assumption has a strong impact on the turbine outlet temperature and, as a consequence, on the modeled after treatment devices' light off. This article will present a study for characterization and modelling of turbocharger friction losses. First a specific experimental campaign is conducted on a test bench using a standard automotive turbocharger. To eliminate the influence of thermal transfers, an adiabatic measurement methodology was developed. A second test campaign is performed with a modified turbocharger. It is based on the moment of inertia. The influence of oil viscosity was tested by using three different oil grades. The influence of oil inlet temperature and pressure was also tested to characterize the friction power. Finally a synthesis is made and hints are given in the view to generate a 0D/1D turbocharger friction model.

Extension and Validation of a 1D Model Applied to the Analysis of a Water Injected Turbocharged Spark Ignited Engine at High Loads and over a WLTP Driving Cycle

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The technique of liquid Water Injection (WI) at the intake port of downsized boosted SI engines is a promising solution to improve the knock resistance at high loads. In this work, an existing 1D engine model has been extended to improve its ability to simulate the effects of the water injection on the flame propagation speed and knock onset. The new features of the 1D model include an improved treatment of the heat subtracted by the water evaporation, a newly developed correlation for the laminar flame speed, explicitly considering the amount of water in the unburned mixture, and a more detailed kinetic mechanism to predict the auto-ignition characteristics of fuel/air/water mixture. The extended 1D model is validated against experimental data collected at different engine speeds and loads, including knock-limited operation, for a twin-cylinder turbocharged SI engine. The model predictions are compared with the experimental data, in terms of in-cylinder pressure cycle, burn rate profile and knock propensity. The numerical model correctly reproduces the experimental findings of fuel consumption, turbine inlet temperature and in-cylinder peak pressure. The combustion process, both with and without water addition, is predicted quite well, except for some inaccuracies in the early stage of combustion. Both experimental and numerical data confirm that the WI technology is able to improve significantly the fuel consumption of the tested engine under high-load knock-limited operation. Main drivers of the above advantages are a reduced over-fueling and a better combustion phasing. In a second stage, the validated model is used to build-up a complete engine operating map aimed at investigating the potential of WI technique to improve the fuel economy of a segment A vehicle. Engine maps with and without WI are introduced in a vehicle model to estimate the grams of CO2 per kilometer over a WLTP driving cycle. A reduced impact of WI is observed, since a knock-free operation occurs along most of the WLTP cycle. Nevertheless, some limited benefits can be still appreciated.

Numerical Study of the Potential of a Variable Compression Ratio Concept Applied to a Downsized Turbocharged VVA Spark Ignition Engine

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Nowadays different technical solutions have been proposed to improve the performance of internal combustion engines, especially in terms of Brake Specific Fuel Consumption (BSFC). Its reduction of course contributes to comply with the CO_2 emissions legislation for vehicle homologation. Concerning the spark ignition engines, the downsizing coupled to turbocharging demonstrated a proper effectiveness to improve the BSFC at part load. On the other hand, at high load, the above solution highly penalizes the fuel consumption mainly because of knock onset, that obliges to degrade the combustion phasing and/or enrich the air/fuel mixture. A promising technique to cope with the above drawbacks consists in the Variable Compression Ratio (VCR) concept. An optimal Compression Ratio (CR) selection, in fact, allows for further improvements of the thermodynamic efficiency at part load, while at high load, it permits to mitigate knock propensity, resulting in more optimized combustions. Of course, the VCR implementation involves increased costs and mechanical complexity, which can be only accepted if actual and relevant efficiency benefits are achieved. In this work, the potential advantages of VCR technique are numerically investigated with reference to a small turbocharged SI engine. First, a 1D model of the tested engine is implemented in GT-Power™ framework and is integrated with "in-house developed" sub-models for the description of in-cylinder phenomena. The engine model with the standard CR, selected by the manufacturer, is validated against the experimental data over the complete range of speed and load levels. In a second stage, an engine calibration strategy is proposed, aiming to automatically identify, for each operating point, the optimal spark timing, throttle valve opening, intake valve strategy, air-to-fuel ratio and turbocharger setting, complying with proper limitations on allowable levels of boost pressure, in-cylinder peak pressure, turbine inlet temperature, and knock intensity. This effort is hence considered to numerically reproduce the actual engine calibration process, resulting in a realistic prediction of the performance maps, at various CRs. The calibration strategy, allowing to select the CR realizing the minimum BSFC for each operating condition, also defines a complete map of the VCR engine. Fixed and variable CR strategies, with two or multiple CR stages, are finally compared in terms of CO_2 emission over a WLTP driving cycle, with reference to a segment A vehicle, denoting interesting advantages for VCR solution.

Wall Heat Transfer in a Multi-Link Extended Expansion SI-Engine

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The real cycle simulation is an important tool to predict the engine efficiency. To evaluate Extended Expansion SI-engines with a multi-link cranktrain, the challenge is to consider all concept specific effects as best as possible by using appropriate submodels. Due to the multi-link cranktrain, the choice of a suitable heat transfer model is of great importance since the cranktrain kinematics is changed. Therefore, the usage of the mean piston speed to calculate a heat-transfer-related velocity for heat transfer equations is not sufficient. The heat transfer equation according to Bargende combines for its calculation the actual piston speed with a simpli ed k-ε model. In this paper it is assessed, whether the Bargende model is valid for Extended Expansion engines. Therefore a single-cylinder engine is equipped with fast-response surface-thermocouples in the cylinder head. The surface heat flux is calculated by solving the unsteady heat conduction equation. By using a surface-ratio related weighting method, it is possible to determine a global wall heat loss from the local heat fluxes. The natural-gas test engine has a multi-link cranktrain to achieve, based on a compression ratio of 12.2, an expansion ratio of 17.6. The cranktrain is later modified by a mechanical adjustment in order to set the strokes to equal lengths, establishing a “conventional” engine process. This enables the comparison of experimentally determined heat transfer characteristics of two different engine processes from the same test engine. The comparison between the experimentally determined and the modeled heat flux at the conventional engine process shows a very good conformity. As well in the Extended Expansion mode, a good conformity of measured and modeled data is shown, so that the heat transfer model is also valid for this engine process. Subsequently, the difference in wall heat losses by Extended Expansion is analyzed using engine process simulation. Compared to a base engine with an equal intake stroke, the Extended Expansion engine has a higher wall heat loss.

Experimental and Computational Investigation of a Quarter-Wave Resonator on a Large-Bore Marine Dual-Fuel Engine

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Large pressure pulsations and a non-uniform distribution of charge air temperature along the intake manifold were detected on a large-bore marine Dual-Fuel engine. These two phenomena were found to impact negatively on the knock resistance of individual cylinders, when the engine is operated in gas-mode. As it happens with marine gas engines, the cylinder most prone to knocking drives the engine tuning for all the others, thus reducing the overall fuel conversion efficiency. In order to effectively tackle this issue, a comprehensive study was carried out, which included both experimental testing and fluid-dynamics simulation. A detailed GT-POWER 1D engine model was built, representing the laboratory 8L (i.e. inline eight-cylinder) engine configuration. The model was extensively correlated against measurements at different speeds and loads and it proved capable of closely reproducing both the pressure fluctuations and the temperature gradient along the intake manifold. Models for the other cylinder configurations (6L, 7L, 9L, 12V, 14V and 16V) were built scaling the validated 8L one. Linear acoustic analyses were then used to investigate the eigenvalues (natural frequencies) of the intake air path, for each engine variant. It was possible to infer that the second natural frequency of the intake volumes is to be considered as the main cause of the pressure fluctuations. The temperature gradient was on the other hand identified as a side-effect of the large pressure oscillations, as they increase locally the heat transfer coefficients between the charge air and the warm manifold walls. A quarter-wave resonator was designed, which was tuned on the resonance frequency to mitigate the pressure pulsations. For packaging reasons, it was decided to place the resonator inside the air receiver. As the resonator length was very close to the manifold's one in some cylinder configurations, a bent resonator pipe was proposed. Its shape, cross-section and dimensions were investigated in detail and optimized by means of 1D and 3D CFD analyses. Eventually, tests on the 8L laboratory engine, fitted with the quarter-wave resonator of choice, supported the simulation results: pressure pulsations decreased by 40% and, after engine re-tuning, brake efficiency increased by 0.3% (absolute) at the same knock-margin.

Estimating the CO_2 Emissions Reduction Potential of Various Technologies in European Trucks Using VECTO Simulator

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Heavy-duty vehicles (HDVs) account for some 5% of the EU's total greenhouse gas emissions. They present a variety of possible con gurations that are deployed depending on the intended use. This variety makes the quantification of their CO_2 emissions and fuel consumption difficult. For this reason, the European Commission has adopted a simulation-based approach for the certification of CO_2 emissions and fuel consumption of HDVs in Europe; the VECTO simulation software has been developed as the official tool for the purpose. The current study investigates the impact of various technologies on the CO_2 emissions of European trucks through vehicle simulations performed in VECTO. The chosen vehicles represent average 2015 vehicles and comprised of two rigid trucks (Class 2 and 4) and a tractor-trailer (Class 5), which were simulated under their reference configurations and official driving cycles. The effects of aerodynamics, auxiliary systems, curb-weight, tyre rolling resistance, engine internal losses, and engine and gearbox efficiency were investigated. Factors exhibited a varying reduction potential that depended on the vehicle category and the driving cycle. Results indicate where focus should be given for improving the energy performance of trucks in view of the Commission's future efforts to propose CO_2 reduction targets for HDVs.

The Sensitivity of Transient Response Prediction of a Turbocharged Diesel Engine to Turbine Map Extrapolation

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Mandated pollutant emission levels are shifting light-duty vehicles towards hybrid and electric powertrains. Heavy-duty applications, on the other hand, will continue to rely on internal combustion engines for the foreseeable future. Hence there remain clear environmental and economic reasons to further decrease IC engine emissions. Turbocharged diesels are the mainstay prime mover for heavy-duty vehicles and industrial machines, and transient performance is integral to maximizing productivity, while minimizing work cycle fuel consumption and CO2 emissions. 1D engine simulation tools are commonplace for "virtual" performance development, saving time and cost, and enabling product and emissions legislation cycles to be met. A known limitation however, is the predictive capability of the turbocharger turbine sub-model in these tools. One specific concern is accurate extrapolation of turbine performance beyond the narrow region populated by supplier-measured data to simulate non-steady conditions, be it either to capture pulsating exhaust flow or, as is the focus here, engine transient events. Extrapolation may be achieved mathematically or by using physics-based correlations, sometimes in combination. Often these extrapolation rules are the result of experience. Due to air system dynamic imbalance, engine transients force instantaneous turbine mass flow and pressure ratio into regions well away from the hot gas bench test data, necessitating great trust in the extrapolation routine. In this study, a 1D heavy-duty turbocharged diesel engine model was used to simulate four transient events, employing a series of performance maps representing the same turbine but with increasing levels of extrapolation, using commonly-adopted methodologies. The comparison was enabled by measuring real turbine performance on the dynamometer at Imperial College London. This testing generated a wide baseline dataset which was used to produce corresponding transient response predictions, and against which cases of increasing degrees of extrapolation could be compared. This paper studies the sensitivity of response time to the degree and technique of the extrapolation applied, demonstrating its importance for reliable transient engine simulations.

A Pre-Design Model to Estimate the Effect of Variable Inlet Guide Vanes on the Performance Map of a Centrifugal Compressor for Automotive Applications

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The onset of aerodynamic instabilities in proximity of the left margin of the operating curve represents one of the main limitations for centrifugal compressors in turbocharging applications. An anticipated stall/surge onset is indeed particularly detrimental at those high boost pressures that are typical of engine downsizing applications using a turbocharger. Several stabilization techniques have been investigated so far to increase the rangeability of the compressor without excessively reducing the efficiency. One of the most exploited solutions is represented by the use of upstream axial variable inlet guide vanes (VIGV) to impart a pre-whirl angle to the inlet ow. In the pre-design phase of a new stage or when selecting, for example, an existing unit from an industrial catalogue, it is however not easy to get a prompt estimation of the attended modifications induced by the VIGV on the performance map of the compressor. A simplified model to this end is presented in the study. Figuring out a typical industrial pre-design phase, the model assumes the availability of the original performance data of the compressor without pre-whirl and only very few geometrical parameters. Based on fluid dynamic considerations and some additional models and correlations, a procedure is defined to correct the attended stage pressure ratio and effiency as a function of the pre-whirl angle imposed by the VIGV. The model has been successfully validated using an experimental literature case study and is thought to represent a new useful preliminary tool for turbocharger designers.

Numerical Investigation on the Effects of Different Thermal Insulation Strategies for a Passenger Car Diesel Engine

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One of the key technologies for the improvement of the diesel engine thermal efficiency is the reduction of the engine heat transfer through the thermal insulation of the combustion chamber. This paper presents a numerical investigation on the effects of the combustion chamber insulation on the heat transfer, thermal efficiency and exhaust temperatures of a 1.6 l passenger car, turbo-charged diesel engine. First, the complete insulation of the engine components, like pistons, liner, redeck and valves, has been simulated. This analysis has showed that the piston is the component with the greatest potential for the in-cylinder heat transfer reduction and for Brake Specific Fuel Consumption (BSFC) reduction, followed by firedeck, liner and valves. Afterwards, the study has been focused on the impact of different piston Thermal Barrier Coatings (TBCs) on heat transfer, performance and wall temperatures. This analysis has been performed using a 1-D engine simulation code coupled with a lumped mass thermal model, representing the engine structure. A time-periodic wall conduction model has been used to calculate the wall temperature swings along the combustion chamber surface and within the engine cycle. Two different TBC materials, Yttria-Partially Stabilized Zirconia (Y-PSZ) and anodized aluminum, and different layer thicknesses have been simulated.

Development of a Spray-Based Phenomenological Soot Model for Diesel Engine Applications

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Diesel engine pollutant emissions legislation is becoming more and more stringent. New driving cycles, including increasingly severe transient engine operating conditions and low ambient-temperature conditions, extend considerably the engine operating domain to be optimized to attain the expected engine performance. Technological innovations, such as high pressure injection systems, Exhaust Gas Recirculation (EGR) loops and intake pressure boosting systems allow significant improvement of engine performance. Nevertheless, because of the high number of calibration parameters, combustion optimization becomes expensive in terms of resources. System simulation is a promising tool to perform virtual experiments and consequently to reduce costs, however models must account for relevant in-cylinder physics to be sensitive to the impact of technology on combustion and pollutant formation. In particular, soot is one of the major pollutants of Diesel engines and its kinetic is highly dependent on local mixture properties into the cylinder. This is a challenge for 0-Dimensional (0D) combustion approaches, as it implies 3-Dimensional (3D) phenomena. In this work, to tackle this aspect, the 0D Dual Flame Model (DFM) combustion model was enriched with quasi dimensional features based on the conceptual spray combustion model proposed by Sandia National Laboratories (SNL). This allows to identify local key phenomena depending on mixture thermochemical properties driving soot kinetics. The model was tested on a comprehensive experimental database generated at IFP Energies nouvelles (IFPEN), to investigate the capability of the new approach to predict the impact of engine operating conditions, injection strategy and dilution rate on soot emissions. The quality of the results and the reduced computational time make this approach suitable for engine design and control activities.

A Flow and Loading Coefficient-Based Compressor Map Interpolation Technique for Improved Accuracy of Turbocharged Engine Simulations

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Internal combustion engines are routinely developed using 1D engine simulation tools. A well-known limitation is the accuracy of the turbocharger compressor and turbine sub-models, which rely on hot gas bench-measured maps to characterize performance. Such discrete map data is inherently too sparse to be used directly in simulation, and so a preprocessing algorithm interpolates and extrapolates the data to generate a wider, more densely populated map. Methods used for compressor map interpolation vary. They may be mathematical or physical in nature, but there is no unified approach, except that they typically operate on input map data in SAE format. For decades it has been common practice for turbocharger suppliers to share performance data with engine OEMs in this form. This paper describes a compressor map interpolation technique based on the nondimensional compressor flow and loading coefficients, instead of SAE-format data. It compares the difference in compressor operating point prediction accuracy when using this method against the standard approach employing dimensional parameters. This is done by removing a speed line from a dataset, interpolating for the removed speed using the two methods, and comparing their accuracy to the original data. Three maps corresponding to compressor diameters of 54, 88, and 108 mm were evaluated. In some cases, the residual sum of squares between the interpolated and original data demonstrated an order of magnitude improvement when using the nondimensional coefficients. When evaluated in a simple engine model, this manifests as a slight shift in interpolated turbocharger speed, resulting in a difference in predicted compressor efficiency of up to 0.89 percentage points. This paper shows how the use of truly nondimensional interpolation techniques can improve the accuracy of processed turbocharger compressor maps, and consequently the value of 1D engine simulations as a reliable performance development tool, at virtually no additional effort or cost.

Numerical Analysis on the Potential of Different Variable Valve Actuation Strategies on a Light Duty Diesel Engine for Improving Exhaust System Warm Up

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The need for achieving a fast warm up of the exhaust system has raised in the recent years a growing interest in the adoption of Variable Valve Actuation (VVA) technology for automotive diesel engines. As a matter of fact, different measures can be adopted through VVA to accelerate the warm up of the exhaust system, such as using hot internal Exhaust Gas Recirculation (iEGR) to heat the intake charge, especially at part load, or adopting early Exhaust Valve Opening (eEVO) timing during the expansion stroke, so to increase the exhaust gas temperature during blowdown. In this paper a simulation study is presented evaluating the impact of VVA on the exhaust temperature of a modern light duty 4-cylinder diesel engine, 1.6 liters, equipped with a Variable Geometry Turbine (VGT). Numerical simulations were carried out by means of a commercially available 1D-CFD software (GT-SUITE) and a predictive combustion model (DIPulse) was adopted in order to properly evaluate the impact of different VVA strategies on the combustion process. The analysis was focused on the assessment of the potential of 3 different VVA strategies for managing the exhaust temperature: Early Exhaust Valve Opening (EEVO), obtained by means of valve lift modi cations, Exhaust Phasing, by changing the valve timing, and Exhaust Valve ReOpening (EVrO) during the intake stroke for iEGR. Moreover, for the EVrO strategy, two different EGR combinations (iEGR-only and low pressure EGR with iEGR, respectively) were evaluated to identify the best trade-off between the exhaust temperature increase and the Brake Speci c Fuel Consumption (BSFC) penalty. Thanks to the abovementioned VVA strategies, in steady state conditions increases in the exhaust temperature up to 70 K with BSFC penalties below 8% at low engine loads were achieved. Finally, the impact of VVA strategies was evaluated under transient conditions over the WLTC (Worldwide harmonized Light vehicles Test Cycle), highlighting a temperature increase of 30 K of the Diesel Oxidation Catalyst after the rst 300 s with a total fuel consumption penalty lower than 1%.

Digital Shaping and Optimization of Fuel Injection Pattern for a Common Rail Automotive Diesel Engine through Numerical Simulation

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Development trends in modern Common Rail Fuel Injection System (FIS) show dramatically increasing capabilities in terms of optimization of the fuel injection pattern through a constantly increasing number of injection events per engine cycle along with a modulation and shaping of the injection rate. In order to fully exploit the potential of the abovementioned fuel injection pattern optimization, numerical simulation can play a fundamental role by allowing the creation of a kind of a virtual injection rate generator for the assessment of the corresponding engine outputs in terms of combustion characteristics such as burn rate, emission formation and combustion noise (CN). This paper is focused on the analysis of the effects of digitalization of pilot events in the injection pattern on Brake Speci c Fuel Consumption (BSFC), CN and emissions for a EURO 6 passenger car 4-cylinder diesel engine. The numerical evaluation was performed considering steady-state conditions for 3 key points representative of typical operating conditions in the low-medium load range. The optimization process was carried out through numerical simulation, by means of a suitable target function aiming to minimize BSFC and CN while not exceeding the target NOx emissions level. By means of a previously developed fuel injection system model, possible different injection patterns with high number of pilot injections were evaluated thus obtaining a kind of virtual injection rate generator, the outcomes of which were then used as input for a DIPulse combustion model in order to predict BSFC, combustion noise and emissions. Through numerical optimization of pilot injection pattern digitalization, potential for achieving signi cant reductions in BSFC and CN for low load engine points while not exceeding the target NOx emissions level, was demonstrated.

Gas Exchange and Injection Modeling of an Advanced Natural Gas Engine for Heavy Duty Applications

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The scope of the work presented in this paper was to apply the latest open source CFD achievements to design a state of the art, direct- injection (DI), heavy-duty, natural gas-fueled engine. Within this context, an initial steady-state analysis of the in-cylinder ow was performed by simulating three different intake ducts geometries, each one with seven different valve lift values, chosen according to an estabilished methodology proposed by AVL. The discharge coef cient (C_d) and the Tumble Ratio (TR) were calculated in each case, and an optimal intake ports geometry con guration was assessed in terms of a compromise between the desired intensity of tumble in the chamber and the satisfaction of an adequate value of C_d. Subsequently, full-cycle, cold- flow simulations were performed for three different engine operating points, in order to evaluate the in-cylinder development of TR and turbulent kinetic energy (TKE) under transient conditions. The latest achievements in open source mesh generation and motions were applied, along with time-varying and case- tted inizialization values for the elds of intake pressure and temperature. Finally, direct-injection of natural gas in the cylinder was incorporated in full-cycle simulations, to evaluate the effects of injection on charge motions and charge homogeneity at the estimated spark timing. Three speci c engine operating points were simulated and different combinations of turbochargers and valve lift laws were tested. Results consistency was veri ed by means of validations with data from 1D simulations and literature.

Chemical Kinetics and Computational Fluid-Dynamics Analysis of $H_2/CO/CO_2/CH_4$ Syngas Combustion and NOx Formation in a Micro-Pilot-Ignited Supercharged Dual Fuel Engine

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A chemical kinetics and computational uid-dynamics (CFD) analysis was performed to evaluate the combustion of syngas derived from biomass and coke-oven solid feedstock in a micro-pilot ignited supercharged dual-fuel engine under lean conditions. For this analysis, a reduced syngas chemical kinetics mechanism was constructed and validated by comparing the ignition delay and laminar ame speed data with those obtained from experiments and other detail chemical kinetics mechanisms available in the literature. The reaction sensitivity analysis was conducted for ignition delay at elevated pressures in order to identify important chemical reactions that govern the combustion process. We have con rmed the statements of other authors that $HO_2+OH=H_2O+O_2$, $H_2O_2+M=OH+OH+M$ and $H_2O_2+H=H_2+HO_2$ reactions showed very high sensitivity during high-pressure ignition delay times and had considerable uncertainty. The chemical kinetics of NOx formation was analyzed for $H_2/CO/CO_2/CH_4$ syngas mixtures by using counter ow burner and premixed laminar ame speed reactor. The new mechanism showed a very good agreement with experimental measurements and accurately reproduced the effect of pressure, temperature and equivalence ratio on NOx formation. In order to identify the species important for NOx formation, a sensitivity analysis was conducted for pressures 4 bar, 10 bar and 16 bar and preheat temperature 300 K. The results show that the NOx formation is driven mostly by hydrogen based species while other species, such as N_2, CO_2 and CH_4, have also important effects on combustion. Finally, the new mechanism was used in a multidimensional CFD simulation to predict the combustion of syngas in a micro-pilot- ignited supercharged dual-fuel engine and results were compared with experiments. The mechanism showed the closest prediction of the in-cylinder pressure and the rate of heat release (ROHR).

Large-Eddy Simulations of a Speed Transient Performed on a Motored Gasoline Engine

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This study presents a preliminary application of Large-Eddy Simulations (LES) of a speed transient performed on a motored single-cylinder engine. The numerical setup follows a methodology which has been validated and optimized for stabilized operating points in previous work, and adapted to run a speed transient of 31 cycles, from 1000 to 1800 rpm. Analysis of the results contributes to characterize the impact of the transient on the engine charge, tumble motion and velocity distribution. These simulations, which have never been performed in the past (to the best of our knowledge), represent a decisive step towards modeling and understanding transient in GDI engines, and particularly their impact on soot particle emissions in real driving conditions.

Experimental Validation of Combustion Models for Diesel Engines Based on Tabulated Kinetics in a Wide Range of Operating Conditions

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Computational uid dynamics represents a useful tool to support the design and development of Heavy Duty Engines, making possible to test the e ects of injection strategies and combustion chamber design for a wide range of operating conditions. Predictive models are required to ensure accurate estimations of heat release and the main pollutant emissions within a limited amount of time. For this reason, both detailed chemistry and turbulence chemistry interaction need to be included. In this work, the authors intend to apply combustion models based on tabulated kinetics for the prediction of Diesel combustion in Heavy Duty Engines. Four di erent approaches were considered: well-mixed model, presumed PDF, representative interactive amelets and amelet progress variable. Tabulated kinetics was also used for the estimation of NO_x emissions. The proposed numerical methodology was implemented into the Lib-ICE code, based on the OpenFOAM®technology, and validated against experimental data from a light-duty FPT engine. Ten points were considered at di erent loads and speeds where the engine operates under both conventional Diesel combustion and PCCI mode. A detailed comparison between computed and experimental data was performed in terms of in-cylinder pressure and NO_x emissions.

A Zonal-LES Study of Steady and Reciprocating Engine-Like Flows Using a Modified Two-Equation DES Turbulence Model

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A two-equation Zonal-DES (ZDES) approach has been recently proposed by the authors as a suitable hybrid URANS/LES turbulence modeling alternative for Internal Combustion Engine ows. This approach is conceptually simple, as it is all based on a single URANS- like framework and the user is only required to explicitly mark which parts of the domain will be simulated in URANS, DES or LES mode. The ZDES rationale was initially developed for external aerodynamics applications, where the flow is statistically steady and the transition between zones of di erent types usually happens in the URANS-to-DES or URANS-to-LES direction. The same “one-way” transition process has been found to be fairly e cient also in steady-state internal ows with engine-like characteristics, such as abrupt expansions or intake ports with xed valve position. However, assuming that a pure LES treatment is applied on the in-cylinder region, the reciprocating nature of a real engine ow implies a “two-way” URANS-LES-URANS transition during the engine cycle. In the present work, we further validate the Zonal-LES mode (i. e. with only pure URANS and pure LES zones) of our simulation methodology on a xed intake port case and, moreover, we study its behavior in a standard moving piston reference ow. Simulations are all carried out by means of the open source CFD toolbox OpenFOAM® and results are compared against both experimental measurements and computational studies from other authors.

Influence of Nozzle Eccentricity on Spray Structures in Marine Diesel Sprays

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Large two-stroke marine Diesel engines have special injector geometries, which di er substantially from the con gurations used in most other Diesel engine applications. One of the major di erences is that injector ori ces are distributed in a highly non-symmetric fashion affecting the spray characteristics. Earlier investigations demonstrated the dependency of the spray morphology on the location of the spray orifice and therefore on the resulting ow conditions at the nozzle tip. Thus, spray structure is directly in uenced by the flow formation within the orifice. Following recent Large Eddy Simulation resolved spray primary breakup studies, the present paper focuses on spray secondary breakup modelling of asymmetric spray structures in Euler-Lagrangian framework based on previously obtained droplet distributions of primary breakup. Firstly, the derived droplet distributions were assigned via user coding to RANS 3D-CFD simulation of nozzle bore geometries having 0.0, 0.4 and 0.8 normalized eccentricities. Spray secondary breakup then calculated by using the KH-RT breakup model. The simulations compared to a widely used industrial methodology and validated against experimental measurements performed in a unique Spray Combustion Chamber. Furthermore, e ects of nozzle eccentricity were assessed under non-reactive and reactive conditions using a computationally e cient combustion solver. The methodology was found to be promising for future implementation of droplet mapping techniques under marine diesel engine conditions.

Evaluation of Wall Heat Flux Models for Full Cycle CFD Simulation of Internal Combustion Engines under Motoring Operation

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The present work details a study of the heat ux through the walls of an internal combustion engine. The determination of this heat ux is an important aspect in engine optimization, as it in uences the power, e ciency and the emissions of the engine. Therefore, a set of simulation tools in the OpenFOAM® software has been developed, that allows the calculation of the heat transfer through engine walls for ICEs. Normal practice in these types of engine simulations is to apply a wall function model to calculate the heat ux, rather than resolving the complete thermo-viscous boundary layer, and perform simulations of the closed engine cycle. When dealing with a complex engine, this methodology will reduce the overall computational cost. It however increases the need to rely on assumptions on both the initial ow eld and the behavior in the near-wall region. As the engine studied in the present work, a Cooperative Fuel Research (CFR) engine, is a simple single cylinder pancake engine, it was possible to implement more complex and numerically demanding methodologies, while still maintaining an acceptable computation time. Both closed and full cycle simulations were therefore performed, for which the heat ux was calculated by both implementing various wall function models and by resolving the complete thermo-viscous boundary layer. The results obtained from the di erent kind of simulations were then compared to experimental heat ux data, which was measured using a thermopile type heat ux sensor in di erent locations in the CFR engine. By comparing the results from the di erent types of simulations, a performance evaluation of the used methodology could be carried out. It was found that the heat ux obtained by resolving the thermo-viscous layer was accurate compared to experiments, while the wall functions were not able to correctly capture the heat ux. Full cycle simulations resulted in a slightly improved result, especially when resolving the boundary layer, but due to the increased computational cost, this method does not seem bene cial.

Effect of EGR on Performance and Emission Characteristics of a GDI Engine - A CFD Study

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Future stringent emission norms are impelling researchers to look for new emission control techniques. Today, gasoline direct injection (GDI) engines are becoming more popular because of high potential to reduce exhaust emissions over a wide operating load range, unlike conventional port fuel injection (PFI) engines. Also, turbocharged GDI engines allow engine downsizing with a certain restriction on compression ratio (CR) due to knocking tendency, thereby limiting the fuel economy. However, use of exhaust gas recirculation (EGR) delays combustion and lowers the knocking tendency which will aid in improving the fuel economy. Therefore, this study is aimed to evaluate the e ect of EGR rate on the performance and emission characteristics of a two-liter turbocharged four-stroke GDI engine by computational uid dynamics (CFD) analysis. For the analysis, the CR of 9.3 and the engine speed of 1000 rev/min., are selected. The engine is operated at full-load conditions in the stoichiometric homogeneous mixture mode. The full cycle CFD simulations are carried out using the CONVERGE. The CFD results are validated by the available experimental data from the literature. The quantity of cooled EGR is varied from 0 to 15% to evaluate its e ect on combustion, performance and emission characteristics of the engine. The results showed that the engine indicated mean e ective pressure (IMEP) is increased by about 2% and the indicated thermal e ciency is increased by about 2.3% at 5% EGR rate as compared to that of no EGR. It is also found that heat release rate decreased with increase in EGR rate. The mean in-cylinder temperature decreased with increase in the EGR rate reducing NOx emissions.

Assessment of Port Water Injection Strategies to Control Knock in a GDI Engine through Multi-Cycle CFD Simulations

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Water injection in highly boosted gasoline direct injection (GDI) engines has become an attractive area over the last few years as a way of increasing e ciency, enhancing performance and reducing emissions. The technology and its e ects are not new, but current gasoline engine trends for passenger vehicles have several motivations for adopting this technology today. Water injection enables higher compression ratios, optimal spark timing and elimination of fuel enrichment at high load, and possibly replacement of EGR. Physically, water reduces charge temperature by evaporation, dilutes combustion, and varies the specific heat ratio of the working uid, with complex e ects. Several of these mutually intertwined aspects are investigated in this paper through computational uid dynamics (CFD) simulations, focusing on a turbo-charged GDI engine with port water injection (PWI). Di erent strategies for water injection timing, pressure and spray targeting are investigated. Two combustion modeling approaches are used and compared, the perfectly stirred reactor model with reduced chemical kinetics for a TPRF surrogate, and the G-equation turbulent combustion model. Combustion rate results are validated against available experimental engine data, in regular and knocking conditions. Multi-cycle simulations are required because of the wall lm dynamics, and therefore have been performed to assess the effect of water injection strategies. The results of the study are an assessment of the optimal injection parameters, in terms of injector location, injection timing and primary atomization quality, for achieving the maximum e ectiveness of water injection. Knock occurrences are in very good agreement with the experimental data and its suppression is demonstrated through the injection of water at a ratio of 30% to the fuel mass.

A Chemical-Kinetic Approach to the Definition of the Laminar Flame Speed for the Simulation of the Combustion of Spark-Ignition Engines

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The laminar burning speed is an important intrinsic property of an air-fuel mixture determining key combustion characteristics such as turbulent ame propagation. It is a function of the mixture composition (mixture fraction and residual gas mass fraction) and of the thermodynamic conditions. Experimental measurements of Laminar Flame Speeds (LFS) are common in literature, but initial pressure and temperature are limited to low values due to the test conditions: typical pressure values for LFS detection are lower than 25 bar, and temperature rarely exceeds 550 K. Actual trends in spark ignition engines are to increase speci c power output by downsizing and supercharging, thus the ame front involves even more higher pressure and temperature since the beginning of combustion. The most widespread models used to extrapolate the experimental data to the engine like conditions are derived from that of Metghalchi and Keck, but they often fail to correctly predict LFS values outside the experimental space. Thanks to the development of accurate chemical kinetic models together with the increase of computer performance, it is possible to numerically predict the laminar ame speed over a wide range of conditions for a range of fuel mixtures, so to overcome some of the limitations of the Metghalchi and Keck model. The aim of the present work is to evaluate the e ectiveness of an exploitable open source chemical solver (Cantera) for the evaluation of laminar ame speed. Results are compared against experimental data available in scienti c literature and a review of the main analytical correlation for LFS is accomplished. Finally, a new correlation is proposed to better t the numerical results in the high pressure and temperature range of the real engine design space.

Effect of Mixture Distribution on Combustion and Emission Characteristics in a GDI Engine - A CFD Analysis

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Mixture distribution in the combustion chamber of gasoline direct injection (GDI) engines significantly affects combustion, performance and emission characteristics. The mixture distribution in the engine cylinder, in turn, depends on many parameters viz., fuel injector hole diameter and orientation, fuel injection pressure, the start of fuel injection, in-cylinder uid dynamics etc. In these engines, the mixture distribution is broadly classified as homogeneous and stratified. However, with currently available engine parameters, it is dificult to objectively classify the type of mixture distribution. In this study, an attempt is made to objectively classify the mixture distribution in GDI engines using a parameter called the "strati cation index". The analysis is carried out on a four-stroke wall-guided GDI engine using computational uid dynamics (CFD). All CFD sub-models used, in this study, are validated with the available experimental and CFD results from the literature before carrying out the analysis. Three types of mixture distributions viz., ideally homogeneous, ideally stratified and mal-distributed mixtures are de ned and their e ect on combustion, performance and emission characteristics of the engine are analyzed. Further, the e ect of fuel injector orientation on the mixture distribution in the combustion chamber is analyzed for three di erent orientations of the fuel injector viz., -15, 0 and 15° with the vertical. From the results, it is found that the early fuel injection doesn't produce an ideally homogeneous mixture. Also, among the cases of the strati ed mixtures, it is found that, the fuel injector orientation of 15° results in a mixture that is closer to the ideally strati ed one. This is characterized by the value of strati cation index that is close to 1.

Sensitivity of Flamelet Combustion Model to Flame Curvature for IC Engine Application

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Engines with reduced emissions and improved e ciency are of high interest for road transport. However, achieving these two goals is challenging and various concepts such as PFI/DI/HCCI/PCCI are explored by engine manufacturers. The computational uid dynamics is becoming an integral part of modern engine development programme because this method provides access to in-cylinder ow and thermo-chemical processes to develop a closer understanding to tailor tumble and swirling motions to construct green engines. The combustion modelling, its accuracy and robustness play a vital role in this. Out of many modelling methods proposed in the past flamelet based methods are quite attractive for SI engine application. In this study, FlaRe (Flamelets revised for physical consistencies) approach is used to simulate premixed combustion inside a gasoline PFI single-cylinder, four-stroke SI engine. This approach includes a parameter representing the e ects of ame curvature on the burning rate. Since the reactant temperature and pressure inside the cylinder are continually varying with time, the mutual in uence of ame curvature and thermo-chemical activities may be stronger in IC engines and thus this parameter may not be constant. The sensitivity of engine simulation results to this parameter is investigated for a range of engine speed and load conditions. The results indicate some sensitivity and so a careful calibration may be required for URANS calculation which can be avoided using dynamic evaluations for LES.

Development of a Reduced Chemical Mechanism for Combustion of Gasoline-Biofuels

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Bio-derived fuels are drawing more and more attention in the internal combustion engine (ICE) research eld in recent years. Those interests in use of renewable biofuels in ICE applications derive from energy security issues and, more importantly, from environment pollutant emissions concerns. High delity numerical study of engine combustion requires advanced computational uid dynamics (CFD) to be coupled with detailed chemical kinetic models. This task becomes extremely challenging if real fuels are taken into account, as they include a mixture of hundreds of di erent hydrocarbons, which prohibitively increases computational cost. Therefore, along with employing surrogate fuel models, reduction of detailed kinetic models for multidimensional engine applications is preferred. In the present work, a reduced mechanism was developed for primary reference fuel (PRF) using the directed relation graph (DRG) approach. The mechanism was generated from an existing detailed mechanism. The adjustment of reaction rate constants of selected reactions was performed and the present reduced mechanism was validated against experiments in terms of ignition delay times, ame speed and HCCI combustion. Employing similar procedures, reduced reaction mechanisms for ethanol and butanol were generated and incorporated into the PRF mechanism to be able to model multi- component gasoline-primary alcohols combustion. The results show that the present reduced mechanism demonstrates reliable performance in combustion predictions, as well as signi cant improvement of computational e ciency in multi-dimensional CFD simulations.

Investigation of Sub-Grid Model Effect on the Accuracy of In-Cylinder LES of the TCC Engine under Motored Conditions

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The increasing interest in the application of Large Eddy Simulation (LES) to Internal Combustion Engines (hereafter ICEs) ows is motivated by its capability to capture spatial and temporal evolution of turbulent ow structures. Furthermore, LES is universally recognized as capable of simulating highly unsteady and random phenomena driving cycle-to-cycle variability (CCV) and cycle- resolved events such as knock and mis re. Several quality criteria were proposed in the recent past to estimate LES uncertainty: however, de nitive conclusions on LES quality criteria for ICEs are still far to be found. This paper describes the application of LES quality criteria to the TCC-III single-cylinder optical engine from University of Michigan and GM Global R&D; the analyses are carried out under motored condition. In particular, attention is focused on sub-grid scale (SGS) model e ects, which are evaluated using single grid estimators to compare three di erent sub- lter models: static Smagorinsky, dynamic Smagorinsky and dynamic structure model. Information on LES quality criteria are cross-linked to the analysis of in-cylinder gas-dynamics and ow structures. These are in turn analyzed by comparing experimental results (Particle Image Velocimetry (PIV) velocity elds) with a dataset of consecutive LES cycles on four di erent cutting planes at engine-relevant crank angle positions. Finally, phase-dependent Proper Orthogonal Decomposition is used to draw further considerations on the connection between LES quality indices and the accuracy of simulation results and conclusions are drawn to be used as guidelines in future LES analyses of ICEs.

A 3D CFD Simulation of GDI Sprays Accounting for Heat Transfer Effects on Wallfilm Formation

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During gasoline direct injection (GDI) in spark ignition engines, droplets may hit piston or liner surfaces and be rebounded or deposit in the liquid phase as wall lm. This may determine slower secondary atomization and local enrichments of the mixture, hence be the reason of increased unburned hydrocarbons and particulate matter emissions at the exhaust. Complex phenomena indeed characterize the in-cylinder turbulent multi-phase system, where heat transfer involves the gaseous mixture (made of air and gasoline vapor), the liquid phase (droplets not yet evaporated and wall lm) and the solid walls. A reliable 3D CFD modelling of the in-cylinder processes, therefore, necessarily requires also the correct simulation of the cooling e ect due to the subtraction of the latent heat of vaporization of gasoline needed for secondary evaporation in the zone where droplets hit the wall. The related conductive heat transfer within the solid is to be taken into account. In this work, a preliminarily validated spray model is speci cally implemented by solving the strongly coupled heat and mass transfer problem describing the liquid and vapor phases thermo- uidynamics after impact and the wall change of temperature. The discussion is made considering a di erent boundary condition with respect to standard simulations. Sprays are assumed from to di erent injectors in order to verify the wallfilm simulation model: the impact over heated walls of the ECN "Spray G" is first discussed, by comparing numerical results with experimental measurements deriving from a combined use of the schlieren and Mie-scattering techniques, then the footprint on the wall of the spray delivered from a 6-hole Bosch injector is related with infrared thermography and LIF measurements taken from the literature.

Experimental Investigation of an In-Cylinder Sampling Technique for the Evaluation of the Residual Gas Fraction

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Residual gas plays a crucial role in the combustion process of SI engines. It acts as a diluent and has a huge impact on pollutant emissions (NOx and CO emissions), engine e ciency and tendency to knock. Therefore, characterizing the residual gas fraction is an essential task for engine modelling and calibration purposes. Thus, an in-cylinder sampling technique has been developed on a spark ignition VVT engine to measure residual gas fraction. Two gas sampling valves were ush mounted to the combustion chamber walls; they are located between the 2 intake valves and between intake and exhaust valves respectively. In-cylinder gas was sampled during the compression stroke and stored in a sampling bag using a vacuum pump. The process was repeated during a large number of engine cycles in order to get a su cient volume of gas which was then characterized with a standard gas analyzer. This paper describes in details the sampling technique and proposes a methodology allowing the evaluation of the residual gas fraction. For this purpose, ve kinds of tests were undertaken. First, tests were achieved to reach di erent volumes of gas in the sampling bag in order to study gas analyzer response and establish the minimum volume required. The system uncertainty and the engine repeatability were tested to determine the maximum sampling error. Then, a short sampling interval was tested throughout the compression stroke using the rst sampling valve to identify the temporal disparity in the chamber and determine the maximum permissible crank angle interval for a stable measurement. Several samplings were then performed for di erent engine operating points to compare the results obtained with the two sampling valves and study spatial inhomogeneity. Results were compared to mis ring samples from the end of the expansion stroke. An accurate and rather simple estimation of the residual fraction was then provided.

Generation of Turbulence in a RCEM towards Engine Relevant Conditions for Premixed Combustion Based on CFD and PIV Investigations

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The interaction of turbulent premixed methane combustion with the surrounding ow eld can be studied using optically accessible test rigs such as a rapid compression expansion machine (RCEM). The high exibility o ered by such a test rig allows its operation at various thermochemical conditions at ignition. However, limitations inherent to such test rigs due to the absence of an intake stroke do not allow turbulence production as found in IC-engines. Hence, means to introduce turbulence need to be implemented and the relevant turbulence quantities have to be identified in order to enable comparability with engine relevant conditions. A dedicated high-pressure direct injection of air at the beginning of the compression phase is considered as a measure to generate adjustable turbulence intensities at spark timing and during the early ame propagation. Based on former engine measurements and corresponding CFD simulations, the regime of relevant operating conditions in terms of velocity and length scale ratios in the Borghi diagram was derived for the RCEM. The main goal of this study is A) to characterize experimentally the flow field evolution for the optically accessible part of the domain in the spark plug vicinity to assess if the target conditions can be reached, and, B) support interpretation of the experimental data by means of CFD calculations which provide insights w.r.t. the flow field evolution also in the non-observable regions. To this end, the underexpanded jet of the angled single-orifice air injector used for the secondary air injection was experimentally and numerically assessed rst in a constant volume setup and thereafter under transient conditions (moving piston). Schlieren imaging of the Mach disc location and time-resolved Particle Image Velocimetry (PIV) measurements around the spark plug were conducted to deduce the characteristics of the injection and the resulting tumbling air motion respectively. The numerical ndings suggest that the underexpanded jet rst impinges on the piston and then interacts also with the cylinder liner leading to the formation of a tumbling motion which is subsequently compressed due to

piston motion. Reasonable agreement with the experiment is reported at the end of this process chain for the observable part of the domain. It has been shown that the use of an underexpanded secondary air injection in the RCEM allows for reproduction of the desired velocity and length scale ratios representative of the engine under consideration.

Development of a Research-Oriented Cylinder Head with Modular Injector Mounting and Access for Multiple In-Cylinder Diagnostics

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Alternative fuel injection systems and advanced in-cylinder diagnostics are two important tools for engine development; however, the rapid and simultaneous achievement of these goals is often limited by the space available in the cylinder head. Here, a research- oriented cylinder head is developed for use on a single cylinder 2-litre engine, and permits three simultaneous in-cylinder combustion diagnostic tools (cylinder pressure measurement, infrared absorption, and 2-color pyrometry). In addition, a modular injector mounting system enables the use of a variety of direct fuel injectors for both gaseous and liquid fuels. The purpose of this research-oriented cylinder head is to improve the connection between thermodynamic and optical engine studies for a wide variety of combustion strategies by facilitating the application of multiple in-cylinder diagnostics. The cylinder head design was derived from the original production cylinder head used on this engine, which was sectioned and laser scanned to create a parametric model. This model was used as the basis for the design and analysis of the new cylinder head with provisions for a modular injector mounting scheme, multiple simultaneous diagnostics, and to reduce intake swirl for imaging purposes. Finite element analysis was used to evaluate the mechanical strength and computational uid dynamics was used to optimize coolant ow, and to minimize in-cylinder charge swirl. The cylinder head was cast in nodular iron, using a 3D-printed sand mold. The utility of the developed research engine head is demonstrated through simultaneous cylinder pressure, IR absorption, multi-color pyrometry, spatially-resolved OH*-chemiluminescence, and spatially- resolved natural luminosity measurements of pilot-ignited, non- premixed combustion of natural gas using Westport Fuel Systems' high-pressure direct injection (HPDI) injector. Equivalent operating conditions are compared for all-metal (thermodynamic) and optical (Bowditch piston) engine con gurations. This paper presents a low-investment, low-risk method for the development of research- oriented cylinder heads with multiple diagnostic accesses and exible injector mounting.

In-Cylinder Temperature Measurements Using Laser Induced Grating Spectroscopy and Two-Colour PLIF

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In-cylinder temperature measurements are vital for the validation of gasoline engine modelling and useful in their own right for explaining di erences in engine performance. The underlying chemical reactions in combustion are highly sensitive to temperature and affect emissions of both NOx and particulate matter. The two techniques described here are complementary, and can be used for insights into the quality of mixture preparation by measurement of the in-cylinder temperature distribution during the compression stroke. The in uence of fuel composition on in-cylinder mixture temperatures can also be resolved. Laser Induced Grating Spectroscopy (LIGS) provides point temperature measurements with a pressure dependent precision in the range 0.1 to 1.0 % when the gas composition is well characterized and homogeneous; as the pressure increases the precision improves. The well-established method of Two-Colour Planar Laser-Induced Fluorescence, TC-PLIF allows 2-D temperature distributions to be determined from measurement of uorescence signals at two di erent wavelengths. However, the challenge with PLIF is making the qualitative temperature measurements quantitative, so simultaneous LIGS measurements have been used for *in situ* calibration.

Optical Techniques that can be Applied to Investigate GDI Engine Combustion

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The increased e ciency and speci c output with Gasoline Direct Injection (GDI) engines are well known, but so too are the higher levels of Particulate Matter emissions compared with Port Fuel Injection (PFI) engines. To minimise Particulate Matter emissions, then it is necessary to understand and control the mixture preparation process, and important insights into GDI engine mixture preparation and combustion can be obtained from optical access engines. Such data is also crucial for validating models that predict ows, sprays and air fuel ratio distributions. The purpose of this paper is to review a number of optical techniques; the interpretation of the results is engine speci c so will not be covered here. Mie scattering can be used for semi-quantitative measurements of the fuel spray and this can be followed with Planar Laser Induced Fluorescence (PLIF) for determining the air fuel ratio and temperature distributions. With PLIF, very careful in-situ calibration is needed, and for temperature this can be provided by Laser Induced Thermal Grating Spectroscopy (LITGS). LITGS temperature measurements can also be used to quantify the di erences in evaporative cooling with di erent fuels, thereby explaining observed changes in the volumetric e ciency. Natural light photography can be used for tracking ame fronts, and with suitable calibration of the colour lter array in a high speed colour video camera, then soot pyrometry can be employed to estimate the temperature and soot loading. The rich information derived from optical techniques drives their proliferation in research.

Soot Characterization of Diesel/Gasoline Blends Injected through a Single Injection System in CI engines

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In the past few years' various studies have shown how the application of a highly premixed dual fuel combustion for CI engines leads a strong reduction for both pollutant emissions and fuel consumption. In particular a drastic soot and NOx reduction were achieved. In spite of the most common strategy for dual fueling has been represented by using two di erent injection systems, various authors are considering the advantages of using a single injection system to directly inject blends in the chamber. In this scenario, a characterization of the behavior of such dual-fuel blend spray became necessary, both in terms of inert and reactive ambient conditions. In this work, a light extinction imaging (LEI) has been performed in order to obtain two-dimensional soot distribution information within a spray ame of di erent diesel/gasoline commercial fuel blends. All the measurements were conducted in an optically accessible two-stroke engine equipped with a single-hole injector. According to previous research, operating conditions with three different flame soot amounts were investigated. Commercial gasoline and diesel fuels were employed in four di erent blending percentages. Thus, this work aims at evaluating and quantifying the soot emission variation according to the di erent composition of the blend and thermodynamic characteristics of ambient. As expected the soot amount increases with higher ambient gas temperature and lower injection pressure as well as with the Diesel proportion in the blend, and so with the reactivity of the injected fuel.

Boost Pressure Control in Transient Engine Load with Turbocharger Speed Sensing

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The new driving cycles require a greater focus on a wider engine operative area and especially in transient conditions where a proper air path control is a challenging task for emission and drivability. In order to achieve this goal, turbocharger speed measurement can give several bene ts during boost pressure transient and for over-speed prevention, allowing the adoption of a smaller turbocharger, that can further reduce turbo-lag, also enabling engine down-speeding. So far, the use of turbocharger speed sensor was considered expensive and rarely affordable in passenger car applications, while it is used on high performance engines with the aim of maximizing engine power and torque, mainly in steady state, eroding the safe-margin for turbocharger reliability. Thanks to the availability of a new cost e ective turbocharger speed technology, based on acoustic sensing, turbocharger speed measurement has become a ordably also for passengers car application. In this paper, a new model-based boost pressure control employing the speed measurement, is proposed. In particular, a cascade controller based on boost pressure, turbocharger speed and VGT position measurements has been developed. Furthermore, the open loop term and the speed target ltering have been calculated by means of a simpli ed physical model of the plant. The control has been designed and validated by means of a 1-D model of a small turbocharged Diesel engine for passenger cars. Moreover the achievable bene ts have been analyzed.

Surge Detection Using Knock Sensors in a Heavy Duty Diesel Engine

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Improving turbocharger performance to increase engine e ciency has the potential to help meet current and upcoming exhaust legislation. One limiting factor is compressor surge, an air ow instability phenomenon capable of causing severe vibration and noise. To avoid surge, the turbocharger is operated with a safety margin (surge margin) which, as well as avoiding surge in steady state operation, unfortunately also lowers engine performance. This paper investigates the possibility of detecting compressor surge with a conventional engine knock sensor. It further recommends a surge detection algorithm based on their signals during transient engine operation. Three knock sensors were mounted on the turbocharger and placed along the axes of three dimensions of movement. The engine was operated in load steps starting from steady state. The steady state points of operation covered the vital parts of the engine speed and load range. The collected data was analysed with the objective of extracting information of a surging or non-surging compressor. In the charging system studied, the knock sensors detected a profound frequency peak between 5.0 Hz to 7.0 Hz. Another surge related frequency component of about 25 kHz was also observed, dependent on the turbocharger speed. Two surge detection algorithms were evaluated, one based on short time Fourier transform (STFT) and one based on the correlation integral (CI). These algorithms where then validated against temperature measurements at the compressor inlet and visual observation of oscillations of the air inlet piping. The surge detection algorithms were compared for accuracy and repeatability. The accuracy of the methods was found to be 73 % and 71 % respectively when compared to the temperature rise in the compressor inlet.

Real Time Prediction of Particle Sizing at the Exhaust of a Diesel Engine by Using a Neural Network Model

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In order to meet the increasingly strict emission regulations, several solutions for NOx and PM emissions reduction have been studied. Exhaust gas recirculation (EGR) technology has become one of the more used methods to accomplish the NOx emissions reduction. However, actual control strategies do not consider, in the definition of optimal EGR, its effect on particle size and density. These latter have a great importance both for the optimal functioning of after-treatment systems, but also for the adverse e ects that small particles have on human health. Epidemiological studies, in fact, highlighted that the toxicity of particulate particles increases as the particle size decreases. The aim of this paper is to present a Neural Network model able to provide real time information about the characteristics of exhaust particles emitted by a Diesel engine. In particular, the model acts as a *virtual sensor* able to estimate the concentration of particles with a specific aerodynamic diameter on the basis of some engine parameters such as engine speed, engine load and EGR ratio.

Investigation of Water Injection Effects on Combustion Characteristics of a GDI TC Engine

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This paper presents simulation and experimental results of the e ects of intake water injection on the main combustion parameters of a turbo-charged, direct injection spark ignition engine. Water injection is more and more considered as a viable technology to further increase specific output power of modern spark ignition engines, enabling extreme downsizing concepts and the associated effciency increase benefits. The paper initially presents the main results of a one-dimensional simulation analysis carried out to highlight the key parameters (injection position, water-to-fuel ratio and water temperature) and their effects on combustion (in-cylinder and exhaust temperature reduction and knock tendency suppression). The main results of such study have then been used to design and conduct preliminary experimental tests on a prototype direct-injection, turbocharged spark ignition engine, modified to incorporate a new multi-point water injection system in the intake runners. The experiments allowed to validate the model results, demonstrating the effectiveness of the proposed technology, and to further investigate on the mechanisms that allow controlling thermal load and knocking tendency by varying the water-to-fuel ratio.

A Correlation Methodology between AVL Mean Value Engine Model and Measurements with Concept Analysis of Mean Value Representation for Engine Transient Tests

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The use of state of the art simulation tools for effective front-loading of the calibration process is essential to support the additional efforts required by the new Real Driving Emission (RDE) legislation. The process needs a critical model validation where the correlation in dynamic conditions is used as a preliminary insight into the bounds of the representation domain of engine mean values. This paper focuses on the methodologies for correlating dynamic simulations with emissions data measured during dynamic vehicle operation (fundamental engine parameters and gaseous emissions) obtained using dedicated instrumentation on a diesel vehicle, with a particular attention for oxides of nitrogen NOx specie. This correlation is performed using simulated tests run within AVL's mean value engine and engine aftertreatment (EAS) model MoBEO (Model Based Engine Optimization). A conceptual analysis is dedicated to the intrinsic uncertainties of a mean value representation (measurements and simulations) with respect to an ideal high-resolution dynamic representation; this is carried out for two purposes: (i) to understand the intrinsic uncertainties of a mean value representation domain and (ii) to understand how to correlate at best the simulated value with the measurements during transient cycles, particularly when the fundamental parameters (e.g. emission mass ow rate, temperatures or the EGR rate calculated from CO2 measurements) depend on factors characterized by heterogeneous dynamics and di erent transport/ propagation times. Furthermore, elementary methods to compensate the time lag/delays and the sensors response time are discussed to obtain a proper correlation between measurements and simulations. Using these methods, the objective is to explain how the correlated engine values and the small differences between simulated and measured results can be sourced by specific dynamic phenomena and how they impact the final results. The analysis concludes with a global assessment of model to measurements correlation and with the expected level of confidence for the model based calibration process based on the achieved level of correlation.

A Model-Based Computer Aided Calibration Methodology Enhancing Accuracy, Time and Experimental Effort Savings Through Regression Techniques and Neural Networks

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In the last few years, the automotive industry had to face three main challenges: compliance with more severe pollutant emission limits, better engine performance in terms of torque and drivability and simultaneous demand for a significant reduction in fuel consumption. These conflicting goals have driven the evolution of automotive engines. In particular, the achievement of these mandatory aims, together with the increasingly stringent requirements for carbon dioxide reduction, led to the development of highly complex engine architectures needed to perform advanced operating strategies. Therefore, Variable Valve Actuation (VVA), Exhaust Gas Recirculation (EGR), Gasoline Direct Injection (GDI), turbocharging, powertrain hybridization and other solutions have gradually and widely been introduced into modern internal combustion engines, enhancing the possibilities of achieving the required goals. However, none of the improvements would have been possible without the contextual development of electronics. In fact, that solutions have highly increased the complexity of engine control and management because of the degrees of freedom available for the engine regulation, thus resulting in a long calibration time. In particular, base calibration is the most onerous phase of the engine control, both in terms of experimental and computational effort and costs. This paper addresses some critical issues concerning the calibration of control parameters through the use of a specific Model-Based Computer Aided Calibration algorithm developed by the authors to automate the calibration process and minimize calibration errors. The proposed methodology is also based on the use of neural networks (NN). In particular, starting from a reduced number of experimental data, NN provide a detailed engine data sheets used as input to the actual calibration process itself. The proposed algorithm provides optimal portability and reduced calibration time. The research also highlights how the developed methodology could be useful to identify possible enhancements for speci c ECU engine models that can improve the accuracy of

the calibration process by using more detailed physically based functions. The results of the proposed research clearly highlight how, in engine control, more accurate physical modeling may lead to promising results and better performance, ultimately enhancing the accuracy, time, experimental e ort and cost savings of the calibration process.

A Control-Oriented Knock Intensity Estimator

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The performance optimization of modern Spark Ignition engines is limited by knock occurrence: heavily downsized engines often are forced to work in the Knock-Limited Spark Advance (KLSA) range. Knock control systems monitor the combustion process, allowing to achieve a proper compromise between performance and reliability. Combustion monitoring is usually carried out by means of accelerometers or ion sensing systems, but recently the use of cylinder pressure sensors is also becoming frequent in motorsport applications. On the other hand, cylinder pressure signals are often available in the calibration stage, where SA feedback-control based on the pressure signal can be used to avoid damages to the engine during automatic calibration. A predictive real-time combustion model could help optimizing engine performance, without exceeding the allowed knock severity. Several knock models are available in the literature: most of those proposed for real-time applications are single zone or two-zone models, grounded on more complex CFD simulations. However, since the knock phenomenon is influenced by several factors, the real-time determination of KLSA requires the model to be adapted to the engine actual behavior. The approach proposed in the present paper, is based on the constant adaptation of a two-zone model to measured cylinder pressure data: typical results of the indicating analysis, available cycle-by-cycle and cylinder-by-cylinder, are used as inputs for the model, with the aim of predicting KLSA for the current running condition, without exceeding the maximum allowed knock intensity. The approach has been applied to indicating data referring to non-knocking, light and heavy knocking conditions, showing a good prediction capability.

Model-Based Control of BMEP and NOx Emissions in a Euro VI 3.0L Diesel Engine

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A model-based approach to control BMEP (Brake Mean E ective Pressure) and NOx emissions has been developed and assessed on a FPT F1C 3.0L Euro VI diesel engine for heavy-duty applications. The controller is based on a zero-dimensional real-time combustion model, which is capable of simulating the HRR (heat release rate), in-cylinder pressure, BMEP and NOx engine-out levels. The real-time combustion model has been realized by integrating and improving previously developed simulation tools. A new discretization scheme has been developed for the model equations, in order to reduce the accuracy loss when the computational step is increased. This has allowed the required computational time to be reduced to a great extent. The real-time combustion model has been first calibrated and assessed at both steady-state and transient conditions, on the basis of experimental data acquired at the highly dynamic test bench of ICEAL-PT (Internal Combustion Engines Advanced Laboratory - Politecnico di Torino), in the frame of a research activity in collaboration with FPT Industrial. The model has then been used to realize a model-based control of BMEP and NOx emissions. In particular, the controller provides the injected fuel quantity and the injection timing of the main pulse, for given targets of BMEP and engine-out NOx levels. Finally, the developed controller has been tested on a rapid prototyping device (ETAS ES910) through HiL (Hardware-in-the-Loop) techniques, and demonstrated to have real-time capability.

Engine Modeling and Controls

Engine Combustion

Fuels and Lubricants Technologies

Emissions and Emissions Controls

New Engines, Components, Actuators, & Sensors

Hybrid and Electric Powertrains, including Range Extending Engines

Highly Efficient Natural Gas Engines

Massimo Ferrera
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The 2020+ CO_2 and regulated noxious emission limits will impose drastic technological choices. Even though in 2030 65% of road transportation vehicles will be still powered by internal combustion engines, a progressive increase of hybrids and battery electric vehicles is expected. In parallel, the use of low-carbon alternative fuels, such as natural gas/ biomethane, will play a fundamental role in accelerating the process of de-carbonization of the transportation sector supporting the virtuous circular economy. Since the nineties FCA has invested in CNG (Compressed Natural Gas) powered vehicles becoming leader with one of the largest related product portfolios in Europe. A progressive improvement of this technology has been always pursued but, facing the next decades, a further improvement of the current CNG powertrain technology is mandatory to achieve even higher effciency and remove residual gaps versus conventional fuels. CNG direct injection technology will be a step forward because it can be easily applied on new generation spark ignited engines providing simultaneous benefits in terms of performance (gasoline-like) and engine efficiency (4-6%), particularly in combination with variable valve actuation, advanced boosting, high compression ratio and alternative combustion cycles. The paper shows a comprehensive overview of this technology evolution, focusing on a related large collaborative project named "GasOn" supported by the EU commission.

Investigation of Knock Damage Mechanisms on a GDI TC Engine

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The recent search for extremely efficient spark-ignition engines has implied a great increase of in-cylinder pressure and temperature levels, and knocking combustion mode has become one of the most relevant limiting factors. This paper reports the main results of a specific project carried out as part of a wider research activity, aimed at modelling and real-time controlling knock-induced damage on aluminum forged pistons. The paper shows how the main damage mechanisms (erosion, plastic deformation, surface roughness, hardness reduction) have been identified and isolated, and how the corresponding symptoms may be measured and quantified. The second part of the work then concentrates on understanding how knocking combustion characteristics affect the level of induced damage, and which parameters are mainly responsible for piston failure. For this purpose, steady-state tests have been conducted controlling different and constant levels of knock intensity (i.e., pressure waves oscillation amplitude) and thermal load (i.e., average temperature and pressure levels inside the combustion chamber). Since these parameters are strictly interrelated for a given engine operating condition and for a given fuel, fuels with di erent knock resistance (i.e., RON number) have been employed, to allow a clearer understanding of the damage distribution in the knock intensity-thermal load domain.

The Reduced Effectiveness of EGR to Mitigate Knock at High Loads in Boosted SI Engines

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Numerous studies have demonstrated that exhaust gas recirculation (EGR) can attenuate knock propensity in spark ignition (SI) engines at naturally aspirated or lightly boosted conditions [1]. In this study, we investigate the role of cooled EGR under higher load conditions with multiple fuel compositions, where highly retarded combustion phasing typical of modern SI engines was used. It was found that under these conditions, EGR attenuation of knock is greatly reduced, where EGR doesn't allow significant combustion phasing advance as it does under lighter load conditions. Detailed combustion analysis shows that when EGR is added, the polytropic coefficient increases causing the compressive pressure and temperature to increase. At sufficiently highly boosted conditions, the increase in polytropic coefficient and additional trapped mass from EGR can sufficiently reduce fuel ignition delay to overcome knock attenuation effects. Kinetic modeling demonstrates that the effectiveness of EGR to mitigate knock is highly dependent on the pressure-temperature condition. Experiments at 2000 rpm have confirmed reduced fuel ignition delay under highly boosted conditions relevant to modern downsized boosted SI engines, where in-cylinder pressure is higher and the temperature is cooler. At these conditions, charge reactivity increases compared to naturally aspirated conditions, and attenuation of knock by EGR is reduced.

Water Injection: a Technology to Improve Performance and Emissions of Downsized Turbocharged Spark Ignited Engines

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Knock occurrence and fuel enrichment, which is required at high engine speed and load to limit the turbine inlet temperature, are the major obstacles to further increase performance and effciency of down-sized turbocharged spark ignited engines. A technique that has the potential to overcome these restrictions is based on the injection of a precise amount of water within the mixture charge that can allow to achieve important bene ts on knock mitigation, engine efficiency, gaseous and noise emissions. One of the main objectives of this investigation is to demonstrate that water injection (WI) could be a reliable solution to advance the spark timing and make the engine run at leaner mixture ratios with strong benefits on knock tendency and important improvement on fuel efficiency. Experiments were carried out on a downsized port fuel injection (PFI) twin-cylinder turbocharged spark ignition engine equipped with a variable valve actuation (VVA) system over the speed range from 2500 to 4500rpm (step of 500 rpm) under a medium- high load condition. The engine was equipped with a prototype low-pressure injection system including two solenoid injectors installed in the runners, upstream of the gasoline ones, able to inject, at phased timing, a controlled amount of water within the intake ports. Experiments were carried out at wide open throttle (WOT) conditions choosing a water to gasoline mass ratio of 0.2, as a result of a previous investigation carried out to optimize the water amount in terms of engine performance. At the different engine speeds and at full gasoline operations, the relative air-fuel ratio (λ - measured by a lambda meter located in the exhaust, upstream of the three-way catalyst) was that set by the standard electronic control unit (ECU) map corresponding to the knock limited spark advance. As the WI was activated the amount of fuel was steadily reduced up to reach the stoichiometric condition and a sweep was performed up to the most advanced spark timing without knock occurrence.
In-cylinder pressure data, acquired by pressure sensors ush-mounted within the combustion chamber of both cylinders, allowed estimating the main combustion parameters such as the rate of heat release and the combustion phasing. The

effect of water injection on turbine inlet temperature and combustion effciency, estimated from the exhaust gaseous emissions (HC, CO, CO_2), are also presented. Further, combustion noise analysis carried out post-processing the in-cylinder pressure signal, decomposed into three sub-signals corresponding to the relevant physical phenomena: pseudo-motored operation (compression-expansion), combustion, and combustion chamber resonance. Such pressure signal decomposition was applied to find cause-effect relationships between the source signal generated by the engine during combustion process and both the objective and subjective parameters of the noise. The results coming from such analysis are discussed to determine the capability of water injection to reduce combustion noise level and improve sound quality index.

CFD Optimization of n-Butanol Mixture Preparation and Combustion in an Research GDI Engine

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The recent interest in alternative non-fossil fuels has led researchers to evaluate several alcohol-based formulations. However, one of the main requirements for innovative fuels is to be compatible with existing units' hardware, so that full replacement or smart exible- fuel strategies can be smoothly adopted. n-Butanol is considered as a promising candidate to replace commercial gasoline, given its ease of production from bio-mass and its main physical and chemical properties similar to those of Gasoline. The compared behavior of n-butanol and gasoline was analyzed in an optically-accessible DISI engine in a previous paper [1]. CFD simulations explained the main outcomes of the experimental campaign in terms of combustion behavior for two operating conditions. In particular, the first-order role of the slower evaporation rate of n-butanol compared to gasoline was highlighted when the two fuels were operated under the same injection phasing. The poor n-butanol/air mixture homogeneity was found to be a major limiting factor on the potential benefit of the use of n-butanol. This outcome is further deepened in this paper by numerically exploring different mixture preparation strategies for n-butanol. To this aim, variations of the injection phasing and profile are analyzed, including the use of multiple injection strategies. An optimized fuel injection strategy is then numerically identified considering mixture homogeneity, engine torque output and tailpipe emissions of soot and NOx. In order to confirm the validity of the CFD approach, this strategy is experimentally tested to finally draw conclusions on the potential of n-butanol in modern GDI units.

Simulation Research on the Combustion Characteristics of Lean-Burn Natural Gas Engine under Different Ignition Timings and Ignition Energies

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A CFD model of natural gas engine was established, and working process from intake stroke to combustion stroke was simulated in this paper. Based on the validation of CFD model through experimental method, the combustion characteristics of lean-burn natural gas engine are studied under different ignition timings and different ignition energies. Results indicate that, the in-cylinder indicated mean effective pressure increases with the ignition timing advancing from 22°CA BTDC to 32°CA BTDC at the same load level. Meanwhile, the heat release rate is increased by 23.18J/°CA and its peak phase is advanced by 9°CA. The peak pressure is also increased by 45.95% and its phase is advanced by 4.5°CA. On the other hand, when the ignition energy decreases from 91.97mJ to 33.1mJ at the same load level, the in-cylinder indicated mean effective pressure decreases. Moreover, the heat release rate is decreased by 15.18J/°CA and its peak phase is delayed by 6.5°CA, the peak pressure is decreased by 22.46% and its phase is delayed by 4.5°CA. The advancing ignition timing and increasing ignition energy enlarge the flame surface density and accelerate the burning rate at the same crank angle and lead to higher combustion intensity, so they are effective to shorten post-combustion period, and advantageous to improve the economy and dynamic performance of natural gas engine. However, due to faster combustion, the in-cylinder temperature raises, which results in slight increase of NO emission.

A Study on Charge Motion Requirements for a Class-Leading GTDI Engine

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An integral part of combustion system development for previous NA gasoline engines was the optimization of charge motion towards the best compromise in terms of full load performance, part load stability, emissions and, last but not least, fuel economy. This optimum balance may potentially be different in GTDI engines. While it is generally accepted that an increased charge motion level improves the mixture preparation in direct injection gasoline engines, the tradeoff in terms of performance seems to become less dominant as the boosting systems of modern engines are typically capable enough to compensate the flow losses generated by the more restrictive ports. Nevertheless, the increased boost level does not come free; increased charge motion generates higher pumping- and wall heat losses. Hence it is questionable and engine dependent, whether more charge motion is always better. Besides from the above mentioned tradeoff between pumping / wall heat losses and burn rate, emissions etc. another aspect is the optimum charge motion level for best knock performance at high load. A high charge motion level leads to a faster combustion and by that the knock critical end-gas areas are burned faster. On the other hand, the faster burn rate leads to increased pressure in the end-gas area which then reduces the self-ignition time of the unburnt mass. Hence the optimum charge motion level to suppress knock is a parameter which needs to be tuned carefully. To understand the influence of charge motion level on fuel consumption, stability, emissions, and performance, the very successful Ford 1.0l 3-cylinder gasoline Ecoboost® engine, which is available in many Ford vehicles worldwide, has been modi ed such that di erent tumble levels could be realized. Furthermore, the intake valvetrain system has been modified in a way that asynchronous valve opening timings for each of the two intake valves of the cylinders could be selected individually. By this measure, the intake event could be varied and a swirl flow is introduced. With the above mentioned engine hardware modifications, this study investigates the influence of charge motion on important combustion characteristics. To improve the understanding of the dyno-based results, 1D and 3D simulations have been conducted. The results obtained during this project will be discussed in depth in this paper. It is shown that an increased charge motion level improves dilution tolerance and burn

velocity but the associated increase in pumping and wall heat losses leads to a deterioration in fuel consumption. For full load operation the higher charge motion level leads to increased knocking. The overlay of swirl and tumble has a significant effect on mixture preparation and homogenization. In this case this combination of charge motion types leads to lean areas around the spark plug.

X-Ray Radiography Measurements of the Thermal Energy in Spark Ignition Plasma at Variable Ambient Conditions

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The sparking behavior in an internal combustion engine affects the fuel effciency, engine-out emissions, and general drivability of a vehicle. As emissions regulations become progressively stringent, combustion strategies, including exhaust gas recirculation (EGR), lean-burn, and turbocharging are receiving increasing attention as models of higher efficiency advanced combustion engines with reduced emissions levels. Because these new strategies affect the working environment of the spark plug, ongoing research strives to understand the influence of external factors on the spark ignition process. Due to the short time and length scales involved and the harsh environment, experimental quantification of the deposited energy from the sparking event is difficult to obtain. In this paper, we present the results of x-ray radiography measurements of spark ignition plasma generated by a conventional spark plug. These measurements were performed at the 7-BM beamline of the Advanced Photon Source at Argonne National Laboratory. The synchrotron x-ray source enables time-resolved measurements of the density change due to glow discharge in the spark gap with 153 ns temporal and 5 μm spatial resolutions. We explore the effects of charging time, EGR-relevant gas compositions, and gas pressure on the sparking behavior. We also quantify the influence of the measurement technique on the obtained results.

Performance Improvement and Emission Control of a Dual Fuel Operated Diesel Engine

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The present study deals with the simulation of a Diesel engine fuelled by natural gas/diesel in *dual fuel* mode to optimize the engine behaviour in terms of performance and emissions. In *dual fuel* mode, the natural gas is introduced into the engine's intake system. Near the end of the compression stroke, diesel fuel is injected and ignites, causing the natural gas to burn. The engine itself is virtually unaltered, but for the addition of a gas injection system. The CO_2 emissions are considerably reduced because of the lower carbon content of the fuel. Furthermore, potential advantages of dual-fuel engines include diesel-like efficiency and brake mean effective pressure with much lower emissions of oxides of nitrogen and particulate matter. In previous papers, the authors have presented some CFD results obtained by two 3D codes by varying the diesel/ NG ratio and the diesel pilot injection timing at different loads. The calculations have been referred to a light duty direct injection diesel engine, of which some experimental data were available, obtained both in full diesel and *Dual Fuel* operating conditions. These data have allowed to realize a fitting of the models. The phenomena involved in the cylinder are very complex and the numerical results obtained demonstrate a strong dependence on the boundary conditions imposed at the cylinder control system, provided by experimental data. Therefore, a comprehensive simulation of all engine should be necessary, by testing numerous operating conditions. In fact, the reduced experimental test cases available do not allow an overall view of the engine behaviour in the different operating conditions and cannot provide appreciable inlet conditions in cylinder for 3D combustion calculations. At the same time, the 3D results can de ne some inputs (turbulence, combustion law, etc.) for the one-dimensional simulation of the entire system fora preliminary calibration of some engine parameters. In particular, the calculations have been made by using an advanced 1D engine cycle simulation software enable to carry out performance simulations based on virtually any intake, combustion, exhaust system and turbocharger design, at different operating conditions, by varying large number of parameters. The code is based on one-dimensional ow through ducts and zero-dimensional in-cylinder calculation. Detailed modelling of individual components is included to specify the phenomena in the singular components.

Soot Oxidation in Periphery of Diesel Spray Flame via High-Speed Sampling and HR-TEM Observation

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In order to better understand in-flame diesel soot oxidation processes, soot particles at the oxidation-dominant periphery of diesel spray flame were sampled by a newly developed “suck” type soot sampler employing a high-speed solenoid valve and their morphology and nanostructure were observed via high-resolution transmission electron microscopy (HR-TEM). A single-shot diesel spray flame for the soot sampling experiment was achieved in a constant-volume vessel under a diesel-like condition. The sampler instantaneously sucks out a small portion of soot laden gases from the ame. A TEM grid holds inside the flow passage close to its entrance is immediately exposed to the gas flow induced by the suction at the upstream of the solenoid valve, so that the quick thermophoretic soot deposition onto the grid surface can effectively freeze morphology variation of soot particles during the sampling processes. The morphology of soot particles sampled by the novel suck sampler and a conventionally used “skim” sampler directly exposing a TEM grid to the flame was compared and did not show notable qualitative differences. The on-grid concentration of soot sampled by the suck sampler was lower than the ones by the skim sampler, while the repeatability of the sampled on-grid soot concentration was improved especially at downstream in-flame sampling locations. The HR-TEM observations of soot particles sampled from the oxidation-dominant periphery of diesel spray flame showed that the outer layers of the soot particles exhibit lumpy surfaces which is possibly due to stripping and disintegration of the layers by rapid oxidation and makes it difficult to identify boundaries of primary particles within the aggregates. High-resolution images of the whole aggregates produced by stitching of multiple HR-TEM images showed that these nano-structural features are only partially seen in the aggregates sampled from the core regions of diesel spray flame especially at the perimeters of the aggregates, while the aggregates sampled from the flame periphery mostly exhibits wholly collapsed outer layers.

Neural-Network Based Approach for Real-Time Control of BMEP and MFB50 in a Euro 6 Diesel Engine

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A real-time approach has been developed and assessed to control BMEP (brake mean effective pressure) and MFB50 (crank angle at which 50% of fuel mass has burnt) in a Euro 6 1.6L GM diesel engine. The approach is based on the use of feed-forward ANNs (artificial neural networks), which have been trained using virtual tests simulated by a previously developed low-throughput physical engine model. The latter is capable of predicting the heat release and the in-cylinder pressure, as well as the related metrics (MFB50, IMEP - indicated mean effective pressure) on the basis of an improved version of the accumulated fuel mass approach. BMEP is obtained from IMEP taking into account friction losses. The low-throughput physical model does not require high calibration effort and is also suitable for control-oriented applications. However, control tasks characterized by stricter demands in terms of computational time may require a modeling approach characterized by a further lower throughput. To this aim, feed-forward NNs have been trained to predict MFB50 and BMEP using a large dataset of virtual tests generated by the well-calibrated low-throughput physical engine model. The real-time approach has also been applied to derive the start of injection of the main pulse and the injected fuel quantity to achieve specific targets of MFB50 and BMEP. The accuracy of the real-time approach has been assessed based on experimental data taken at GM-GPS (General Motors - Global Propulsion Systems) facilities and its computational time has been compared to that of the low-throughput physical engine model, at steady-state and transient conditions over the WLTP cycle.

Spray and Combustion of Diesel Fuel under Simulated Cold- Start Conditions at Various Ambient Temperatures

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The spray and combustion of diesel fuel were investigated to provide a better understanding of the evaporation and combustion process under the simulated cold-start condition of a diesel engine. The experiment was conducted in a constant volume combustion chamber and the engine cranking period was selected as the target ambient condition. Mie scattering and shadowgraph techniques were used to visualize the liquid- and vapor-phase of the fuel under evaporating non-combustion conditions (oxygen concentration=0%). In-chamber pressure and direct flame visualization were acquired for spray combustion conditions (oxygen concentration=21%). The fuel was injected at an injection pressure of 30 MPa, which is the typical pressure during the cranking period. The liquid length of the fuel at an ambient temperature of 573 K increased by about 14% compared to that at 663 K due to the lower ambient temperature and fuel temperature as well as the increased fuel density and viscosity from the lower fuel temperature. The vapor penetration of the fuel was also slightly increased at 573 K. However, the vapor phase area was reduced by about 30% at 573 K compared to that at 663 K, which is due to the deteriorated spray atomization and the lower ambient temperature. In the spray combustion condition, only part of the diesel spray was ignited at 573 K, while all of the spray was successfully ignited at 663 K. The ignition delay was increased at 573 K due to the increased injection delay, the deteriorated atomization, and the evaporation of the fuel. The heat release from the premixed combustion was reduced at 573 K, despite the increased ignition delay. This can be explained by the limited formation of the combustible fuel-air mixture as indicated by a reduced vapor-phase area. The heat release from the mixing-controlled combustion was also reduced at 573 K, which resulted in lowering the in-chamber pressure rise by about 42% compared to 663 K.

Zero Dimensional Models for EGR Mass-Rate and EGR Unbalance Estimation in Diesel Engines

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A precise estimation of the recirculated exhaust gas rate and oxygen concentration as well as a predictive evaluation of the possible EGR unbalance among cylinders are of paramount importance, especially if non-conventional combustion modes, which require high EGR flow-rates, are implemented. In the present paper, starting from the equation related to convergent nozzles, the EGR mass flow-rate is modeled considering the pressure and the temperature upstream of the EGR control valve, as well as the pressure downstream of it. The restricted flow-area at the valve-seat passage and the discharge coeffcient are carefully assessed as functions of the valve lift. Other models were fitted using parameters describing the engine working conditions as inputs, following a semi-physical and a purely statistical approach. The resulting models are then applied to estimate EGR rates to both conventional and non-conventional combustion conditions. In a following step, a correlation was proposed between EGR rate and combustion metrics. This function was then applied to check the possibility of estimating the EGR unbalance, which can negatively affect combustion stability, in particular at high EGR rates. EGR unbalance was also evaluated considering the measurements of the temperature of the charge entering each cylinder. These two methods to evaluate EGR unbalance were then compared to CFD calculations.

N-Heptane Ignition Delay Time Model for Two Stage Combustion Process

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Ignition delay time is key to any hydrocarbon combustion process. In that sense, this parameter has to be known accurately, and especially for internal combustion engine applications. Combustion timing is one of the most important factors influencing overall engine performances like power output, combustion efficiency, emissions, in-cylinder peak pressure, etc. In the case of low temperature combustion (LTC) mode (e.g. HCCI mode), this parameter is controlled by chemical kinetics. In this paper, an ignition delay time model including 7 direct reactions and 13 species coupled with a temperature criterion is described. This mechanism has been obtained from the previous 26-step n-heptane reduced mechanism, focusing on the low temperature region which is the most important phase during the two stage combustion process. The complete model works with 7 reactions until the critical temperature is reached, leading to the detection of the ignition delay time value. The resulting ignition delay times obtained with the 7-step model have been compared to those of a calculation using a full kinetics of n-heptane developed by Lawrence Livermore National Laboratory. This comparison has pointed out that the model reproduces the ignition delay time with a good accuracy with differences smaller than 2 CAD.

Functional Requirements to Exceed the 100 kW/l Milestone for High Power Density Automotive Diesel Engines

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The paper describes the challenges and results achieved in developing a new high-speed Diesel combustion system capable of exceeding the imaginative threshold of 100 kW/l. High-performance, state-of-art prototype components from automotive diesel technology were provided in order to set-up a single-cylinder research engine demonstrator. Key design parameters were identified in terms boost, engine speed, fuel injection pressure and injector nozzle flow rates. In this regard, an advanced piezo injection system capable of 3000 bar of maximum injection pressure was selected, coupled to a robust base engine featuring ω-shaped combustion bowl and low swirl intake ports. The matching among the above-described elements has been thoroughly examined and experimentally parameterized. The tests confirmed the benefits of the employment of very high fuel injection pressures as a way to decouple the trade-off between an excellent power rating and emissions / NVH / CO_2 at part load, whose combination truly defines the leading edge of modern diesel engines for automotive application. The paper also discusses the system sensitivity to the boundary conditions, of the charging and exhaust systems, and develops a balanced set of targets for the entire system based on thermo-structural, fluid-dynamics and effciency considerations. This would represent, in the authors' view, the 'recipe' for the next generation of premium diesel engines for automotive application.

Analysis of a Prototype High-Pressure "Hollow Cone Spray" Diesel Injector Performance in Optical and Metal Research Engines

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Technologies for direct injection of fuel in compression ignition engines are in continuous development. One of the most investigated components of this system is the injector; in particular, main attention is given to the nozzle characteristics as hole diameter, number, internal shape, and opening angle. The reduction of nozzle hole diameter seems the simplest way to increase the average fuel velocity and to promote the atomization process. On the other hand, the number of holes must increase to keep the desired mass flow rate. On this basis, a new logic has been applied for the development of the next generation of injectors. The tendency to increase the nozzle number and to reduce the diameter has led to the replacement of the nozzle with a circular plate that moves vertically. The plate motion allows to obtain an annulus area for the delivery of the fuel on 360 degrees; while the plate lift permits to vary the atomization level of the spray. The experimental activities have been performed on a single-cylinder metal engine in order to evaluate the new injector concept functionality in typical engine working conditions. Then a deeper investigation of injector the characteristics has been performed in an optical single-cylinder diesel engine via high speed digital imaging in order to catch information on its operation. The results have shown a good response of the injector fuel delivery control but penalties in terms of emissions and effciency compared to multihole nozzles. Images of the injection process showed that the fuel assumed an asymmetric shape at the exit of the injector affecting the mixing quality and, then, the combustion effciency.

Comparing the Effect of Fuel/Air Interactions in a Modern High-Speed Light-Duty Diesel Engine

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Modern diesel cars, fitted with state-of-the-art aftertreatment systems, have the capability to emit extremely low levels of pollutant species at the tailpipe. However, diesel aftertreatment systems can represent a significant cost, packaging and maintenance requirement. Reducing engine-out emissions in order to reduce the scale of the aftertreatment system is therefore a high priority research topic. Engine-out emissions from diesel engines are, to a significant degree, dependent on the detail of fuel/air interactions that occur in-cylinder, both during the injection and combustion events and also due to the induced air motion in and around the bowl prior to injection. In this paper the effect of two different piston bowl shapes are investigated. Experiments are performed in a single-cylinder engine fitted with a production cylinder head and fuel injector in order to quantify the effect of the bowl shape and spray targeting-varied by varying the injector nozzle tip protrusion-on emissions and fuel consumption. Multi-dimensional CFD modelling is used to detail the effect of these geometry changes on the in-cylinder flow and fuel/air mixing processes thereby guiding the interpretation and understanding of the experimental results. The results suggest that improvements in engine-out emissions, as well as fuel consumption, may be obtained from current diesel engines by the careful matching of combustion system geometry with fuel injection hardware and strategy, and that an integrated approach with experimental and numerical studies working in parallel is essential to maximise these benefits.

A Kinetic Modelling Study of Alcohols Operating Regimes in a HCCI Engine

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Pursuing a sustainable energy scenario for transportation requires the blending of renewable oxygenated fuels such as alcohols into commercial hydrocarbon fuels. From a chemical kinetic perspective, this requires the accurate description of both hydrocarbon reference fuels (*n*-heptane, *iso*-octane, toluene, etc.) and oxygenated fuels chemistry. A recent systematic investigation of linear C_2-C_5 alcohols ignition in a rapid compression machine at p = 10-30 bar and T = 650-900 K has extended the scarcity of fundamental data at such conditions, allowing for a revision of the low temperature chemistry for alcohol fuels in the POLIMI mechanism. Heavier alcohols such as *n*-butanol and *n*-pentanol present ignition characteristic of interest for application in HCCI engines, due to the presence of the hydroxyl moiety reducing their low temperature reactivity compared to the parent linear alkanes (i.e. higher octane number). The promising performances of ethanol in a HCCI engine have been recently discussed by Bissoli et al. (*Energy & Fuels, 2017, Submitted*), observing wider stable operability conditions in terms of fuel/air load (λ) and exhaust gas recirculation (EGR) extent compared to PRF80 and PRF100. The aim of this study is to present briefly the reliability of the updated POLIMI mechanism for heavier alcohols and to investigate the fundamental role of chemical kinetics on the performance maps of HCCI engines fueled with *n*-butanol and *n*-pentanol, in terms of operability limits and engine effciency.

Compression Ignition of Light Naphtha and Its Multicomponent Surrogate under Partially Premixed Conditions

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Light naphtha is the light distillate from crude oil and can be used in compression ignition (CI) engines; its low boiling point and octane rating (RON = 64.5) enable adequate premixing. This study investigates the combustion characteristics of light naphtha (LN) and its multicomponent surrogate under various start of injection (SOI) conditions. LN and a five-component surrogate for LN, comprised of 43% n-pentane, 12% n-heptane, 10% 2-methylhexane, 25% iso- pentane and 10% cyclo-pentane, has been tested in a single cylinder optical diesel engine. The transition in combustion homogeneity from CI combustion to homogenized charge compression ignition (HCCI) combustion was then compared between LN and its surrogate. The engine experimental results showed good agreement in combustion phasing, ignition delay, start of combustion, in-cylinder pressure and rate of heat release between LN and its surrogate. The low temperature reaction (LTR) phase exhibited by LN and its surrogate were comparable, while ignition delay was prolonged as SOI is advanced from CI to HCCI combustion. Combustion images for LN and its surrogate were nearly similar, showing equal behaviour in both fuels. The level of stratification estimated from the intensity of the images was comparable between LN and its surrogate at various SOI. Stratification analysis showed stratified combustion, and the decay of stratification was slower under PPC conditions than under CI conditions. Emissions such as nitrogen oxide (NO_x), carbon monoxide (CO) and soot concentration were comparable for the real and surrogate fuels. Overall, this study demonstrates that the surrogate resembles its real fuel (LN) under the current set of engine test conditions.

Combustion Indexes for Innovative Combustion Control

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The continuous development of modern Internal Combustion Engine (ICE) management systems is mainly aimed at combustion control improvement. Nowadays, performing an effcient combustion control is crucial for drivability improvement, effciency increase and pollutant emissions reduction. These aspects are even more crucial when innovative combustions (such as LTC or RCCI) are performed, due to the high instability and the high sensitivity with respect to the injection parameters that are associated to this kind of combustion. Aging of all the components involved in the mixture preparation and combustion processes is another aspect particularly challenging, since not all the calibrations developed in the setup phase of a combustion control system may still be valid during engine life. The most important quantities used for combustion control are engine load (Indicated Mean Effective Pressure or Torque delivered by the engine) and center of combustion (CA50), i.e. the angular position in which 50% of fuel burned within the engine cycle is reached. All these quantities can be directly evaluated starting from in-cylinder pressure measurement; however, the use of in-cylinder pressure sensors would significantly increase the cost of the whole engine management system. Due to these reasons, over the past years, many methodologies have been developed by the authors of this paper in order to evaluate combustion characteristics using low-cost sensors or sensors that are already present on-board. The approaches considered in this paper are based on engine speed fluctuations and engine block vibration. These measurements are performed through the magnetic pick-up facing the toothed wheel already present on-board and a low-cost accelerometer mounted on engine block. Each of these measurements allows estimating a combustion characteristic that can be used for combustion control, such as IMEP, pressure peak position, CA50. The paper presents how the combination of the information that can be extracted from the low or zero cost sensors employed enables the control of innovative combustions, as for example dual-fuel RCCI combustion.

The Influence of High Reactivity Fuel Properties on Reactivity Controlled Compression Ignition Combustion

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Reactivity controlled compression ignition (RCCI) is a form of dual-fuel combustion that exploits the reactivity difference between two fuels to control combustion phasing. This combustion approach limits the formation of oxides of nitrogen (NO_x) and soot while retaining high thermal effciency. The research presented herein was performed to determine the influences that high reactivity (diesel) fuel properties have on RCCI combustion characteristics, exhaust emissions, fuel effciency, and the operable load range. A 4-cylinder, 1.9 liter, light-duty compression-ignition (CI) engine was converted to run on diesel fuel (high reactivity fuel) and compressed natural gas (CNG) (low reactivity fuel). The engine was operated at 2100 revolutions per minute (RPM), and at two different loads, 3.6 bar brake mean effective pressure (BMEP) and 6 bar BMEP. A matrix of nine different diesel fuels with varying cetane number (CN), aromatic content (AC), and distillation temperatures was used to identify high reactivity fuel property effects on RCCI combustion characteristics, exhaust emissions, fuel effciency, and the operable load range. Results demonstrated that CN of the diesel fuel had a dominant effect on nearly all facets of RCCI operation. RCCI with fuels whose CN was lower than 33 resulted in higher NOX emissions and in-cylinder pressure rise rates (PRRs) compared to fuels with a CN ranging from 44 to 54. High CN fuels with a low AC (<23%) required the largest percentage CNG to maintain combustion phasing, 70.5% to 78.6% of total fuel energy input as CNG at 3.6 bar BMEP and 73.4% to 83.0% at 6 bar BMEP. High CN, low AC fuels also operated at the highest fuel conversion efficiency, 27.3% to 30.2% at 3.6 bar BMEP and 38.0% to 39.4% at 6 bar BMEP. In-cylinder PRR decreased as CN of the diesel fuel increased which would allow for higher loads to be achieved.

Effects of Low Temperature Combustion on Particle and Gaseous Emission of a Dual Fuel Light Duty Engine

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In recent years the use of alternative fuels for internal combustion engines has had a strong push coming from both technical and economic-environmental aspects. Among these, gaseous fuels such as liquefied petroleum gas and natural gas have occupied a segment no longer negligible in the automotive industry, thanks to their adaptability, anti-knock capacity, lower toxicity of pollutants, reduced CO_2 emissions and cost effectiveness. On the other hand, diesel engines still represent the reference category among the internal combustion engines in terms of fuel consumptions. The possibility offered by the dual fuel systems, to combine the efficiency and performance of a diesel engine with the environmental advantages of gaseous fuels, has been long investigated. However the simple replacement of diesel fuel with natural gas does not allow to optimize the performance of the engine due to the high THC emissions particularly at lower loads. Increasing the injection timing of pilot diesel fuel helps to reduce THC, but cause an increase of the nitrogen oxides. Therefore more complex combustion strategies should be realized to meet vehicles emission standards. In this paper, the benefits obtainable through the activation of the low combustion temperatures have been evaluated. LTC can be activated by means of very early diesel injection timings and with the maximum by natural gas share tolerable for stable combustion. The experimental activity was also focused to analyze the particle emissions which, as is well known, represent together with the nitrogen oxide emissions, the main pollutants resulting from the combustion of diesel fuel. The activation of LTC has shown the potential to simultaneously reduce both THC and NO_X emissions as well as ensuring ultra-low particle emissions. Therefore LTC should be considered as a key- strategy to make DF engines compliant with the limits imposed for the vehicles approval.

Blending Behavior of Ethanol with PRF 84 and FACE A Gasoline in HCCI Combustion Mmode

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The blending of ethanol with PRF (Primary reference fuel) 84 was investigated and compared with FACE (Fuels for Advanced Combustion Engines) A gasoline surrogate which has a RON of 83.9. Previously, experiments were performed at four HCCI conditions but the chemical effect responsible for the non-linear blending behavior of ethanol with PRF 84 and FACE A was not understood. Hence, in this study the experimental measurements were simulated using zero-dimensional HCCI engine model with detailed chemistry in CHEMKIN PRO. Ethanol was used as an octane booster for the above two base fuels in volume concentration of 0%, 2%, 5% and 10%. The geometrical data and the intake valve closure conditions were used to match the simulated combustion phasing with the experiments. Low temperature heat release (LTHR) was detected by performing heat release analysis. LTHR formation depended on the base fuel type and the engine operating conditions suggesting that the base fuel composition has an important role in the formation of LTHR. The effect of ethanol on LTHR was explained by low temperature chemistry reactions and OH/HO_2 evolution. A strong correlation of low temperature oxidation reactions of base fuels with ethanol was found to be responsible for the observed blending effects.

Influence of Blend Ratio and Injection Parameters on Combustion and Emissions Characteristics of Natural Gas-Diesel RCCI Engine

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RCCI strategy gained popularity in automotive applications due to lower fuel consumption, less emissions formation and higher engine performance in compared with other diesel combustion strategies. This study presents results of an experimental and numerical investigation on RCCI combustion using natural gas as a low reactivity premixed fuel with advanced injection of diesel fuel as a high reactivity fuel in a CI engine. An advanced three dimensional CFD simulation coupled with chemical kinetic developed to examine the effects of diesel injection timing, diesel/natural gas ratio and diesel fuel included spray angle on combustion and emissions formation in various engine loads and speeds, in a heavy duty diesel engine. The computational results of baseline operation was validated with experimental data achieved from a RCCI combustion process and reasonable agreement between calculated and measured mean in-cylinder pressure, rate of heat release and emissions such as NOx, CO and HC was obtained. The results showed that, amount and timing of direct injected diesel fuel is critical factor to control combustion phasing related to engine load and speed and also, increasing diesel fuel quantity leads to decrease HC and CO emissions. In other side, air fuel mixture quality has considerable effects on combustion process. For this reason, the effects of fuel spray angle on engine performance and amounts has been studied. It has been found that, diesel fuel targeting inside the combustion chamber has a simultaneous beneficial effects on emissions formation and engine performance due to more homogeneous air fuel mixture.

Parametric Analysis of the Effect of Pilot Quantity, Combustion Phasing and EGR on Effciencies of a Gasoline PPC Light-Duty Engine

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In this paper, a parametric analysis on the main engine calibration parameters applied on gasoline Partially Premixed Combustion (PPC) is performed. Theoretically, the PPC concept permits to improve both the engine efficiencies and the NOx-soot trade-off simultaneously compared to the conventional diesel combustion. This work is based on the design of experiments (DoE), statistical approach, and investigates on the engine calibration parameters that might affect the effciencies and the emissions of a gasoline PPC. The full factorial DoE analysis based on three levels and three factors (3^3 factorial design) is performed at three engine operating conditions of the Worldwide harmonized Light vehicles Test Cycles (WLTC). The pilot quantity (Q_{pil}), the crank angle position when 50% of the total heat is released (CA50), and the exhaust gas recirculation (EGR) factors are considered. The goal is to identify an engine calibration with high efficiency and low emissions. The experiments are conducted on a 2l Volvo Euro 6 diesel engine. The fuels tested are Gasoline RON75 and MK1 diesel. Gasoline RON75 permits operation from low to high engine load conditions. A pilot/main injection strategy is adopted, necessary to control the peak pressure rise rate (PRR_{max}) to acceptable values and to extend the maximum engine load operating area in PPC. The experimental results show that increasing the EGR rate from 0 to 30%, the net efficiency improves approximately of 1.5% units, due to the shorter combustion duration. For all the conditions examined in PPC, the soot levels are about two times lower than diesel combustion. With a high level of EGR, combined with optimized pilot quantity and combustion phasing, high-effciency PPC combustion can be achieved without penalties in terms of NOx emissions compared to diesel combustion.

Particulates Size Distribution of Reactivity Controlled Compression Ignition (RCCI) on a Medium-Duty Engine Fueled with Diesel and Gasoline at Different Engine Speeds

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This work investigates the particulates size distribution of reactivity controlled compression ignition combustion, a dual-fuel concept which combines the port fuel injection of low-reactive/gasoline-like fuels with direct injection of highly reactive/diesel-like fuels. The particulates size distributions from 5-250 nm were measured using a scanning mobility particle sizer at six engine speeds, from 950 to 2200 rpm, and 25% engine load. The same procedure was followed for conventional diesel combustion. The study was performed in a single-cylinder engine derived from a stock medium-duty multi-cylinder diesel engine of 15.3:1 compression ratio. The combustion strategy proposed during the tests campaign was limited to accomplish both mechanical and emissions constraints. The results confirms that reactivity controlled compression ignition promotes ultra-low levels of nitrogen oxides and smoke emissions in the points tested. However, in spite of having similar or lower smoke emissions, the number of particles in some conditions is higher for the reactivity controlled compression ignition than for conventional diesel combustion. Nucleation mode dominates the particle formation for the reactivity controlled compression ignition mode, while accumulation mode dominates the particle formation for conventional diesel combustion. Thus, it is confirmed that the smoke measurement in filter smoke number units cannot be used to correlate the total particle mass for the reactivity controlled compression ignition mode, as typically done for conventional diesel combustion.

Effect of Aromatics on Combustion Stratification and Particulate Emissions from Low Octane Gasoline Fuels in PPC and HCCI Mode

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The objective of this study was to investigate the effect of aromatic on combustion stratification and particulate emissions for PRF60. Experiments were performed in an optical CI engine at a speed of 1200 rpm for TPRF0 (100% v/v PRF60), TPRF20 (20% v/v toluene + 80% PRF60) and TPRF40 (40% v/v toluene + 60% PRF60). TPRF mixtures were prepared in such a way that the RON of all test blends was same (RON = 60). Single injection strategy with a fuel injection pressure of 800 bar was adopted for all test fuels. Start of injection (SOI) was changed from early to late fuel injection timings, representing various modes of combustion viz HCCI, PPC and CDC. High-speed video of the in-cylinder combustion process was captured and one-dimensional stratification analysis was performed from the intensity of images. Particle size, distribution and concentration were measured and linked with the in-cylinder combustion images. Results showed that combustion advanced from CDC to PPC and then attained a constant value in HCCI mode. In PPC and HCCI region, the soot mass concentration was significantly reduced as premixing was improved due to longer ignition delay. The particle number was lower for the late injection and becomes higher as the injection timing advanced to PPC and HCCI mode. While the soot particles were almost nuclear model with the size range of 5nm~17nm and as combustion transited from CDC via PPC to HCCI, the particle size became larger. For TPRF blends, the increased intake air temperature was required to maintain same combustion phasing as that of PRF60. With the addition of toluene to PRF60, the soot concentration increased, which was in-line with the increased intensity (yellow) of combustion images. The degree of stratification was higher for TPRF20 and TPRF40 when compared to PRF60.

Ammonia-Hydrogen Blends in Homogeneous-Charge Compression-Ignition Engine

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Ammonia and hydrogen can be produced from water, air and excess renewable electricity (Power-to-fuel) and are therefore a promising alternative in the transition from fossil fuel energy to cleaner energy sources. An Homogeneous-Charge Compression-Ignition (HCCI) engine is therefore being studied to use both fuels under a variable blending ratio for Combined Heat and Power (CHP) production. Due to the high auto-ignition resistance of ammonia, hydrogen is required to promote and stabilize the HCCI combustion. Therefore the research objective is to investigate the HCCI combustion of varying hydrogen-ammonia blending ratios in a 16:1 compression ratio engine. A specific focus is put on maximizing the ammonia proportion as well as minimizing the NO_x emissions that could arise from the nitrogen contained in the ammonia. A single-cylinder, constant speed, HCCI engine has been used with an intake pressure varied from 1 to 1.5 bar and with intake temperatures ranging from 428 to 473 K. Stable combustion was achieved with up to 70 %vol. ammonia proportion by increasing the intake pressure to 1.5 bar, the intake temperature to 473 K, and the equivalence ratio to 0.28. From pure hydrogen to 60 %vol. ammonia proportion, the combustion efficiency only lost 0.6 points. Pure hydrogen Indicated Mean Effective Pressure (IMEP) was limited to 2.7 bar to avoid ringing (i.e. too high pressure rise rate) but blended with ammonia the IMEP safely reached 3.1 bar. For pure hydrogen, NO_x emissions were below 6 ppm. For hydrogen-ammonia blends, NO_x were between 750 and 2000 ppm. Exhaust Gas Recirculation (EGR) operations significantly reduced NO_x emissions through a reduced oxygen availability but with a noticeable negative effect on combustion effciency due to lower in-cylinder temperatures. Moreover, performed simulations showed the production of significant N_2O quantities for combustion temperatures under 1400 K. Ammonia showed to be an effective fuel for HCCI conditions and EGR revealed itself as a promising NO_x reducing technique through a decreased oxygen availability. Still, further effort is required when using EGR to keep the combustion temperature above 1400 K to maintain good combustion effciencies and avoid N_2O production.

RCCI Combustion Regime Transitions in a Single-Cylinder Optical Engine and a Multi-Cylinder Metal Engine

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Reactivity Controlled Compression Ignition (RCCI) is an approach to increase engine effciency and lower engine-out emissions by using in-cylinder stratification of fuels with differing reactivity (i.e., autoignition characteristics) to control combustion phasing. Stratification can be altered by varying the injection timing of the high-reactivity fuel, causing transitions across multiple regimes of combustion. When injection is sufficiently early, combustion approaches a highly-premixed autoignition regime, and when it is sufficiently late it approaches more mixing-controlled, diesel-like conditions. Engine performance, emissions, and control authority over combustion phasing with injection timing are most favorable in between, within the RCCI regime. To study charge preparation phenomena that dictate regime transitions, two different optical diagnostics are applied in a single-cylinder heavy-duty optical engine, and conventional engine diagnostics are applied in a multi-cylinder, light-duty all-metal engine. Both engines are operated with iso-octane and n-heptane as the low- and high-reactivity fuels, respectively. The iso-octane fuel fraction delivers 80% of the total fuel energy, the global equivalence ratio is 0.35, and no exhaust gas recirculation is used. In the optical engine, single-shot, band-pass infrared (IR) imaging of emission near 3.3 microns measures thermal *C-H* stretch-band emission of hot fuel vapor and intermediate combustion products, providing qualitative information about the fuel-vapor distribution and ignition locations during low-temperature heat release. Additionally, high-speed 7.2 kHz visible-light imaging of natural luminosity, optimized to detect chemiluminescence, indicates the spatial and temporal evolution of high-temperature heat release and combustion. Similar combustion regimes are observed for both engine platforms, allowing an opportunity for optical engine

data to provide insight into fundamental phenomena affecting regime ranges and transitions in production engines. Key findings from imaging diagnostics indicate that at the late-injection limit of RCCI control authority, low-temperature ignition occurs when clearly identifiable jet structures are still intact, and during high-temperature combustion there is prevalent and persistent soot incandescence representative of locally mixing-limited (i.e., fuel-rich) combustion. At the early-injection limit of RCCI control, observed stratification during low-temperature ignition is subtle; however, high-temperature combustion still occurs sequentially from the bowl rim radially inwards.

Fuel Effect on Combustion Stratification in Partially Premixed Combustion

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The literature study on PPC in optical engine reveals investigations on OH chemiluminescence and combustion strati cation. So far, mostly PRF fuel is studied and it is worthwhile to examine the effect of fuel properties on PPC. Therefore, in this work, fuel having different octane rating and physical properties are selected and PPC is studied in an optical engine. The fuels considered in this study are diesel, heavy naphtha, light naphtha and their corresponding surrogates such as heptane, PRF50 and PRF65 respectively. Without EGR (Intake O_2 = 21%), these fuels are tested at an engine speed of 1200 rpm, fuel injection pressure of 800 bar and pressure at TDC = 35 bar. SOI is changed from late to early fuel injection timings to study PPC and the shift in combustion regime from CI to PPC is explored for all fuels. An increased understanding on the effect of fuel octane number, physical properties and chemical composition on combustion and emission formation is obtained. High-speed images of the combustion process are analyzed for each and every fuel and in-cylinder phenomenon is associated with rate of heat release and in-cylinder pressure. Based on the intensity of the images, stratification analysis is performed. The results of the analysis show that CA50 decreases for all fuels from late to early SOI wherein PPC is realized. According to the reactivity of fuels, intake air temperature is increased to comply with the combustion phasing of baseline diesel. When studying the effect of physical properties of fuels, premixed effect and lean combustion are observed for PRF0 compared to diesel. The engine emissions of THC and CO are higher for PRF0 than diesel, while soot concentration is reduced. Diesel showed more stratified combustion than PRF0 despite having same RON due to the effect of physical properties. The effect of fuel octane number on PPC is suppressed due to temperature effect; intake air temperature is increased to 140°C and 90°C for PRF65 and PRF50. PRF0 lacked LTR phase and combustion was noted to be more premixed than PRF50 and PRF65 at SOI = -10 CAD (aTDC). The intensity of the combustion

images is brighter for high RON fuels than PRF0 due to physical effects, while octane number effect is not realized due to higher intake air temperature. While THC and CO emissions decreased with the increase in RON, NO_X emission increased due to increased intake air temperature. When comparing real fuels, soot concentration is lower for light naphtha when compared to diesel and heavy naphtha.

A Late Injection Combustion Strategy Using a Novel Ramped Combustion System

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Traffic related NOx and particle emission remain a significant concern particularly in the urban environment. Electrification offers a medium to long term solution, but there remains a need to significantly reduce internal combustion engine emissions in the short and medium term, and potentially in the long term for long range inter city transportation. Late injection low temperature combustion (LTC) has the potential to achieve ultra-low emissions levels in a compression ignition engine by increasing the lean pre-mixed burn fraction. However, significant quantities of diluent are normally required to achieve the required delay in ignition and pre-mixing to achieve LTC. This results in high boost requirements, increased pumping work and the complexity of the air handling system and potentially adversely impacting fuel economy. In this paper, results from a single cylinder light duty research engine are presented using a novel ramped combustion chamber focused at mid to high engine loads. The ramped combustion chamber improves mixing and enables more retarded injection timings than those possible on conventional bowl designs. This combustion strategy has enabled LTC conditions to be achieved at lower dilution rates, typically 20-30% at loads up to 15bar IMEP. CFD analysis of the air-fuel interaction indicates the ramped bowl effectively deflects fuel away from the squish region enabling very late injection timings. One dimensional analysis of the engine system was used to investigate the potential of late exhaust valve opening in improving work recovery, resulting in improved fuel consumption over the baseline LTC valve timings.

Low RON Gasoline Calibration on a Multi-Cylinder Compression Ignition Engine to Fulfill the Euro 6d Regulation

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Reducing the CO_2 footprint, limiting the pollutant emissions and rebalancing the ongoing shift demand toward middle-distillate fuels are major concerns for vehicle manufacturers and oil refiners. In this context, gasoline-like fuels have been recently identified as good candidates. Straight run naphtha, a refinery stream derived from the atmospheric crude oil distillation process, allows for a reduction of both NOx and particulate emissions when used in compression- ignition engines. CO_2 benefits are also expected thanks to naphtha's higher H/C ratio and energy content compared to diesel. In previous studies, wide ranges of Cetane Number (CN) naphtha fuels have been evaluated and CN 35 naphtha fuel has been selected. The assessment and the choice of the required engine hardware adapted to this fuel, such as the compression ratio, bowl pattern, nozzle design and air-path technology, have been performed on a light-duty single cylinder compression-ignition engine. The purpose of this paper is to demonstrate the potential of a recalibrated light-duty multi-cylinder compression-ignition engine running with CN 35 naphtha fuel with the just necessary engine and after-treatment hardware modification. The implementation of a specific global Design of Experiment (DoE) methodology developed by IFPEN was applied in steady-state conditions to calibrate the engine. The behavior of an after-treatment exhaust line (ATS) with DOC, DPF and SCR systems, was evaluated by 0D simulation. To be compliant with the Euro 6d regulation, several DoEs, considering the coolant temperature were performed to fully cover the WLTC cycle range and models representing the engine behavior in a large part of the engine map were then created. The Euro 6 regulation was met with a reduction of almost 7% of CO_2 on WLTC, using a Euro 6 diesel like ATS design. Noise levels were comparable to a Euro 5 diesel reference engine. Different ATS efficiencies were also assessed with a significant impact on the CO_2 potential. Engine calibration and after-treatment are, de facto, strongly linked.

Particle Formation and Emissions in an Optical Small Displacement SI Engine Dual Fueled with CNG DI and Gasoline PFI

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Fuel depletion as well as the growing concerns on environmental issues prompt to the use of more eco-friendly fuels. The compressed natural gas (CNG) is considered one of the most promising alternative fuel for engine applications because of the lower emissions. Nevertheless, recent studies highlighted the presence of ultra fine particle emissions at the exhaust of CNG engines. The present study aims to investigate the effect of CNG on particle formation and emissions when it was direct injected and when it was dual fueled with gasoline. In this latter case, the CNG was direct injected and the gasoline port fuel injected. The study was carried out on a transparent single cylinder SI engine in order to investigate the in-cylinder process by real time non-intrusive diagnostics. In-cylinder 2D chemiluminescence measurements from UV to visible were carried out. Two filters, at 310 and 431 nm, were used to obtain OH* and CH* spatial distribution as well as to evaluate the local air fuel ratio (AFR) in the cylinder. The OH* and air fuel ratio (AFR) spatial distribution influence the in-cylinder soot formation and oxidation. The exhaust emissions were characterized by means of gaseous analyzers and an opacimeter. The particle size distribution function was measured by an Engine Exhaust Particle Sizer (EEPS) in the size range from 5.6 to 560 nm. The in-cylinder optical analysis was correlated to exhaust particle emissions. It was observed that particle emissions, in terms of number and size, are strongly related to the AFR distribution in the combustion chamber.

Natural Gas Fueled Engines Modeling under Partial Stratified Charge Operating Conditions

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Using natural gas in internal combustion engines (ICEs) is emerging as a promising strategy to improve thermal efficiency and reduce exhaust emissions. One of the main benefits related to the use of this fuel is that the engine can be run with lean mixtures without compromising its performances. However, as the mixture is leaned out beyond the Lean Misfire Limit (LML), several technical problems are more likely to occur. The flame propagation speed gradually decreases, leading to a slower heat release and a low combustion quality, thus increasing the occurrence of misfiring and incomplete combustions. This in turn results in a sharp increment in CO and UHC emissions, as well as in cycle-to-cycle variability. In order to limit the above-mentioned problems, different solutions have been proposed over the last decade. Among them, the stratification or the partial stratification of the charge has been shown to successfully extend the lean limit with respect to conventional lean burn engines. During the development and optimization of such strategies, Computational Fluid Dynamics (CFD) is a fundamental tool to thoroughly understand the phenomena occurring during the mixing and combustion phases. In order to reliably simulate the combustion process, a proper model is required which takes account of the Turbulence-Chemistry Interaction (TCI). In the present work the Partially Stirred Reactor (PaSR) model was used in the numerical simulation of a natural gas fueled single cylinder research engine. Several tests with different relative air-to-fuel ratios were carried on in order to evaluate the robustness of the model, without performing any tuning operation across the various test cases. For this purpose, both homogeneous and partially stratified charge (PSC) cases were run. Results were compared against the experimental data gathered at the University of British Columbia by E.Chan et al., showing a good agreement between such data and the numerical ones in terms of pressure trace over time. The solver was able to correctly capture the performance enhancement of PSC engines with respect to the homogeneous counterparts, thus confirming the potential of CFD as a valid alternative to experimental investigation.

Experimental and Numerical Investigation of the Engine Operational Conditions' Influences on a Small Un-Scavenged Pre-Chamber's Behavior

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Despite significant benefits in terms of the ignition enhancement, the strength and timing of the turbulent flame jets subsequently issuing into the main chamber strongly depend on the pre-chamber combustion process and, thus, are sensitive to the specific engine operating conditions it experienced. This poses considerable difficulties in optimizing engine operating conditions as well as controlling engine performance. This paper investigates the influence of engine operating conditions on the pre-chamber combustion event using both experimental and numerical methods. A miniaturized piezo-electric pressure transducer was designed to be placed inside the engine cylinder head to record the pre-chamber inner volume pressure, in addition to conventional pressure indication inside the main chamber. The pressure difference between the main chamber and the pre-chamber ($\Delta p = p_{pre\text{-}chamber} - p_{main\ chamber}$) served as an indicator of the pre-chamber combustion event, through the study of the crank angle resolved Δp under different engine operating conditions. The variations include spark timing, air-fuel ratio and engine speed, as well as engine intake air temperature and boost pressure, for which a single-parameter sensitivity approach was carried out. 3D-CFD simulation in the RANS context and 0D modeling was further employed to estimate the turbulence level and thermo-physical conditions inside the pre- and main chambers in dependence of the engine operating conditions. The results indicate that the Δp peak value and its timing show the highest sensitivity to the air-fuel ratio variation, followed by the intake air temperature, while the sensitivity of Δp peak value and its timing to the pressure difference and the absolute pressure level at spark timing were observed to be considerably lower. Based on the observations, two correlations were proposed to predict the Δp peak value and its timing for which successful validation against a large number of engine operating conditions was demonstrated.

Analysis of Scavenged Pre-Chamber for Light Duty Truck Gas Engine

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An ongoing research and development activities on the scavenged pre-chamber ignition system for an automotive natural gas fueled engine is presented in this paper. The experimental works have been performed in engine laboratory at steady state conditions on a gas engine with 102 mm bore and 120 mm stroke, converted to a single cylinder engine. The in-house designed scavenged pre-chamber is equipped with a spark plug, fuel supply and a miniature pressure sensor for detailed combustion diagnostics. The engine was operated at constant speed, fully open throttle valve and four different fueling modes with or without spark discharge. A partly motored mode allowed direct evaluation of the pre-chamber heat release. The experimental data acquired in this research served as a validation data for the numerical simulations. The performed tests of prototypes and calculations have recently been expanded to include 3-D flow calculations in the Ansys Fluent software. The work presents results from the coupled 1-D and 3-D numerical simulation of the flow in the pre-chamber. The main goal of the computational fluid dynamic (CFD) simulation was to describe the uid dynamics inside the pre-chamber (without combustion), mixture distribution and assessment of the scavenging quality. The pre-chamber interior volume is analyzed in detail for the operating condition. The outputs of the simulation serve as a base for optimization of the pre-chamber design. It is also a valuable input for the optimal control setting to improve overall functionality of the scavenged pre-chamber. The simulation results were compared with the experiments.

Experimental Investigation of Orifice Design Effects on a Methane Fuelled Prechamber Gas Engine for Automotive Applications

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Due to its molecular structure, methane provides several advantages as fuel for internal combustion engines. To cope with nitrogen oxide emissions high levels of excess air are beneficial, which on the other hand deteriorates the ammability and combustion duration of the mixture. One approach to meet these challenges and ensure a stable combustion process are fuelled prechambers. The flow and combustion processes within these prechambers are highly influenced by the position, orientation, number and overall cross-sectional area of the orifices connecting the prechamber and the main combustion chamber. In the present study, a water-cooled single cylinder test engine with a displacement volume of 0.5 l is equipped with a methane-fuelled prechamber. To evaluate influences of the aforementioned orifices several prechambers with variations of the orientation and number of nozzles are used under different operating conditions of engine speed and load. The orifices and therefore the intermediate products of the combustion emanating the prechamber are either aimed towards the squish area of the main chamber or perpendicular to the piston surface. With a constant diameter of the orifices the overall flow area varies proportional to the number of nozzles. Thereby, the impact of timing and duration of the methane injection into the different prechambers, the extension of the lean misfire limit and a variation of the ignition timing are investigated. To rate the overall combustion process the exhaust emissions of unburnt hydrocarbons and nitrogen oxides are examined. Considering the reference point the combustion duration was reduced between 30 and 45 percent compared to conventional spark plug operation using prechambers, whereby the combination of number and orientation of orifices plays an important role.

Fundamental Aspects of Jet Ignition for Natural Gas Engines

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Large-bore natural gas engines may use pre-chamber ignition. Despite extensive research in engine environments, the exact nature of the jet, as it exits the pre-chamber orifice, is not thoroughly understood and this leads to uncertainty in the design of such systems. In this work, a specially-designed rig comprising a quartz pre-chamber fit with an orifice and a turbulent flowing mixture outside the pre-chamber was used to study the pre-chamber flame, the jet, and the subsequent premixed flame initiation mechanism by OH* and CH* chemiluminescence. Ethylene and methane were used. The experimental results are supplemented by LES and 0D modelling, providing insights into the mass flow rate evolution at the orifice and into the nature of the fluid there. Both LES and experiment suggest that for large orifice diameters, the flow that exits the orifice is composed of a column of hot products surrounded by an annulus of unburnt pre-chamber fluid. At the interface between these layers, a cylindrical reaction zone is formed that propagates in the main chamber in the axial direction assisted by convection in the jet, but with limited propagation in the cross-stream direction. For small orifice diameters, this cylinder is too thin, and the stretch rates are too high, for a vigorous reaction zone to escape the pre-chamber, making the subsequent ignition more difficult. The methane jet flame is much weaker than the one from ethylene, consistent with the lower flame speed of methane that suggests curvature-induced quenching at the nozzle and by turbulent stretch further downstream. The velocity of the jet is too high for the ambient turbulence to influence the jet, although the latter will affect the probability of initiating the main premixed flame. The experimental and modelling results are consistent with ongoing Direct Numerical Simulations at ETH Zurich.

Spray Model Based Phenomenological Combustion Description and Experimental Validation for a Dual Fuel Engine

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The operation of dual fuel engines, operated with natural gas as main fuel, offers the potential of substantial savings in CO2. Nevertheless, the operating map area where low pollutant emissions are produced is very narrow. Especially at low load, the raw exhaust gas contains high concentrations of unburned methane and, with high pilot fuel portions due to ignition limitations, also soot. The analysis of the combustion in those conditions in particular is not trivial, since multiple combustion modes are present concurrently. The present work focuses on the evaluation of the individual combustion modes of a dual fuel engine, operated with natural gas as main and diesel as pilot fuel, using a combustion model. The combustion has been split in two partwise concurrent combustion phases: the auto-ignition phase and the premixed flame propagation phase. In order to calculate the amount of fuel and equivalence ratio distribution of the diesel and substrate at ignition, a simplified spray model is used. The trapped natural gas within the spray volume provides the basis for the distribution of fuel burnt in the auto-ignition phase and in the premixed flame propagation. The sum of the auto-ignition combustion mode and the premixed flame propagation combustion mode represents the total of the heat released, disregarding the cool flame, heat losses and unburned fuel. The description has been calibrated on a 4 cylinder, 2 litre Volkswagen Industrial Diesel Engine, modified to include natural gas port injection. The engine was operated with a wide variation of settings, ranging from low to high load, globally lean and stoichiometric with pilot fuel mass ratio from 2% to 50% and di erent EGR rates. The heat release rate derived from the pressure curve shows very good agreement with the sum of the individual combustion modes in all the abovementioned engine operating conditions. The ability to distinguish between the individual combustion modes, offered by the developed combustion description herein aids in the understanding of the engine operation limitations. The predictive model shows a strong dependency on the ignition delay which is itself challenging to model. Consequently the accuracy of predicted combustion characteristics are limited to the accuracy of the modelled ignition delay.

Characterization of Knock Tendency and Onset in a GDI Engine by Means of Conventional Measurements and a Non-Conventional Flame Dynamics Optical Analysis

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Gasoline direct injection (GDI) allows knock tendency reduction in spark-ignition engines mainly due to the cooling effect of the in-cylinder fuel evaporation. However, the charge formation and thus the injection timing and strategies deeply affect the flame propagation and consequently the knock occurrence probability and intensity. In particular, split injection allows a reduction of knock intensity by inducing different AFR gradient and turbulent energy distribution. Present work investigates the tendency to knock of a GDI engine at 1500 rpm full load under different injection strategies, single and double injections, obtained delivering the same amount of gasoline in two equal parts, the first during intake, the second during compression stroke. In these conditions, conventional and non-conventional measurements are performed on a 4-stroke, 4-cylinder, turbocharged GDI engine endowed of optical accesses to the combustion chamber. Imaging in the UV-visible range is carried out by means of a high spatial and temporal resolution camera through a wide transparent window in the piston head allowing the view of the whole combustion chamber almost until the cylinder walls, to include the end-gas zones. Optical data are correlated to in-cylinder pressure-based indicated analyses and ion current data, on a cycle resolved basis. Normal flame front propagation before knock onset, end-gas auto-ignition and the effect of in-cylinder pressure waves of knock on the residual ame are deeply investigated. This synergic analysis is used to explore the effect of modulating injection on the charge formation optimization and the deriving improvement of combustion and reduction of knock tendency. Split injection reduces engine cycle-by-cycle variability with respect to the single injection case, all the others relevant parameters remaining unchanged. It is also able to increase the resistance to knock also changing relevantly the location of the knock onset. A new methodology based on high temporal resolution optical diagnostics for the determination of the knock intensity and onset has been proposed. This procedure is focused on the cycle resolved analysis of the centroid of luminosity dynamics under the knock pressure waves. It allows the precise determination of knock onset timing and spatial location within the combustion chamber. Furthermore, the amplitude of the luminous centroid oscillation has been found

in good agreement with the knock index obtained by in-cylinder pressure and the ion current based analyses. This work and the proposed methodology can contribute to give a further insight to knock mechanism under real engine conditions.

The Effect of Cycle-to-Cycle Variations on the NOx-SFC Tradeoff in Diesel Engines under Long Ignition Delay Conditions

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Cycle-to-cycle variations in internal combustion engines are known to lead to limitations in engine load and efficiency, as well as increases in emissions. Recent research has led to the identification of the source of cyclic variations of pressure, soot and NO emissions in direct injection common rail diesel engines, when employing a single block injection and operating under long ignition delay conditions. The variations in peak pressure arise from changes in the diffusion combustion rate, caused by randomly occurring in-cylinder pressure fluctuations. These fluctuations result from the excitation of the first radial mode of vibration of the cylinder gases which arises from the rapid premixed combustion after the long ignition delay period. Cycles with high-intensity fluctuations present faster diffusion combustion, resulting in higher cycle peak pressure, as well as higher measured exhaust NO concentrations. In this study the effects of pressure fluctuations on the NOx-specific fuel consumption (SFC) tradeoff are determined. The investigation is performed on a single-cylinder heavy-duty diesel engine, and focuses on the variation of injection parameters (injection timing and pressure) under constant, long ignition delay conditions. Single-cycle NO concentrations are measured using a fast-NO analyzer placed near the exhaust valve, whereas the indicated SFC is determined from the measured cylinder pressure. The results show that the presence of pressure fluctuations is not beneficial for the NOx-SFC tradeoff, with the cycles showing higher fluctuation intensities leading to higher emission levels for constant indicated SFC.

Engine Modeling and Controls
Engine Combustion
Fuels and Lubricants Technologies
Emissions and Emissions Controls
New Engines, Components, Actuators, & Sensors
Hybrid and Electric Powertrains, including Range Extending Engines

Numerical Simulation of a Direct-Acting Piezoelectric Prototype Injector Nozzle Flow for Partial Needle Lifts

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Actual combustion strategies in internal combustion engines rely on fast and accurate injection systems to be successful. One of the injector designs that has shown good performance over the past years is the direct-acting piezoelectric. This system allows precise control of the injector needle position and hence the injected mass ow rate. Therefore, understanding how nozzle flow characteristics change as function of needle dynamics helps to choose the best lift law in terms of delivered fuel for a determined combustion strategy. Computational fluid dynamics is a useful tool for this task. In this work, nozzle flow of a prototype direct-acting piezoelectric has been simulated by using CONVERGE. Unsteady Reynolds-Averaged Navier-Stokes approach is used to take into account the turbulence. Results are compared with experiments in terms of mass flow rate. The nozzle geometry and needle lift profiles were obtained by means of X-rays in previous works. Simulations are able to properly capture the relationship between instantaneous partial needle lifts and the corresponding rate of injection. The difference in mass flow rates between simulations and experiments is below 5%, although experiments show some oscillations that are not predicted by the model employed here. In order to simulate the experimental rising slope of the injected mass, the pressure evolution at the inlet boundary condition had to be modified, increasing the pressure from the discharge value up to the injection pressure. This modification in the upstream pressure value seems to be in accordance with the literature. Cavitation phenomenon and flow detachment have been observed downstream the needle seat for low lift values. The converging shape of the orifices overrides cavitation inside them, and also allows the flow to reattach even when the length to diameter ratio is below 10. However, fuel vapor is still present at the orifices exit for low needle lift cases, which affects velocity and fuel distributions within the sprays.

Two Concepts of Pumping Fuel in a Gas

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In this paper, two concepts of fuel pumping methods using solenoid, for gasoline injection in engines, are discussed. The fuel pump is integrated within the injector in these concepts, which makes the fueling system, simple, compact and less expensive. This integrated gasoline pump injector (GPI) is aimed at catering to the upcoming stringent emission norms, as it enables the usage of closed-loop fuel correction with the help of an electronic control unit (ECU), based on the exhaust lambda feedback. A solenoid and spring arrangement is used in this injector design, where the fuel gets pressurized in a pumping chamber, and the pressurized fuel is then injected through orifices to produce spray in the intake port. Two concepts are used for pressurizing the fuel. First concept uses a spring to pump the fuel and a solenoid to retract the plunger. Second concept uses solenoid to pump the fuel and spring to retract the plunger. The magnetic and hydraulic behaviors of the injector are different in the studied cases and offers choice to choose the concept according to the application. The first concept relies on the spring for the injector's hydraulic performance and control, whereas the second one relies on the solenoid. The solenoid responds faster than the spring, and by virtue of this, the second concept is seen more suitable for better hydraulic discharge control. The electromagnetic and hydraulic characteristics of both the concepts are studied using simulation and tests, and the results are presented in this work.

Fuel Injection Analysis with a Fast Response 3D-CFD Tool

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Main limiting factor in the application of 3D-CFD simulations within an engine development is the very high time demand, which is predominantly influenced by the number of cells within the computational mesh. Arbitrary cell coarsening, however, results in a distinct distortion of the simulation outcome. It is rather necessary to adapt the calculation models to the new mesh structure in order to ensure reliability and predictability of the 3D-CFD engine simulation. In the last decade, a fast response 3D-CFD tool was developed at FKFS in Stuttgart. It aims for a harmonized interaction between computational mesh, implemented calculation models and defined boundary conditions in order to enable fast running simulations for engine development tasks. Their susceptibility to errors is significantly minimized by various measures, e.g. extension of the simulation domain (full engine) and multi-cycle simulations. In this way, a predictive analysis of influencing parameters on the engine flow field allows a thorough definition of the engine design and operating strategy. Comparable measures were taken for the numerical description of injection processes. The fuel injection, which essentially influences the combustion performance, is highly sensitive to a variety of parameters. These include the fuel properties, injector geometry and injection conditions. However, their numerical description has no general validity. It is rather reasonable to follow application specific procedures in order to meet the demand for injection simulations in accordance to the "fast response" methodology. The paper addresses recent analyses and findings on the numerical characterization of fuel injection processes with a focus on spatial and temporal discretization as well as the fuel modeling and their respective influence on macroscopic spray properties.

Statistical Approach on Visualizing Multi-Variable Interactions in a Hybrid Breakup Model under ECN Spray Conditions

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The Direct Numerical Simulation (DNS) approach to solving the fundamental transport equations down to the smallest scales of motion is favorable should the requirement be a truly predictive solution of fluid dynamic problems, but the simulation run times are unacceptable for most practical industrial applications. Despite the steadily increasing computational capabilities, Reynolds Averaged Navier-Stokes (RANS) based frameworks remain the most commercially viable option for high volume sectors, like automotive. The sub models within RANS simplify the description of key physical phenomena and include several numerical constants. These so-called "tuning constants" introduce multivariable dependencies that are almost impossible to untangle with local sensitivity studies. This paper addresses the prevailing difficulties in setting up an adequate diesel spray simulation which arise from the mentioned multi-variable interactions of these "tuning constants", by applying a statistical approach named Design of Experiments (DoE). Often combined with an optimizer, DoE is commonly used to find an optimum set of engine parameters for set criteria at reduced experimental effort. In this case, the methodology was applied to determine an optimal set of "tuning constants" for the simulations which best matched experimental data at five conditions taken from the Engine Combustion Network (ECN) database. Multi-variable DoE were run for each condition. Stochastic response models (SPM's) highlighted crucial simulation sensitivities of the turbulent dissipation constant C_2 and liquid/gas-phase momentum transfer at injection pressure swings. Further, a comparison of the breakup models which produced matching simulations exhibited patterns which correspond with physical processes. Lastly, it was shown that while a single set of the constants can give reasonable results in the space explored, there is merit in adjusting key constants to suit the operating condition in the search for accuracy.

Parametric Analysis of the Effect of the Fluid Properties and the Mesh Setup by Using the Schnerr-Sauer Cavitation Model

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The primary target of the internal combustion engines design is to lower the fuel consumption and to enhance the combustion process quality, in order to reduce the raw emission levels without performances penalty. In this scenario the direct injection system plays a key role for both diesel and gasoline engines. The spray dynamic behaviour is crucial in defining the global and the local air index of the mixture, which in turns affects the combustion process development. At the same time it is widely recognized that the spray formation is influenced by numerous parameters, among which also the cavitation process inside every single hole of the injector nozzle. The proper prediction of the cavitation development inside the injector nozzle holes is crucial in predicting the liquid jet emerging from them. In this mechanism the CFD simulation is of great importance because of the too small dimension of the nozzle holes, which are mostly non suitable for an accurate experimental investigation and, when they are, these analyses need to be limited to a few cases for cost reasons. Nowadays the most used cavitation model is the two-phase homogeneous mixture model, especially with the Raleigh-Plesset closure model. In the literature it is possible to find out multiple examples of validation attempts of such a model versus experimental data: generally they fail because of the systematic overestimation of the mass ow with respect to the experimental data. The main parameters identified as responsible are the fluid properties, mostly in terms of the liquid density value, and the mesh setup. The focus of the present paper is to investigate the effective weight of each single fluid parameter, both for liquid and vapor phase, plus the mesh setup on the final pressure difference-mass flow rate curve, in terms of curve shape, curve values and evaluation of the cavitation onset/development.

A "Dynamic System" Approach for the Experimental Characterization of a Multi-Hole Spray

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The analysis of a spray behavior is confined to study the fuid dynamic parameters such as axial and radial velocity of the droplets, size distribution of the droplets, and geometrical aspect as the penetration length. In this paper, the spray is considered like a dynamic system and consequently it can be described by a number of parameters that characterize its dynamic behavior. The parameter chosen to describe the dynamic behavior is the external cone angle. This parameter has been detected by using an experimental injection chamber, a multi-hole (8 holes) injector for GDI applications and recorded by a high-speed C-Mos camera. The images have been elaborated by a fuzzy logic and neural network algorithm and are processed by using a chaos deterministic theory. This procedure carries out a map distribution of the working point of the spray and determines the stable (signature of the spray) and instable behavior. This approach allows using the acquired information as a first step to define an advanced control of the injection of a GDI system.

Transient Heat Transfer Effects on a Gasoline Spray Impact against Hot Surfaces: Experimental and Numerical Study

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Gasoline direct injection (GDI) engines are characterized by complex phenomena involving spray dynamics and possible spray-wall interaction. Control of mixture formation is indeed fundamental to achieve the desired equivalence ratio of the mixture, especially at the spark plug location at the time of ignition. Droplet impact on the piston or liner surfaces has also to be considered, as this may lead to gasoline accumulation in the liquid form as wall film. Wall films more slowly evaporate than free droplets, thus leading to local enrichment of the charge, hence to a route to diffusive flames, increased unburned hydrocarbons formation and particulate matter emissions at the exhaust. Local heat transfer at the wall obviously changes if a wall film is present, and the subtraction of the latent heat of vaporization necessary for secondary phase change is also an issue deserving a special attention. In Computational Fluid Dynamics (CFD) studies of engine combustion this effect has rarely been taken into account and a constant temperature has been often set as Dirichlet condition for the solution of the in-cylinder turbulent flow even in the presence of impacting sprays. Present work aims at giving a contribution to the validation of a 3D CFD model for the simulation of the in-cylinder thermo-fluidynamic processes underlying energy conversion. Results of a numerical model accounting for the conductive heat transfer mechanism within the piston are compared with basic experimental measurements carried out to achieve an insight into the dynamics and the impact over walls of multi-hole sprays for GDI applications through combined optical schlieren and Mie scattering techniques.

Outward-Opening Hollow-Cone Spray Characterization by Experimental and Numerical Approach in Evaporative and Non-Evaporative Conditions

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In the present paper, a new concept of open nozzle spray was investigated as possible application for compression ignition engines. The study concerns an experimental and numerical characterization of a spray generated through a prototype high-pressure hollow-cone nozzle (HCN). The experimental description of the injection process was carried out under evaporative and non-evaporative conditions injecting the fuel in a constant-volume combustion vessel controlled in pressure and temperature in order to measure the spatial and temporal fuel pattern at engine-like gas densities. OpenFOAM libraries in the lib-ICE version of the numerical code were employed for simulating the spray dynamics after a first validation phase based on the experimental data. Results show a typical spray structure of the outward-opening nozzle with the overall fluid-dynamic arrangement having a good fuel distribution along the hollow-cone geometry but showing a reduced spatial penetration. The first feature appears very interesting in view of an application to premixed controlled combustion concepts using dedicated piston geometries.

Instantaneous Flow Rate Testing with Simultaneous Spray Visualization of an SCR Urea Injector at Elevated Fluid Temperatures

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Selective Catalytic Reduction (SCR) diesel exhaust aftertreatment systems are virtually indispensable to meet NO_x emissions limits worldwide. These systems generate the NH_3 reductant by injecting aqueous urea solution (AUS-32/AdBlue®/DEF) into the exhaust for the SCR NO_x reduction reactions. Understanding the AUS-32 injector spray performance is critical to proper optimization of the SCR system. Specifically, better knowledge is required of urea sprays under operating conditions including those where fluid temperatures exceed the atmospheric fluid boiling point. Results were previously presented from imaging of an AUS-32 injector spray which showed substantial structural differences in the spray between room temperature fluid conditions, and conditions where the fluid temperature approached and exceeded 104° C and " ash boiling" of the fluid was initiated. Subsequent testing was conducted using a novel instantaneous flow meter (dINJ) which gave further insight into injector flow behavior under ash boiling conditions. The current work presents results obtained with the dINJ flow meter which for the first time are combined with simultaneous high speed video imaging to give a unique ability to analyze the injector flow and spray behavior. A description of the dINJ flow meter is provided. Testing was conducted at liquid spray and ash boiling operating points using a prototype design actively heated injector. A detailed analysis is presented of the injector flow and spray characteristics during the opening and closing transients, and some conclusions are drawn confirming previous observations of fluid evacuation from the sac volume after injector closing.

Injection Rate Measurement of GDI Systems Operating against Sub-Atmospheric and Pressurized Downstream Conditions

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In order to optimize gasoline direct injection combustion systems, a very accurate control of the fuel flow rate from the injector must be attained, along with appropriate spray characteristics in terms of drop sizing and jets global penetration/diffusion in the combustion chamber. Injection rate measurement is therefore one of the crucial tasks to be accomplished in order both to develop direct injection systems and to properly match them with a given combustion system. Noticeably, the hydraulic characteristics of GDI injectors should be determined according to a non-intrusive measuring approach. Unfortunately, the operation of all conventional injection analyzers requires the injection in a volume filled with liquid and the application of a significant counter-pressure downstream of the injector. This feature prevents any operation with low pressure injection systems such as PFIs. Also with GDI systems the need for a pressurized and liquid-filled volume or pipe downstream the injector can represent a significant limitation with respect to standard operating conditions, in which the injection takes place in a gaseous environment with counter-pressure ranging from sub-atmospheric to pressurized conditions. Further, the application of any diagnostics to the resulting spray is unfeasible. In the present paper an innovative Injection Analyzer called dINJ, which has been specifically developed to remove the need for a high downstream counter-pressure boundary condition, is assessed for GDIs in comparison with a conventional Zeuch's Method-based Analyzer. In previous papers, the efficacy of the dINJ for the injection rate analysis of low pressure injection systems has been demonstrated. The proposed instrument is based on the detection of the pressure time-history in a closed vessel acting as an isolated fuel rail during the injection process. The GDI can inject in atmosphere or in a closed vessel where the gaseous environment is maintained at the desired pressure level. By this approach, the prescribed upstream/ downstream operating conditions are obtained and the simultaneous application of diagnostics for the resulting spray analysis is allowed. Using the proposed instrument, the shot-to-shot injected quantity and injection rate time-profile detection can be determined for GDI injectors while operating against any pressure level.

Effect of Injector Nozzle Hole Geometry on Particulate Emissions in a Downsized Direct Injection Gasoline Engine

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In this study, the effect of the nozzle tip geometry on the nozzle tip wetting and particulate emissions was investigated. Various designs for the injector nozzle hole were newly developed for this study, focusing on the step hole geometry to reduce the nozzle tip wetting. The laser induced fluorescence technique was applied to evaluate the fuel wetting on the nozzle tip. A vehicle test and an emissions measurement in a Chassi-Dynamo were performed to investigate the particulate emission characteristics for injector nozzle designs. In addition, the in-cylinder combustion light signal measurement by the optical fiber sensor was conducted to observe diffusion combustion behavior during the vehicle test. Results showed that the step hole surface area is strongly related to nozzle tip wetting and particulate emissions characteristics. Injectors without the step hole and with a smaller step hole geometry showed significant reduction of nozzle tip wetting and number of particulate emissions.

Development of Air-Assisted Urea Injection Systems for Medium Duty Trucks

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Urea injection is required to meet EU IV to EU VI emission regulations as a main stream technical route to reduce nitrogen oxides (NOx). In heavy and medium duty trucks, compressed air at 3-5 bar is often available, therefore can assist urea injection by mixing with urea, forming liquid droplets, and releasing mixed fluid into the exhaust gases. The development of air assisted urea pump and injectors, or the assembly, seemingly simpler than airless counterparts, however poses multiple challenges. One challenge is to properly mix urea in the mixing chamber inside pump with the compressed air, leaving no residual deposits while achieving high mixing efficiency. Another is to maintain good spray quality for a given length of delivery pipe as the liquid phase and gas phase tend to coalesce as they propagate along the pipe flow direction. In addition, the urea pump and injector need to provide robust and reliable performance under stringent road conditions. Given these challenges, this paper addresses key development aspects for air assisted urea pump and injector with goals to provide insights on design improvements and validations.

Experimental and Numerical Characterization of Diesel Injection in Single-Cylinder Research Engine with Rate Shaping Strategy

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The management of multiple injections in compression ignition (CI) engines is one of the most common ways to increase engine performance by avoiding hardware modifications and after-treatment systems. Great attention is given to the profile of the injection rate since it controls the fuel delivery in the cylinder. The Injection Rate Shaping (IRS) is a technique that aims to manage the quantity of injected fuel during the injection process via a proper definition of the injection timing (injection duration and dwell time). In particular, it consists in closer and centered injection events and in a split main injection with a very small dwell time. From the experimental point of view, the performance of an IRS strategy has been studied in an optical CI engine. In particular, liquid and vapor phases of the injected fuel have been acquired via visible and infrared imaging, respectively. Injection parameters, like penetration and cone angle have been determined and analyzed. The data have been collected by running an engine condition of the homologation cycle New European Driving Cycle (NEDC) with two values of the swirl ratio. Computational activities, aiming at the simulation of the in-cylinder phenomena and specifically the injection process starting from experimental data, have been performed by adopting the 3D Ansys-Fluent solver. In particular, the fluid-dynamic calculations performed in a 3D domain, allowed to describe the spray evolution in the combustion chamber and carrying out the spray characteristics such as tip penetrations, Sauter mean diameters and droplets distributions. Besides, the spatial vapor distributions allowed detecting the mixing rate and the regions where the first flame spots should appear. After a proper identification of the parameters of the atomization model by a comparison with the experimental results, the CFD model potentialities for the prediction of the main features of new injection strategies should be verified. Such combined experimental and numerical activity would be able to point out the potential of IRS strategy with reduced nozzle diameter to improve the air/fuel mixing.

Preliminary Investigation of a Bio-Based Low Sulfur Heavy Fuel Oil

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Recently introduced sulfur caps on marine fuels in so-called sulfur emission control areas (SECAs) are forcing shipping companies to sail on more or less automotive grade diesel in lieu of the considerably less expensive, but sulfur-laden heavy fuel oil (HFO) to which they were accustomed. This development is an opportunity for a bio-based substitute, given that most biomass is sulfur free by default. Moreover, given that biomass is typically solid to start with, cracking it to an HFO grade, which is highly viscous in nature, will involve fewer and/or less harsh process steps than would be the case if an automotive grade fuel were to be targeted. In this study, a renewable low sulfur heavy fuel oil (LSHFO) has been produced by means of subcritical water assisted lignin depolymerization in the presence of a short length surfactant, ethylene glycol monobutyl ether (EGBE). The resulting oil contains a lignin derived content of 75 wt.-%, with the remainder consisting of EGBE and water (reusable). The derived LSHFO has a 20% higher heating value than the lignin feedstock. It is still roughly 20% and 30% lower when compared to the HFO and low sulfur marine gas oil (LSMGO) benchmarks, respectively. The lower heating value can be attributed to the fuel bond oxygen (10%) and water present in the LSHFO. Viscosity and sulfur levels, however, are within the HFO and LSMGO range and target respectively. Future work will examine what impact lignin particle size and surfactant type/concentration will have on the results.

Experimental Investigation of Fuel Injection and Spark Timing for the Combustion of n-Butanol and iso-Butanol and Their Blends with Gasoline in a Two-Cylinder SI Engine

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In this study, the combustion of butanol, neat and mixed with gasoline, was investigated on a 0.6 liter two-cylinder spark ignition engine with fully adjustable fuel injection and spark timing, coupled with an eddy current dynamometer. Two isomers of butanol, n-butanol and iso-butanol, were examined. This basic parameter study gives information about potential requirements of engine control systems for butanol FFV. Compared to the traditionally used ethanol, butanol does not exhibit hygroscopic behaviour, is chemically less aggressive and has higher energy density. On other hand, different laminar burning velocity and higher boiling temperature of butanol, compared to gasoline, requires some countermeasures to keep the engine operation reliable and efficient. Optimum spark timing for n-butanol, iso-butanol and their mixtures with gasoline, response to both lean and rich mixture composition, and three-way catalyst performance are reported and discussed for selected steady state operating conditions. For low loads, the results suggest a spark advance decrease, larger for n-butanol than for iso-butanol, while at higher loads, the optimal timing is comparable for all fuels. Deviation from stoichiometric mixture composition did not affect significant points of heat release of and its variability for all tested fuels and fuel mixtures. The three-way catalyst performance is generally comparable when either isomer of butanol in any concentration is used. Furthermore, for some components at certain conditions observed conversion efficiency was increased or decreased when butanol is combusted. Overall, the combustion of both n-butanol and iso-butanol and their mixtures with gasoline was, at steady state operation with fully heated engine, and after adjustments of spark timing and of fueling rate, comparable with gasoline. Starting of a cold engine, a known problematic aspect of using any alcohol fuel, was not addressed in this study.

Experimental Investigation on a DI Diesel Engine Using Waste Plastic Oil Blended with Oxygenated Fuels

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In this study, two oxygenated fuels consisting of butanol and diethyl ether (DEE), both possess same number of carbon, hydrogen and oxygen atom but difference functional group, were blended with the waste plastic pyrolysis oil to use in a 4-cylinder direct injection diesel engine without any engine modification. In addition, the effect of castor oil addition to such fuel blends was also investigated. Four tested fuels with same oxygen content were prepared for engine test, comprising DEE16 (84% waste plastic oil blended with 16% DEE), BU16 (84% waste plastic oil blended with 16% butanol), DEE11.5BIO5 (83.5% waste plastic oil blended with 11.5% DEE and 5% castor oil) and BU11.5BIO5 (83.5% waste plastic oil blended with 11.5% butanol and 5% castor oil). The results found that the DEE addition to waste plastic oil increased more HC and smoke emissions than the butanol addition at low engine operating condition. However the benefit to reduce HC and smoke was observed when the DEE blend was tested at high engine operating condition compared to the butanol blend, while CO and NOx was similar. The fuel blend with the combination of DEE and castor oil showed a more advantage to decrease HC, CO, NOx and smoke emissions at both engine operating conditions tested.

Numerical Analysis of a Spark-Ignition Engine Fueled by Ethanol-Gasoline and Butanol-Gasoline Blends: Setting the Optimum Spark Advance

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In this paper, the behavior of a downsized spark-ignition engine ring with alcohol/gasoline blends has been analyzed. In particular, different butanol-gasoline and ethanol-gasoline blends have been examined. All the alcohol fuels here considered are derived from biomasses. In the paper, a numerical approach has been followed. A one dimensional model has been tuned in order to simulate the engine operation when it is fueled by alcohol/gasoline mixtures. Numerous operating points, characterized by two different engine speeds and several low-medium load values, have been analyzed. The objective of the numerical analysis is determining the optimum spark advance for different alcohol percentages in the mixtures at the different engine operating points. Once the best spark timing has been selected, the differences, in terms of both indicated torque and efficiency, arising in the different kinds of fueling have been evaluated. Butanol-gasoline blends have led to torque values comparable to those obtainable with pure gasoline; while ethanol-gasoline blends have shown slightly higher torque values. The indicated efficiency increases by adding alcohol to gasoline, both using butanol and ethanol. Both engine torque and efficiency result almost linearly depending on the biofuel percentage in the fuel mixture. The spark advance results linearly decreasing with the biofuel amount in the mixture. This result allowed the authors writing an equation aimed to redefine the spark advance values to be implemented in the engine ECU in order to restore the best performances when fueling is switched from pure gasoline to alcohol-gasoline blends.

Assessment of the Full Thermodynamic Potential of C8-Oxygenates for Clean Diesel Combustion

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Within the Cluster of Excellence “Tailor-Made Fuels from Biomass” (TMFB) at the RWTH Aachen University, two novel biogenic fuels, namely 1-octanol and its isomer dibutyl ether (DBE), were identified and extensively analyzed in respect of their suitability for combustion in a Diesel engine. Both biofuels feature very different properties, especially regarding their ignitability. In previous works of the research cluster, promising synthesis routes with excellent yields for both fuels were found, using lignocellulosic biomass as source material. Both fuels were investigated as pure components in optical and thermodynamic single cylinder engines (SCE). For 1-octanol at lower part load, almost no soot emission could be measured, while with DBE the soot emissions were only about a quarter of that with conventional Diesel fuel. At high part load (2400 min^{-1}, 14.8 bar IMEP), the soot reduction of 1-octanol was more than 50% and for DBE more than 80 % respectively. Based on these promising initial results, this paper will report about additional experimental investigations that were initiated to exploit the complete potential of both advanced biofuels in terms of emissions and efficiency. A single cylinder research engine was utilized and the engine calibration was optimized using design of experiments at lower and higher part load. At high part load, it was possible to increase the efficiency by more than one percent point compared to the Diesel reference in the same load point. Furthermore, the already low soot emissions of both biofuels, compared to Diesel fuel, could also be further halved compared to the base calibration. In a last step, a sensitivity analysis was performed in order to validate the previously built models and to get further insight into the influence of the single calibration parameters on engine performance.

Spray Combustion Analysis of Humins

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Second generation biomass is an attractive renewable feedstock for transport fuels. Its sulfur content is generally negligible and the carbon cycle is reduced from millions to tens of years. One hitherto non-valorized feedstock are so-called humins, a residual product formed in the conversion of sugars to platform chemicals, such as hydroxymethylfurfural and methoxymethylfurfural, intermediates in the production of FDCA, a building block used to produce the polyethylene furanoate (PEF) bottle by Avantium. The focus of this study is to investigate the spray combustion behavior of humins as a renewable alternative for heavy fuel oil (HFO) under large two-stroke engine-like conditions in an optically accessible constant volume chamber. To reduce the viscosity to HFO levels of the otherwise crystalline humins, methyl levulinate (ML), another side-stream from the same sugar dehydration process, is blended to the former compound at 25 wt.-%; a ratio comparable to that actually produced in many dehydration processes. Various fuel properties of interest, including elemental composition, heating value, density, ignition quality, acid number, ash point, pour point, carbon residue, sediment, water and ash content are measured for the resulting humins-ML blend. The blend is injected into an optically accessible constant volume chamber, the dimensions, injector characteristics and prevailing ambient conditions of which are representative of those found in large two-stroke marine engines. Commercial HFO is used as a benchmark. The combustion process is evaluated by means of shadow imaging and OH*-chemiluminescence. The former and latter optical techniques are used to determine the phasing and overall magnitude of the heat release event, and ignition delay/location and flame lift off length, respectively. From the results becomes clear that the average ignition delay is comparable to that of HFO, albeit at a higher cycle-to-cycle variation. Notwithstanding a longer lift off length and more downstream ignition kernels, the overall results suggest that the proposed bio-blend is a feasible renewable alternative for HFO in terms of technical feasibility.

Engine Modeling and Controls
Engine Combustion
Fuels and Lubricants Technologies

Emissions and Emissions Controls

New Engines, Components, Actuators, & Sensors
Hybrid and Electric Powertrains, including Range Extending Engines

Exhaust Emissions Control: 60 Years of Innovation and Development

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The earliest public domain reference regarding full engine testing of an automotive catalyst was from January 1959, written by GM and presented at the annual SAE meeting in Detroit. This current publication will review the first public domain paper referencing different aftertreatment technologies (such as TWC, LNT, DPF and SCR, but not limited to these technologies) and compare the technologies to the current state of the art in aftertreatment technology. This historical review using a range of databases, will show how exhaust aftertreatment technologies have significantly enhanced emissions control over the last 60 years for both gasoline and diesel applications. A timeline will be given showing when various technologies were first presented into the public domain. This will indicate how long it has taken certain emissions control technologies to enter the market.

Control Oriented Modeling of SCR Systems for Automotive Application

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In the last decades, NO_x emissions legislations for Diesel engines are becoming more stringent than ever before and the selective catalytic reduction (SCR) is considered as the most suitable technology to comply with the upcoming constraints. Model-based control strategies are promising to meet the dual objective of maximizing NO_x reduction and minimizing NH_3 slip in urea-selective catalytic reduction. In this paper, a control oriented model of a Cu-zeolite urea-SCR system for automotive diesel engines is presented. The model is derived from a quasi-dimensional four-state model of the urea-SCR plant. To make it suitable for the real-time urea-SCR management, a reduced order one-state model has been developed, with the aim of capturing the essential behavior of the system with a low computational burden. Particularly, the model allows estimating the NH_3 slip that is fundamental not only to minimize urea consumption but also to reduce this unregulated emission. Parameters identification and model validation have been performed vs. simulation data achieved by a commercial code of the SCR system, based on the four-state quasi-dimensional modeling approach. The accuracy of the reduced-order model is demonstrated by comparing NO, NO_2 and NH_3 concentrations with those simulated by the more complex reference model. It is observed that the one state model allows estimating the SCR behavior with good accuracy and low computational demand thus being suitable for real-time application.

Robust DPF Regeneration Control for Cost-Effective Small Commercial Vehicles

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Small commercial vehicles (SCV) with Diesel engines require efficient exhaust aftertreatment systems to reduce the emissions while keeping the fuel consumption and total operating cost as low as possible. To meet current emission legislations in all cases, a DOC and DPF and some NOx treatment device (e,g. lean NOx trap or SCR) are required. Creating a cost-effective SCV also requires keeping the cost for the exhaust aftertreatment system as low as possible because the contribution to total vehicle cost is high. By using more sophisticated and more robust operating strategies and control algorithms, the hardware cost can be reduced. To keep the calibration effort at a low level, it is necessary to apply only algorithms which have a time-efficient calibration procedure. This paper will focus on the active regeneration of the DPF. For safe and efficient DPF regeneration, a very reliable and stable DOC out temperature control is required. DOC characteristics and design are often limited by cost and available space but also strongly influence the control requirements and thus the performance. This leads to more sophisticated and more robust control algorithms. In this paper an advanced control algorithm for DOC outlet temperature control for a SCV is presented. The control algorithm applies model-based control and gain-scheduling techniques. An overview over the control algorithm is given and its performance is evaluated on engine test bench, chassis dynamometer and on the public road and compared to the traditional concept which was used before. The results and experiences are presented and analyzed.

Investigations of Lean NOx Trap (LNT) Regeneration Strategies for Diesel Engines

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To minimize nitrogen oxide (NOx) as well as carbon monoxide (CO) and hydrocarbon (HC) emissions to fulfil the new European real driving emissions (RDE) legislation, the LNT operation strategy - especially for DeNOx events (rich mode) - has to be optimized. On one hand the DeNOx purges should be long enough to fully regenerate the lean NOx trap, on the other hand the purges should be as short as possible to reduce the fuel consumption penalty from rich mode. Fundamental experiments have been conducted on a synthetic-gas- test-bench, purposely designed to test LNT catalysts. This methodology allowed to remove NOx from the gasfeed after the lean storage phase. The actually reduced amount of NOx could be easily calculated from the NOx storage before a regeneration event minus the NOx that was desorbed during the DeNOx event and afterwards thermally desorbed NOx. The results show the effect of different space velocities, catalyst temperatures and DeNOx durations (as a function of purge duration and purge splitting) on the DeNOx efficiency and rich gas emissions as well as secondary emissions. Temperature variations indicated that the LNT could be easier regenerated at 300°C than at 250°C. Higher space velocities led to shorter regeneration durations than lower space velocities. The DeNOx pulse duration was varied by DeNOx pulse splitting at a constant cumulated rich time per regeneration event. The results showed that shorter pulses could lead to the same DeNOx efficiency as a long single purge, to lower CO and HC emissions but also to an increased dinitrogen oxide formation. By varying the purge duration with single pulses it was observed, that the regeneration efficiency was highest in the first seconds of the DeNOx. By a reduction of DeNOx pulse duration CO and HC emissions were reduced without decreasing the LNT regeneration performance.

A Comparative Analysis of Active and Passive Emission Control Systems Adopting Standard Emission Test Cycles

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The aim of the present work is to analyse and compare the energetic performances and the emissions conversion capability of active and passive aftertreatment systems for lean burn engines. To this purpose, a computational one-dimensional transient model has been developed and validated. The code permits to assess the heat exchange between the solid and the exhaust gas, to evaluate the conversion of the main engine pollutants, and to estimate the energy effectiveness. The response of the systems to variations in engine operating conditions have been investigated considering standard emission test cycles. The analysis highlighted that the active flow control tends to increase the thermal inertia of the apparatus and then it appears more suitable to maintain higher temperature level and to guarantee higher pollutants conversion at low engine loads after long full load operation. Conversely, the unidirectional flow is preferable when a rapid heating (i.e., cold start, warm up phase, etc.) is required. Depending on the engine load and the requested converter thermal level, the coupled operation of active and passive flow represents the possible strategy apt to improve the system performances.

Optical and Analytical Studies on DPF Soot Properties and Consequences for Regeneration Behavior

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The removal of particulate matter (PM) from diesel exhaust is necessary to protect the environment and human health. To meet the strict emission standards for diesel engines an additional exhaust aftertreatment system is essential. Diesel particulate filters (DPF) are established devices to remove emitted PM from diesel exhaust. But the deposition and the accumulation of soot in the DPF influence the filter back pressure and therefore the engine performance and the fuel consumption. Thus a periodical regeneration through PM oxidation is necessary. The oxidation behavior should result in an effective regeneration mode that minimizes the fuel penalty and limits the temperature rise while maintaining a high regeneration efficiency. Excessive and fast regenerations have to be avoided as well as uncontrolled oxidations, which may lead to damages of the filter and fuel penalty. The thermal control during the soot oxidation poses a challenge resulting from the lack of knowledge concerning the operation behavior of the DPF. In this study, a method to investigate the influences of operating conditions on the inflow and the soot deposition inside the DPF as well as the following regeneration is presented. For that purpose, the inflow is visualized by Particle Image Velocimetry (PIV) to identify the origins of the nonuniform soot distribution inside the DPF. Structural changes of the deposited soot are studied via Raman Spectroscopy. The distribution of inorganic ash components is studied via laser ablation with Inductively-coupled plasma mass spectrometry (LA-ICP-MS). Soot reactivity is quantified with Thermogravimetric Analysis (TGA) and the calculation of oxidation kinetics. By combining analytical and optical measurement techniques the influences of the physical and chemical properties of the soot on the regeneration process can be derived. Furthermore, possibilities can be demonstrated how to manage regeneration processes at lower exhaust temperatures which result from improvements of combustion engines and hybridization.

Fundamental Study of GPF Performance on Soot and Ash Accumulation over Artemis Urban and Motorway Cycles - Comparison of Engine Bench Results with GPF Durability Study on Road

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With the increased use of engines utilizing direct fuel injection and the upcoming introduction of more stringent emissions legislation that regulates not only particulate mass (PM) but also particulate number (PN), the emissions from Direct Injection Spark Ignition Engines (DISI) are an increasing concern. Gasoline Particle Filters (GPF) represent a potential way to reduce particle number emissions from DISI engines and are particularly effective considering the tough performance requirements during cold start and over RDE operation. Even though some learning from the development and application of particulate filters to diesel engines can be transferred to gasoline engines, the particle composition, mass to number ratio as well as the exhaust gas temperature and composition from gasoline engines are significantly different to diesel engines. Therefore, there is the need to study the application of particulate filters to gasoline engines in more depth. Of particular concern, is the understanding of the ash accumulation mechanism within the GPF and its negative impact on the backpressure over lifetime. This paper presents the results from a fundamental study of an uncoated ceramic GPF in the exhaust after-treatment system of a 1.6 litre turbo DISI engine. Soot and ash accumulation data are reported comparing two aggressive driving cycles (Artemis Urban vs. Artemis Motorway). Each cycle was operated for 20k km on a dynamic engine bench. PN emissions were then measured over WLTC and NEDC test cycles after 20k km. The results are discussed with respect to the differences from each cycle for the ash formation and backpressure increase; it also considers the possibility of extrapolating the results to a more balanced driving pattern over 160km. Results from the engine bench investigation are compared to a vehicle durability run, using the same engine and type of GPF in the under-floor (UF) location. Results show PN filtration efficiency of the GPF, above 70% in fresh condition and above 90%

with increasing mileage. Further, low soot accumulation and low ash amounts were detected after the durability run was completed. Ash is mainly related to the oil consumption of the engine and small differences were observed between the two Artemis cycles. In particular the Artemis Urban cycle shows higher ash amount over 20k km (1.26 g/l) compared to the Artemis Motorway (0.4 g/l). These ash values from the engine bench correlate well with the findings of the vehicle durability run. Post mortem analysis (PMA) of the GPF after both engine bench and vehicle durability tests are also reported.

Evaluating Performance of Uncoated GPF in Real World Driving Using Experimental Results and CFD modelling

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Environmental authorities such as EPA, VCA have enforced stringent emissions legislation governing air pollutants released into the atmosphere. Of particular interest is the challenge introduced by the limit on particulate number (PN) counting (#/km) and real driving emissions (RDE) testing; with new emissions legislation being shortly introduced for the gasoline direct injection (GDI) engines, gasoline particulate filters (GPF) are considered the most immediate solution. While engine calibration and testing over the Worldwide harmonized Light vehicles Test Cycle (WLTC) allow for the limits to be met, real driving emission and cold start constitute a real challenge. The present work focuses on an experimental durability study on road under real world driving conditions. Two sets of experiments were carried out. The first study analyzed a gasoline particulate filter (GPF) (2.4 liter, diameter 5.2" round) installed in the under floor (UF) position and driven up to 200k km. A 1.6 liter Gasoline Direct Injection (GDI) engine was used for the investigation. Ash accumulation versus mileage and soot loading were of interest. A parallel investigation up to 160k km with same engine (2 identical vehicles on an "average customer driving" cycle) and GPF installed in close-coupled (CC) position was also carried out. Both UF and CC GPF are NGK 360 cpsi (i.e. cells per square inch), 5 mil wall thickness. As a route to develop a robust 3-D Computational Fluid Dynamics (CFD) model to gather information on the fluid flow and pressure loss characteristics of GPF, a baseline model is introduced in this work. The computational domain refers to full length individual 3-D channels and focuses on two quarters of an inlet and two quarters of an outlet channel with the aim of reducing complexity of the problem and its computational cost. Although this baseline version does not include yet the soot and ash loading models, it can be used for understanding real physical problems and gather insight on velocity and pressure distributions inside filter and its channels.

Rig Test of Diesel Combustion Chamber with Piston Coated by Optically Simulated Semitransparent PSZ-Ceramic

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Running efficiency of LHR diesel has been confirmed by mean of well-known types of heat-insulating (HICs) or thermal barrier (TBCs) coatings. These materials are considered as a semitransparent media SHICs (STBCs) in the form of an ensemble of diffraction objects, forming own thermoradiative fields under the scattering theory laws. This problem is relevant for a diesel with combustion chamber (CC) in which intensive IR radiation reaches ~50% of total thermal flux. The authors indicate that predetermined selection of optical and thermoradiative parameters in the same spectrum for coatings (due to specific structural composition and porosity) can change their temperature fields inside its subsurface zone and hence in the CC gas volume. Previous author's research of optical parameters for ceramic semitransparent materials allowed offering SHIC (STBC) samples for rig testings. Optically simulated absorption and scattering indices for SHICs fix their thermoradiative fields which determine the formation of optimal temperature profile inside ceramic coatings at the type conditions of diesel CC operation. A number of the latest rig testings of diesel engines with coated piston by PSZ-ceramics were studied from the point of influence on the radiant heat exchange by semitransparent coatings deposited on the CC internal surfaces. Analysis and reasons of reducing the specific fuel consumption at high speeds using SHICs (STBCs) were carried out. In view of the known literature data on rig testings of LHR diesel and also experimentally measured optical parameters of semitransparent and opaque coatings it became possible for the first time to calculate correctly its temperature fields. Subsurface heating of semitransparent ceramic coats specifies the possibility of thermoregulation for the piston surface with SHICs (by varying its structure) in contrast to the use of opaque HICs. Such PSZ-ceramics were recommended for application and improvement of operating conditions of diesel CC piston protected by means of coats with selected optical and thermal physical characteristics. The usage of the suggested methodology in contemporary

industry enables to intensify significantly R&D for LHR diesel and to ensure advanced management of its combustion-exhaust system temperatures, the required regime of thermoregulation for heat-insulated CC wall surfaces and generation reduction of the most toxic NO_x.

Improvement of the Control-Oriented Model for the Engine-Out NO_x Estimation Based on In-Cylinder Pressure Measurement

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Nowadays, In-Cylinder Pressure Sensors (ICPS) have become a mainstream technology that promises to change the way the engine control is performed. Among all the possible applications, the prediction of raw (engine-out) NO_x emissions would allow to eliminate the NO_x sensor currently used to manage the after- treatment systems. In the current study, a semi-physical model already existing in literature for the prediction of engine-out nitric oxide emissions based on in-cylinder pressure measurement has been improved; in particular, the main focus has been to improve nitric oxide prediction accuracy when injection timing is varied. The main modification introduced in the model lies in taking into account the turbulence induced by fuel spray and enhanced by in-cylinder bulk motion. The effectiveness of the new model has been tested with data acquired during an extensive experimental campaign during which a 2.0l 4 cylinders Diesel engine, whose after-treatment system allows to fulfil the EU6 legislation limits, has been operated on the overall engine map. It is shown that, comparing measured and estimated NO_x on a wide range of engine settings, the improved model is quite effective in capturing the effect of injection timing on engine-out NO_x emissions: the average error between measured and estimated NO_x is reduced of about 10% while the correlation coefficient is increased from 0.86 to 0.97.

Dynamic Validation and Sensitivity Analysis of a NOx Estimation Model Based on In-Cylinder Pressure Measurement

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The incoming RDE regulation and the on-board diagnostics -OBD- pushes the research activity towards the set-up of a more and more efficient after treatment system. Nowadays, the most common after treatment system for NOx reduction is the selective catalytic reduction -SCR- . This system requires as an input the value of engine out NOx emission -raw- in order to control the Urea dosing strategy. In this work, an already existing grey box NOx raw emission model based on in-cylinder pressure signal (ICPS) is validated on two standard cycles: MNEDC and WLTC using an EU6 engine at the test bench. The overall results show a maximum relative error of the integrated cumulative value of 12.8% and 17.4% for MNEDC and WLTC respectively. In particular, the instantaneous value of relative error is included in the range of ± 10% in the steady state conditions while during transient conditions is less than 20% mainly. Finally, a sensitivity analysis is conducted in order to understand how the model "answers" to any air and fuel parameter deviation.

The Impact of WLTP on the Official Fuel Consumption and Electric Range of Plug-in Hybrid Electric Vehicles in Europe

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Plug-in Hybrid Electric Vehicles (PHEVs) are one of the main technology options for reducing vehicle CO_2 emissions and helping vehicle manufacturers (OEMs) to meet the CO_2 targets set by different Governments from all around the world. In Europe OEMs have introduced a number of PHEV models to meet their CO_2 target of 95 g/km for passenger cars set for the year 2021. Fuel consumption (FC) and CO_2 emissions from PHEVs, however, strongly depend on the way they are used and on the frequency with which their battery is charged by the user. Studies have indeed revealed that in real life, with poor charging behavior from users, PHEV FC is equivalent to that of conventional vehicles, and in some cases higher, due to the increased mass and the need to keep the battery at a certain charging level. The discrepancy between official and real life figures of FC, electric range, and CO_2 emissions has been often attributed, at least partly, to the inadequacy of the New European Driving Cycle (NEDC) to represent the real-world conditions of vehicle use. In an attempt to deal with this problem, which has strong implications on the effectiveness of the CO_2-reduction policies, the European Commission has decided to introduce already in 2017 the Worldwide Harmonized Light Vehicles Test Procedure (WLTP). Aim of the present work is to compare WLTP and NEDC procedures for what concerns the determination of fuel consumption (FC), CO_2 emissions and electric ranges of two plug-in hybrid vehicles tested in the Joint Research Centre (JRC) of the European Commission laboratories. Results show that the electric range determined following the WLTP procedure is significantly shorter than the NEDC electric range. On the contrary, results show that WLTP-based FC and CO_2 will tend to be lower than the corresponding NEDC-based values with the increase in the battery size and corresponding electric range.

Development of a Gasoline Particulate Filter for China 6(b) Emission Standards

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New emissions regulations of light-duty vehicles (China 6) will be implemented in China from July 1, 2020. This standard includes two stages, China 6a and China 6(b), in which the PM limits of 4.5 mg/ km and 3.0 mg/km are introduced respectively; the PN limit is set to be 6×10^{11}#/km for both stages. The WLTC testing cycle will be implemented in China 6 regulation as well. In this study a light-duty vehicle satisfying China 6(b) emission standards was developed by improving the engine raw emissions, optimizing the calibration and adding a coated GPF to the after-treatment system. The impacts of ash content and consumption of engine oil and the fast ash accumulation to vehicle emissions and backpressure were analyzed through dynamometer testing. The vehicle after-treatment system was then designed and developed to meet China 6(b) emission standards. The characteristics of soot accumulated through mimicking routine driving under cold environments were tested. The critical conditions of passive regeneration and the controlling strategies of active regenerations of GPF were also studied.

Further Analysis of the Effect of Oxygen Concentration on the Thermal Aging of Automotive Catalyst

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With emission legislations becoming ever more stringent there is an increased pressure on the after-treatment systems, and more specifically the three-way catalysts. With recent developments in emission legislations, there is requirement for more complex after-treatment systems and understanding of the aging process. With future legislation introducing independent inspection of emissions at any time under real world driving conditions throughout a vehicle life cycle this is going to increase the focus on understanding catalyst behavior during any likely conditions throughout its lifetime and not just at the beginning and end. In recent years it has become a popular approach to use accelerated aging of the automotive catalysts for the development of new catalytic formulations and for homologation of new vehicle emissions. To accelerate the catalyst aging, the samples experience high temperatures of 800°C and higher on a recognized aging cycle for a specific time which can be related back to vehicle mileage. As opposed to using large gasoline engines, alternative bench-aging techniques are becoming more frequently used, including synthetic gas bench reactors. Bench reactors offer more exibility, greater repeatability and opportunity for more precise control over variables providing greater development possibilities. Whilst the body of understanding on catalyst deactivation and, in particular, catalyst aging is growing, there are still significant gaps in understanding, particularly how real world variations in temperature, flow rate and gas concentrations affect catalyst behavior. Under normal driving conditions the catalyst can experience varying oxygen concentrations, such as under heavy acceleration or cruising down a hill will show a variation in oxygen from the engine emissions. The effect of varying oxygen concentrations has on the rate of aging is not fully understood and hence the total deactivation and efficiencies are not known throughout the catalyst lifetime. Current algorithms used in industry do not fully account for these variations in oxygen concentrations. This paper presents a continuation of previous work into the investigation of the effect of varying oxygen concentration on the rate of catalyst aging. A number of commercially available

palladium three-way catalysts were aged over a precise temperature cycle at varying oxygen concentrations for different aging times related back to a mileage. The results were analyzed in detail and compared with predictions based on the standard aging algorithm and with others proposed in literature.

Fast Hybrid Sensor for Soot of Production CI Engines

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During transients, engines tend to produce substantially higher peak emissions like soot - the main fraction of particular matter (PM) - which are the longer the more important as the steady state emissions are better controlled. While Diesel particulate filters are normally able to block them, preventing their occurrence would of course be more important. In order to achieve this goal, however, they must be measurable. While for most emissions commercial sensors of sufficient speed and performance are available, the same is not true for PMs, especially for production engines. Against this background, in the last years the possible use of a full stream 50Hz sensor based on Laser Induced Incandescence (LII) was investigated, and the results were very encouraging, showing that the sensor could recognize transient changes undetected by conventional measurement systems (like the AVL Opacimeter) but confirmed by the analysis of combustion. This was also related to the position of the sensor which can be mounted upstream or downstream of the turbine in a turbocharged CI engine. The measurement is instantaneous, without dilution or transport, and this raises also the question about accuracy, as the variability of the particulate flow near to the sensor will be directly visible in the sensor output. To reduce this effect, we propose a hybrid sensor approach in which the final reading is computed by a suitable combination of the output of the photodiodes and operation information of the engine, e.g. the pressure and temperature near to the sensor location. This paper presents the methodology as well as an experimental assessment. All measurements have been done on a production 2 lt Euro 5 CI engine.

Statistical Determination of Local Driving Cycles Based on Experimental Campaign as WLTC Real Approach

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In the context of a transport sustainability, some solutions could be proposed from the integration of many disciplines, architects, environmentalists, policy makers, and consequently it may be addressed with different approaches. These solutions would be applied at different geographical levels, i.e. national, regional or urban scale. Moreover, the assessment of cars emissions in real use plays a fundamental role for their reductions. This is also the direction of the new harmonized test procedures (WLTP). Furthermore, it is fundamental to keep in mind that the new WLTC cycle will reproduce a situation closer to the reality comparing to the EUDC/NEDC driving cycle. In this paper, we will be focused on vehicle kinematic evaluation aimed at valuation of traffic situation and emissions. For this purpose, driving data and emissions were acquired during an experimental campaign through six instrumented vehicles by PEMS for the simultaneous acquisition of emissions, kinematic variables and GPS localization data. Moreover, the analyzed vehicles have different type approval classes and different displacements. At this time, we present a different statistical approach to classify the pieces of speed parts in order to identify typical traffic situation and their emission evaluation. Finally, apply some statistical criteria, and going in the same direction of WLTC, a driving cycle composed by a succession of speed parts was built.

Estimation of DPF Soot Loading through Steady-State Engine Mapping and Simulation for Automotive Diesel Engines Running on Petroleum-Based Fuels

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The aim of the present study is to improve the effectiveness of automotive diesel engine and aftertreatment calibration process through the critical evaluation of several methodologies to estimate the soot mass flow produced by diesel engines fueled by petroleum fuels and filtered by Diesel Particulate Filters (DPF). In particular, its focus has been the development of a reliable simulation method for the accurate prediction of the engine-out soot mass flow starting from Filter Smoke Number (FSN) measurements executed in steady state conditions, in order to predict the DPF loading considering different engine working conditions corresponding to NEDC and WLTP cycles.
In order to achieve this goal, the study was split into two main parts:

- Correlation between 'wet PM' (measured by soot filter weighing) and the 'dry soot' (measured by the Micro Soot Sensor MSS). Test activities have been carried out taking into account different boundaries conditions such as calibration, driving cycle, sampling probes positions;
- Identification of a reliable and accurate method that allows estimating the 'dry soot' starting from the FSN measurements. Different equations available in literature have been investigated. According to the test results, it has been selected the one which allows to better correlate the simulation output with the MSS sensor measurement over different test cycles.

Therefore, by linking the steady-state FSN measurements to MSS instantaneous readings, and in turn, the MSS cumulative reading to soot filter weighting, the study helped to contribute a simulation method which bridges the gap between the commonly available FSN readings and the reference technique used in the literature, the soot filter weighting, which for several reasons may not be easily available during the engine development process. Furthermore, the performed test activities lead the Authors to a few best practices for the soot measurement in both steady-state and transient conditions, including sampling probes installation. They allow to measure repeatable data during the test activities and avoid inconsistencies during the engine development.

Analysis of the Influence of Outdoor Temperature in Vehicle Cold-Start Operation Following EU Real Driving Emission Test Procedure

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Due to the need to properly quantify vehicle emissions in real world operation, Real Driving Emissions (RDE) test procedures will be used for measuring gaseous emissions on new EURO 6 vehicles at the RDE 1 & 2: Commission Regulation (EU) 2016/427 of 10 March 2016 amending Regulation (EC) No 692/2008 as regards emissions from light passenger and commercial vehicles. Updated regulations have been enhanced to define RDE tests boundaries and data analysis procedures, in order to provide an accurate way to obtain representative results. The boundary conditions defined for vehicle testing include external atmospheric temperature, which can range from 0°C to around 30°C, for moderate conditions and -7°C up to 35°C for extended conditions in RDE tests. As a result of this range of possible test ambient temperature, pollutant emissions and energy consumption can vary considerably. Since the cold start phenomenon occurs in internal combustion engine (ICE) powered vehicles before the ICE reaches its most effective operation temperature, it affects both fuel consumption (due to higher heat losses) and pollutant emissions (mainly due to low exhaust temperature below activating temperature for after-treatment devices like SCR). This is an issue relevant in regular daily operations of a vehicle, which will also pose uncertainties in RDE tests. Consequently, this work studies the effect of external environmental temperature in RDE tests, focusing on the analysis of the cold-start period in energy consumption and NO_x emissions. Two vehicles (one diesel and one gasoline) were monitored, covering external temperatures from circa 1°C to 17°C (considered ranges of 5°C up to 15°C) in Lisbon, Portugal. A Portable Emissions Measurement System (PEMS) was used to collect 1 Hz data on vehicle dynamics, road topography, engine data and exhaust gas composition.

Data collected on both powertrain configurations is compared and analyzed using European Commission proposed method for RDE tests, as well as other methods to observe the impact of the cold-start phenomena in the normal day-to-day usage of vehicles. For the determination of cold-start periods, coolant temperature data was used as proxy to determine cold and normal operation. Results indicate that the initial ambient temperature have impacts in the duration of the cold-start period during a RDE test but not as relevant as expected, mostly at low temperatures compared to higher temperatures. NO_x emissions can be around 30% higher in near 5°C temperatures for the diesel vehicle tested when compared with the other temperatures range. For the gasoline vehicle tested, the effect of the ambient outdoor temperature is not as significant as in diesel vehicles.

Experimental Investigations on the Sources of Particulate Emission within a Natural Gas Spark-Ignition Engine

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The aim of the present work is to provide further guidance into better understanding the production mechanisms of soot emissions in Spark-Ignition SI engines fueled with compressed natural gas. In particular, extensive experimental investigations were designed with the aim to isolate the contribution of the fuel from that of lubricant oil to particle emissions. This because the common thought is that particulate emerging from the engine derives mainly from fuel, otherwise the contribute of lubricant oil cannot be neglected or underestimated, especially when the fuel itself produces low levels of soot emissions, such as in the case of premixed natural gas. The fuel-derived contribution was studied by analyzing the influence that natural gas composition has on soot emitted from a single cylinder Spark-Ignition (SI) engine. To achieve this purpose, methane/propane mixtures were realized and injected into the intake manifold of a Single-Cylinder SI engine. The results were compared with pure methane and propane, as well as with natural gas. The lubricant-derived contribution was investigated by injecting lubricant oil either into the intake manifold or directly within the combustion chamber of an optically-accessible version of the engine, requiring no lubrication, in order to mimic the different ways by which lubricant may reach the combustion chamber. The influence on soot emission was assessed in terms of particle number and size distributions. Gaseous emissions and engine performance were also analyzed in order to globally monitor the combustion process. The results indicated that variations in propane content can have strong effects on both performance and emissions. In all tests, natural gas showed the highest PN values. In addition, the results demonstrated that the number of ultrafine particles was very sensitive to the propane fraction at high speeds, because adding propane increased the number of particles between 5 and 30 nm. The effect of feeding the extra lubricant oil was to increase the particles emitted in the lowest range size, independent of the way it was added within the engine.

Combustion Characteristics and Particulate Matter Number Size Study of Ethanol and Diesel Reactivity Controlled Compression Ignition Engine

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The main aim of this work is to characterize the combustion phenomena and particulate matter in nano-size from the reactivity controlled compression ignition (RCCI) engine using neat hydrous ethanol as a low reactivity fuel. A four-cylinder diesel engine fueled with diesel (the volumetric blend of 95% petroleum diesel and 5% palm-based biodiesel) was operated on low and medium loads at 2,500 rpm without main diesel fuel injection modification and exhaust gas recirculation. Ethanol was injected at 1 bar pressure into the intake manifold while the w/w ratios of ethanol:diesel were varied between 0 and 0.77. An engine indicating system composed of an in-cylinder pressure transducer and a shaft encoder was used to investigate combustion characteristics using the first law of thermodynamics. A Scanning Mobility Particle Sizer and an Optical Particle Sizer were used to determine the particle number concentration and distribution over nano-size range. The increased portion of ethanol pre-mixture results in longer ignition delay corresponding to the reduction in main diesel fuel consumption. Compared with diesel fuel combustion, the higher ethanol pre- mixture leads to a smaller average size of the particles but gives rise to a higher number concentration.

How Much Regeneration Events Influence Particle Emissions of DPF-Equipped Vehicles?

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Diesel particulate filter (DPF) is the most effective emission control device for reducing particle emissions (both mass, PM, and number, PN) from diesel engines, however many studies reported elevated emissions of nanoparticles (<50 nm) during its regeneration. In this paper the results of an extensive literature survey is presented. During DPF active regeneration, most of the literature studies showed an increase in the number of the emitted nanoparticles of about 2-3 orders of magnitude compared to the normal operating conditions. Many factors could influence their amount, size distribution, chemical- physical nature (volatiles, semi-volatiles, solid) and the duration of the regenerative event: i.e. DPF load and thermodynamic conditions, lube and fuel sulfur content, engine operative conditions, PN sampling and measurement methodologies. Moreover some experimental tests were performed at Istituto Motori' labs with three Diesel vehicles (a Euro 5 2.2 liter van, and two medium size passenger cars) to estimate the effect of regeneration events in terms of both occurrences and emissions output. ELPI (Electrical Low Pressure Impactor) by Dekati, sampling directly from the tailpipe with a double stage dilution FPS, was employed to measure the size distributions of the total emitted particles in the range 7 nanometer up to 10 micron. Regeneration events were studied during NEDC, WLTC and Artemis driving cycles and they exhibited considerable variations in the time for cleaning as well as in the amount of PN emissions.

Catalytic Activity of Nanostructured Ceria-Based Materials Prepared by Different Synthesis Conditions

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In this work, several nanostructured ceria-based catalysts were prepared by the hydrothermal technique varying two synthesis parameters (namely, temperature and pH). Then, cerias with different shapes (*i.e.*, cubes, rods, combination of them, other polyhedra) and structural properties were obtained. The prepared materials were tested for the CO oxidation and soot oxidation efficiency. The results have shown that, for the CO oxidation, activities depend on the surface properties of the catalysts. Conversely, for the soot oxidation, the most effective catalysts exhibit better soot-catalyst contact conditions.

Engine Modeling and Controls
Engine Combustion
Fuels and Lubricants Technologies
Emissions and Emissions Controls
<u>New Engines, Components, Actuators, & Sensors</u>
Hybrid and Electric Powertrains, including Range Extending Engines

Resonance Charging Applied to a Turbo Charged Gasoline Engine for Transient Behavior Enhancement at Low Engine Speed

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Upcoming regulations and new technologies are challenging the internal combustion engine and increasing the pressure on car manufacturers to further reduce powertrain emissions. Indeed, RDE pushes engineering to keep low emissions not only at the bottom left of the engine map, but in the complete range of load and engine speeds. This means for gasoline engines that the strategy used to increase the low end torque and power by moving out of lambda one conditions is no longer sustainable. For instance scavenging, which helps to increase the enthalpy of the turbine at low engine speed cannot be applied and thus leads to a reduction in low-end torque. Similarly, enrichment to keep the exhaust temperature sustainable in the exhaust tract components cannot be applied any more. The proposed study aims to provide a solution to keep the low end torque while maintaining lambda at 1. The tuning of the air intake system helps to improve the volumetric efficiency using resonance charging effects. Actually it is possible to set up the intake line geometry to get high wave amplitude even at low frequency and thus low engine speed. Impact on combustion and mainly on knocking risk has to be taken into account. The system benefits are evaluated directly for steady conditions using simulation and measurement data. As the dynamic behavior is also a main target some transient load measurements are conducted. These tests simulate a strong torque demand while keeping the same engine speed. The last criteria consists of the simulation of vehicle behavior, considering its weight and drag coefficient, and applying the torque demand to the engine on the test bench. The results are the acceleration time for a defined speed range, such as the well-known 80-120km/h.

Development of an Innovative Combustion Process: Spark-Assisted Compression Ignition

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In the competition for the powertrain of the future the internal combustion engine faces tough challenges. Reduced environmental impact, higher mileage, lower cost and new technologies are required in order to maintain its global position both in public and private mobility. For a long time, researchers have been investigating the so called Homogeneous Charge Compression Ignition (HCCI) that promises a higher efficiency due to a rapid combustion - i.e. closer to the ideal thermodynamic Otto cycle - and therefore more work and lower exhaust gas temperatures. Consequently, a rich mixture to cool down the turbocharger under high load may no longer be needed. As the combustion does not have a distinguished flame front it is able to burn very lean mixtures, with the potential of reducing HC and CO emissions. However, until recently, HCCI was considered to be reasonably applicable only at part load operating conditions. The 3D-CFD engine development tool QuickSim, which has been developed at the FKFS in cooperation with the IVK/University of Stuttgart, is able to simulate the entire flow path of the engine, including both flame propagation and HCCI combustion. In a recent project with the German Aerospace Center (DLR) it was possible to calibrate the parameters of the auto-ignition HCCI model using a highly variable free piston linear generator. This paper addresses the potential of virtual engine development in the creation of a new combustion process for series engines. The described process is called Spark-Assisted Compression Ignition (SACI). It utilizes a pre-chamber spark plug to initialize and control the following auto-ignition. This prevents accidental combustion and also ensures an auto-ignition that is less dependent on the environment and transient conditions, while maintaining the efficiency and emission advantages of a conventional HCCI combustion (auto-ignition of the air-fuel mixture merely regulated by local thermodynamic variables in the combustion chamber).

Extension of Dilution Limit in Propane-Air Mixtures Using Microwave Discharge Igniter

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Imagineering Inc.

Exhaust gas recirculation (EGR) has proven to be beneficial for not only fuel economy improvement but also knock and emissions reduction. Combined with lean burning, it can assist gasoline engines to become cleaner, more effcient and to meet the stringent emissions limit. However, there is a practical limit for EGR percentage in current engines due to many constraints, one of which being the ignition source. The Microwave Discharge Igniter (MDI), which generates, enhances and sustains plasma discharge using microwave (MW) resonance was tested to assess its ability in extending the dilution limit. A combination of high-speed Schlieren imaging and pressure measurements were performed for propane-air mixture combustion inside a constant volume chamber to compare the dilution limits between MDI and conventional spark plug. Carbon dioxide addition was carried out during mixture preparation to simulate the dilution condition of EGR and limit the oxygen fraction. Results indicated that the MDI can successfully outperform the conventional spark plug and have better dilution performance for similar input energy. By increasing the energy delivered to plasma, it is possible to further extend the dilution limit using MDI. The reasons for better performance of MDI were investigated by analyzing the high speed Schlieren movies. The effect of microwave duty ratio during plasma sustainment period was also investigated for optimization.

Evaluation of the Potential of Water Injection for Gasoline Engines

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Gasoline engine powertrain development for 2025 and beyond is focusing on nding cost optimal solutions by balancing electrification and combustion engine efficiency measures. Besides Miller cycle application, cooled exhaust gas recirculation and variable compression ratio, the injection of water has recently gained increased attention as a promising technology for significant CO_2 reduction. This paper gives deep insight into the fuel consumption reduction potential of direct water injection. Single cylinder investigations were performed in order to investigate the influence of water injection in the entire engine map. In addition, different engine configurations were tested to evaluate the influence of the altering compression ratios and Miller timings on the fuel consumption reduction potential with water injection. Based on the single cylinder investigations, drive cycle simulations covering a low, intermediate, and high load profiles were performed to evaluate the fuel consumption reduction potential as well as the corresponding water consumption under varying load demands for the different engine configurations. Furthermore, these simulations were used to optimize the water injection rate for the altering boundary conditions regarding the trade-off between the fuel and water consumption by the comparison of different criteria. Finally, the most promising criterion regarding a maximal fuel consumption reduction at a given water consumption in all of the investigated driving cycles is used to calculate the trade-off curves between fuel and water consumption as well as possible ranges with for a suitable water tank size.

Ignition of Propane-Air Mixtures by Miniaturized Resonating Microwave Flat-Panel Plasma Igniter

Srinivas Padala, Minh Khoi Le, Atsushi Nishiyama, and Yuji Ikeda
Imagineering Inc.

Recent trend in gasoline-powered automobiles focuses heavily on reducing the CO_2 emissions and improving fuel efficiency. Part of the solutions involve changes in combustion chamber geometry to allow for higher turbulence, higher compression ratio which can greatly improve efficiencies. However, the changes are limited by the ignition-source and its location constraint, especially in the case of direct injection SI engines where mixture stratification is important. A new compact microwave plasma igniter based on the principle of microwave resonance was developed and tested for propane combustion inside a constant volume chamber. The igniter was constructed from a thin ceramic panel with metal inlay tuned to the corresponding resonance frequency. Microwaves generated by semiconductor based oscillator were utilized for initiation of discharge. The small and flat form factor of the flat panel igniter allows it to be installed at any locations on the surface of the combustion chamber. Furthermore, the plasma discharged can also be enhanced and sustained using the microwave from the same antenna, which is highly beneficial for combustion performance. High-speed, Schlieren imaging together with pressure measurement were obtained. Successful discharge, ignition and combustion were achieved for a range of equivalence ratios.

Technology Comparison for Spark Ignition Engines of New Generation

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New gasoline engine design is highly influenced by CO_2 and emission limits defined by legislations, the demand for real conditions fuel economy, higher torque, higher specific power and lower cost. To reach the requirements coming from the end-users and legislations, especially for SI engines, several technologies are available, such as downsizing, including turbocharging in combination with direct injection. These technologies allow to solve the main issues of gasoline engines in terms of efficiency and performance which are knocking, part-load losses, and thermal stress at high power conditions. Moreover, other possibilities are under evaluation to allow further steps of enhancement for the even more challenging requirements. However, the benefits and costs given by the mix of these technologies must be accurately evaluated by means of objective tools and procedures in order to choose among the best alternatives. This work presents a comparison at concept level between the main technologies that are currently being developed, considering not only the technical benefits, but also their cost-effectiveness. The analysis is carried out on the basis of studies from the technical literature, integrating missing data by means of evaluations performed with engine-vehicle simplified models, considering the most important powertrain architectures.

Development of a High Performance Natural Gas Engine with Direct Gas Injection and Variable Valve Actuation

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Natural gas is a promising alternative fuel for internal combustion engine application due to its low carbon content and high knock resistance. Performance of natural gas engines is further improved if direct injection, high turbocharger boost level, and variable valve actuation (VVA) are adopted. Also, relevant effciency benefits can be obtained through downsizing. However, mixture quality resulting from direct gas injection has proven to be problematic. This work aims at developing a mono-fuel small-displacement turbocharged compressed natural gas engine with side-mounted direct injector and advanced VVA system. An injector configuration was designed in order to enhance the overall engine tumble and thus overcome low penetration. Gas injection, interaction thereof with charge motion and geometrical bounding walls, and the resultant mixture formation process was investigated in detail by the combination of planar laser-induced uorescence (LIF) in an optical engine and computational fluid dynamics (CFD) analysis with moving injector model to verify the design of the injector and combustion chamber. Then a prototype engine was tested to compare the rated torque against target performance. The planar LIF investigation underlined the influence of the Coandă effect whereby the gas jet was deflected to the adjacent injector niche and then to the combustion chamber roof. Such effect was inhibited at early injection timings due to strong intake air flow. CFD analysis confirmed this behavior and pointed out that the mixing process is dominated by the gas jet during injection and flow patterns promoted by it. It was concluded that the principal mixing mechanism is the jet-promoted tumble and elliptical swirl motion, and the mixing rate is thereby scaled with absolute time, rather than crank angle degree, and mainly determined by the strength of these two motion patterns. It was in addition found that the injection contributes to combustion-relevant turbulence mainly by intensifying the large-scale charge motion. Overall high mixing capacity was

observed, and the injector and combustion chamber design deemed efficacious. The engine design has been successfully accomplished and the prototype multi-cylinder engine (MCE) is ready for extensive performance and emission analysis on the test rig.

Emission Spectroscopy Study of the Microwave Discharge Igniter

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Requirements for reducing consumption of hydrocarbon fuels, as well as reducing emissions force the scientific community to develop new ignition systems. One of possible solutions is an extension of the lean ignition limit of stable combustion. With the decrease of the stoichiometry of combustible mixture the minimal size of the ignition kernel (necessary for development of combustion) increases. Therefore, it is necessary to use some special techniques to extend the ignition kernel region. Pulsed microwave discharge allows the formation of the ignition kernels of larger diameters. Although the microwave discharge igniter (MDI) was already tested for initiation of combustion and demonstrated quite promising results, the parameters of plasma was not yet studied before. Present work demonstrates the results of the dynamics of spatial structure of the MDI plasma with nanosecond time resolution. It was shown that the size of the plasma region increases from 2-4 to 10-15 mm^3 during the discharge development. Gas temperature and vibrational temperature were measured with optical emission spectroscopy. The electric field in the discharge was measured from the analysis of emission intensities of the first negative ($N^+_2(B^2\Sigma^+_u) \rightarrow N^+_2(X^2\Sigma^+_u)$) and the second positive ($N_2(C^3\Pi_u) \rightarrow N_2(B^3\Pi_g)$) systems of molecular nitrogen. The electron density was estimated from the atomic line broadening.

Redesign of a Radial Turbine Variable Stator Geometry with Optimized Free Space Parameter for Improved Efficiency

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The Free Space Parameter (FSP) is evaluated as a predictor for the efficiency of a Variable Geometry Turbine (VGT). Experiments show an optimum value at 2 times the vane height. However, the optimum was found to be dependent on the pressure ratio, yielding an optimum closer to 2.5 at pressures of 2 and 2.5 bar. After this validation the FSP of a conventional VGT is evaluated and an attempt is made to improve the efficiency of this turbine using the FSP. A new geometry is proposed which yields more favorable FSP values. Experiments show that at the original design point the efficiency is unchanged. However, at both larger and smaller nozzle area's the turbine efficiency improves as predicted by the FSP values. A relative efficiency improvement of 3 to 28 % is attained.

Achieving the Max-Potential from a Variable Compression Ratio and Early Intake Valve Closure Strategy by Combination with a Long Stroke Engine Layout

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The combination of geometrically variable compression (VCR) and early intake valve closure (EIVC) proved to offer high potential for increasing efficiency of gasoline engines. While early intake valve closure reduces pumping losses, it is detrimental to combustion quality and residual gas tolerance due to a loss of temperature and turbulence. Large geometric compression ratio at part load compensates for the negative temperature effect of EIVC with further improving efficiency. By optimizing the stroke/bore ratio, the reduction in valve cross section at part load can result in greater charge motion and therefore in turbulence. Turbocharging means the basis to enable an increase in stroke/bore ratio, called β in the following, because the drawbacks at full load resulting from smaller valves can be only compensated by additional boosting pressure level. In this publication, the potential of an optimized stroke/bore ratio in combination with EIVC and VCR at part and full load is effectively assessed with a combination of 1D/QD and 3D-CFD simulation. In order to obtain reliable results, additional model approaches, such as turbulence, combustion and knock models were applied in 1D/QD simulation. Increasing the stroke/bore (β) ratio from 1.07 to 1.4 is capable of increasing the turbulent kinetic energy by 30 % at the operating point n = 2000 rpm/BMEP = 2 bar with EIVC. Together with a compression ratio of 16.5, this results in 7 % higher residual gas tolerance which significantly reduces pumping losses. The reduced wall heat losses on increasing the stroke/bore ratio leading to an even further increased optimum compression ratio by 1.5 units to 18. By combining EIVC, high compression and optimum stroke/bore ratio of 1.4, it was possible to determine fuel consumption of BSFC = 317 g/ kWh at 2000 rpm/2 bar (FMEP = 0.65 bar). This means a reduction in fuel consumption of about 9 % compared to the basis with stroke/ bore ratio 1.07, EIVC and compression ratio 10. By taking into consideration new driving cycles and new powertrain concepts, the low-load range is becoming increasingly less relevant or significant. Therefore, the useful maximum compression ratio for part load decreases. A reasonable

spread of geometric compression ratio for part and full load would appear to be just 4 units in the range of 12 - 16.

Control of Microwave Plasma for Ignition Enhancement Using Microwave Discharge Igniter

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The Microwave Discharge Igniter (MDI) was developed to create microwave plasma for ignition improvement inside combustion engines. The MDI plasma discharge is generated using the principle of microwave resonance with microwave (MW) originating from a 2.45 GHz semiconductor oscillator; it is then further enhanced and sustained using MW from the same source. The exibility in the control of semiconductors allows multiple variations of MW signal which in turn, affects the resonating plasma characteristics and subsequently the combustion performance. In this study, a wide range of different MW signal parameters that were used for the control of MDI were selected for a parametric study of the generated Microwave Plasma. Schlieren imaging of the MDI-ignited propane flame were carried out to assess the impact on combustion quality of different MW parameters combinations. Optical emission spectroscopy of the plasmas generated from the same parameter set was also performed to help determine its characteristics. Based on the results, the ignition enhancement mechanism when using MDI-generated plasma was characterized and the most effective parameters for achieving such plasma conditions were determined. Power and duty cycle of the plasma-sustainment MW pulse appears to be the most critical parameters in improving combustion quality. The ignition enhancement is most likely the effect of additional radicals produced from the MW plasma of MDI.

Diesel Engine Technologies Evolution for Future Challenges

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Final Euro6d emission legislation with the new homologation cycle and Real Driving Emission requirements has set a strong challenge for the ICE Passenger Car applications. Thanks to their well-known low fuel consumption characteristics, Diesel Engines can play a key role for the fulfillment of the European 2020 CO_2 fleet target but need to confirm their capability to fully control noxious emissions even in extreme operating conditions, while restraining the overall engine costs and complexity. CO_2 and NO_x emissions reduction are considered the main drivers for diesel engine evolution. In this perspective, Exhaust Gas After-treatment and Combustion System have been identified as the two main technology aspects to be developed. The purpose of this paper is to describe the evolution paths of these two technologies and the results achieved so far in terms of noxious emissions reduction. A methodology has been developed to predict Diesel combustion evolution and its main characteristics. Various combustion chambers and fuel injection systems have been analyzed through simulations, selecting the most promising ones to be tested on the engine test bench. Having the NSC (NOx Storage Catalyst) + DPF (Diesel Particulate Filter) as reference, a new after-treatment system has been defined integrating active SCR (Selective Catalytic Reduction) and DPF in a single component (SCRF - SCR on Filter), installed in close-coupled position. The right combination of an Advanced Combustion system with a highly efficient SCRF After-treatment system, clearly indicated the potential for the diesel engine to reduce fuel consumption while keeping a very low NO_x emissions level. The activity described in this paper has been co-funded by the European REWARD project.

In-Situ Measurements of the Piston and Connecting Rod Dynamics Correlated with TEHL-Simulation Techniques

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High combustion pressure in combination with high pressure gradient, as they e.g. can be evoked by high efficient combustion systems and e.g. by alternative fuels, acts as broadband excitation force which stimulates natural vibrations of piston, connecting rod and crankshaft during engine operation. Starting from the combustion chamber the assembly of piston, connecting rod and crankshaft and the main bearings represent the system of internal vibration transfer. To generate exact input and validation values for simulation models of structural dynamic and elasto-hydrodynamic coupled multi-body systems, experimental investigations are done. These are carried out on a 1.5-l inline four cylinder Euro 6 Diesel engine. The modal behaviour of the system was examined in detail in simulation and test as a basis for the investigations. In an anechoic test bench airborne and structure-borne noises and combustion pressure are measured to identify the engine´s vibrational behaviour. To understand the behaviour of the connecting rod as the key component in more detail its elongation, using semiconductor strain gauges at the connecting rod shank and a linkage system, is also measured. Furthermore temperature measurements of piston and liner under red conditions, allow the determination of their warm contours for a better geometrical description. Variation of injection timing and connecting rod stiffness allows the basic adjustment of the simulation model. In a further step the simulation model is calibrated by the results of the measurement of the qualitative oil content in the gap between the liner and the piston. For this purpose a combined gap measurement system consisting of eddy-current and capacitive type sensors was specially developed. To adapt sensor and liner surface these are honed together after sensor installation. Finally the elasto-hydrodynamic simulation model is extended by a new software component to a so called thermo elasto-hydrodynamic coupled multi-body system. This leads, especially on Diesel engines, to an improved robustness of the simulation of NVH behaviour.

ICE Thermal Management: A Model Predictive Control Approach for CO_2 Reduction

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In this paper, we propose a novel control architecture for dealing with the requirements arising in a cooling system of an ICE. The idea is to take advantage of the joint action of an electric pump and of an *ad-hoc* regulation module, which is used to determine adequate flow rates despite engine speeds. Specifically, a robust Model Predictive Control approach is exploited to take care formally of input/output constraints and disturbance effects of the resulting lumped parameter model of the engine cooling system, which incorporates the nucleate boiling heat transfer regime. Numerical simulations and test rig experimental data are presented. The results achieved show that the proposed control scheme is capable of providing effective and safe cooling while mitigating disturbance effects and minimizing coolant flow rates when compared with the action pertaining to standard crankshaft driven pumps.

A Model Approach to the Sizing of an ORC Unit for WHR in Transportation Sector

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Internal combustion engines are actually one of the most important source of pollutants and greenhouse gases emissions. In particular, on-the-road transportation sector has taken the environmental challenge of reducing greenhouse gases emissions and worldwide governments set up regulations in order to limit them and fuel consumption from vehicles. Among the several technologies under development, an ORC unit bottomed exhaust gas seems to be very promising, but it still has several complications when it is applied on board of a vehicle (weight, encumbrances, backpressure effect on the engine, safety, reliability). In this paper, a comprehensive mathematical model of an ORC unit bottomed a heavy duty engine, used for commercial vehicle, has been developed. The model is completed with the sizing of the two exchangers involved in the ORC plant: the heat recovery vapor generator (HRVG), which affects the backpressure at the engine exhaust, and the condenser, which is realized with the similar technology of a radiator, and it affects vehicle frontal area occupation. Also weights have been calculated. Thanks to the model, a wide analysis of the recoverable power and the exchanger sizing has been performed on the ESC-13 engine working points. For each engine working point the backpressure effect due to the presence of the HRVG has been evaluated and overall ORC unit weight has been estimated. The extra propulsive power related to weight increase has been estimated considering the ETC cycle (which is the correspondent transient cycle of the ESC-13 modes) and it is compared to the ORC mechanical power recovered and the overconsumption due the backpressure effect. A real net power recovered is, therefore, assessed.

A Controllable Engine Cooling Pump Based on a Magnetorheological Fluid Clutch

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The activity described in this paper has been carried out in the framework of a funded project aimed at evaluating the feasibility of a controllable water pump based on an integrated magnetorheological fluid clutch. The advantages consist of an improvement of the overall vehicle performance and efficiency, in the possibility of disengaging the water pump when its action is not required, and in the control of the cooling fluid temperature. So, the design constraints have been defined with reference to the available space, required torque, and electrical power. After an iterative procedure, in which both mechanical design and magnetic field analyses have been considered, the most promising solution has been defined and a first physical prototype has been realized and tested. A preliminary experimental characterization of the developed prototype has been presented.

A New Piston Insulation Concept for Heavy-Duty Diesel Engines to Reduce Heat Loss from the Wall

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To reduce heat transfer between hot gas and cavity wall, thin Zirconia (ZrO_2) layer (0.5mm) on the cavity surface of a forged steel piston was firstly formed by thermal spray coating aiming higher surface temperature swing precisely synchronized with flame temperature near the wall resulting in the reduction of temperature difference. However, no apparent difference in the heat loss was analyzed. To find out the reason why the heat loss was not so improved, direct observation of flame impingement to the cavity wall was carried out with the top view visualization technique, for which one of the exhaust valves was modified to a sapphire window. Local flame behavior very close to the wall was compared by macrophotography. Numerical analysis by utilizing a three-dimensional simulation was also carried out to investigate the effect of several parameters on the heat transfer coefficient. From the observation of wall impinged flame, it was revealed that a kind of thermal boundary layer with Zirconia coating was thinner than the baseline, which could be resulted in the increase in heat transfer coefficient. Furthermore, the numerical simulation results suggested that higher wall surface temperature swing with Zirconia coating is not the main cause of thinner boundary layer, but surface roughness and/or porous structure is. To confirm the hypothesis, new pistons with different insulating structures were then experimented. Even though the heat loss was not so improved because of the limited area of insulation, the potential for BTE improvement was confirmed.

Potential of Electric Energy Recuperation by Means of the Turbocharger on a Downsized Gasoline Engine

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The application of a turbocharger, having an electric motor/generator on the rotor was studied focusing on the electric energy recuperation on a downsized gasoline internal combustion engine (turbocharged, direct injection) using 1D-calculation approaches. Using state-of-the art optimization techniques, the settings of the valve timing was optimized to cater for a targeted pre-turbine pressure and certain level of residual gases in the combustion chamber to avoid abnormal combustion events. Subsequently, a steady-state map of the potential of electric energy recuperation was performed while considering in parallel different efficiency maps of the potential generator and a certain waste-gate actuation strategy. Moreover, the results were taken as input to a WLTP cycle simulation in order to identify any synergies with regard to fuel economy. Finally, the value of electric energy, either recuperated via the electric turbocharger, inputting the electric conversion efficiency as a function of the rotor speed of the turbocharger based on measured characteristics, was put in comparison to the same amount of electric energy, supplied by the conventional generator in the front-end accessory drive. The study revealed that the benefit of generating electric energy can be considered as little, and, moreover, results in only a very little difference versus the same amount of electricity, generated by a conventional generator.

Conceptual Design of a Variable Geometry, Axial Flow Turbocharger Turbine

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The modern automotive industry is under strict regulations to reduce emissions to comply with the Kyoto Protocol, a universally acknowledged treaty aiming at reducing exhaust gas emissions. In order to achieve the required future emission reduction targets, further developments on gasoline engines are required. One of the main methods to achieve this goal is the application of engine downsizing. Turbocharging is a cost-effective method of downsizing an engine whilst reducing exhaust gas emissions, reducing fuel consumption and maintaining prior performance outputs. For these reasons, the turbocharging is becoming the most widely adopted technology in the automotive markets. In 2012, 32% of passenger and commercial vehicles sold had a turbocharger installed, and is predicted to be 40% of 2017. Even if the engine turbocharging is a widespread technology, there are still drawbacks present in current turbocharging systems. The main problem is overcoming the issue of turbo-lag, which is the poor initial response of the turbocharger to the driver commands due to its inertia. Indeed, the system turbine plus compressor is characterized by an own rotational inertia, therefore, the turbocharger will take a certain time to accelerate and produce the desired boost when a higher amount of exhaust gas is sent to the system. In this work, an innovative solution to the turbo-lag phenomenon will be analyzed: a vaneless stator-axial flow turbine. The proposed turbine configuration would improve the transient response of the system since the axial turbine has intrinsically a lower inertia than the radial turbine as stated by the research works of Ford first and Honeywell after. The whole design process is presented in this paper and particular relevance has been given to the thermo-fluid-dynamic aspect of the machine. Several CFD investigations have been carried out in order to deeply understand the new turbine behavior and, thanks to a 1D model of the target engine, it has been possible to validate the new design simulating the performance of the system engine + turbocharger.

Evaluation of Different Turbocharger Configurations for a Heavy-Duty Partially Premixed Combustion Engine

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The engine concept partially premixed combustion (PPC) has proved higher gross indicated efficiency compared to conventional diesel combustion engines. The relatively simple implementation of the concept is an advantage, however, high gas exchange losses has made its use challenging in multi-cylinder heavy duty engines. With high rates of exhaust gas recirculation (EGR) to dilute the charge and hence limit the combustion rate, the resulting exhaust temperatures are low. The selected boost system must therefore be efficient which could lead to large, complex and costly solutions. In the presented work experiments and modelling were combined to evaluate different turbocharger configurations for the PPC concept. Experiments were performed on a multi-cylinder engine. The engine was modified to incorporate long route EGR and a single-stage turbocharger, however, with compressed air from the building being optionally supplied to the compressor. Experimental combustion heat release rates and boundary conditions were used to validate a simulation model. This model was then used to compare three different turbochargers: two single-stage turbochargers and one two-stage. The whole speed and load range was covered in the simulations to determine the engine performance. The influence of high EGR rates as well as the effect of charge air and EGR cooler gas outlet temperatures were also investigated. The simulation results showed that the two-stage turbocharger was able to give the highest load over the whole speed range with a brake mean effective pressure of 25.6 bar, whereas the two single-stage turbochargers reached 22.2 and 23.1 bar respectively. The average brake efficiency was 39.3, 39.7 and 40.2 %. It was found that decreasing the inlet temperature is critical for obtaining high loads and system efficiencies. Finally, it was shown that the optimal amount of EGR was dependent on the turbocharger efficiency and cooler temperatures.

Scavenge Ports Ooptimization of a 2-Stroke Opposed Piston Diesel Engine

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This work reports a CFD study on a 2-stroke (2-S) opposed piston high speed direct injection (HSDI) Diesel engine. The engine main features (bore, stroke, port timings, et cetera) are defined in a previous stage of the project, while the current analysis is focused on the assembly made up of scavenge ports, manifold and cylinder. The first step of the study consists in the construction of a parametric mesh on a simplified geometry. Two geometric parameters and three different operating conditions are considered. A CFD-3D simulation by using a customized version of the KIVA-4 code is performed on a set of 243 different cases, sweeping all the most interesting combinations of geometric parameters and operating conditions. The post-processing of this huge amount of data allow us to define the most effective geometric configuration, named baseline. In the second step of the study, the baseline is further optimized, keeping into account some fundamental design constraints, such as the overall dimensions of the manifold. The evolved geometry is then simulated by using KIVA, adopting a refined grid and realistic boundary conditions. The paper presents the calculated scavenging patterns, offering a detailed insight of the process. Finally, the influence of the offset between the crankshafts is analyzed, by using a calibrated CFD-1D engine model.

An Investigation Into the Port Timing of a Burt-McCollum Sleeve Valve and Its Interaction with a Simple Variable Compression Ratio Mechanism

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Modern automotive engines almost exclusively operate on the 4-stroke Otto cycle and utilize poppet valves for gas exchange. This state of affairs has not always been the case, however, and one unusual and relatively successful technology that was once in mass production (albeit in piston aero engines) was the Burt-McCollum single sleeve valve. This paper investigates the timing and angle-area of a Bristol Centaurus engine cylinder, which utilized such a single sleeve valve for gas exchange, using some modern tools. A comparison with poppet valve angle-areas is made. Finally, the results are also used to study the potential of variable valve timing and the interaction with variable compression ratio of a single sleeve mechanism. An opportunity for the sleeve valve is provided by the fact that direct injector placement in the cylinder junk head is effectively completely free, and furthermore multiple ignition sites can be incorporated to increase the delivered ignition energy for dilute mixtures, for example. Furthermore, as there are no mechanical impact loads (as arise from poppet valves hitting their seats, for instance), theoretically ceramics or temperature-swing materials could be more simply applied when using the technology as well, and over a larger proportion of the total combustion chamber surface area than is possible with poppet valves. The motivation for studying the interaction of timing and compression ratio was driven by the observation that it would be relatively simple to incorporate a wide-range continuously-variable compression ratio mechanism without the spatial limitations enforced by the presence of poppet valves and their timing and drive mechanisms in the cylinder head of a conventional 4-stroke engine. The potential range of compression ratio variation is also significantly larger than for poppet-valve engines because the piston does not have to incorporate valve pockets for valve-to-piston clearance at high compression ratio settings. As a result the surface-area-to-volume ratio of the combustion chamber would be expected to be less effected over any given ratio range as well. The results of this study show a very favourable trade-off between port timing, compression and expansion ratios with a simple variable compression ratio mechanism being employed. Furthermore, the system is found to provide a large potential to yield increased Miller cycle operation automatically.

The Recuperated Split Cycle - Experimental Combustion Data from a Single Cylinder Test Rig

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The conventional Diesel cycles engine is now approaching the practical limits of efficiency. The recuperated split cycle engine is an alternative cycle with the potential to achieve higher efficiencies than could be achieved using a conventional engine cycle. In a split cycle engine, the compression and combustion strokes are performed in separate chambers. This enables direct cooling of the compression cylinder reducing compression work, intra cycle heat recovery and low heat rejection expansion. Previously reported analysis has shown that brake efficiencies approaching 60% are attainable, representing a 33% improvement over current advanced heavy duty diesel engine. However, the achievement of complete, stable, compression ignited combustion has remained elusive to date. The challenge is to induct hot high pressure charge air close to top dead centre into the combustion cylinder and then inject and burn the fuel before the piston has travelled significantly down the expansion stroke. In this paper, we report results from a single cylinder split cycle combustion research engine. Stable, rapid combustion was achieved at 800 rpm and 1200 rpm at the retarded timings required for a split cycle engine. The calculated rate of heat release was more rapid than typically observed on conventional compression ignition engine suggesting good mixing of the fuel and air during induction. One dimensional cycle analysis was used to calculate the implications of the test results on the full engine cycle which indicated class leading brake efficiencies approaching and possibly exceeding, 60% are possible from a split cycle engine.

Investigating the Effect of Intake Manifold Size on the Transient Response of Single Cylinder Turbocharged Engines

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This paper evaluates the lag time in a turbocharged single cylinder engine in order to determine its viability in transient applications. The overall goal of this research is to increase the power output, reduce the fuel economy, and improve emissions of single cylinder engines through turbocharging. Due to the timing mismatch between the exhaust stroke, when the turbocharger is powered, and the intake stroke, when the engine intakes air, turbocharging is not conventionally used in commercial single cylinder engines. Our previous work has shown that it is possible to turbocharge a four stroke, single cylinder, internal combustion engine using an air capacitor, a large volume intake manifold in between the turbocharger compressor and engine intake. The air capacitor stores compressed air from the turbocharger during the exhaust stroke and delivers it during the intake stroke. This work builds on previous theoretical and experimental work that shows that a turbocharger could be fitted to a single cylinder engine using an air capacitor to increase intake air density by 43% and peak power output by 29%. Our previous research has shown that the capacitor works in steady state applications where turbocharger lag time does not matter. However, given the transient time to pressurize the capacitor, it will increase the already existing turbocharger lag time. The goal of this work is to show a clear correlation between capacitor size and transient response characteristics. By characterizing the transient response it will be possible to size an air capacitor for transient applications. An experimental setup was constructed to evaluate the time required to respond to an increased load on the engine at a constant speed, and the time it takes to increase engine speed at a constant load. We found that turbocharging had minimal effect on no load transient speed response. However, once load was applied to the engine, turbocharging increased the transient speed response time by a half of a second compared to a naturally aspirated engine. We also found that turbocharging affected the characteristics of the engine's response to a change in torque at a constant speed. Larger Capacitors resulted in quicker initial response to a torque impulse then smaller capacitors but had approximately the same overall response time due to slower response as torque increased.

Engine Modeling and Controls
Engine Combustion
Fuels and Lubricants Technologies
Emissions and Emissions Controls
New Engines, Components, Actuators, & Sensors
Hybrid and Electric Powertrains, including Range Extending Engines

Composition Platform for Conventional and Hybrid Powertrains

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In view of the rapidly increasing complexity of conventional as well as hybrid powertrains, a systematic composition platform seeking for the global optimum powertrain is presented in this paper. The platform can be mainly divided into three parts: the synthesis of the transmission, the synthesis of the internal combustion engine (ICE) and the optimization and evaluation of the entire powertrain. In regard to the synthesis of transmission concepts, a systematical and computer-aided tool suitable both for conventional und hybrid transmissions is developed. With this tool, all the potential transmission concepts, which can realize the desired driving modes or ratios, can be synthesized based on the vehicle data and requirements. As a result of the transmission synthesis, the detailed information of each transmission concept, including the transmission structure, the shifting logic, the estimated efficiency in each gear, and the estimated space arrangement of the transmission can be given out. The synthesis of transmission concepts is complemented by a comprehensive tool able to synthesize internal combustion engines of gasoline and gasoline/Atkinson type. The ICE synthesis precalculates frictional and thermodynamic engine behavior and is validated by an ad hoc created database of 250 engines, which serves as a comparison. Design parameters are deducted from this database in order to minimize the number of input parameters for the ICE synthesis. The result of the ICE synthesis is a map of the specific fuel consumption or an effective efficiency map. The tool is implemented as a function to the overall powertrain synthesis and will be triggered by an optimizer during the future development progress. Successively, the two synthesizing tools are joined to compose complete powertrains. Each powertrain concept consists of design parameters and corresponding configurations of synthesized ICE and transmissions. By varying these parameters, the different powertrains are further optimized and evaluated in consideration of the system effciency and vehicle dynamics within the driving cycle.

Automatic Generation of Online Optimal Energy Management Strategies for Hybrid Powertrain Simulation

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Due to more and more complex powertrain architectures and the necessity to optimize them on the whole driving conditions, simulation tools are becoming indisputable for car manufacturers and suppliers. Indeed, simulation is at the basis of any algorithm aimed at finding the best compromise between fuel consumption, emissions, drivability, and performance during the conception phase. For hybrid vehicles, the energy management strategy is a key driver to ensure the best fuel consumption and thus has to be optimized carefully as well. In this regard, the coupling of an offline hybrid strategy optimizer (called HOT) based on Pontryagin's minimum principle (PMP) and an online equivalent-consumption-minimization strategy (ECMS) generator is presented. Additionally, methods to estimate the efficiency maps and other overall characteristics of the main powertrain components (thermal engine, electric motor(s), and battery) from a few design parameters are shown. Finally, the use of such tool chain to automatically generate the optimal energy management strategy for a given hybrid powertrain configuration, for which the main components are sufficiently specified and characterized is presented. The powertrain configuration illustrating this work is an input-split hybrid configuration.

Influence of Fuel Type on the Performance of a Plug-In Fuel Cell/Battery Hybrid Vehicle with On-Board Fuel Processing

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This paper describes the energy management controller design of a mid-sized vehicle driven by a fuel cell/battery plug-in hybrid powertrain, where an experimentally validated high temperature polymer electrolyte membrane fuel cell model is used. The power management strategy results from the application of the Pontryagin's Minimum Principle, where the optimal control parameter is derived in order to minimize fuel consumption under certain constraints. In particular, the vehicle is also equipped by an autothermal reformer and, in order to minimize the hydrogen buffer size, the control algorithm is subject to constraints on the maximum hydrogen buffer level. The effectiveness of the system is analyzed when feeding the autothermal reformer with different hydrocarbon fuels and over different driving conditions. The obtained solutions are compared in terms of hydrogen consumption, fossil fuel consumption, system effciency, money saving and equivalent CO_2 emissions.

ORAL PRESENTATIONS

Optimization of Emissions Control Components by Particle Size Distribution Measurements

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TSI

Recent changes in regulatory compliance efforts to control both NOX and Particle Number emissions via the Real Driving Emissions rule is pushing OEMs to expand measurement techniques to optimize emissions control components to meet these new standards. One area that has shown promise is employing real time particle spectrometers to support decisions on Engine design, Aftertreatment systems design, Fuel Type & Lubrication to comply with these stringent regulations under a wider range of engine operating conditions and test cycles. The presentation will illustrate how to leverage particle size data for the development of new engines to meet RDE PN standards.

Measurement of aerosol particle number concentrations down to 1 nm from car emissions

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The latest knowledge on combustion engine emissions has shown that the contribution of the very smallest particles can be really high in terms of number concentration. It has been shown that vehicles are a large source of so called nanocluster aerosol (NCA) (Rönkkö et al. 2017). These nanocluster aerosols are in the size range of 1.3 – 3nm and can represent 20-54% of the total particle concentration in the ambient air. New instrument called nano Condensation Nucleus Counter (Airmodus A11) has been used to measure emissions of various combustion engines from diesel with DPF, port fuel, mopeds and also neutral gas engines, as well as ambient air in urban measurement site. In all the measurement aerosol particles with diameter of less than 23nm has been found. With some motor types the fraction of particulate number emissions for sub 10 nm particles can be higher than above 10 nm (Giechaskiel, 2017). Also brakes can be a source of the smallest aerosol particles when the brake contact surfaces reach so called critical temperature (Nosko et al. 2016). Especially low metallic brake pads show high emissions for sub 4 nm particles. Measuring of aerosol particle number concentrations in the whole size range starting from 1 nm are needed to better understand the effects of these particles to human health and to climate.

Combustion analysis under pre-ignition conditions: constraints and recommendations

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Working with abnormal combustion, especially pre-ignition, is a strong constraint during the development of modern turbocharged gasoline engines. Indeed, pre-ignition can lead to the breakage of the engine and its equipment, including the cylinder pressure sensors. Such phenomenon is still difficult to anticipate and even impossible if the cylinder pressure sensor has been damaged. In this study we will evaluate the influence of the sensor's type and its mounting location on the detection and evaluation of pre-ignition events. Several tests have been performed on a 4-cylinder turbocharged gasoline engine and led to concrete recommendations dealing with:

- The sensor itself to prevent from any premature breakage.
- The complete measuring chain, i.e. sensor + signal conditioning + data acquisition, to get a workable cylinder pressure signal and therefore better characterize these pre-ignition events.

Understanding and Measuring Sub-23 nm Particle Emissions from Direct Injection Engines

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A large fraction of the total number of particles emitted by direct injection engines are below the adopted 23 nm diameter threshold and although the EU aims to regulate these emissions and impose limits for new light-duty vehicles, this is not yet possible due to the absence of accurate and reliable quantification methods, especially under real driving conditions. The main reason for this is the lack of adequate knowledge regarding the nature of sub-23 nm particles from different engine/fuel combinations under different engine operating conditions. Four research organisations, three particle measurement instrumentation companies and one automotive OEM have joined forces in the framework of the EU-funded project SUREAL-23 to overcome such barriers by introducing novel technology for the measurement of sub-23 nm exhaust particle concentration, size and composition. In this work, we will present our latest efforts on (a) simplifying and making more robust the exhaust aerosol sample treatment, (b) elucidating the effect of different diesel and gasoline engine operating conditions (fuel additives, bio-content, gas fuel addition, after-treatment type and operation, etc.) on sub-23 nm particle emissions and (c) advancing particle measurement technology with the introduction of novel techniques. Use of a catalytic stripper device and operation of particle measurement systems at higher than the typical temperatures has been found to

reduce the need for treatment/dilution of the exhaust sample, minimising particle losses and artefacts. The understanding of sub-23 nm emissions has been advanced by deploying a variety of fuel-flexible engines and particle generators to produce a wide range of sub-23 nm exhaust particles. With respect to instrumentation, an induced charged aerosol detector was modified for smaller size and higher temperature particle detection, a differential mobility analyser was adapted for high-resolution particle sizing below 23 nm and high temperature operation and, in an effort to obtain real-time composition information, a supercontinuum laser has been applied for the photoacoustic analysis of sub-23 nm exhaust aerosol.

A Review of State-of-the-Art Particle Sensors for Onboard Diagnostics & Emission Monitoring

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Spark-plug sized exhaust sensors for onboard diagnostics (OBD) and emissions monitoring are important addition to internal combustion engines used in on-highway vehicles and later in nonroad applications. The use of such sensors insures that the aftertreatment system functions properly throughout the full vehicle useful life, and flag any malfunction that leads to exceeding an emission threshold. Furthermore, such sensors can be developed to monitor emissions onboard vehicle on a continuous basis and use such data for vehicle compliance and emission inventory on a very large number of vehicles in various localities and worldwide.

Due to the current and future importance of this topic, Southwest Research Institute launched the Particle Sensor Performance and Durability (PSPD) consortium that is now in its fourth year. This year and prior to the PSPD consortium meeting, SwRI held an industry symposium focusing on state of the art particle technology sensing and future policy making ideas that were presented by US EPA and CARB.

This presentation summarizes some important policy making ideas of how to use onboard sensors as emission monitors beyond OBD. Furthermore, the presentation discusses state-of-the-art particle sensor technologies that include resistive-based technology sensors that rely on soot electric conductivity, electric-mobility sensors that rely on particle natural charge, and net charging sensors that rely on particle charging and escaping current measurement. This is in addition to radio frequency sensing that can be used for filter diagnostics and indirect inference of particle emissions.

New modelling process to estimate real-world emission

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Ricardo EUTC

Today's new methods of vehicle simulation could see the virtual vehicle producing virtual emissions on a real driving condition. Agent-Based Modelling (ABM) will allow engineers to simulate a car in an environment which includes traffic, weather and human interaction using measured data. Traffic data is now modelled and could be fed into a simulation program. The combination of these models together with randomization of individuals (pedestrian crossing) will lead to a high fidelity representation of the road which can be used to steer the control logic of future powertrain. This paper will talk about the use of Agent-Based Modelling to create traffic scenario's that feed into a vehicle predictive control system, which in turn will then be used in the Ricardo simulation toolchain to estimate real world fuel consumption.

Chemical Imaging in a Diesel-Ignited Dual-Fuel Optical Engine Using High-Speed Infrared Narrowband Imaging

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Efforts are continuously made to improve internal combustion engines' (ICEs) efficiency. Lowering fuel consumption and reducing soot formation are among the challenges being addressed when seeking to improve engine designs. In this work, ICE characterization was carried out on an optical engine consisting of an elongated single-cylinder diesel engine and a common rail injection system. In this system, the piston's crown is replaced by a sapphire window in order to carry out imaging of the combustion bowl while the engine is in operation by looking at a 45° fixed mirror located in the extended piston axis. In the experiments, air was replaced by a premixed air-methane charge and a pilot amount of diesel fuel was used as an ignition source. Experiments were carried out under different engine speeds, diesel-fuel injection sequences and methane intake conditions. High-speed infrared imaging was carried out at 26 kHz, leading to a temporal resolution of about 0.35° crankshaft angle at 1500 RPM. Chemical imaging was carried out using five different spectral bandpass filters: broadband, carbon dioxide (CO_2), through-flame, hydrocarbon and methane (CH_4). This allows tracking the presence of liquid diesel fuel, gaseous diesel fuel, methane and carbon dioxide during the each engine's cycle. In order to compare different 2D image sequences, cumulative histogram time-series (CHST) diagrams were used. This strategy allows comparing infrared image sequences in a quantifiable manner as recently demonstrated by Rochussen et al. (2016). When comparing the CHTS diagrams obtained under various engine-operating conditions, the impact on the combustion dynamic can readily be visualized. The results illustrate how high-speed IR imaging can provide unique insights for research on ICEs.

Octane sensitivity and the two-stage ignition behaviour

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Octane Sensitivity (OS) is defined as the difference between Research Octane Number (RON) and Motored Octane Number (MON). Knock resistance of high OS fuels is favorable for conventional Spark Ignited (SI) operation with high compression ratio and boosted conditions as well as Homogeneous Charge Compression Ignition (HCCI)/SI dual mode operation. In this study, the relationship between OS and low temperature reactivity is explored focusing on two-stage ignition behavior predicted by detailed kinetic simulations. Different fuels with various ignition characteristics due to the low temperature chemistry are analyzed in this work. Simple metrics that represent the twostage ignition behavior in homogeneous reactor simulations are devised and their correlations against measured OS are tested. It is shown that the weaker the two-stage ignition behavior the higher is OS.

AVL TABKIN^{TM} Maximizing the Efficiency of Detailed Chemistry Simulations

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AVL Dacolt BV M. Tvrdojevic
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AVL List GmbH

Combustion is a reaction process in which only part of the fuel chemistry is known. The simulation through a CFD code needs, furthermore, several simplifications in the model, losing many useful details, in order to avoid a critical computational effort. The goal of this work is to show how, the coupling between AVL TABKIN and AVL FIRE, allows to have a more detailed chemistry process saving a lot of time which would be needed by using only a pure CFD approach involving detailed chemistry. This method has been investigated for different applications. For Diesel engines, it provides a very efficient combustion simulation as well as predictive emissions assessment, with a simulation time comparable with the time needed for empirical models. For gasoline engines combustion the AVL TABKIN-CFD coupling allows to consider over 1000 chemical species, which would take months of calculation time by using a conventional CFD with detailed chemistry. The method has been also used for studying the fuel evaporation and flame stabilization in industrial burners. The validation of the fuel chemistry models in AVL TABKIN is based on a vast amount of experimental data, for instance, it takes into account investigations on the potential of partial fuel stratification for the reduction of knocking propensity of intake-boosted HCCI engines operating on conventional gasoline.

Fuels for sustainable Mobility

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ENI

The Eni strategy for energy transition in the Refining & Marketing area is founded on three main pillars: the production of low emissions and high sustainability fuels like Eni Diesel +, new retail stations for the distribution of LNG to heavy duty vehicles and the study of the potential use of new energy carriers in order to exploit Natural Gas reserves, like methanol. For a large-scale production of low carbon fuels, in the Venice Green Refinery a new-patented technology called Ecofining™ has been implemented; this technology leads to the production of an innovative biofuel, called Green Diesel, with better performances compared to traditional biodiesel. Green Diesel has an almost completely hydrocarburic composition so that it can been added to fossil diesel at higher percentage, overcoming the blending wall of 7% related to the additivation of traditional biodiesel. To exploit the high quality of this product, on January 2016 a new premium diesel, Eni Diesel +, was launched on the market, it contains 15% of renewable component Green Diesel. Eni Diesel + determines a 5% reduction of CO_2 emissions (on average) thanks to a more sustainable production cycle and to the presence of a higher rate of renewable component compared to traditional diesel; also HC and CO emissions decrease up to 40%. As alternative fuel, LNG is considered a promising product for the European decarbonization strategy thanks to its low carbon intensity value and the development of a distribution infrastructure for alternative fuels is promoted by European Institutions. Eni has realized two retail stations in Piacenza and Pontedera to distribute LNG for Heavy Duty Trucks and is engaged in the definition of future commercial and technical scenarios for the development of this product. In the long term, methanol could represent a good opportunity for the exploitment of Natural Gas reserves as an alternative to LNG supply chain. Methanol is a useful energy carrier to increase the rate of Natural Gas in the EU mix, it should be mixed with petrol increasing the octane of the fuel and, using specifically selected and designed engines, can reduce the emission of pollutants, including CO_2 without compromising engine performances.

High Energy Ignition System integrated with Ion Sensing

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ELDOR CORPORATION S.p.A.

Ion sensing is a well-known technology to perform combustion analysis, nevertheless the impact on the ignition coil, that is part of the sensing circuit, can limit the spark energy. To the other side, the new generations of SI engine are demanding a big amount of spark energy to support combustion in highly diluted condition and/or high breakdown voltage. Using a traditional ignition system to achieve high energy will badly affect the ion sensing capabilities due to the long spark duration and the filtering effect of a higher coil inductance. Eldor has studied a way to integrate the ion sensing in an high energy ignition system preserving the quality of ion signal and delivering the high energy when needed.

Experimental investigation of in-cylinder heat transfer during PPC combustion

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Univ of Oxford
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Partially Premixed Combustion (PPC) is being viewed as an attainable way of combining a high thermal efficiency and low emissions of NOx and soot. Unlike a Homogeneous Charge Compression Ignition (HCCI) engine, a PPC engine does not suffer from a low power density or lack of control over the combustion. Similar to an HCCI engine, the combustion is very sensitive to the mixture temperature, because the auto-ignition process is determined by the chemical kinetics of the air-fuel mixture. Consequently, the heat transfer from the bulk gas to the walls of the combustion chamber has a direct effect on the combustion process. However, according to the authors' knowledge, no experimental heat transfer studies have been performed.
The goal of this work is to investigate the heat transfer during PPC operation. The heat flux is measured in the combustion chamber of a Scania D13 engine converted to PPC operation. First, the spatial variation of the heat flux in the combustion chamber is investigated by measuring the heat flux at 2 different locations in the cylinder head: near the injector and near the cylinder wall. Next, measurements are conducted according to the Design of Experiments (DoE) methodology. The DoE approach makes it possible to distinguish between the effects of each varied engine setting (engine speed, fuel mass and air mass) and their interactions. Their effect on the peak heat flux, total heat released and shape of the heat flux trace are reported. A number of measurements are repeated with different fuels to examine the effect of the fuel properties on the heat transfer. Finally, heat transfer measurements under PPC, HCCI and conventional diesel operation are compared.

Passenger vehicle tests with renewable diesel fuel from forest industry residues

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The Finnish bio and forest company, UPM, has built a first of a kind biorefinery producing wood-based advanced biofuels to Lappeenranta, Finland. UPM uses wood-based residue of pulp making process, crude tall oil (CTO), as raw material of the biorefinery.
The biorefinery is based on hydrogenation process and the product has fuel properties comparable to EN590 diesel fuel with significant improvement in other properties, such as cetane number. It can be used as such or as a blending component in all diesel engines without modification.
AVL's objective was to evaluate the UPM BioVerno fuel by performing a series of emission tests. The test vehicle had a diesel engine that meets the Euro 5b emission regulation and is equipped with a diesel particulate filter (DPF). The test fuel matrix consisted of one UPM BioVerno fuel, a commercial market diesel fuel (Mk1) and, to broaden the understanding, a 50/50 mix of the commercial market diesel fuel and UPM BioVerno.
Results from the emission tests showed no significant difference in fuel consumption and emissions of CO_2 and NOX between the evaluated fuels. Measured FC and CO_2 values were almost identical between the fuels, which indicates a very good replication of driving pattern between all tests.
In conclusion, emission tests with a vehicle fuelled by the 50/50 blend and 100% BioVerno show a decrease in CO emissions and potential reduction of PN (100% BioVerno) compared to the commercial market diesel fuel. There are no significant differences in FC, PM and other gaseous emissions.

Investigation of Urea Derived Deposits Composition

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Ideally, complete decomposition of urea should produce only two products in active Selective Catalytic Reduction (SCR) systems: ammonia and carbon dioxide. However, the urea decomposition reaction is actually a two-step process that includes the formation of ammonia and isocyanic acid as intermediate products via thermolysis. Being highly reactive, isocyanic acid is a precursor to formation of larger molecular weight compounds such as cyanuric acid, biuret, melamine, ammeline, ammelide, and dicyandimide. These compounds can be responsible for the formation of deposits on the walls of the decomposition reactor in urea SCR systems. Composition of these deposits varies with temperature exposure, and under certain conditions can create oligomers that are difficult to remove from exhaust pipes, even under the high exhaust temperatures that can be generated during DPF active regeneration conditions. Deposits can affect efficiency of the urea decomposition, and if large enough, can impact the exhaust flow resulting in a negative impact on ammonia distribution for the SCR catalyst. This paper presents results from an analytical method developed by SwRI for quantification of urea and by-products of urea decomposition. This method is able to quantify seven major urea related soluble monomers, as well as fully broken-down insoluble oligomers to monomers. Urea related compounds, including oligomers and elemental composition of deposits collected from a urea decomposition reactor under various exhaust conditions, are compared in the paper.

Comparison of Aircraft Emissions at Los Angeles International Airport (LAX) to Urban Vehicle Traffic Emissions Measured On-road of Major Freeways and assessment of its impact on air quality in Los Angeles

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Among various combustion sources of particulate matter (PM) in urban areas, accurate assessment of airport-related emissions and how they compare to other predominant PM sources such as traffic emissions is essential in understanding the impact of airports on air quality and human health. This study investigates the overall impact of aircraft emissions from the LAX airport and its facilities in comparison to vehicular emissions from three major freeways, within the impact zone of the airport, an area of roughly 100 km2 downwind of the LAX, on air quality on a local scale. Air monitoring measurements of particle number (PN), black carbon (BC) and PM2.5 mass concentrations were performed in the vicinity of the Los Angeles International Airport (LAX) (roughly 150 m downwind of the LAX's south runways) as well as on-road measurements of the aforementioned pollutants using a mobile platform on three major freeways near the airport (i.e., I-110, I-105, and I-405) during May-July 2016. PN concentration was, on average, 4.1±1.2 times greater at the LAX site than on the studied freeways. Particles measured at LAX had an average diameter of about 20 nm, while on-road freeway measurements on I-110, I-105, and I-405 indicated an average particle diameter of >40 nm, a particle size range that is more typical of vehicle traffic and not aircraft emissions in urban areas. Particle number emission factors for takeoffs and landings were comparable, with average values of 8.69 × 〖10〗^15 particles/kg fuel and 8.16 × 〖10〗^15 particles/kg fuel, respectively, and indicated a nearly 4-fold statistically significant reduction in PN emission factors for takeoffs during the past decade. The results also indicated that the LAX's daily contributions to PN, BC, and PM2.5 emissions were approximately 11, 2.5, and 1.4 times greater than those from the three surrounding freeways. These results underscore the significant role of the LAX airport as a major source of pollution within its zone of impact comparing to freeway emissions.

Complete Engine Thermal Model, a Comprehensive Approach

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Volvo cars

Upcoming engine generations are characterized by a general trend of increased specific-power and higher efficiency. This leads to increased thermal loads, compromising reliability, and simultaneously to a limited amount of heat under ordinary engine use. Heat is a valuable resource in providing passenger comfort and emission control. For these reasons the subject of engine thermal management is receiving increasing attention.
This work presents a comprehensive study of the complete engine thermal behavior at relevant running conditions: rated-power, peak-torque and ordinary use. The work is further extended to the engine warm-up period. The result is a high-resolution complete engine thermal model, capable of simultaneously reporting the local temperature of any engine part, and the global engine heat balance at any engine load. All different heat sources and heat sinks are studied in detail and implemented in the same platform, allowing the direct study of their mutual thermal interactions. Among these are: combustion, friction, boiling and external radiation. The space-time resolved boundary-conditions describing heat sources and sinks are obtained from measurements as well as models.
To widen the area of application, the high-resolution (3D) model is further translated in a fast-running (1D) model for direct integration in complete vehicle thermal models in order to perform complete system analysis.

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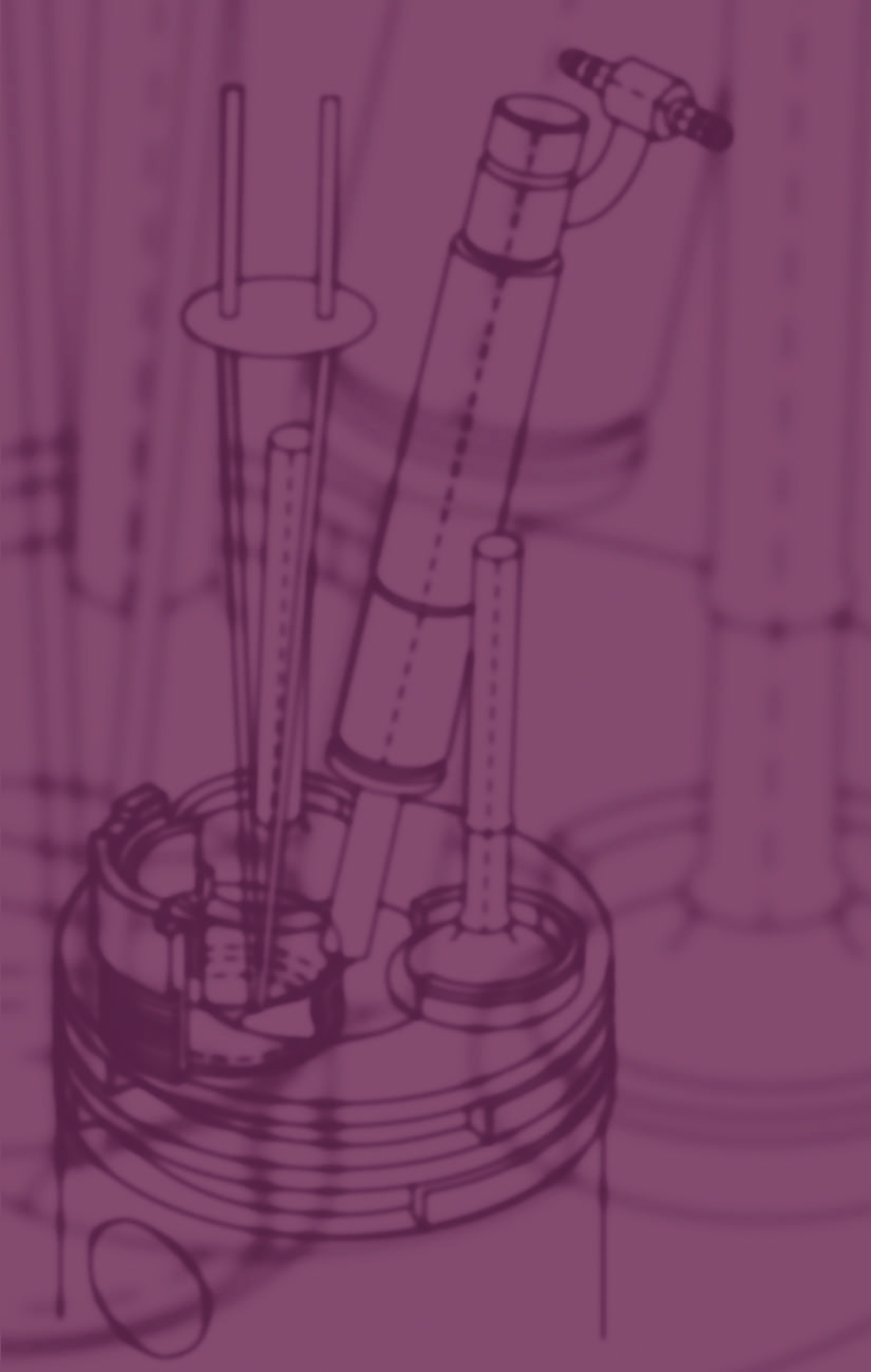

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