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Department of Industrial Engineering

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Estimation of the Effects of Catalyst Substrates on Automotive Engine Performance with a 0D real-time engine model

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Outline of the paper

1. **Ceramic Foams as catalysts substrates**

2. **Modelling tools:**
    a. **CA model of I.C.Engine**
    b. **Exhaust System model**
    c. **Catalyst model**

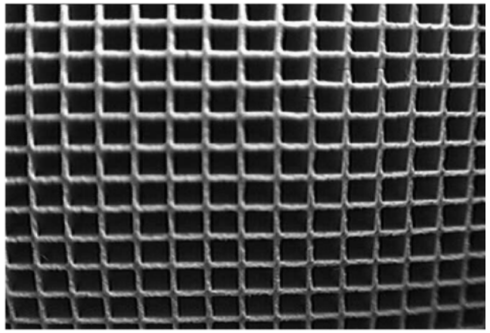
3. **Simulation: 4cyl Diesel engine on EUDC with**
    a. **Honeycomb substrate**
    b. **Foam substrate**

4. **Comparison wrt engine performance (bsfc)**

5. **Conclusions**

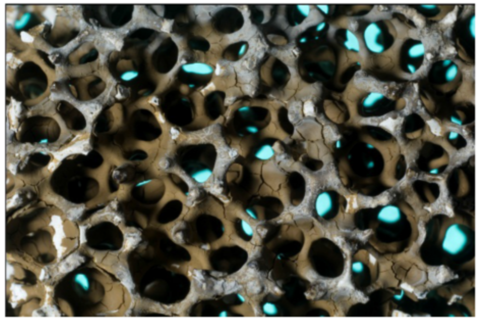
Ceramic Foam as catalysts substrates

Honeycomb



☺ commonly used
☺ cheap
BUT:
☹ low flow uniformity
☹ poor mixing

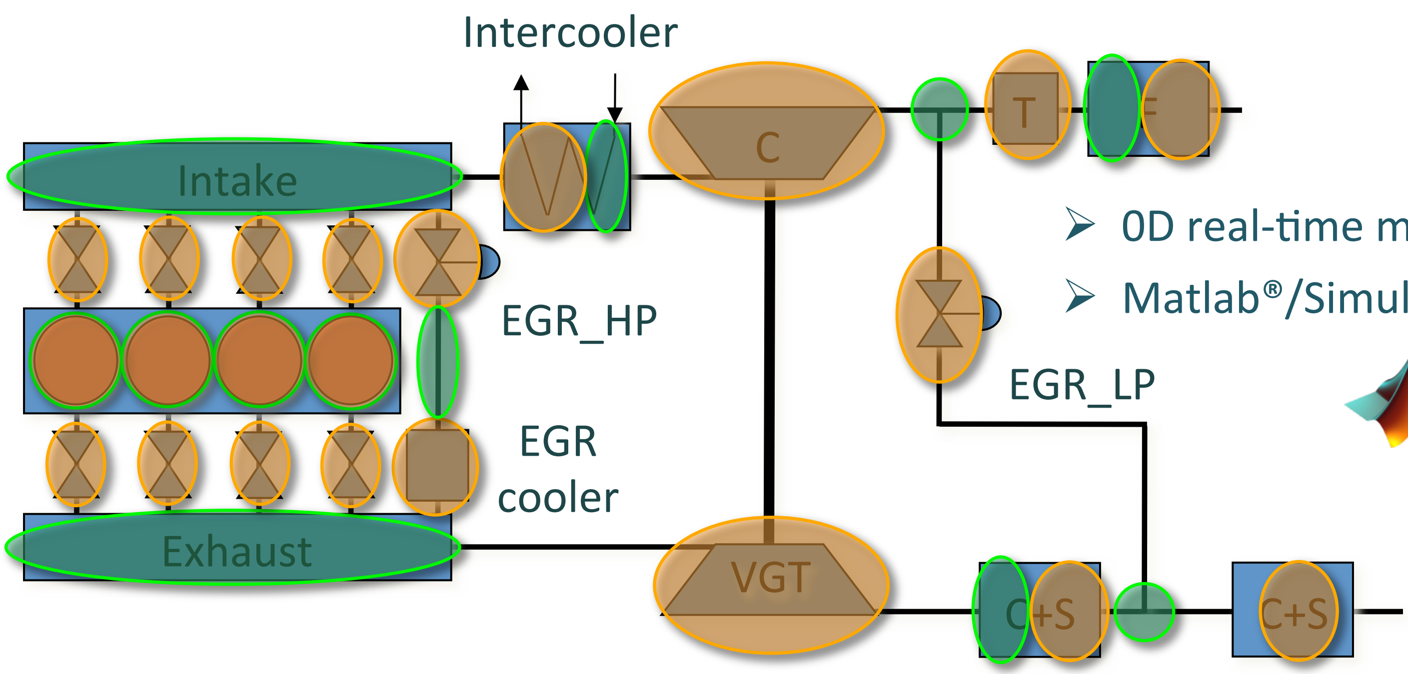
Foam



☺ high porosity, low density, high SSA
☺ improved mixing
☺ low thermal inertia
BUT:
☹ higher pressure losses

Scope: estimate the influence of catalyst substrate structure on fuel consumption and engine performance during transients

CA model of I.C.Engine

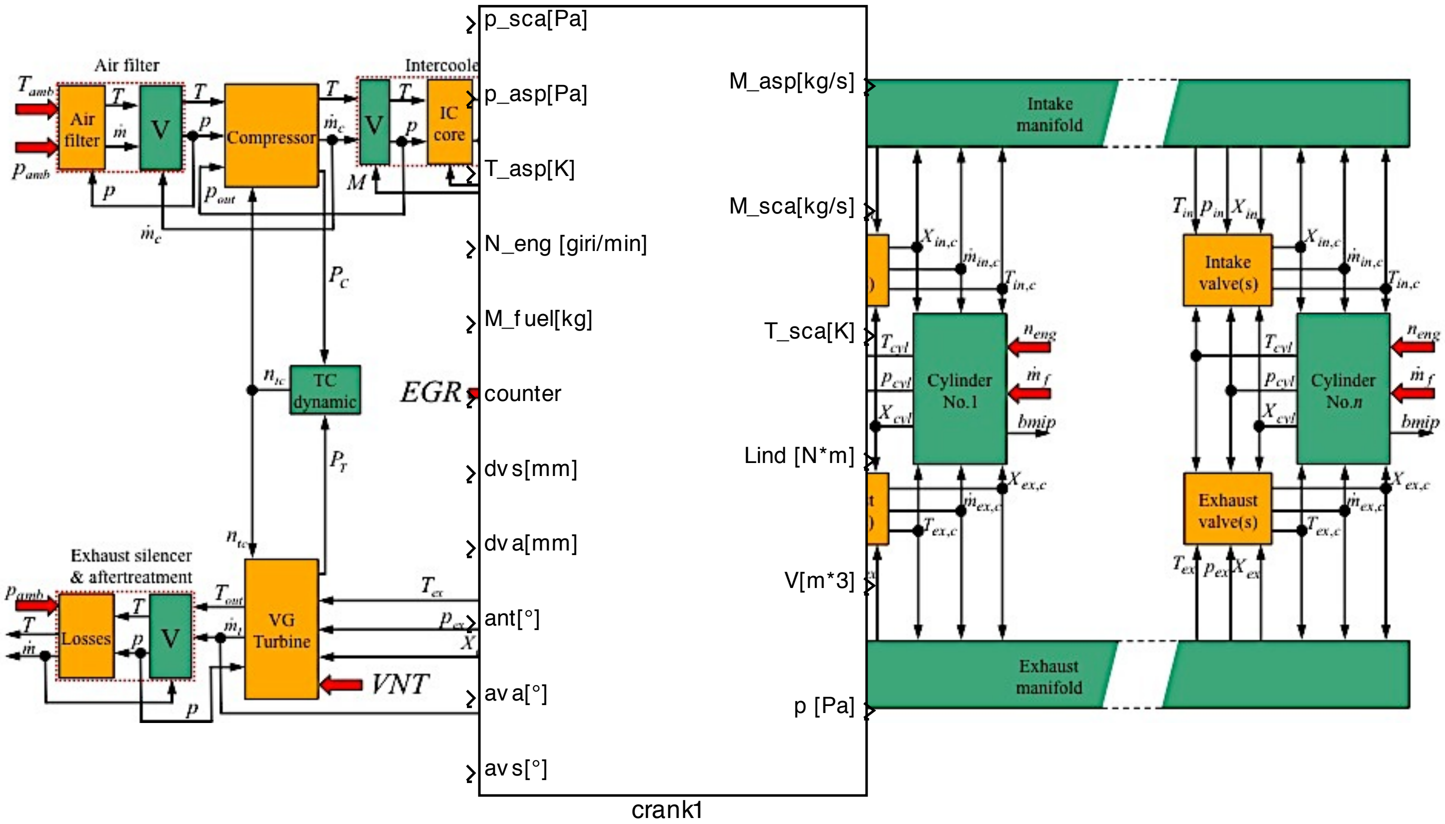


- 0D real-time model
- Matlab®/Simulink®

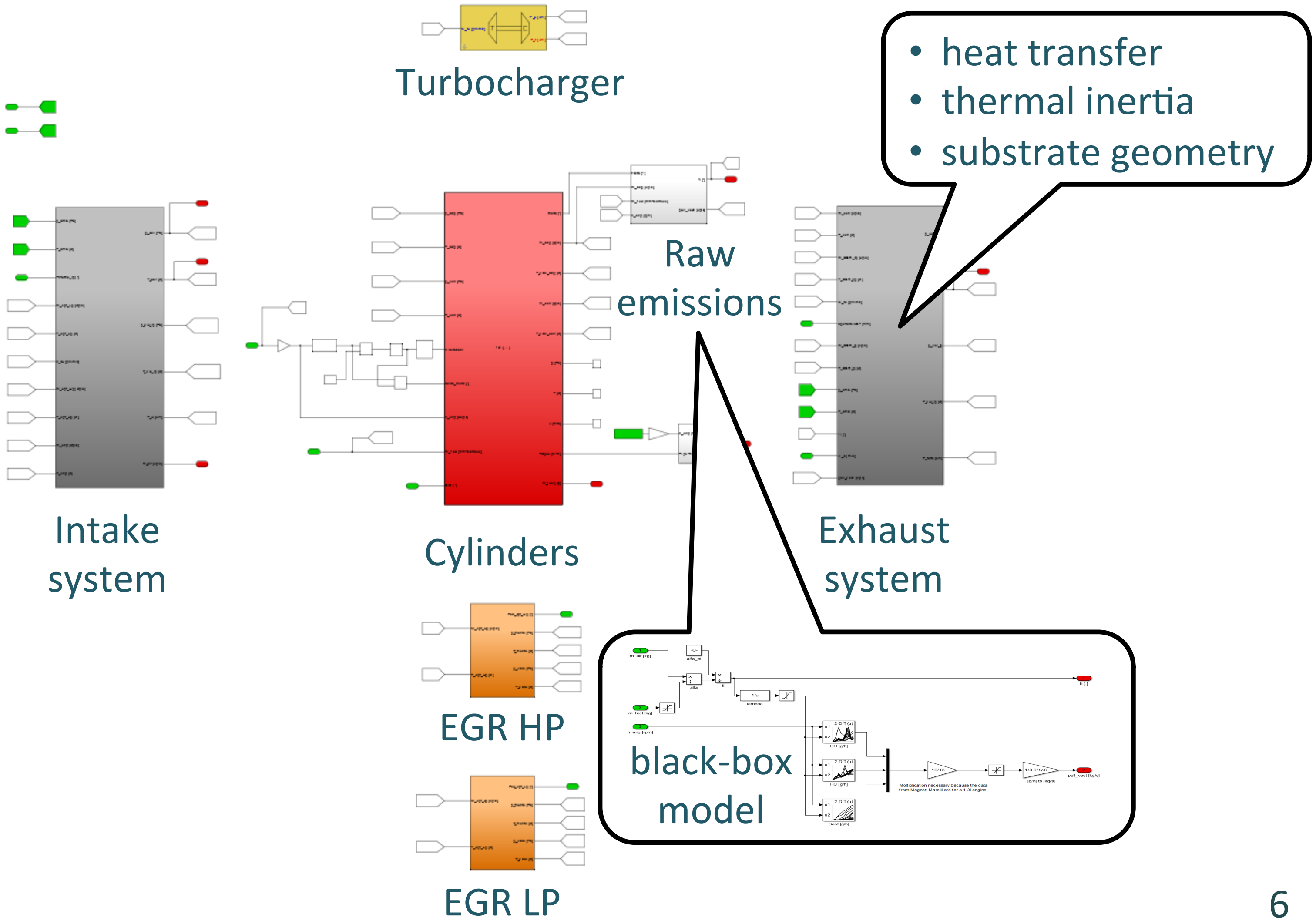
F&E models
- "white box" models
- conservation equations
- differential equations (i.e., state param.)

QSF models
- "black/white box" models
- physical/empirical equations
- algebraic equations (i.e., no state param.)

Model causality and I/O



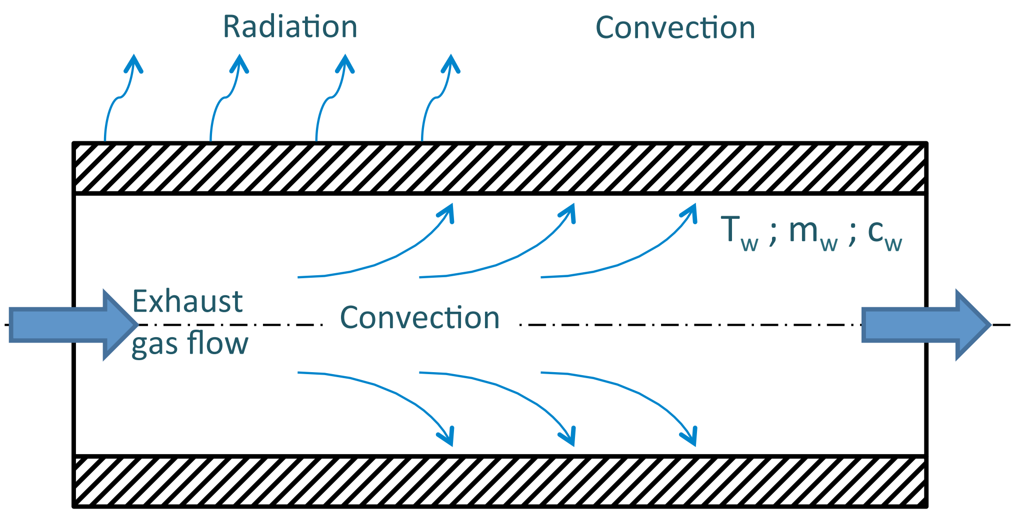
Improvement of the engine model



Exhaust system model: heat exchange

0D energy conservation equation:

$$c_v \frac{dT}{dt} = \dot{m}_{exh} \cdot h_{exh} - \dot{m}_{tur} \cdot h_{tur} - \dot{m}_{EGR} \cdot h_{EGR} - \dot{Q}_{in}$$



- ✓ Wall Temperature dynamic

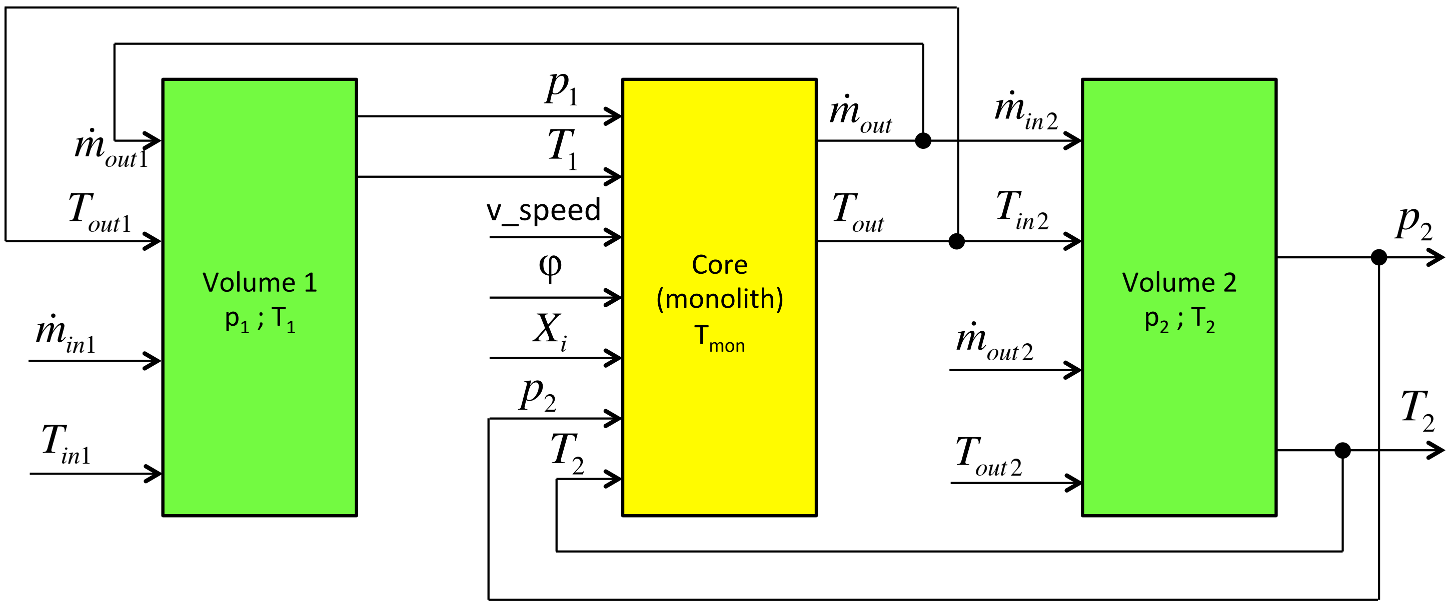
$$\frac{dT_w}{dt} = \frac{1}{m_w \cdot C_w}\left(Q_{in} - Q_{out}\right)$$

- ✓ Transient behaviour
- ✓ General correlations from literature for *Nu*

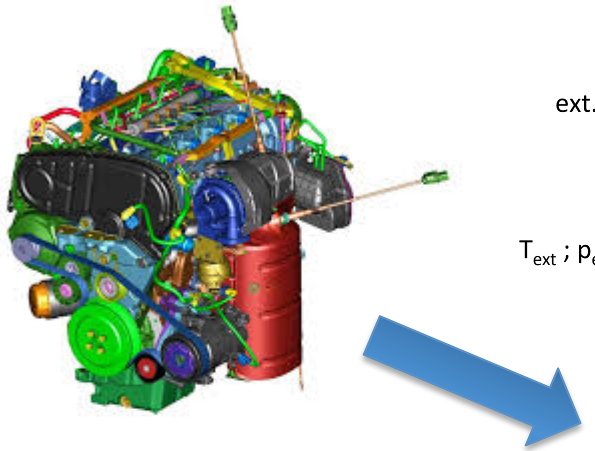
Catalyst model: layout

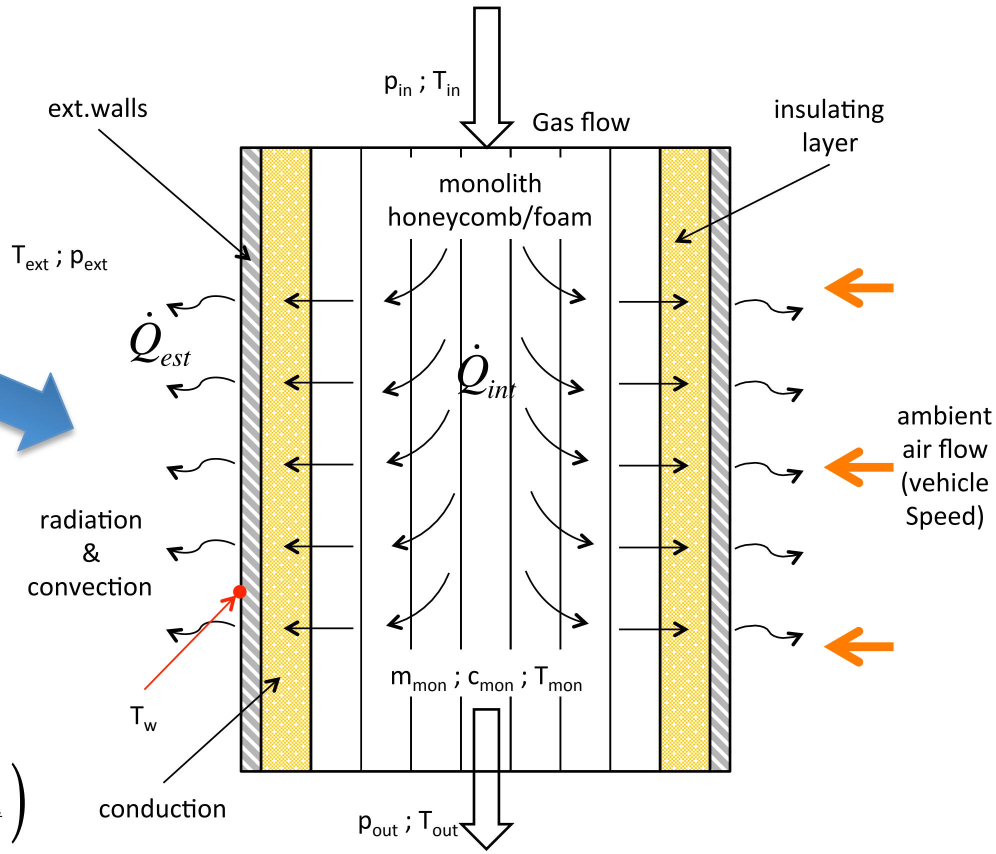
0D lumped parameter model:

- inlet and outlet volumes ➔ F&E approach
- core (monolith): pressure losses & thermal dynamics ➔ QSF approach



Substrate thermal inertia



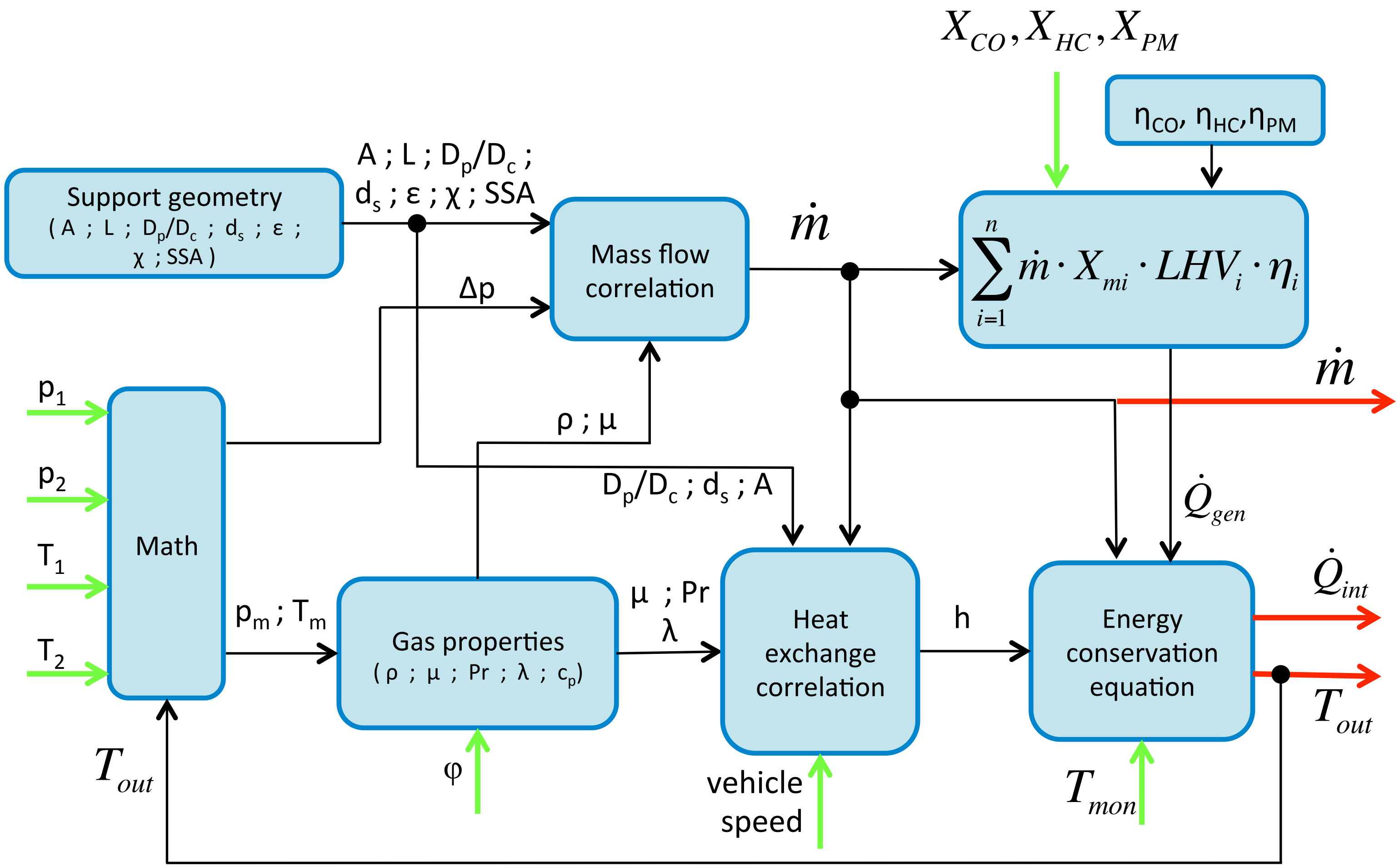


0D lumped parameter model:

- uniform monolith temperature T_{mon}

$$\frac{dT_{mon}}{dt} = \frac{1}{m_{mon} \cdot C_{mon}} \left(\dot{Q}_{int} - \dot{Q}_{ext} \right)$$

Core model: gas flow



Correlations for pressure losses and heat transfer

Mass flow and Heat transfer correlations are defined wrt substrate geometry

Support	Correlations	Pressure losses	Convection coefficient
honeycombs	Giani [12]	$\frac{\Delta p}{L} = \frac{28.46}{Re} \rho u^2 \frac{1}{D_c}$	$Nu = 2.977\left(1 + 0.095 \cdot Re \cdot Pr \frac{D_c}{L}\right)$
foams	Giani [12] (real foam)	$\frac{\Delta p}{L} = \frac{2}{d_h}\left(0.87 + \frac{13.56}{Re}\right)\left(\frac{1}{1 - G(\varepsilon)}\right)^4 \frac{G(\varepsilon)}{4} \rho u^2$	$Nu = 1.2 \cdot Re^{0.43} \cdot Pr^{1/3}$
	Lucci [22] (Kelvin cells)	$\frac{\Delta p}{L} = SSA \frac{\rho u^2}{2} \frac{\chi^2}{\varepsilon^3}\left(0.4 + \frac{30}{Re^{0.8}}\right)$	$Nu = 1.28 \cdot Re^{0.32} \cdot Pr^{1/3} \cdot \varepsilon^{2.34}$

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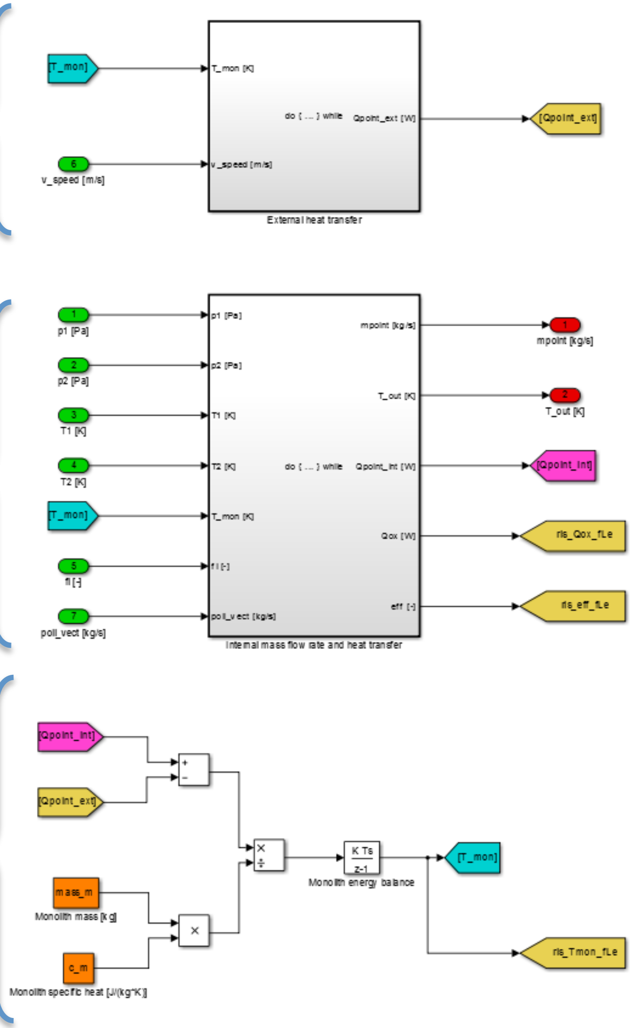
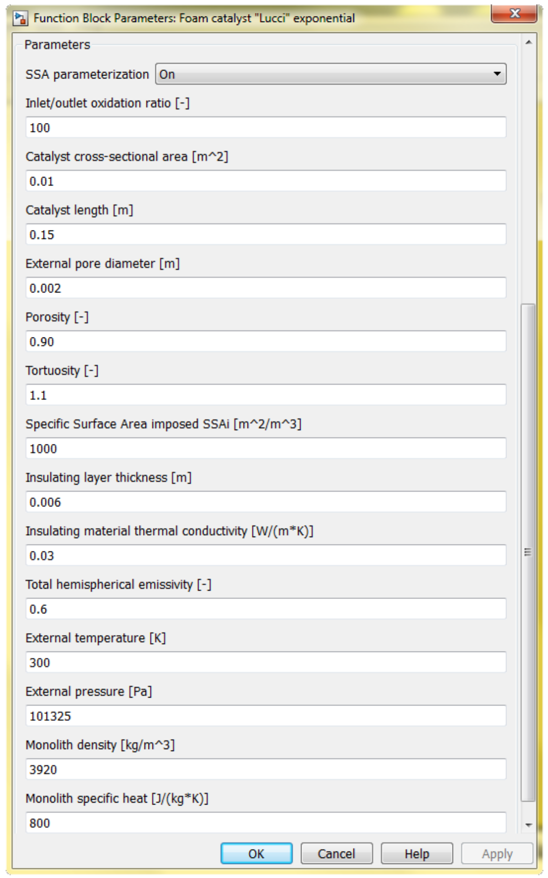
Overall Simulink® model of the catalyst

External Heat Transfer

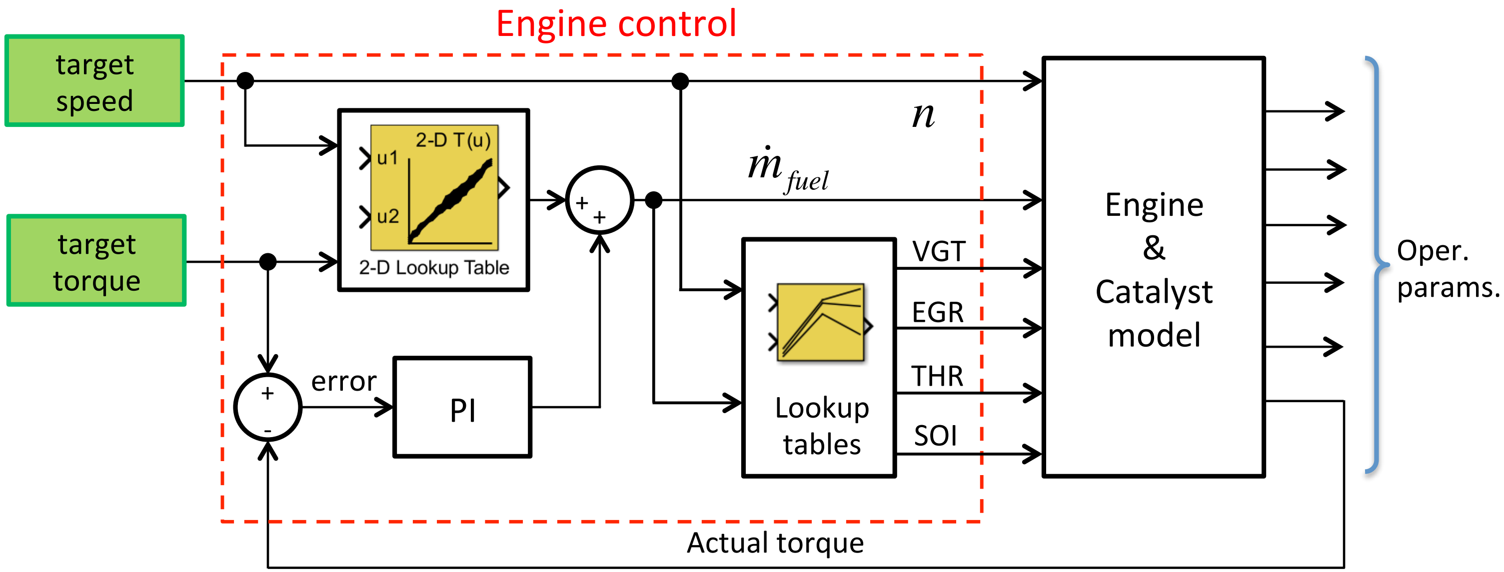
Internal Mass flow & Heat Transfer

Monolith Thermal Inertia





Simulation: 4cyl TC Diesel during EUDC



- feedforward map-based + feedback PI for torque
- idle operating conditions
- fuel “cut-off” during decelerations

Driving cycle Simulations (EUDC)

Layouts:

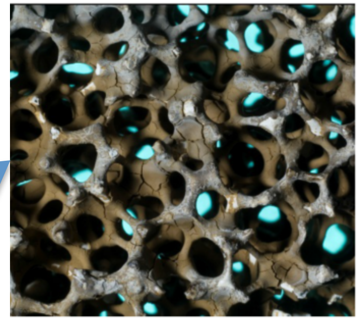
a. **Honeycomb substrate (from "Giani" [12])** (1)

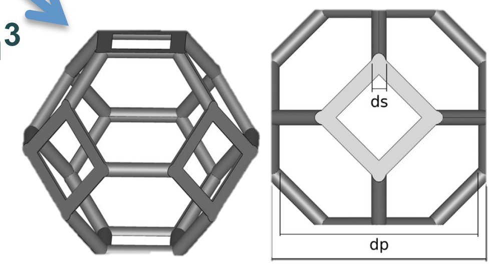
   (1) **V=1,5l, L=15cm, ε=63%, SSA=2700 m^2/m^3**

b. **Real foam substrate (from "Giani" [12])** (2)

c. **Kevin cells substrate (from "Lucci" [22])** (2)

   (2) **V=1,5l, L=15cm, ε=73%, SSA=1000 m^2/m^3**



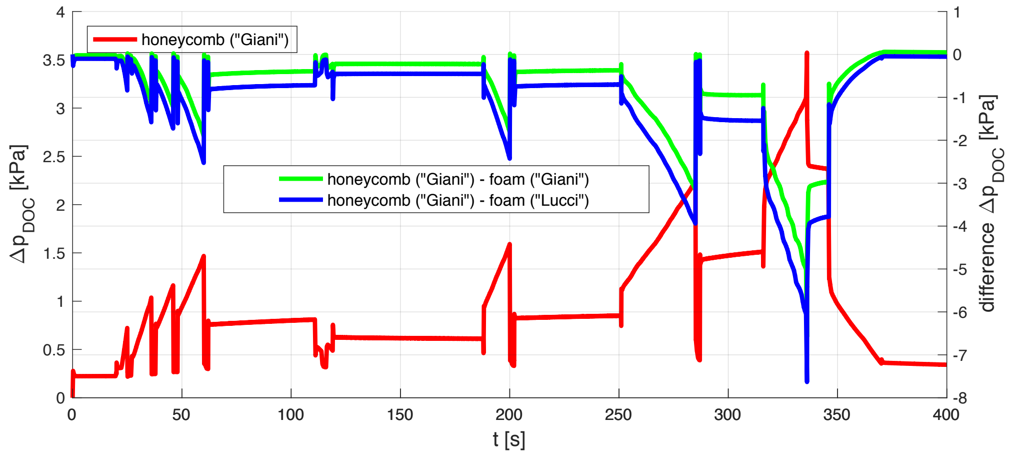


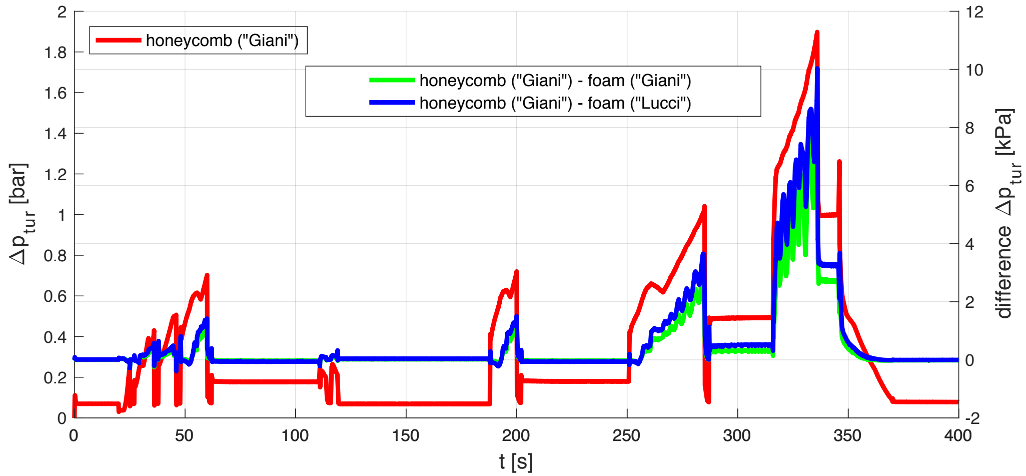
Outputs:

a. **Engine operating parameters**

b. **Cumulative fuel consumption**

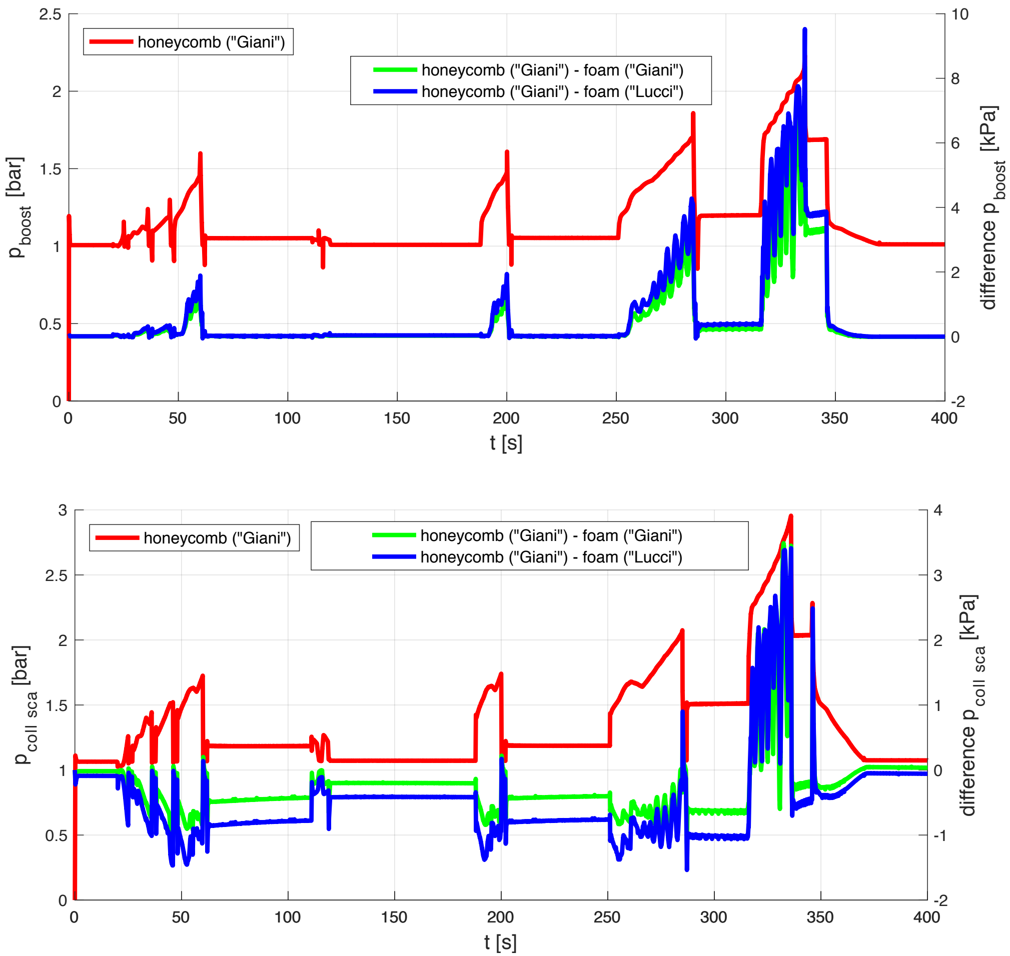
Results: DOC and turbine Δp





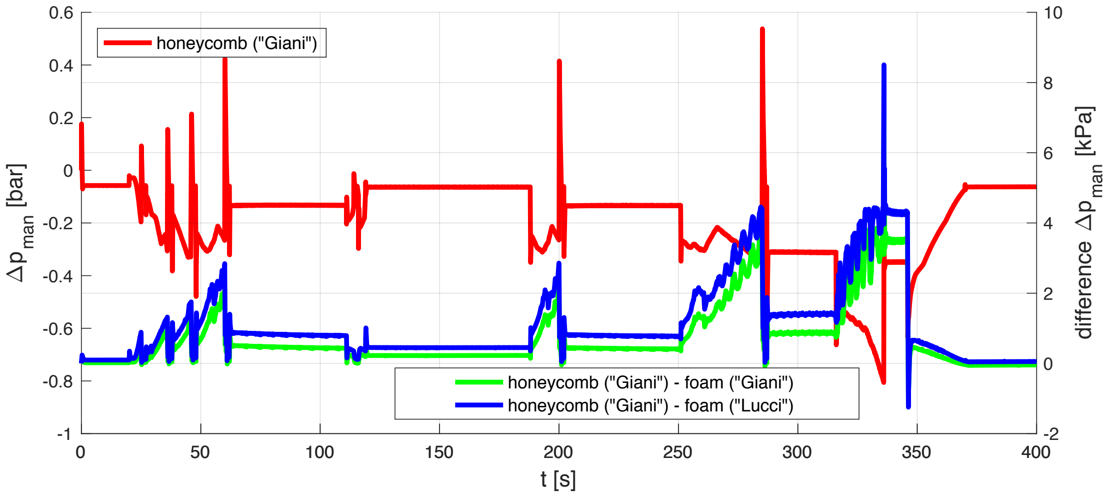
- higher pressure losses when using foams
- lower Δp through the turbine for foams

Results: intake & exhaust manifold pressure



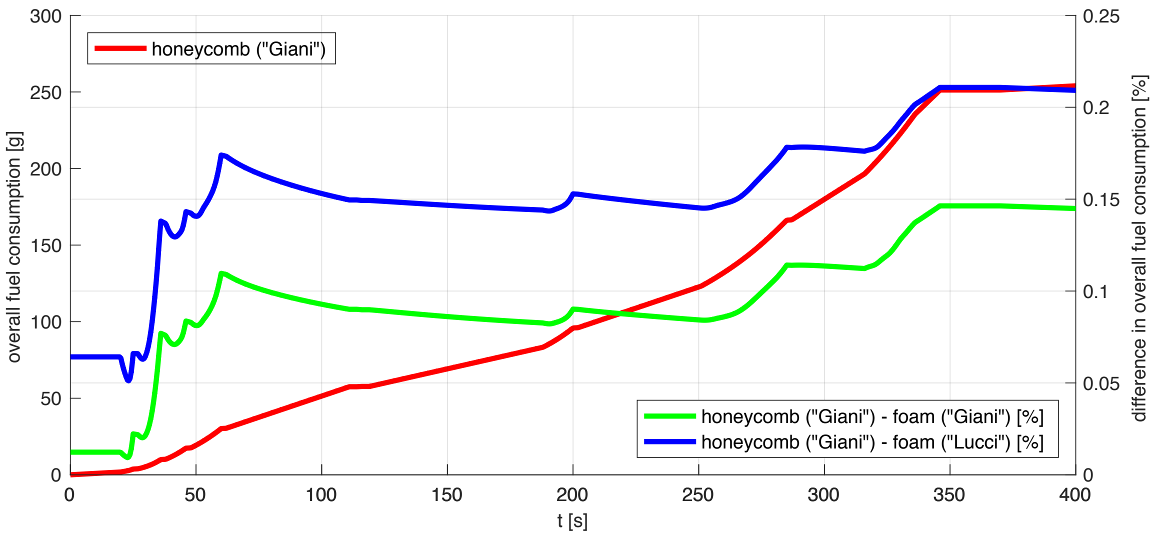
- different operating conditions for the turbocharger
- lower pressure changes in the exhaust manifold

Results: Δp between manifolds



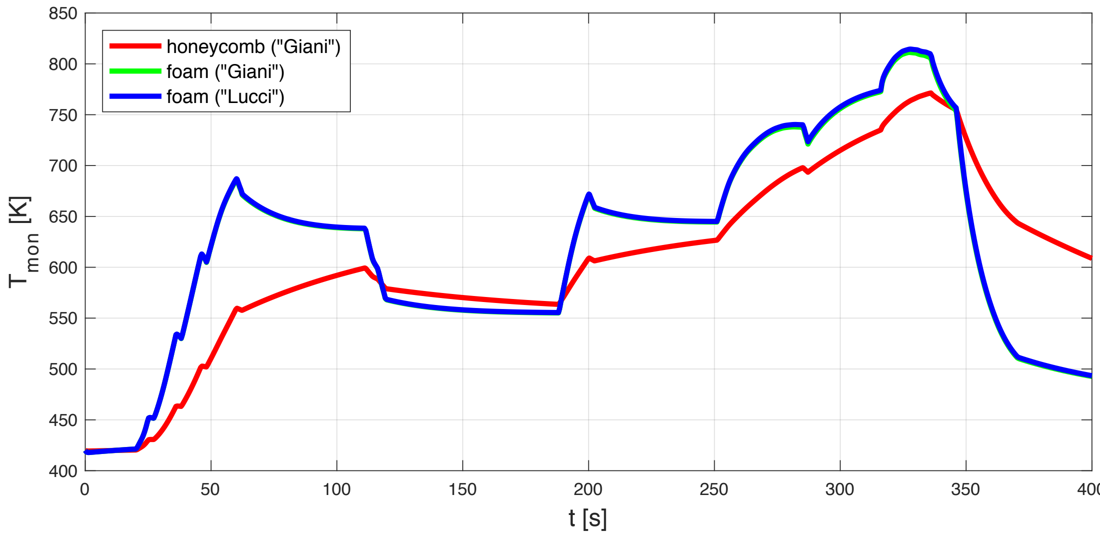
- the higher Δp in the catalyst give rise to a Δp between manifolds that is almost equal
- higher pumping losses when using foams

Results: overall fuel consumption



- differences are low
- overall fuel consumption: Honeycomb = 254 g (22,9 km/l)
  Real foam (“Giani”) +0.15 %
  Kelvin cells (“Lucci”) + 0.21 %

Results: monolith temperature



Foams:

- Higher convection coefficients
- Lower thermal inertia

Faster dynamics of T_{mon}

- lower «light-off» time for cold start
- faster cooling down during «cut-off»

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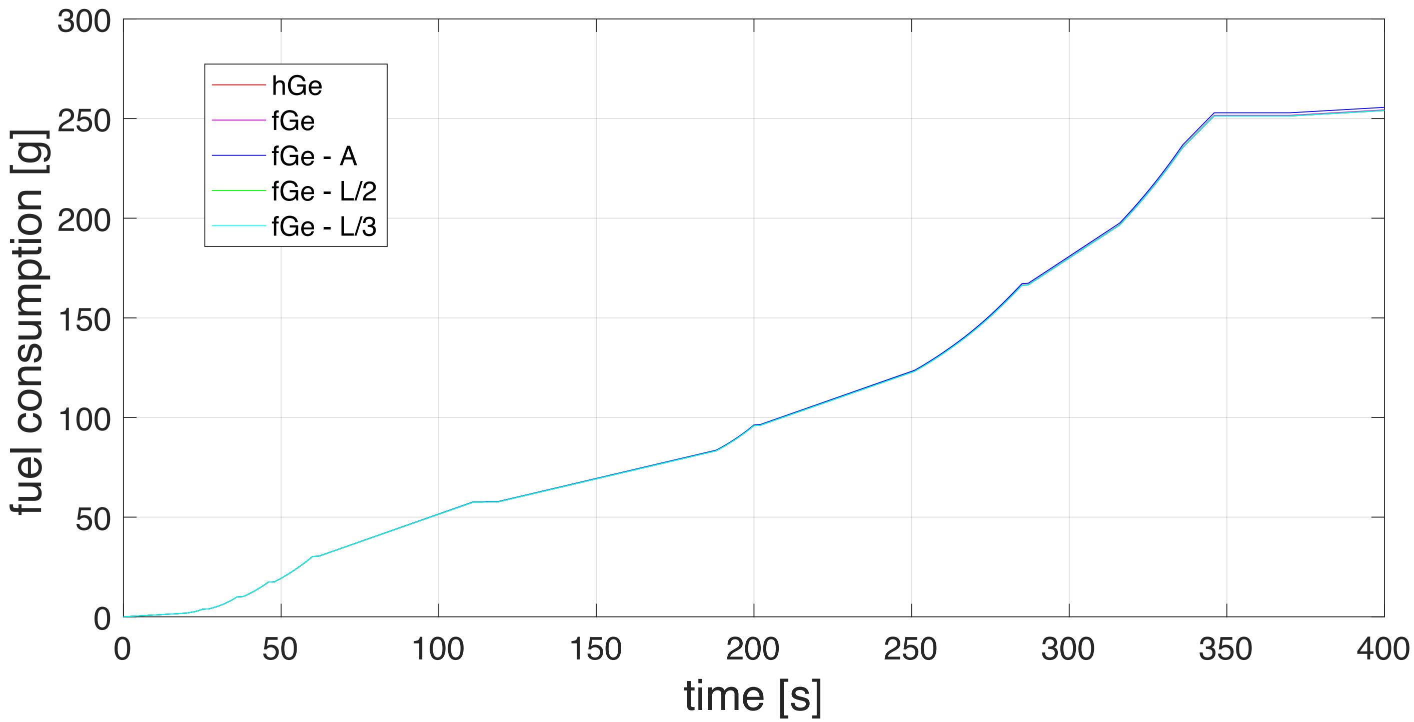
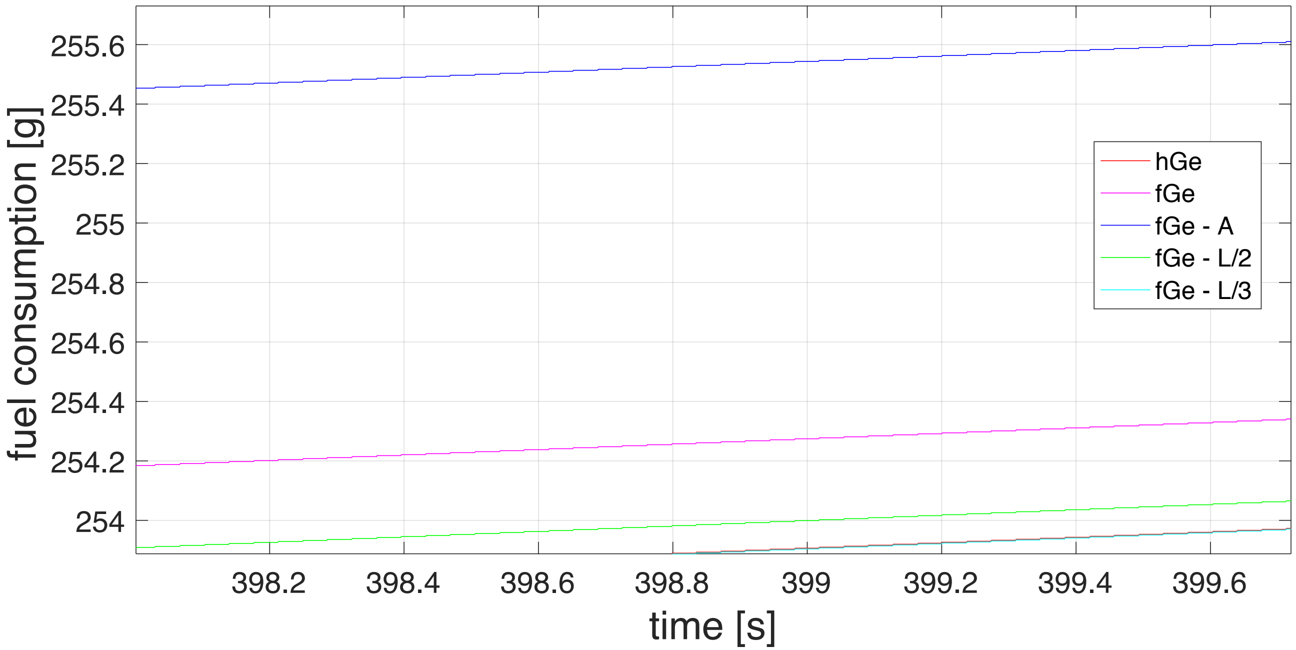
Results: overall fuel consumption



Results: overall fuel consumption



- overall fuel consumption:
  - Honeycomb = 254 g
  - Real foam ("Giani") ➔ = 254,3g +0.15 %
  - Real foam ("Giani") A/2 ➔ = 255,6g +0.63 %
  - Real foam ("Giani") L/2 ➔ = 254,1g
  - Real foam ("Giani") L/3 ➔ = 254g

Conclusions & Future

Conclusions:

- Enhancements in the 0D CA real-time engine model in Simulink®:
  - ✓ Exhaust system model
  - ✓ Catalyst model (gas flow and thermal behaviour) for both honeycomb and foam substrates
- Simulation of the engine behaviour during a driving cycle (EUDC)
- Estimation of the effects of substrate structure on overall fuel consumption within the EUDC:
  - ✓ slight increase in fuel consumption for foam supports
  - ✓ lower thermal inertia of foams (effects on "light-off" & "cut-off")
  - ✓ lower volumes for the foam supports (about L≈1/3 vs. honeycomb) led to the same overall fuel consumption over an EUDC

Conclusions & Future

Future developments:

- Experimental validation of the model
- Matching of the engine model with a vehicle + driver model for a direct simulation of driving cycles
- More detailed models for emissions formation and conversion efficiencies to analyse the effects of thermal inertias (“light-off” & “cut-off” phases)
- VGT/EGR/SOI control strategies
- Development of fast & physically-based models for other after-treatment systems (SCR)
- Extension of the analysis to S.I.engines

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Thank You for your attention !

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"Judge a man by his questions rather than by his answers." Voltaire