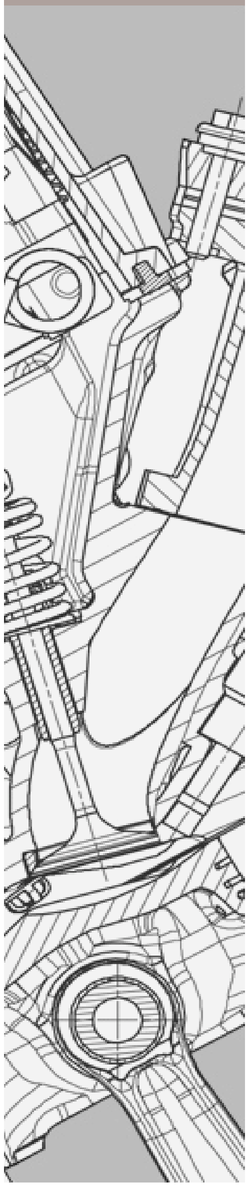
BMW Group
Stefan Heller
09.10.2006



Exhaust system warm-up simulation.
A tool to improve exhaust system design.

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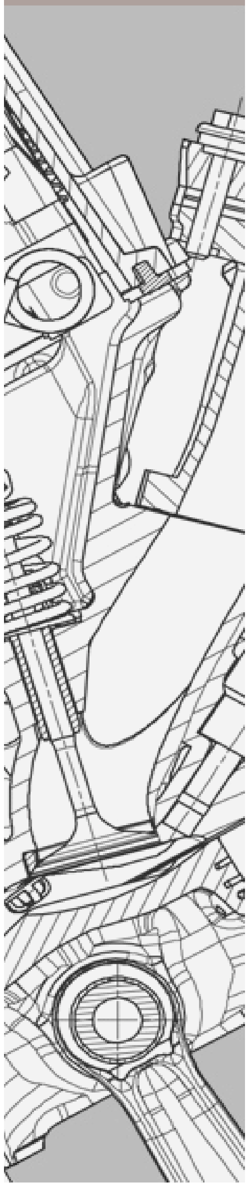
Exhaust system warm-up simulation.
Agenda.



1 Motivation

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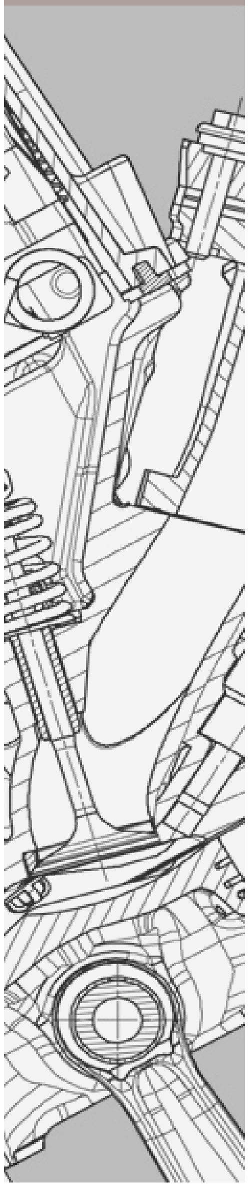
3 Heat transfer during catalyst-heating operation

4 Relevant effects for warm-up simulation

- 4.1 Post-oxidation reactions
- 4.2 Turbulent effects in heat transfer
- 4.3 Condensation effects

5 Conclusion

Exhaust system warm-up simulation.
Motivation.



SI engines emit 80% of the total hydrocarbon emissions during the first 30 seconds after engine cold-start.

Hydrocarbon emission reduction potential:

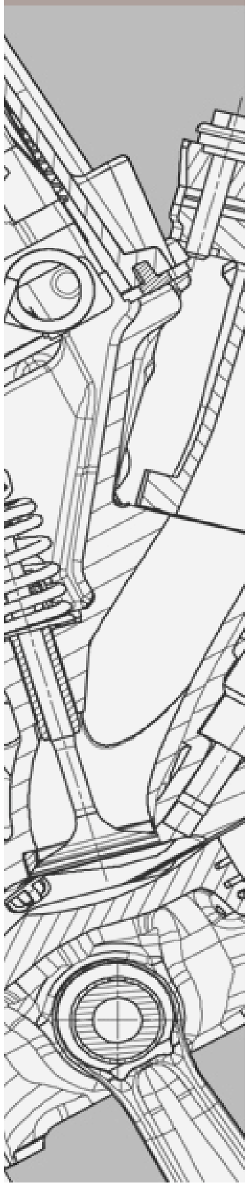
1. **Engine design and operation parameter**
   (HC emissions during catalyst-heating operation, engine-start strategy, …)
2. **Heat losses in the exhaust manifold**
   (Air-gap isolated exhaust manifold, close coupled catalytic converter, …)
3. **Catalytic converter properties**
   (Cell density, precious metal load in wash coat, low thermal capacity brick, …)

Cost-intensive efforts in 3. might be replaced by an improvement in 2.

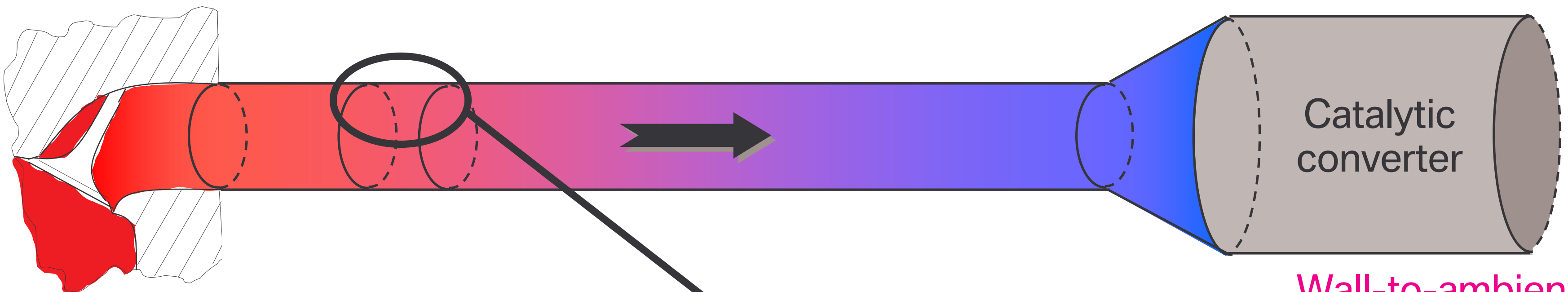
Exhaust system design has

- large influence on tail pipe emissions
- high potential in saving exhaust system costs

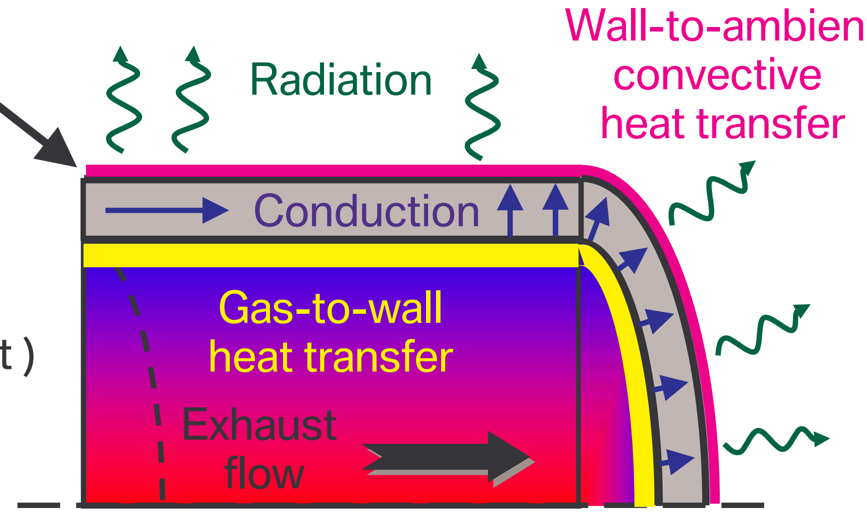
Exhaust system warm-up simulation.
Introduction to SI engine warm-up simulation.



Schematically illustrated SI engine exhaust system



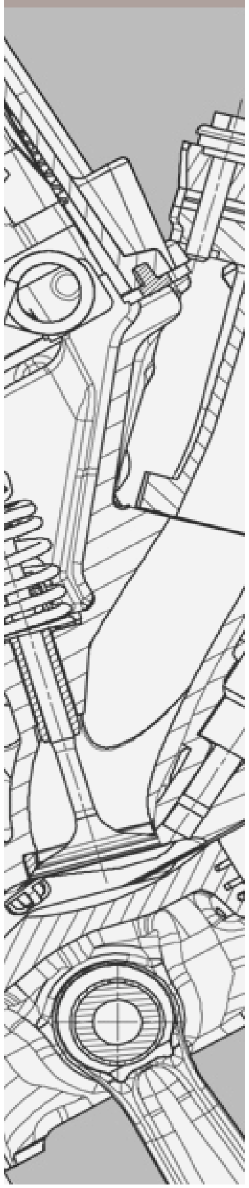
The heat losses are driven by the **gas-to-wall heat transfer.**



Other heat transfer effects
(Conduction, Radiation, Convection to ambient)
do only have an **inferior** importance
during warm-up.

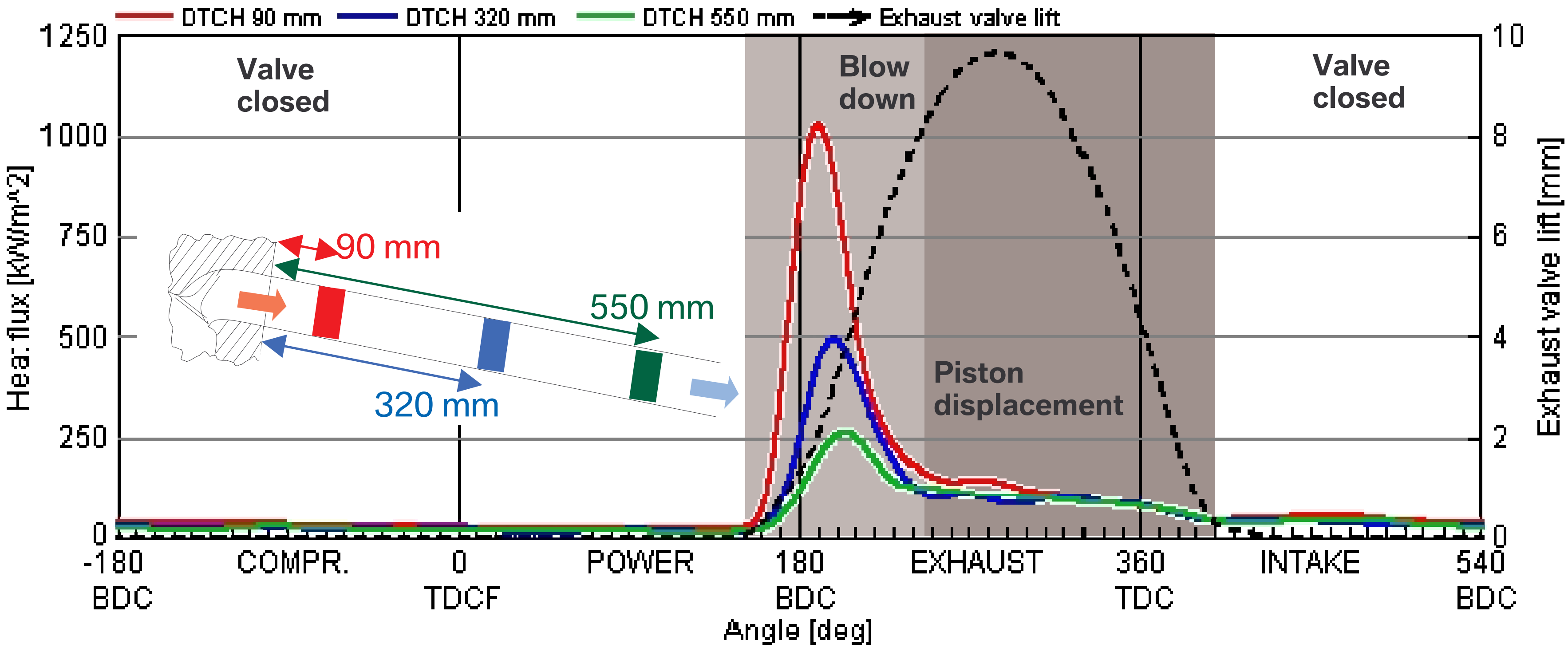
Most potential of decreasing heat losses by engine design are expected by affecting the **gas-to-wall heat transfer** in the exhaust manifold.

Exhaust system warm-up simulation.
Heat transfer during catalyst-heating operation.



Gas-to-wall heat flux

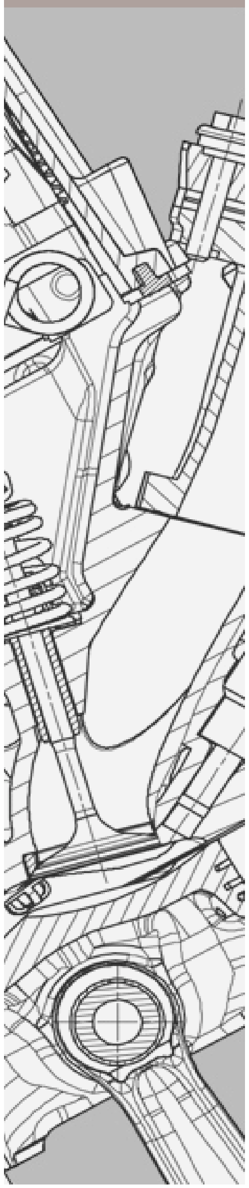
Engine operated with retarded ignition timing at 1000 rpm



- The heat transfer during **blow down** is responsible for the major heat losses.
- Increasing distance ➔ decreasing importance of the “blow down” phase.

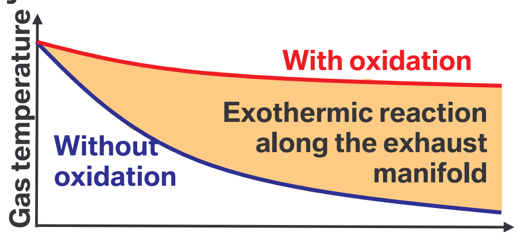
Warm-up simulation needs to predict heat transfer in the “blow down” phase.

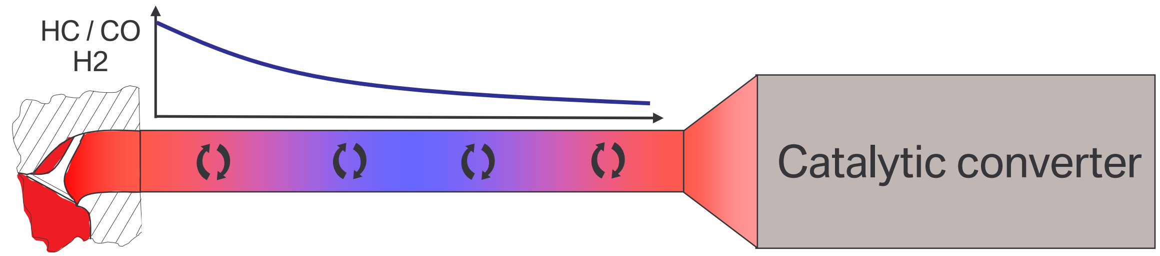
Exhaust system warm-up simulation.
Relevant effects for warm-up simulation.



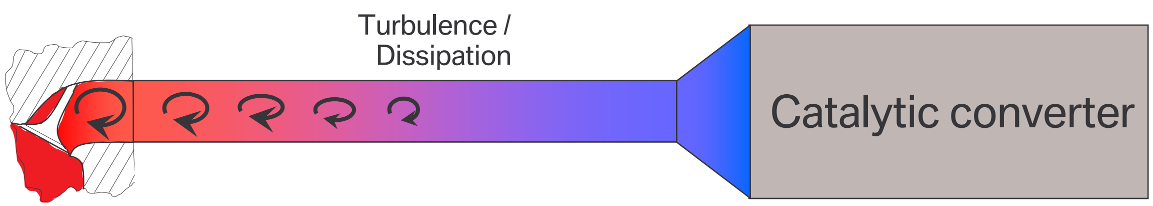
During warm-up of a SI engine exhaust system some **additional effect** should be considered:

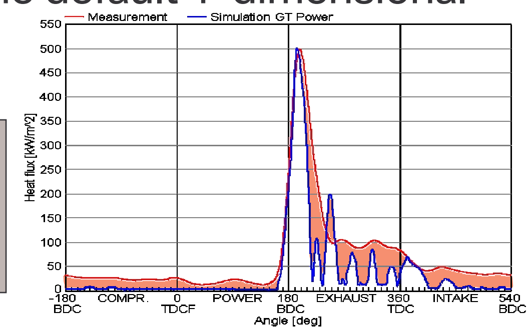
1) **Post-oxidation** in the exhaust flow with retarded ignition timing and secondary air injection



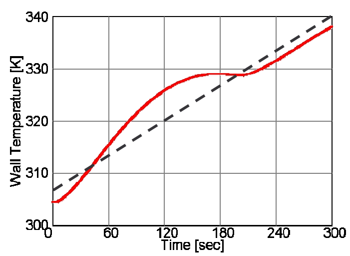


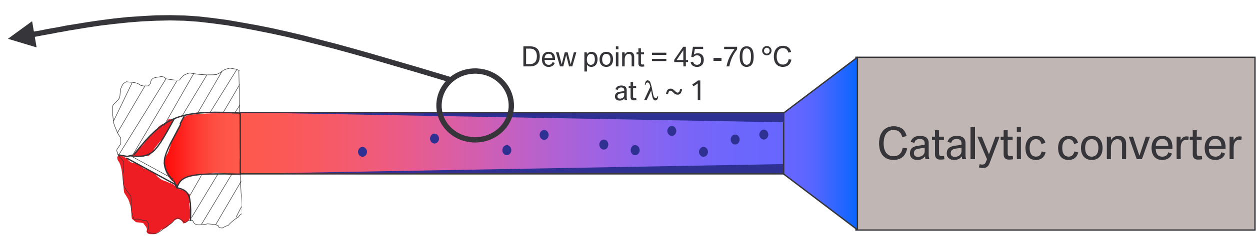
2) **3-dimensional effects / turbulence** not predicted by the default 1-dimensional heat transfer model

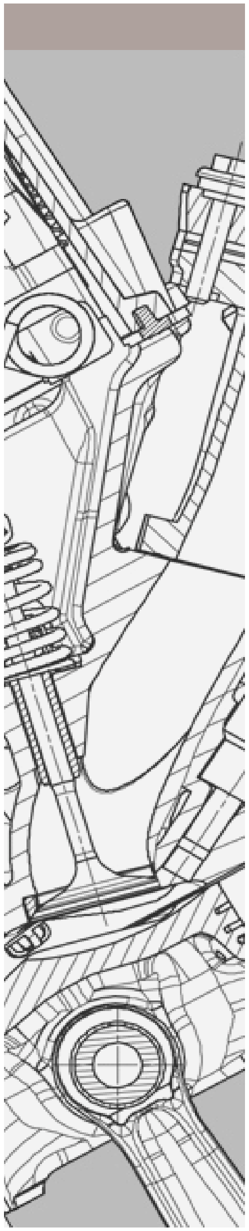




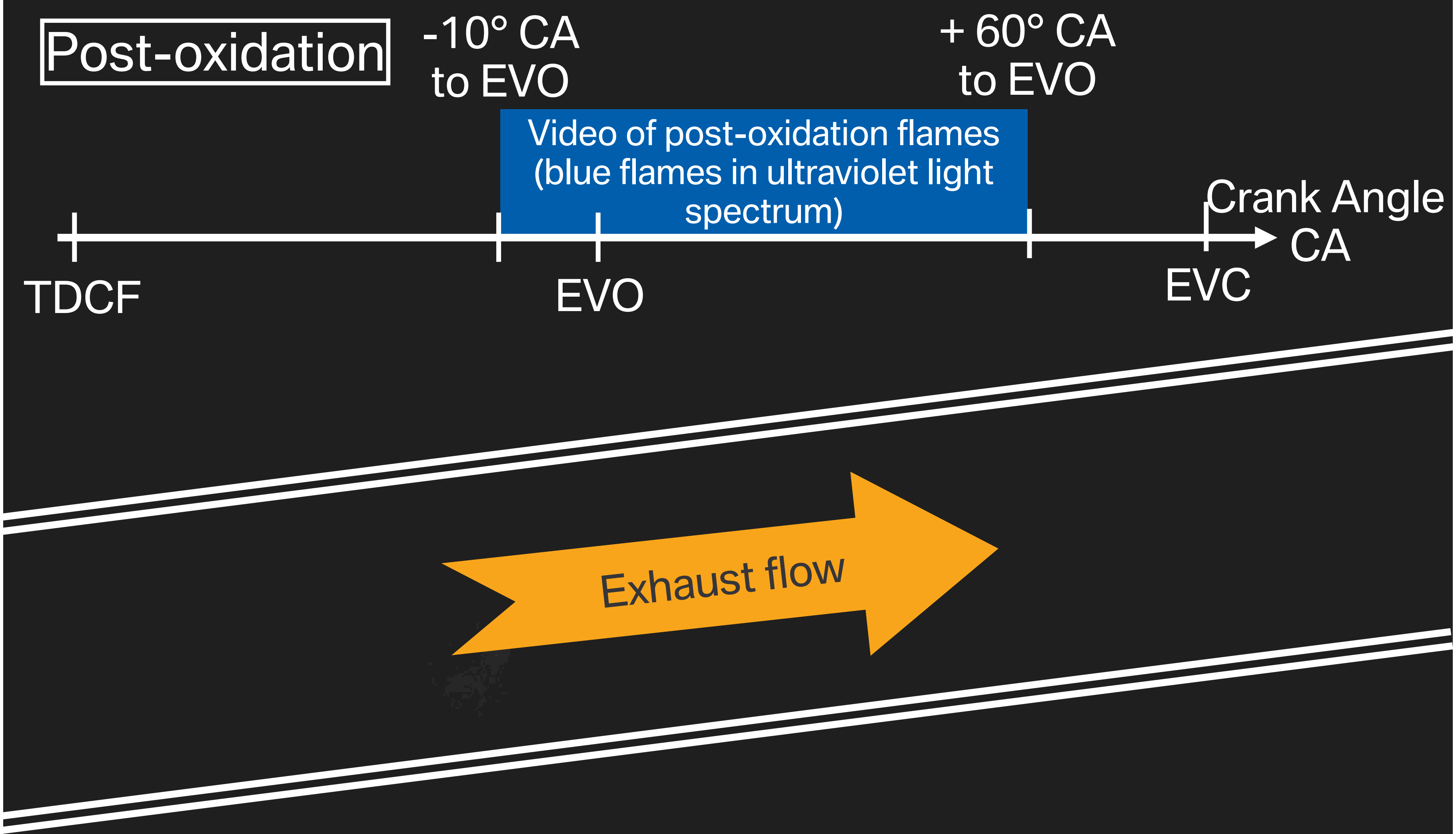
3) **Condensation** of water in the exhaust system







Post-oxidation



Engine operated at 1000 rpm

with retarded ignition timing and $\lambda = 1$

(no secondary air injection)

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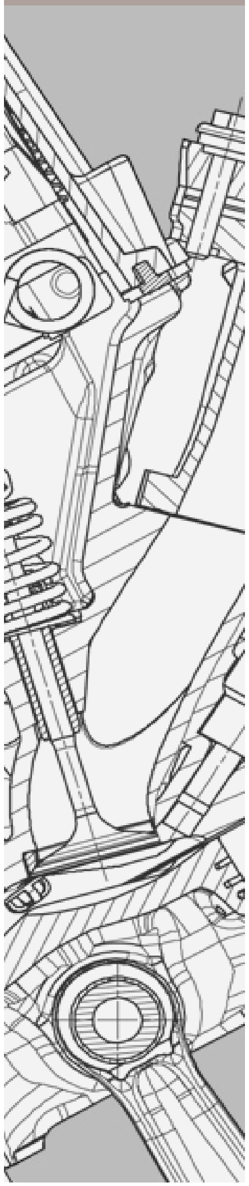
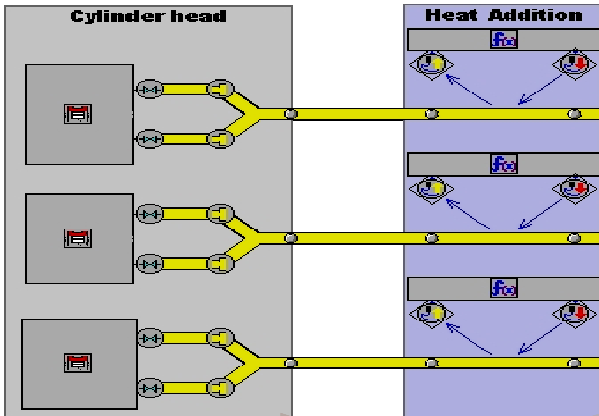
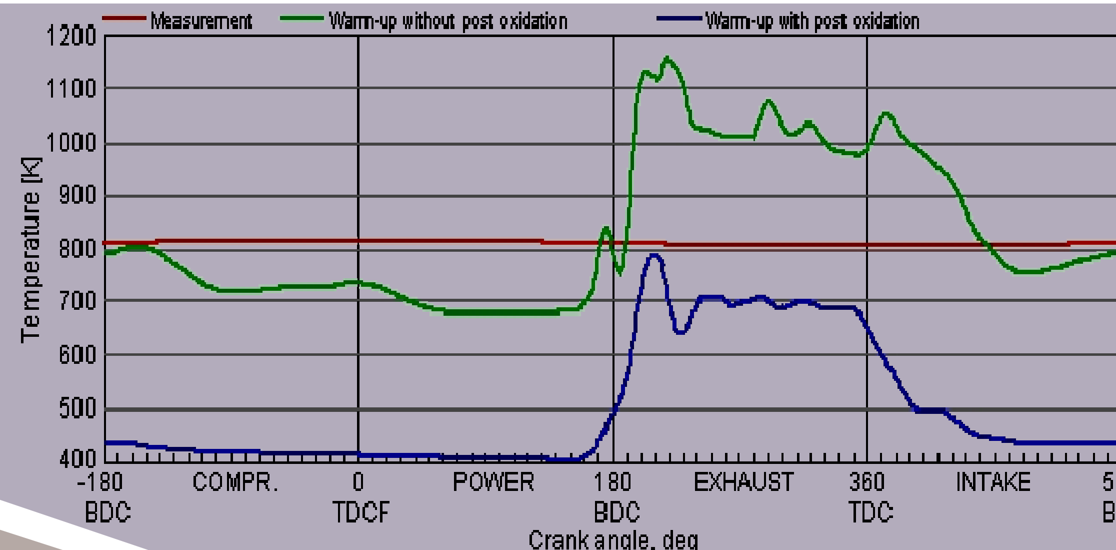
Exhaust system warm-up simulation.
Post-oxidation reactions.



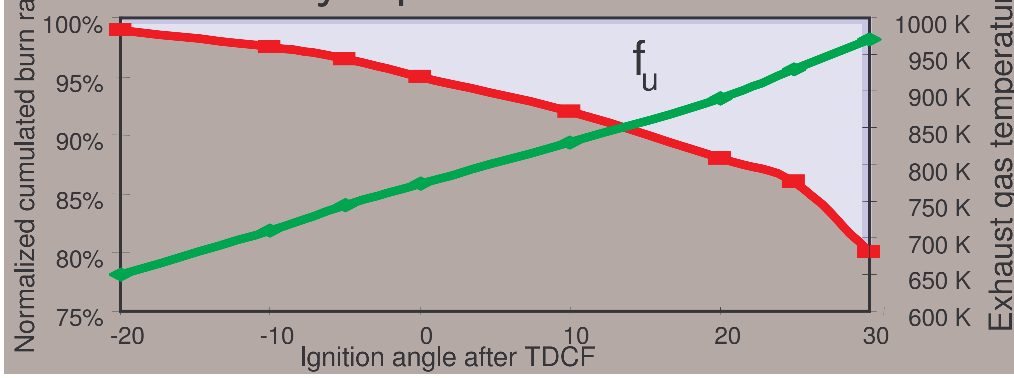
Warm-up simulation model with exothermic reactions in the exhaust manifold





In-cylinder combustion

Retarded ignition timing
- ↗ Unburned mass fraction at EVO
- ↗ Exhaust gas temperature
- ↗ Probability of post-oxidation in the exhaust



Exhaust post-oxidation

Exothermic reaction modeled by

$$\dot{Q} = C_1 \cdot f_u \cdot \frac{\dot{m}}{1+\lambda \cdot L_{st}} \cdot H_u$$

- + Instationary oxidation model
- + Improves exhaust flow dynamic

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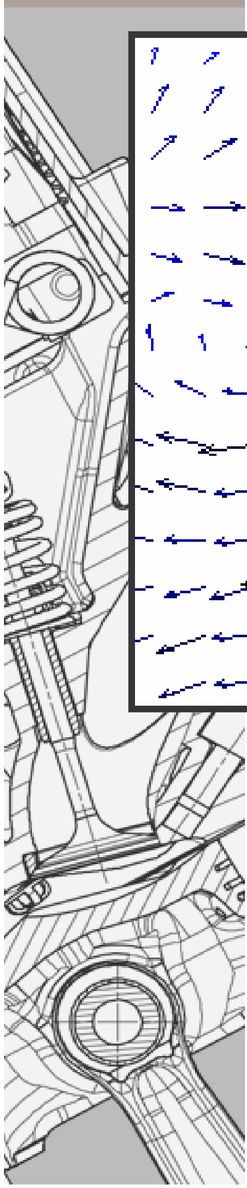
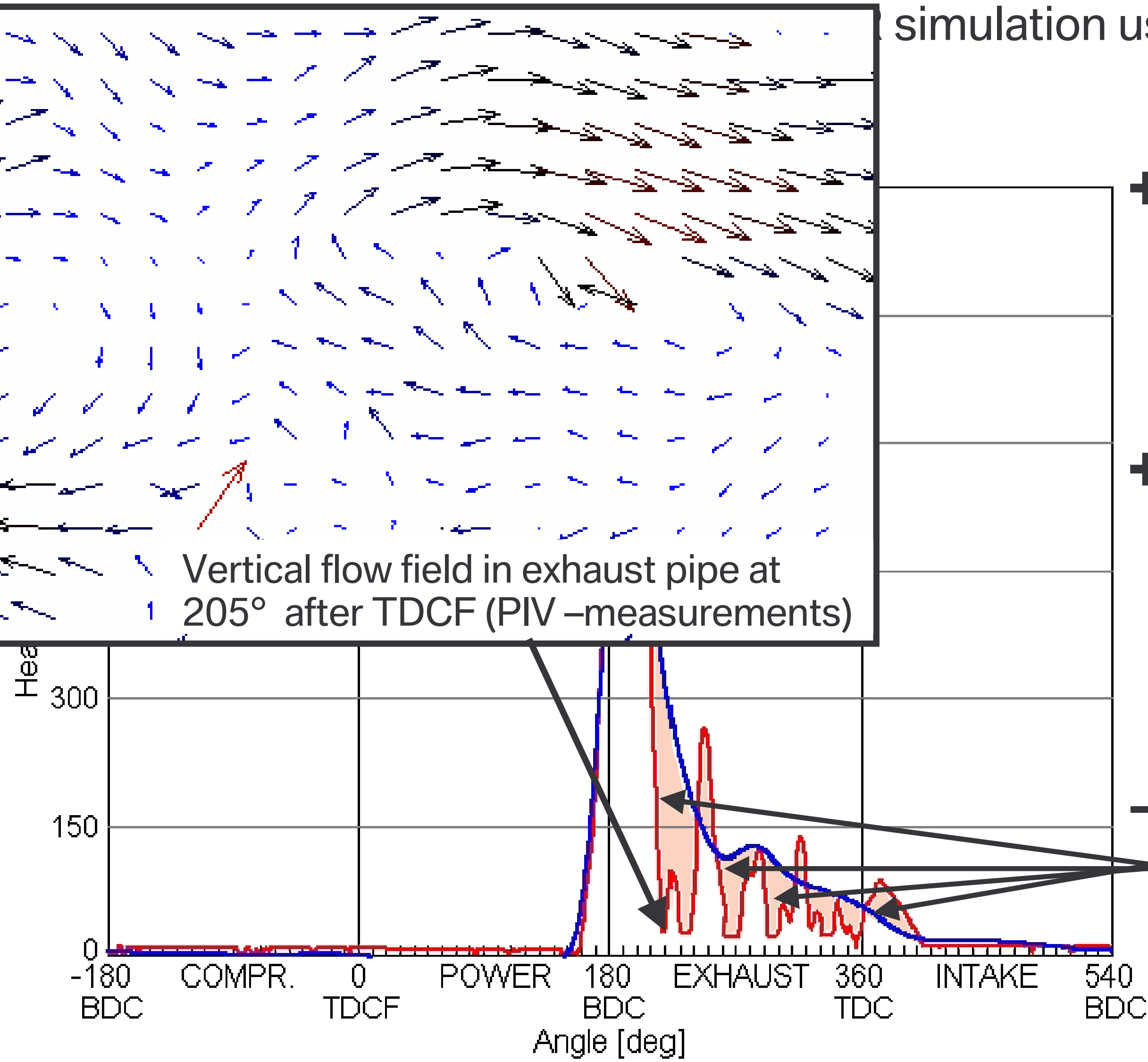
Exhaust system warm-up simulation.
Turbulent effects in heat transfer.

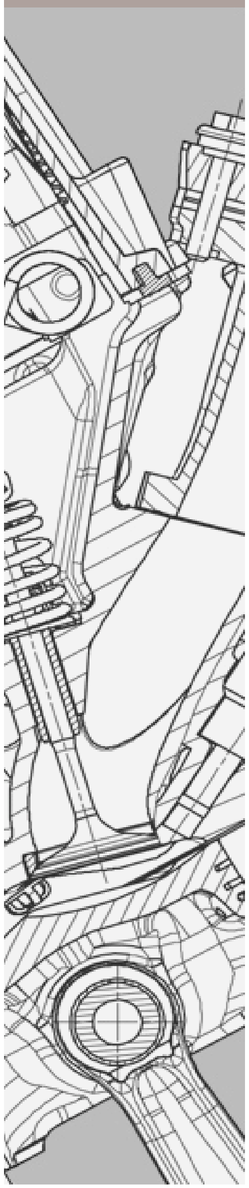


simulation using default heat transfer

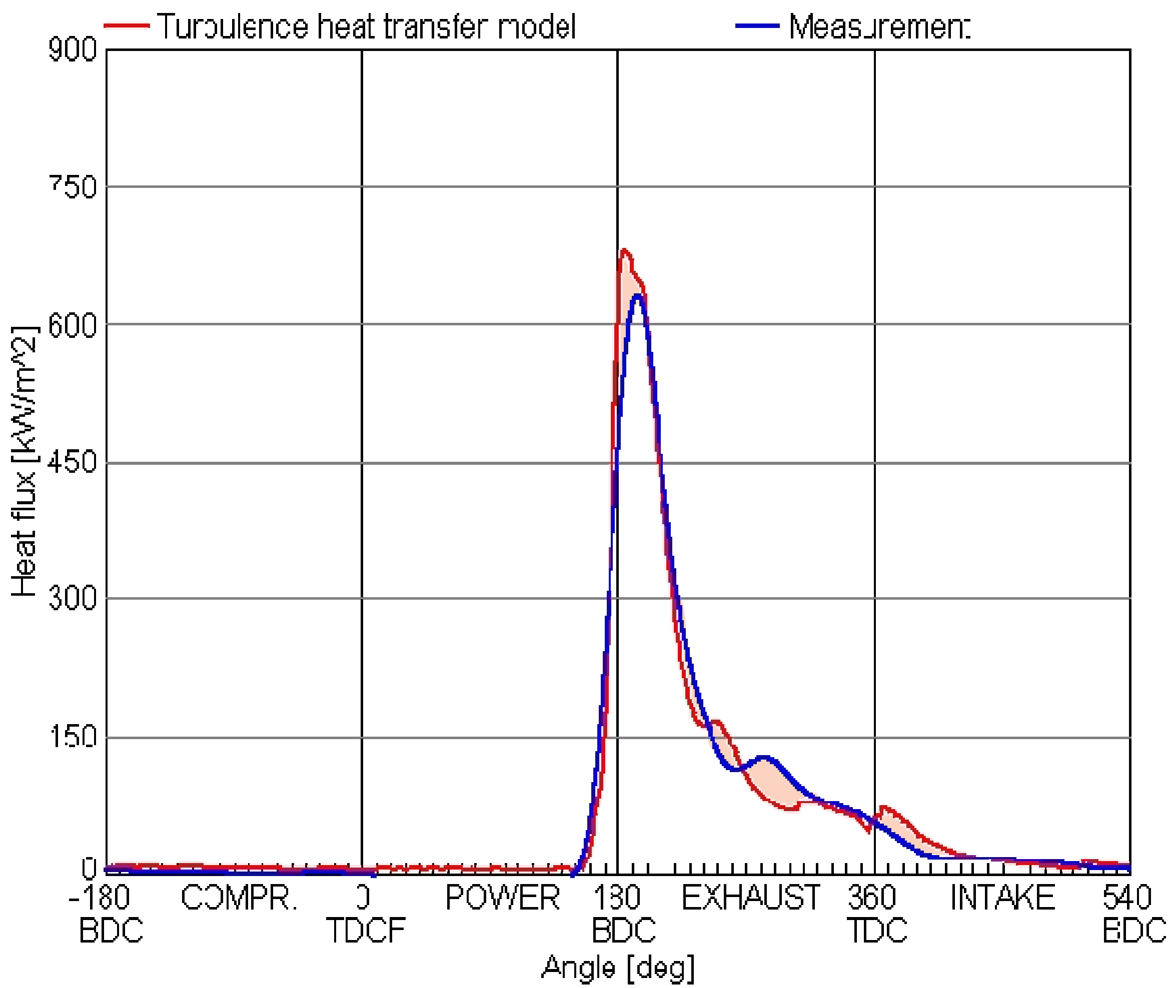


- **+** The overall heat fluxes during engine cycle are identical for simulation and measurement.
- **+** The simulation of GT POWER predicts the main characteristics well
  (Connection between mass and heat transfer)
- **–** Heat transfer enhance-ment at flow velocity change are not predicted by the default heat transfer model

Exhaust system warm-up simulation.
Turbulent effects in heat transfer.



New empirical model for the heat transfer correlation during warm-up:



The flow velocity u_{eff} for the heat transfer calculation is modified

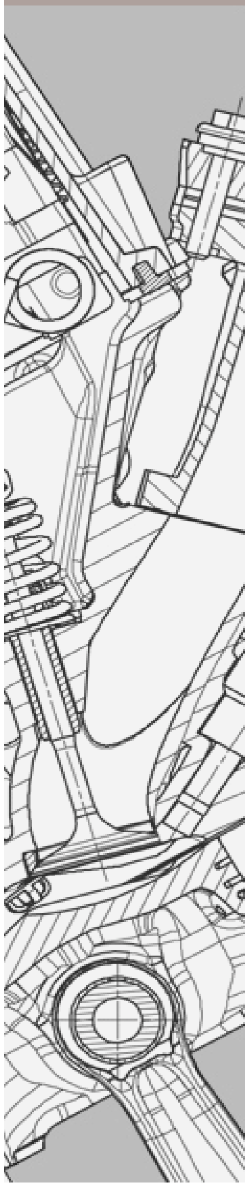
$$u_{qs}^{n} = abs(vel_{n})$$

$$u_{turb}^{n} = u_{eff}^{n-1} \cdot (1 - C_{Dis})$$

$$u_{eff}^{n} = \max\{u_{qs}^{n}, u_{turb}^{n}\}$$

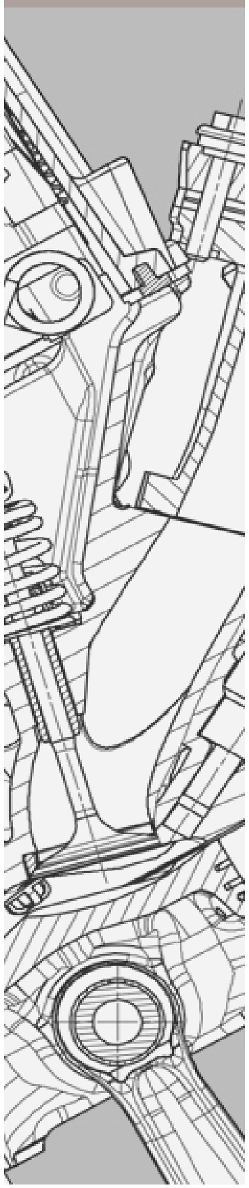
C_{Dis} represents some kind of a dissipation of the turbulent exhaust gas velocity

+ Slight improvements in exhaust dynamics
- Additional parameter for heat transfer calculation

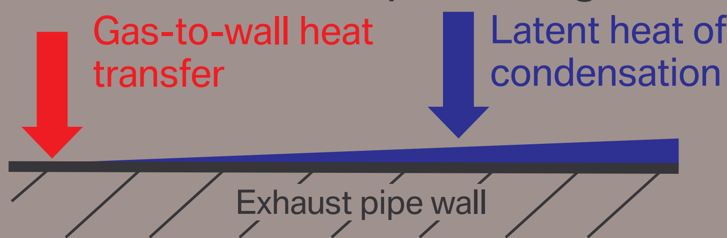


Source: ADA (Abgaszentrum der Automobilindustrie)

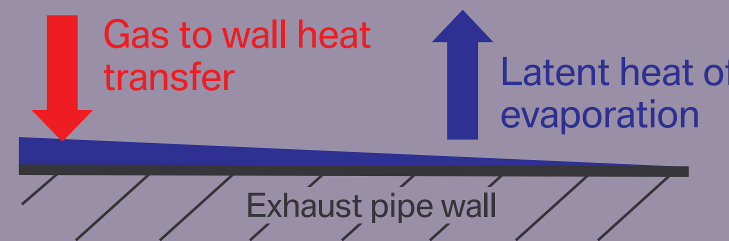
Exhaust system warm-up simulation.
Condensation effects.



Condensation of water
- Release of the latent heat
- Increase of wall temperature gradient

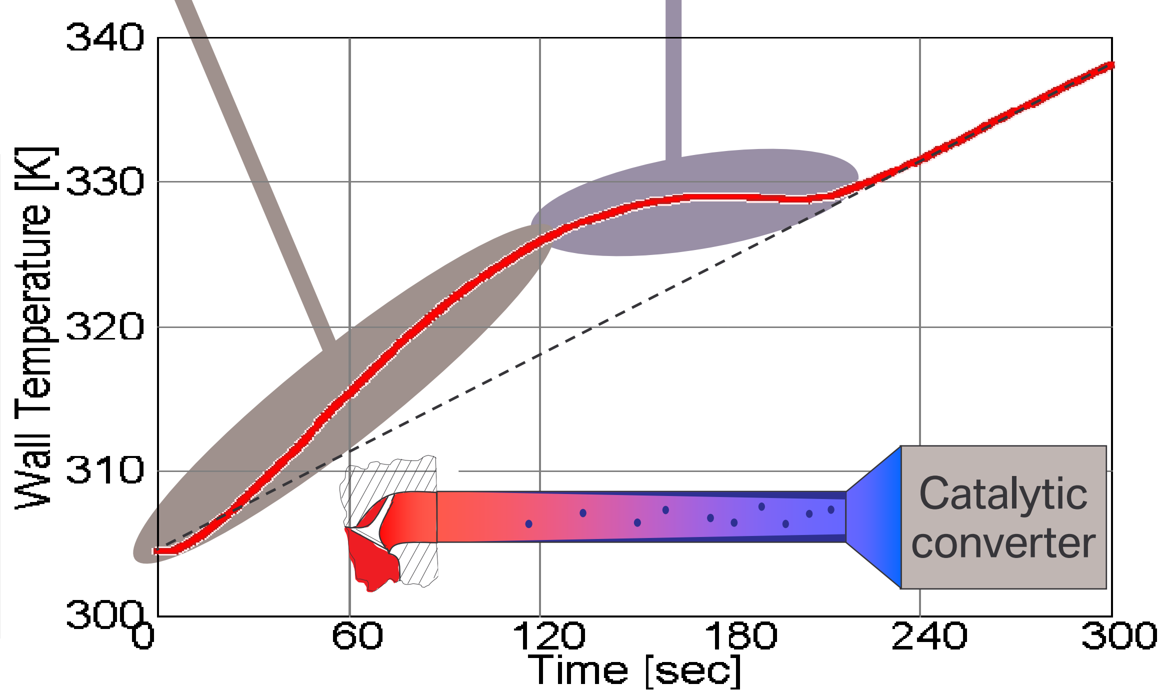


Evaporation of condensed water
- "Plateau" in temperature history

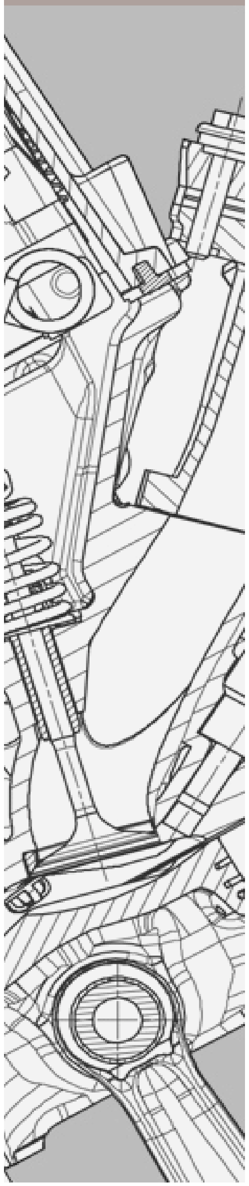


The condensation effect is energetically negligible for:

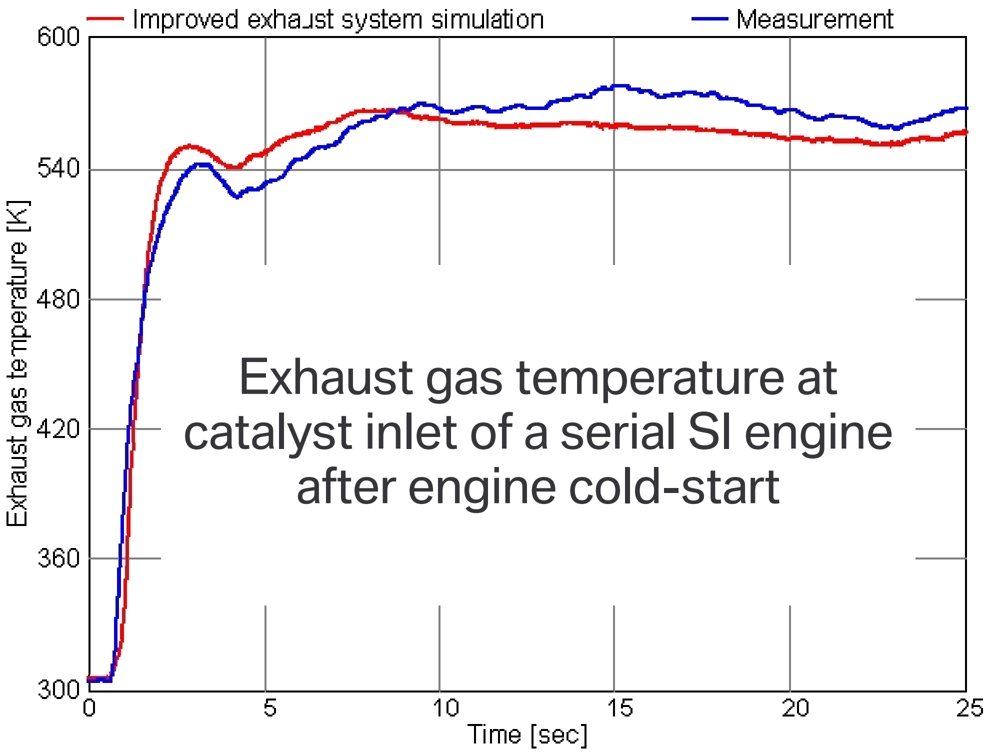
- Close-coupled catalytic converters
- Exhaust manifolds with less water transport



Exhaust system warm-up simulation.
Conclusion.



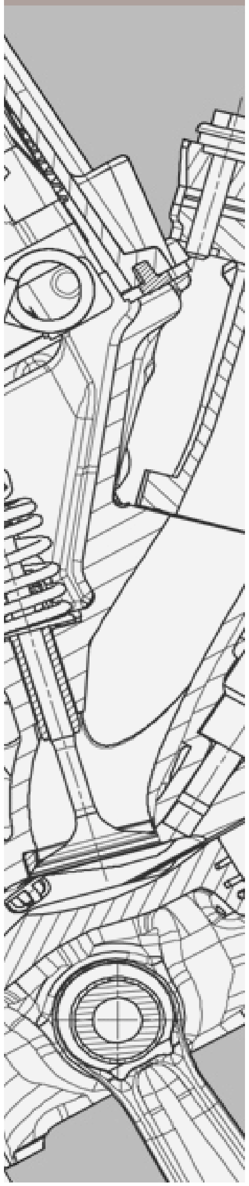
SI engine warm-up simulation with post-oxidation reactions shows an sufficient accuracy for an evaluation of exhaust system configurations



- Evaluation of different exhaust manifold configurations
  (3in1, 6in2in1, 6in1, …)
- Optimization of exhaust system design parameters
  (pipe diameter, length, …)
- Influences of pipe properties on warm-up
  (wall thickness, LSI, …)

+ Warm-up simulation of exhaust systems assists in the early exhaust system design process
- No replacement of detailed 3-dimensional exhaust system investigation

Exhaust system warm-up simulation.
A tool to improve exhaust system design.



Thank you for your attention!