Simulation Supporting the Exhaust Aftertreatment Development Process - 1D Concept and Control Design, 3D Detail Optimization

AVL

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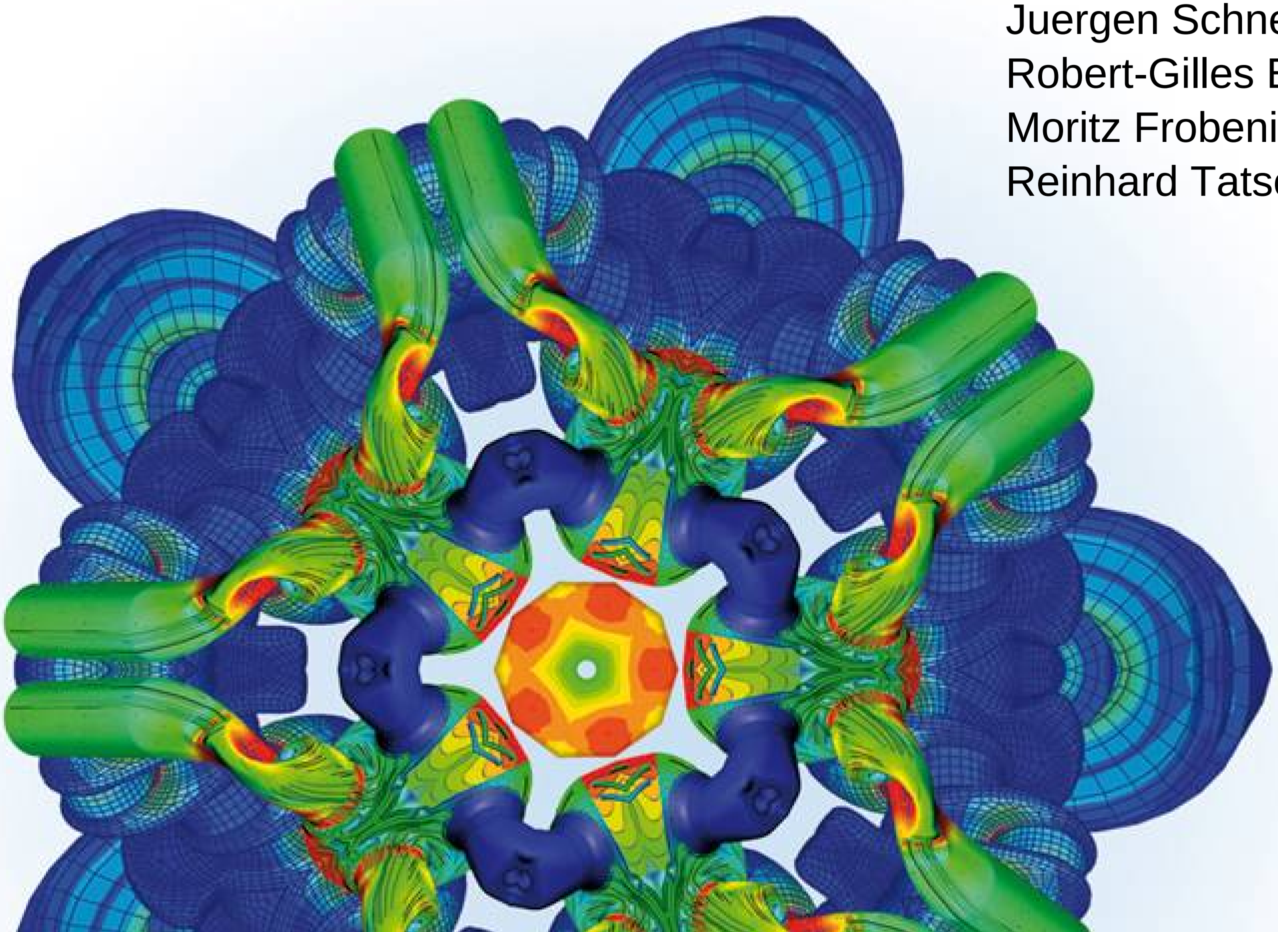

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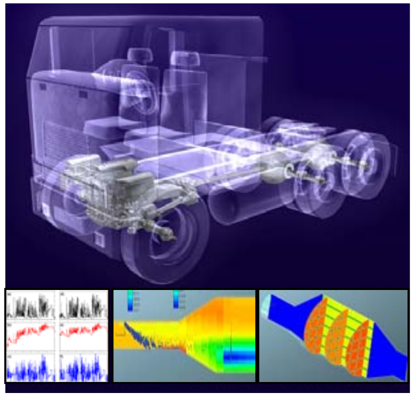
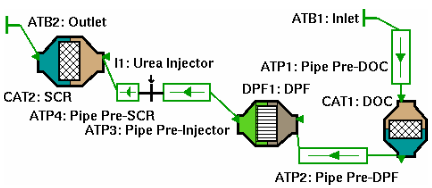
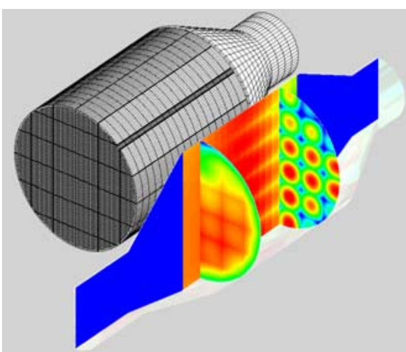




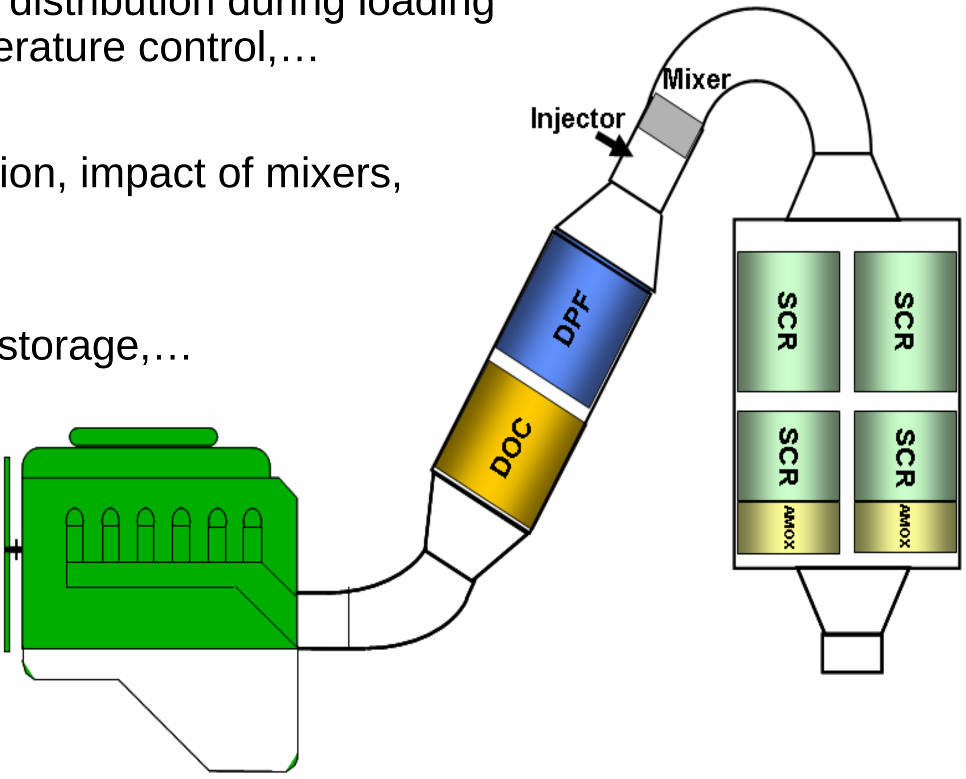


- **EAS Simulation**
- Models and Examples
  - Flow Uniformity
  - DPF
  - DPF, Mixer
  - Urea Injector
  - SCR
  - Overall System
- Summary

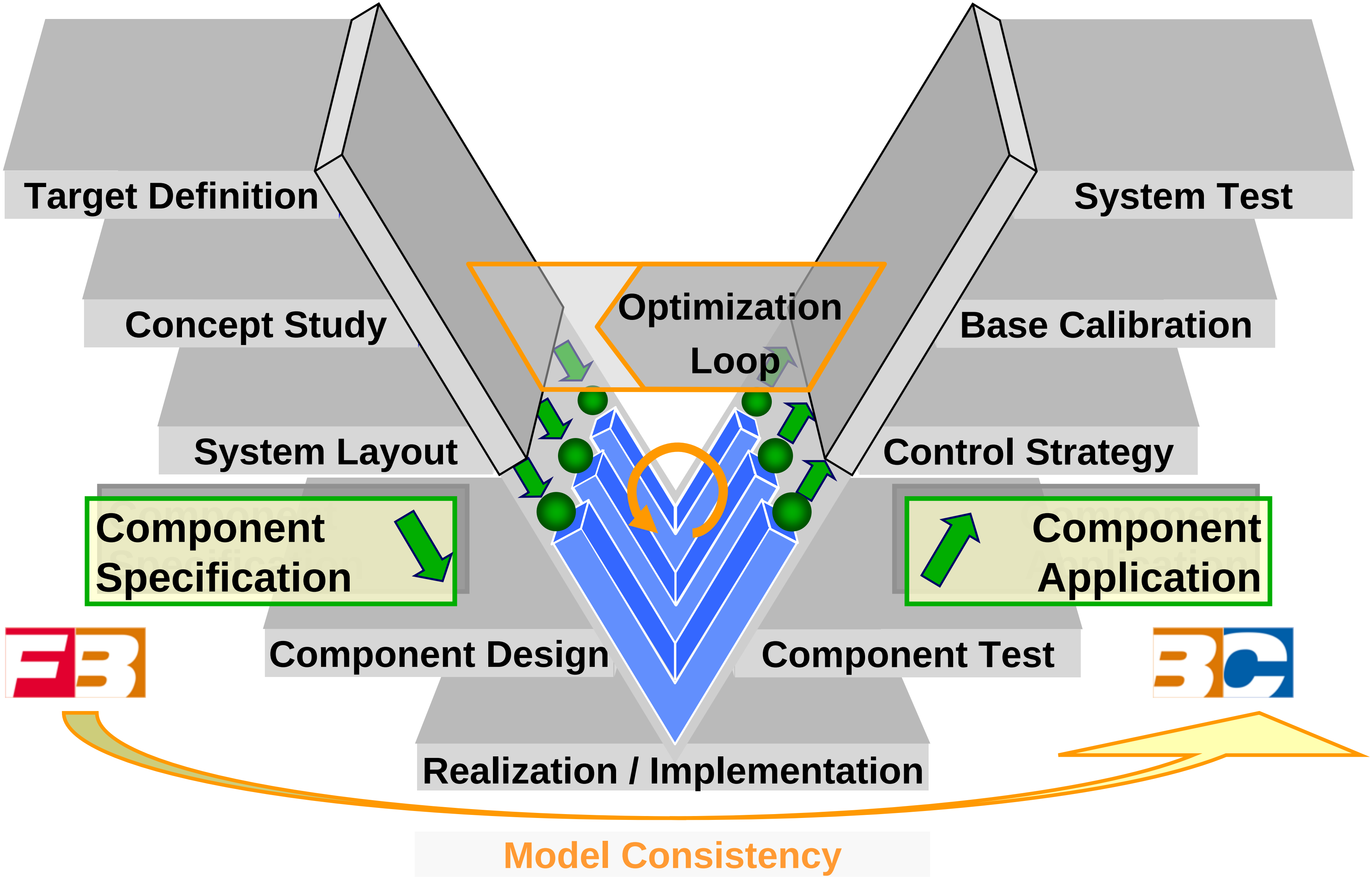
EXHAUST AFTERTREATMENT SYSTEM (EAS) SIMULATION

Areas addressed by 1D/3D simulation

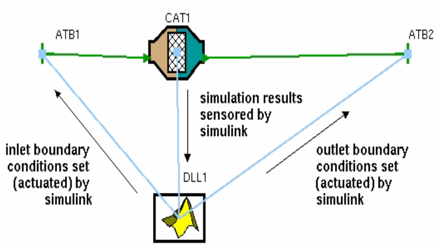
- DOC:
  - Conversion behavior (CO, HC, NOx), pressure drop, flow uniformity,…
- DPF (CSF):
  - Pressure drop, spatial temperature distribution during loading and regeneration, maximum temperature control,…
- Urea Injector, Mixer:
  - Dosing control, radial NH3 distribution, impact of mixers, buildup of wallfilms,…
- SCR:
  - Conversion behavior of NOx, NH3 storage,…
- Slip-Cat:
  - Conversion behavior of NH3
- System:
  - System performance for different component sizes, arrangement of components, control strategies,…

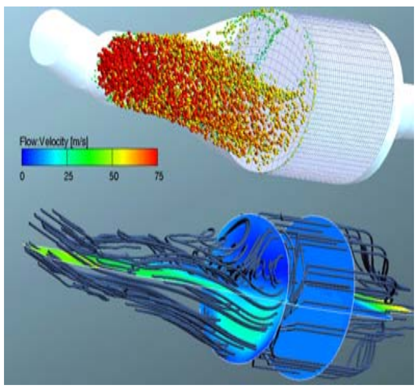


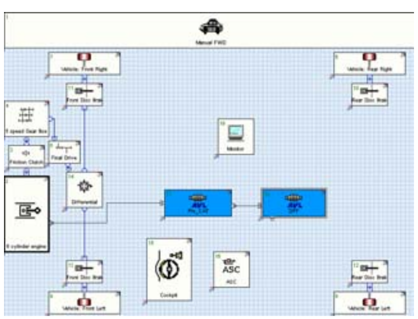
EAS DEVELOPMENT PHASES



TOOLS FOR EAS SIMULATION



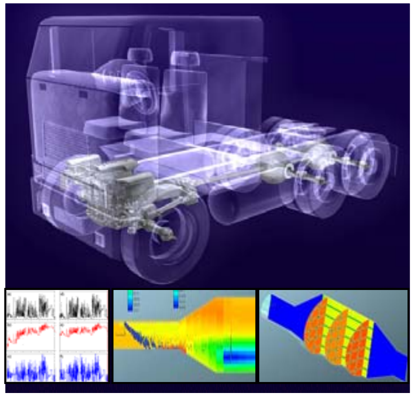


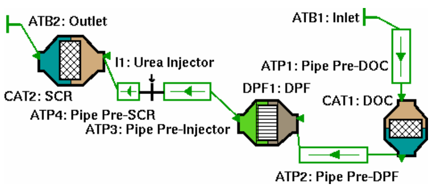


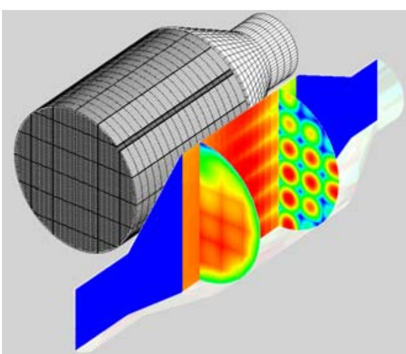
Simulation of Aftertreatment Systems with AVL-Software:

- Identical physical models (gas dynamic, thermal and chemical effects) from 1D to 3D
- Pre-defined kinetic components models
- Development platform for user-defined reaction schemes
- Parameterization of models is based on key experiments
- One single model-structure and parameterization can be used for all different tools and simulation tasks -> flexible approach
- Interface to Simulink for ECU development/calibration

OUTLINE







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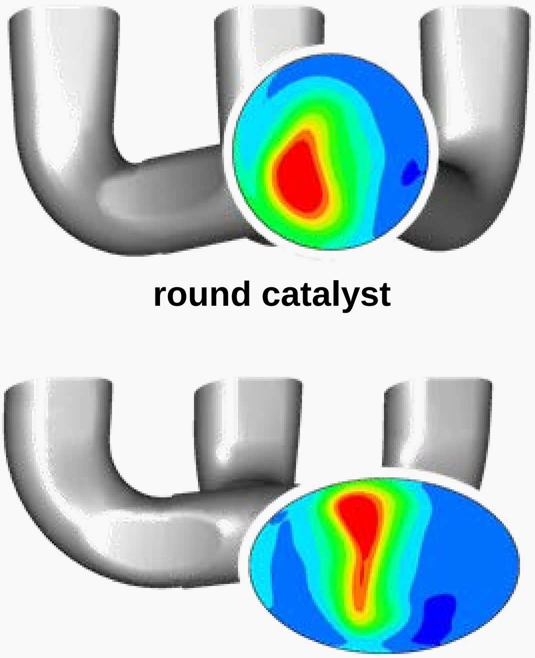
FLOW UNIFORMITY

Velocity distribution at catalyst inlet



round catalyst

oval catalyst

Comparison of Geometries and Concepts

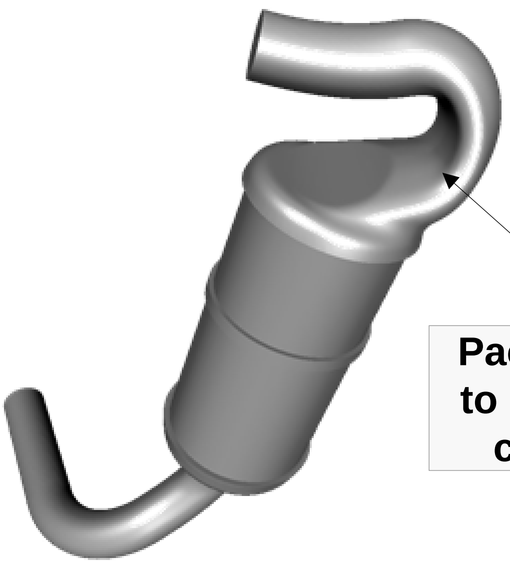
- Calculation of flow uniformity
- Calculation of pressure drop
- Comparison of design variants (i.e. round vs. oval inlet)
- Guidelines for sensor positioning

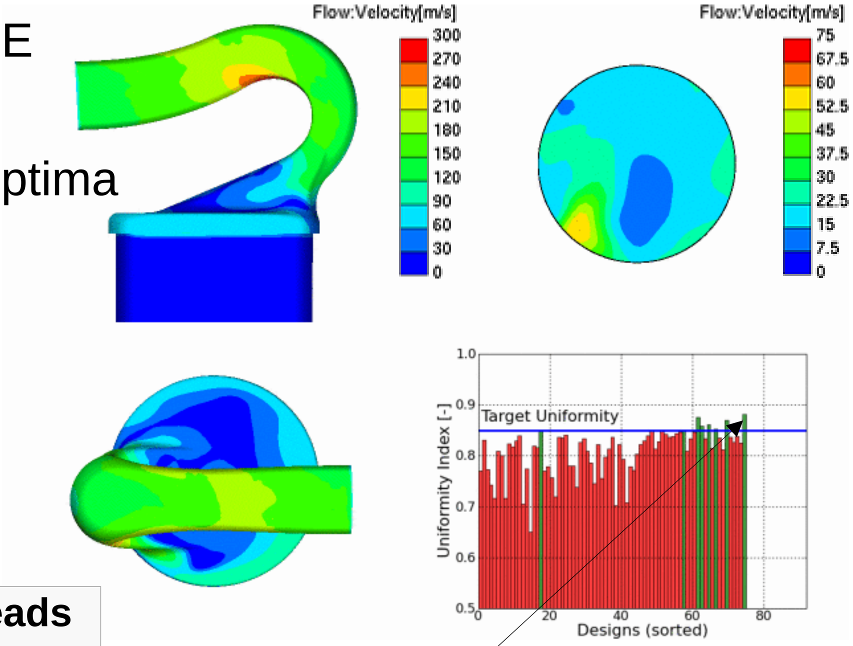
Damage Prediction

- Durability is linked to flow conditions
- Low pressure gradients at component inlet reduce susceptibility of damage
- Uniform component usage and heat-up needs to be ensured

FLOW UNIFORMITY OPTIMZATION EXAMPLE

- Base geometry is fixed
- Fine tuning of inlet geometry to ensure satisfying flow uniformity
- **Time efficient approach using**
  - Parameterized geometries
  - Automatic meshing with AVL FAME
  - Parallel computing
  - Genetic algorithms to find global optima

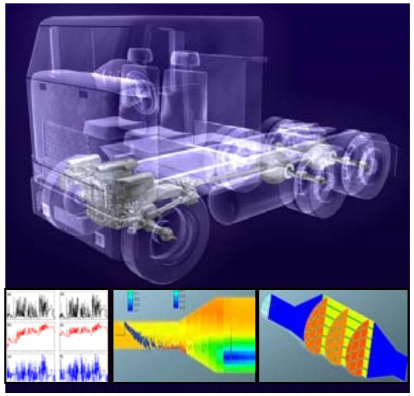


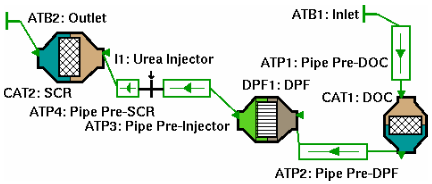


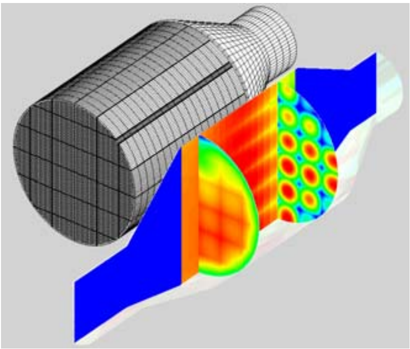
Packaging leads to u-type pipe at catalyst inlet

Uniformity index close to 0.9 is reached due to optimization

OUTLINE







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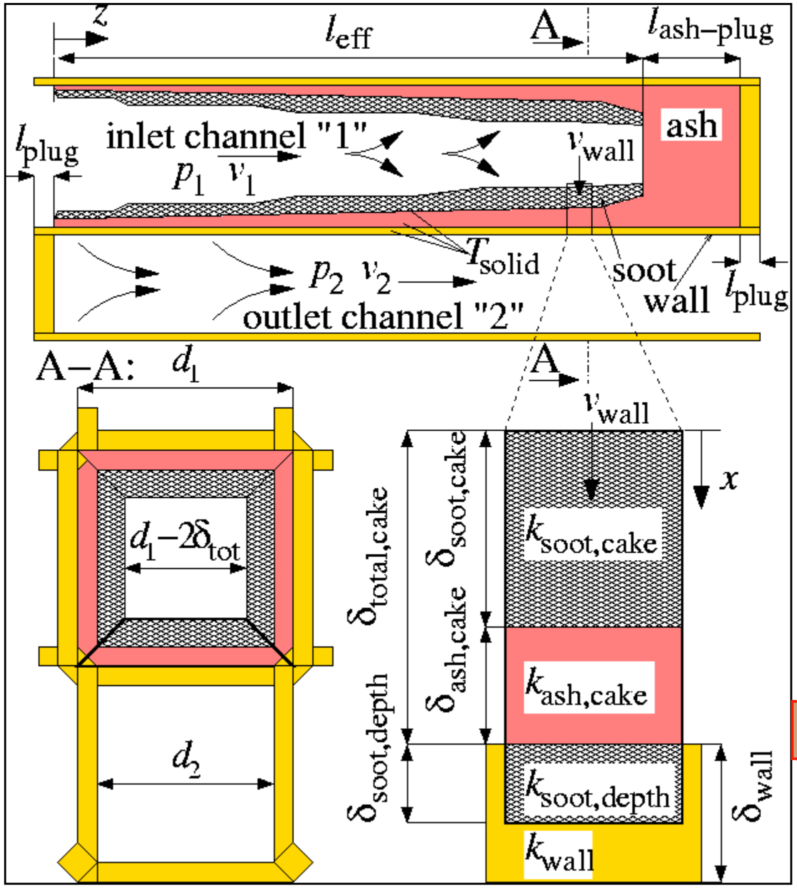
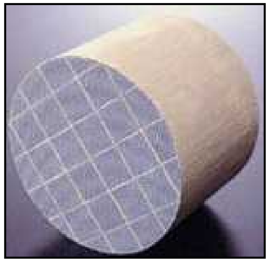
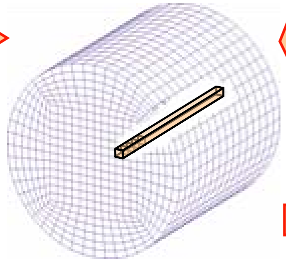
DPF MODEL





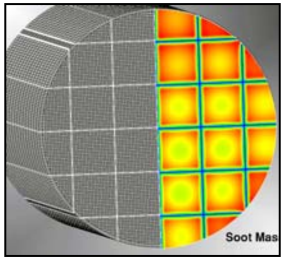


1D DPF flow model:

- Different inlet/outlet channel sizes **and shapes**
- Inlet/outlet plugs
- Ash as layer, plug or combination
- Depth and cake layer deposition

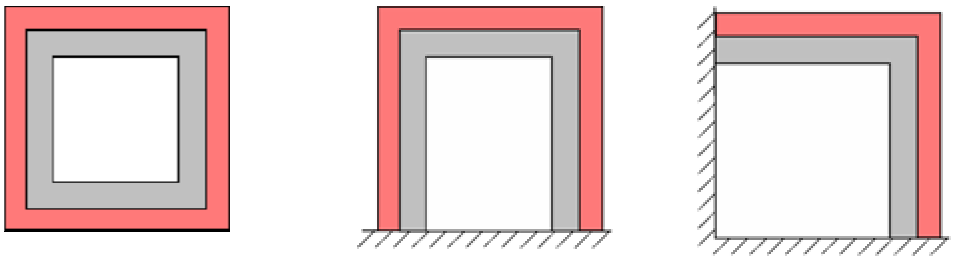
3D DPF model:

Each axial cell raw of the 3D mesh represents one pair of DPF inlet/outlet channels

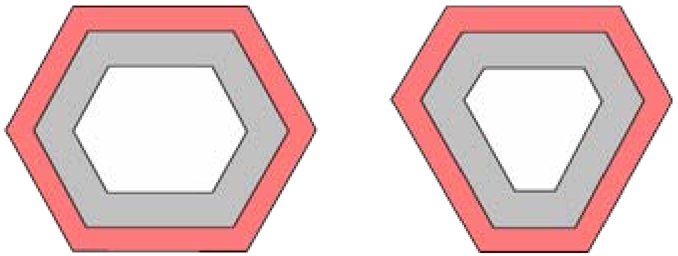


GENERAL DPF CELL GEOMETRIES

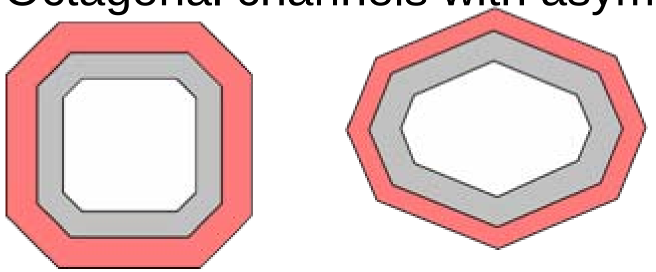
Squared inlet channels with non-active filtration sides (i.e. near segmentation walls)



Hexagonal channels with asymmetric sides



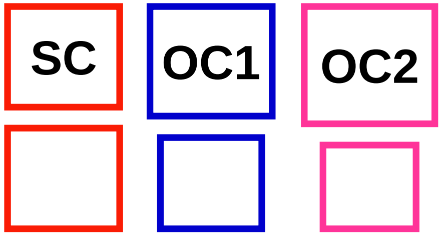
Octagonal channels with asymmetric sides



General DPF cell geometry model enables investigation of:

- Pressure drop during loading
- Temperatures and thermal stresses during regeneration

DPF, PRESSURE DROP OF ASYMMETRIC CHANNELS

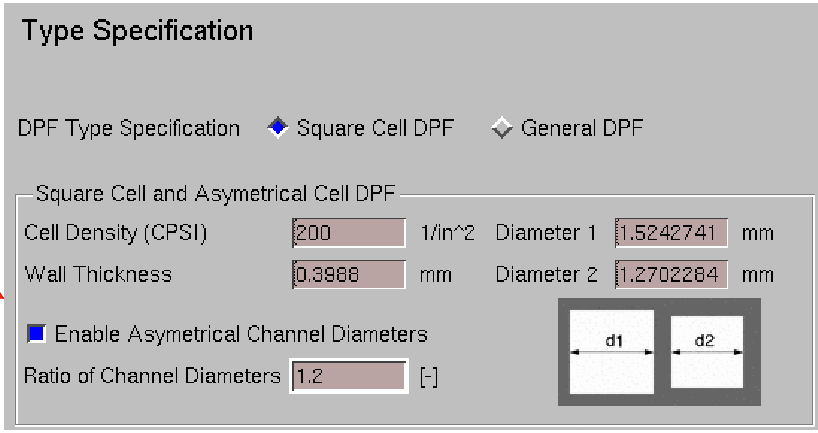


Square Cell (SC)

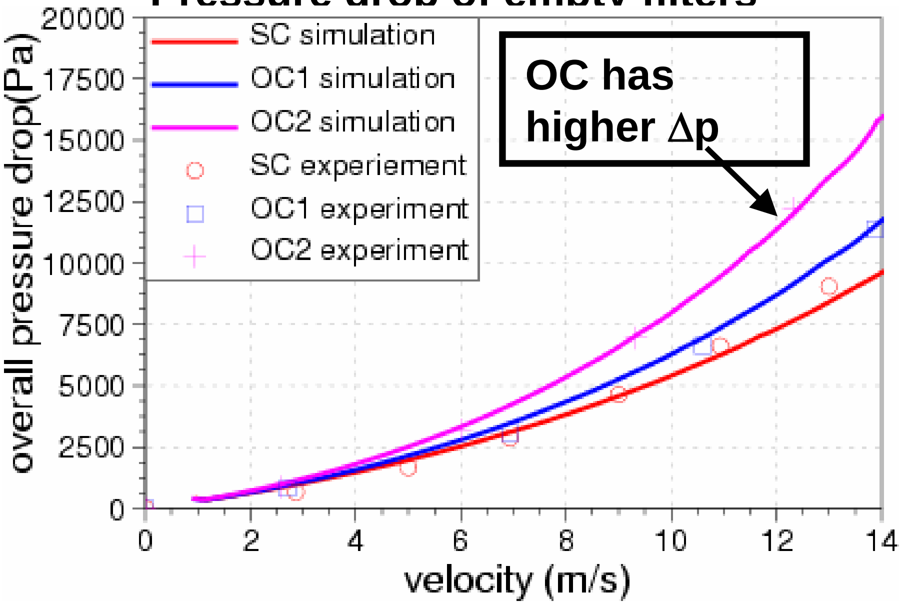
Octo-Square Cell (OC)

OC1: d1/d2=1.2

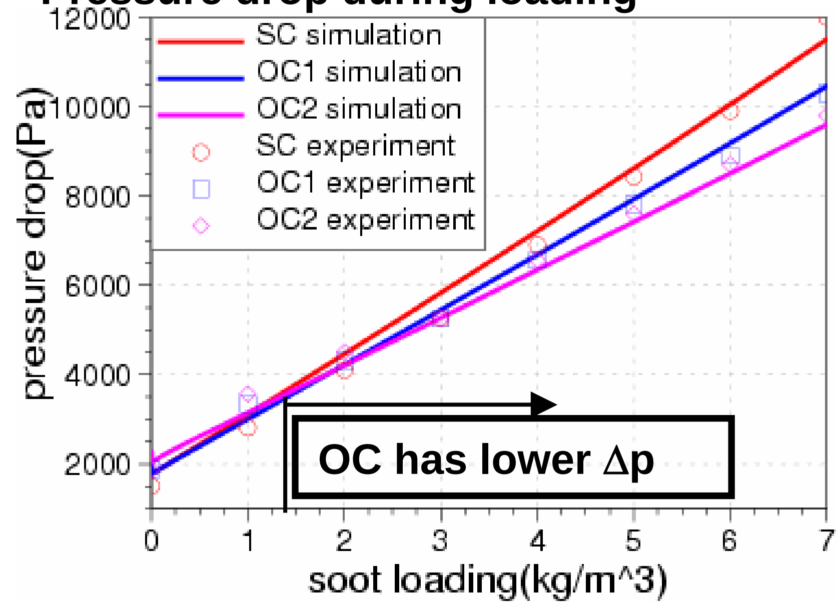
OC2: d1/d2=1.4



Pressure drop of empty filters



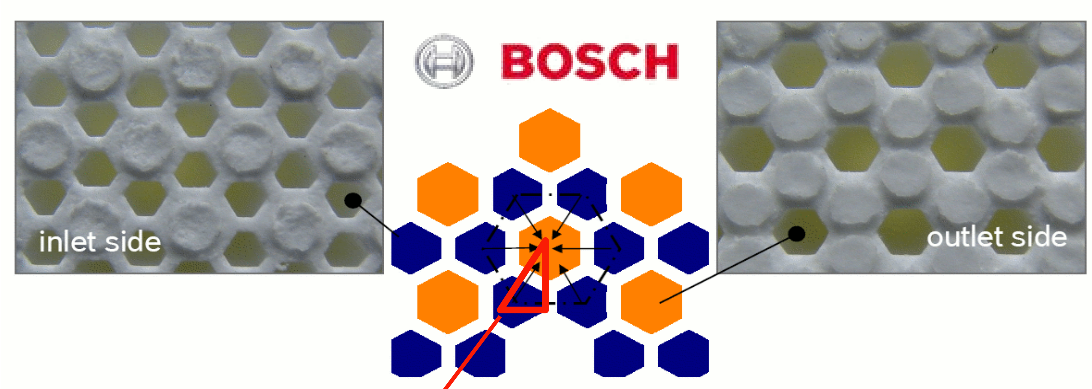
Pressure drop during loading

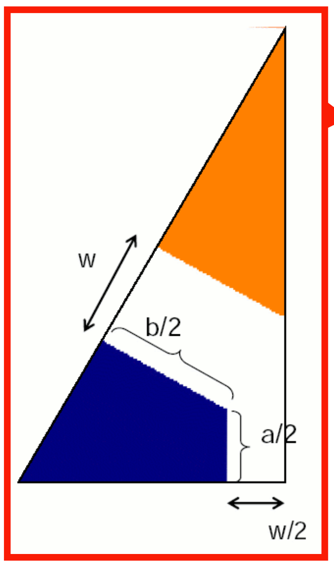


Simulation: SAE-2007-01-1137

Experimental Data: SAE-2005-01-0949, Ibiden

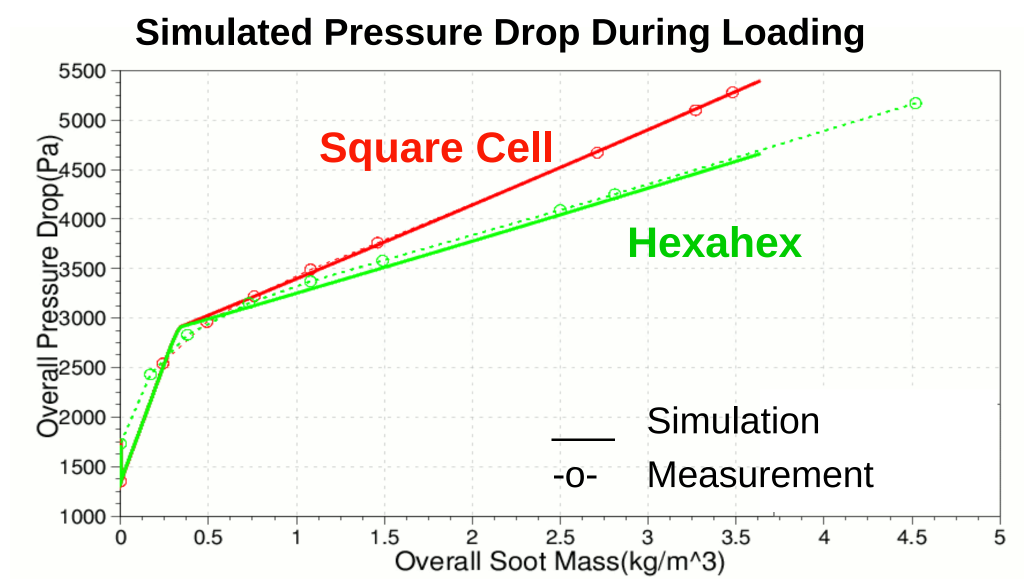
PRESSURE DROP FOR BOSCH HEXAHEX GEOMETRY





Simulation Procedure

- Permeabilities (wall, soot depth and cake layer) are tuned on measured data for a squared cell DPF
- Hexahex model applies the same permeabilities
- Hexahex shows smaller pressure drop increase



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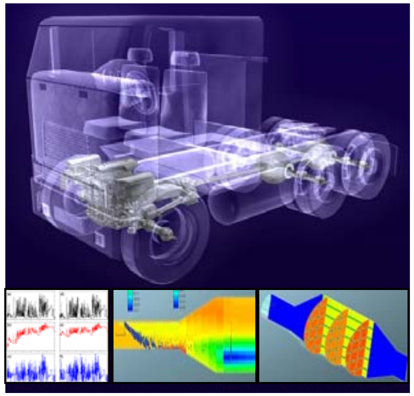

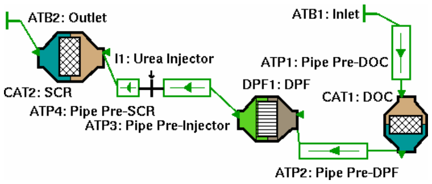

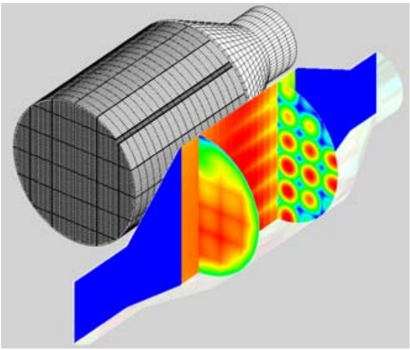

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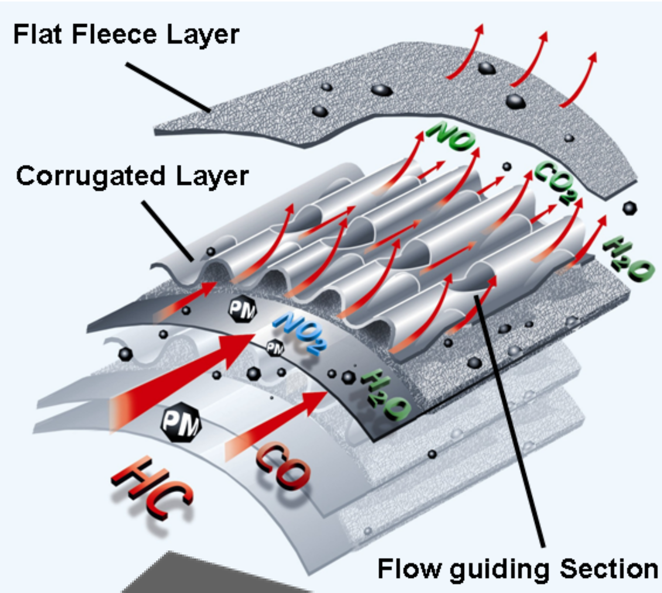
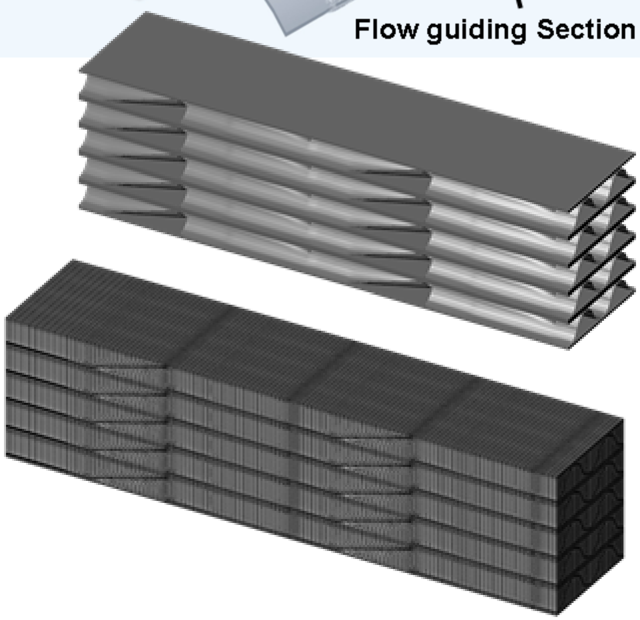
PM-METALIT®, CFD ANALYSIS





CFD analysis of PM filter device regarding to:

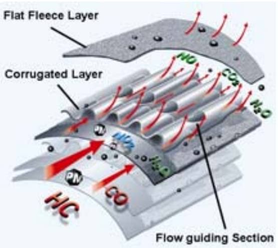
- Flow field (axial and radial velocity distribution)
- Radial mixing behavior of tracer gas introduced at singular point
- Transport of soot particles
- Transport of urea-water droplets
- Interaction of droplet to wall and flies
- water evaporation and urea thermolysis

modeling

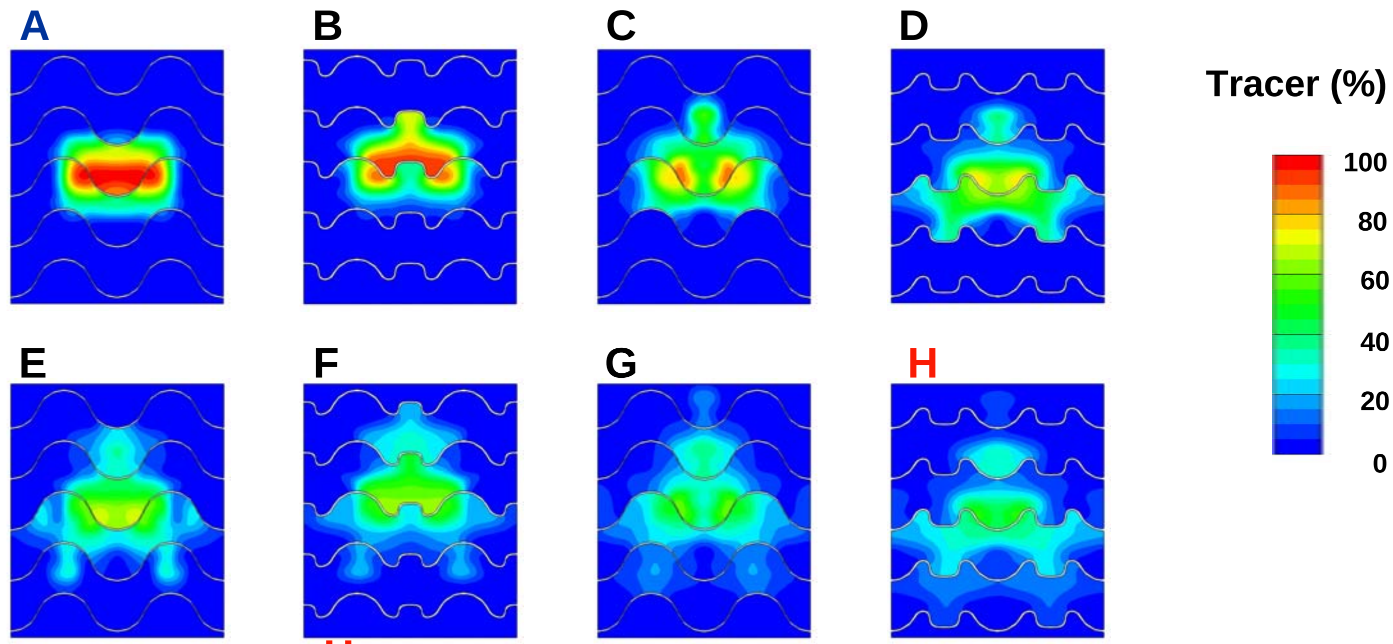
- 5 corrugated layers
- 2 flow guiding sections in axial direction
- 6 fleece layers
- periodic boundaries in radial direction
- 1.4Million computational cells

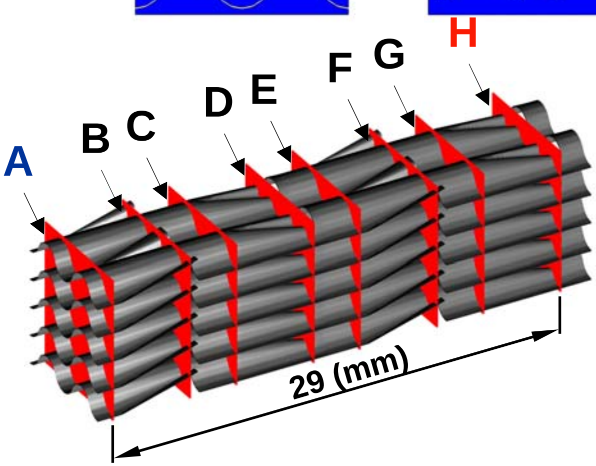
see Brück et. al ICPC 2009

PM-METALIT®, INVESTIGATION OF TRACES GAS



Radial distribution of traces gas



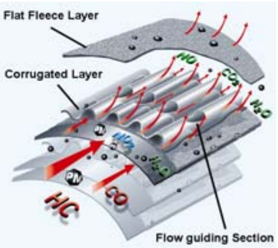


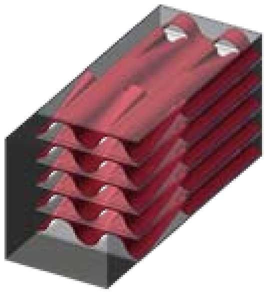
Simulation shows significant radial distribution of the tracer gas over the considered mixing length

~25% of the axial mass flows is exchanged in radial direction through the fleece layers

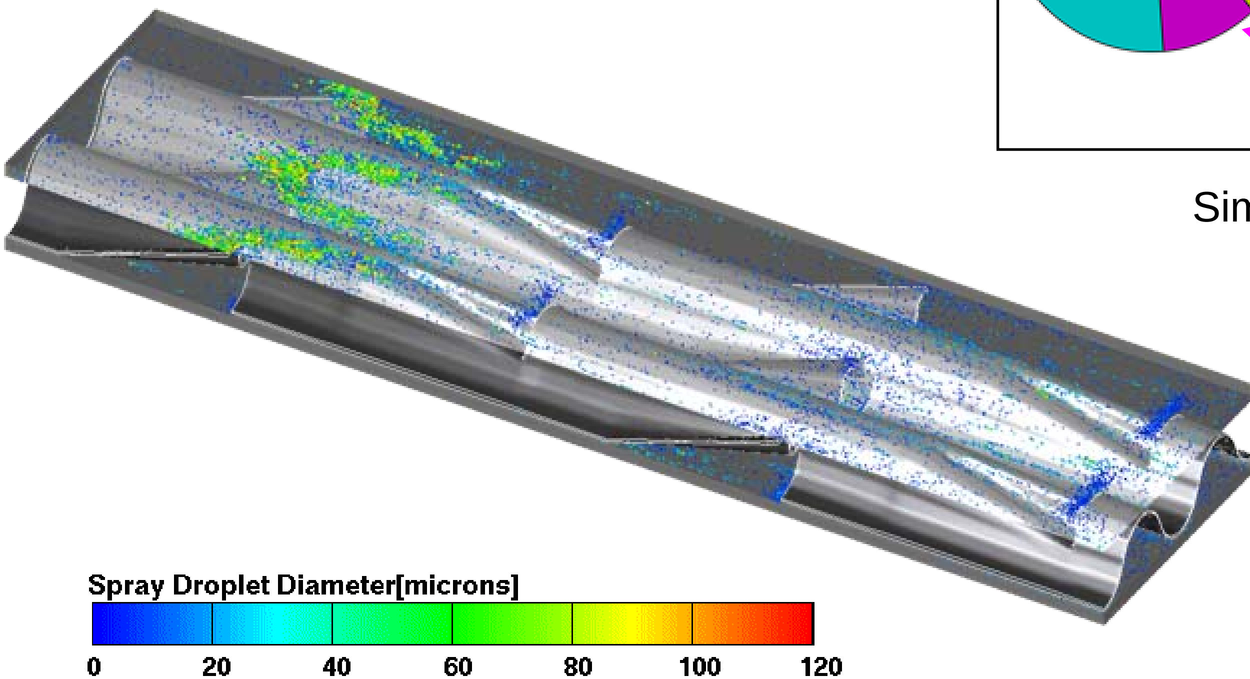
see Brück et. al ICPC 2009

PM-METALIT®, UREA-WATER CONVERSION

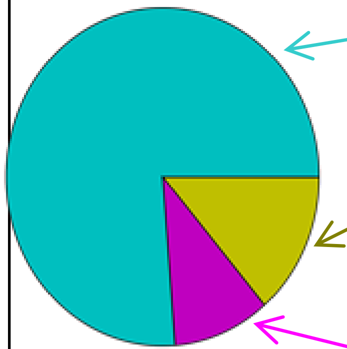




Droplet Deposition



Mass Conversion of Urea-Water Droplets



Evaporated in gas phase 76%

Remaining (stuck and evaporated) in the fleece 14%

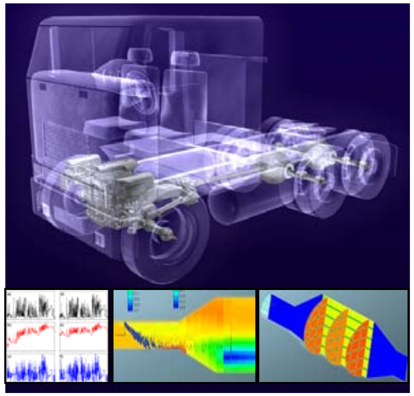
Deserted (non evaporated) 10%

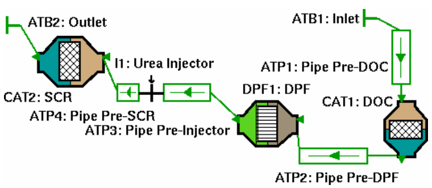
Simulation shows

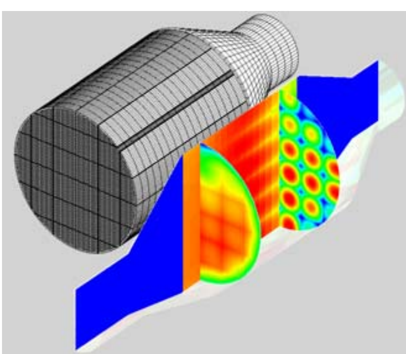
- dominant effect is urea-water evaporation of stuck droplets in the fleece layers
- negligible wall film formation on layers

see Brück et. al ICPC 2009

OUTLINE







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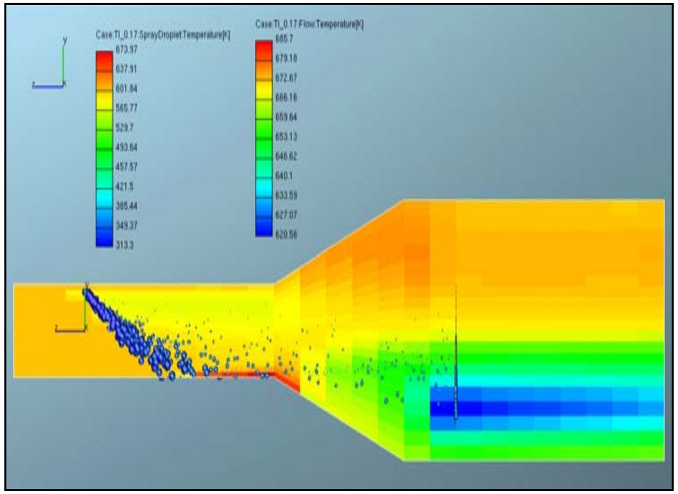
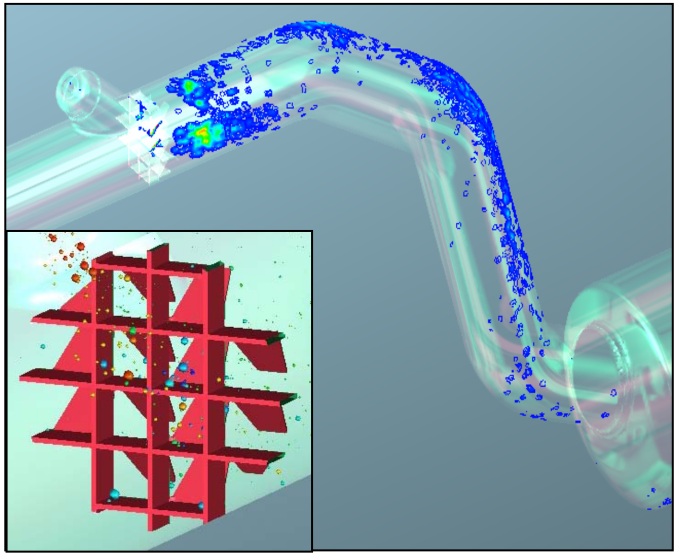
UREA INJECTION, BASIC PHENOMENA

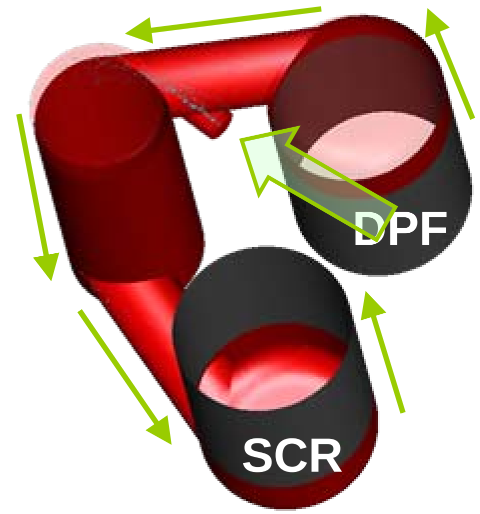




- **Injection of urea-water solution**
- **Spray / gas interaction**
  - Liquid / gaseous momentum exchange
  - Droplet / gas heat transfer
  - Water evaporation / urea thermolysis
- **Spray / wall / wallfilm interaction**
  - Droplet / wall heat transfer
  - Spray impingement
  - Wallfilm formation
  - Wallfilm evaporation / thermolysis
- **Cooling of walls**
  - Lateral heat conduction
- **Hydrolysis**
- **Catalytic reactions**

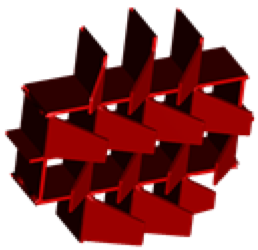
Simulation Variants

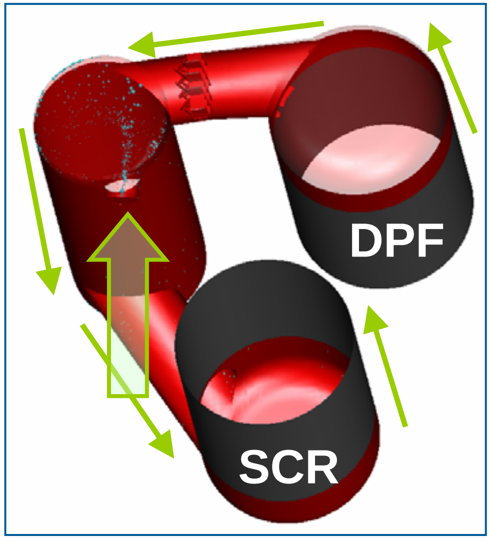
1. System without mixer, injection in flow direction
2. System with mixer, injection downstream the mixer against flow direction



Comparison of

- Wall Film mass
- Wall film thickness
- Wall film distribution
- Completeness of evaporation and thermolysis
- Flow uniformity at SCR inlet
- NH3 uniformity at SCR inlet

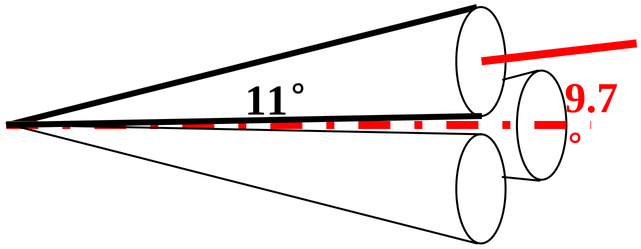




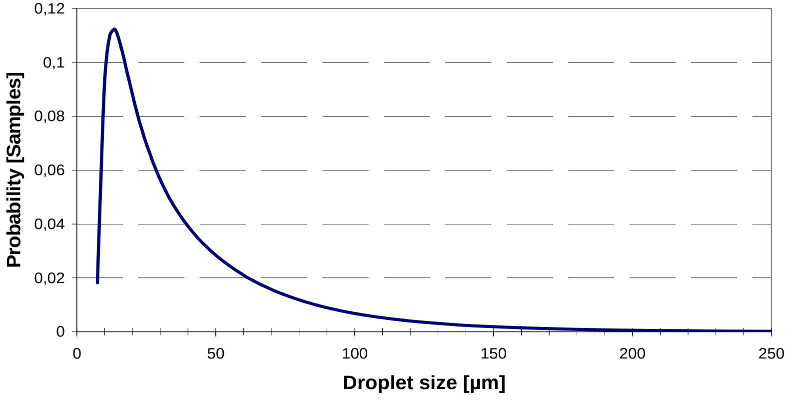
INJECTOR CHARACTERIZATION

Given input data

1. Nozzle geometry

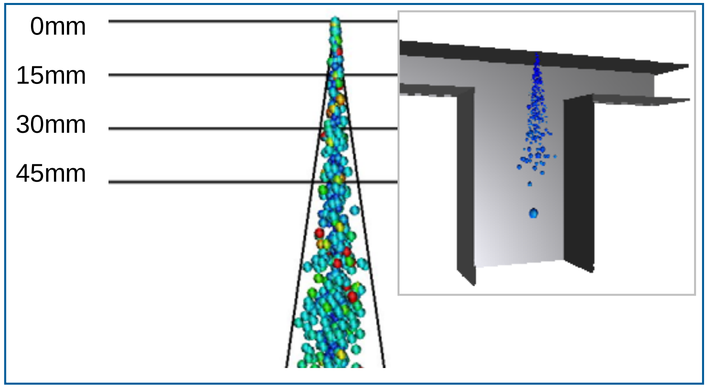


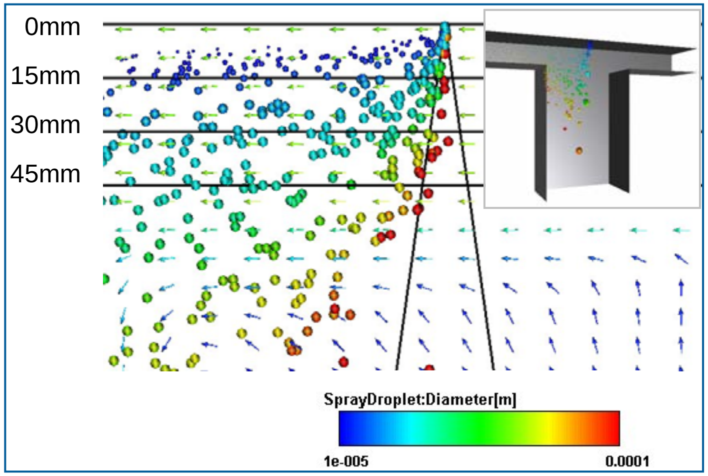
2. droplet size distribution



Spray Box Simulation

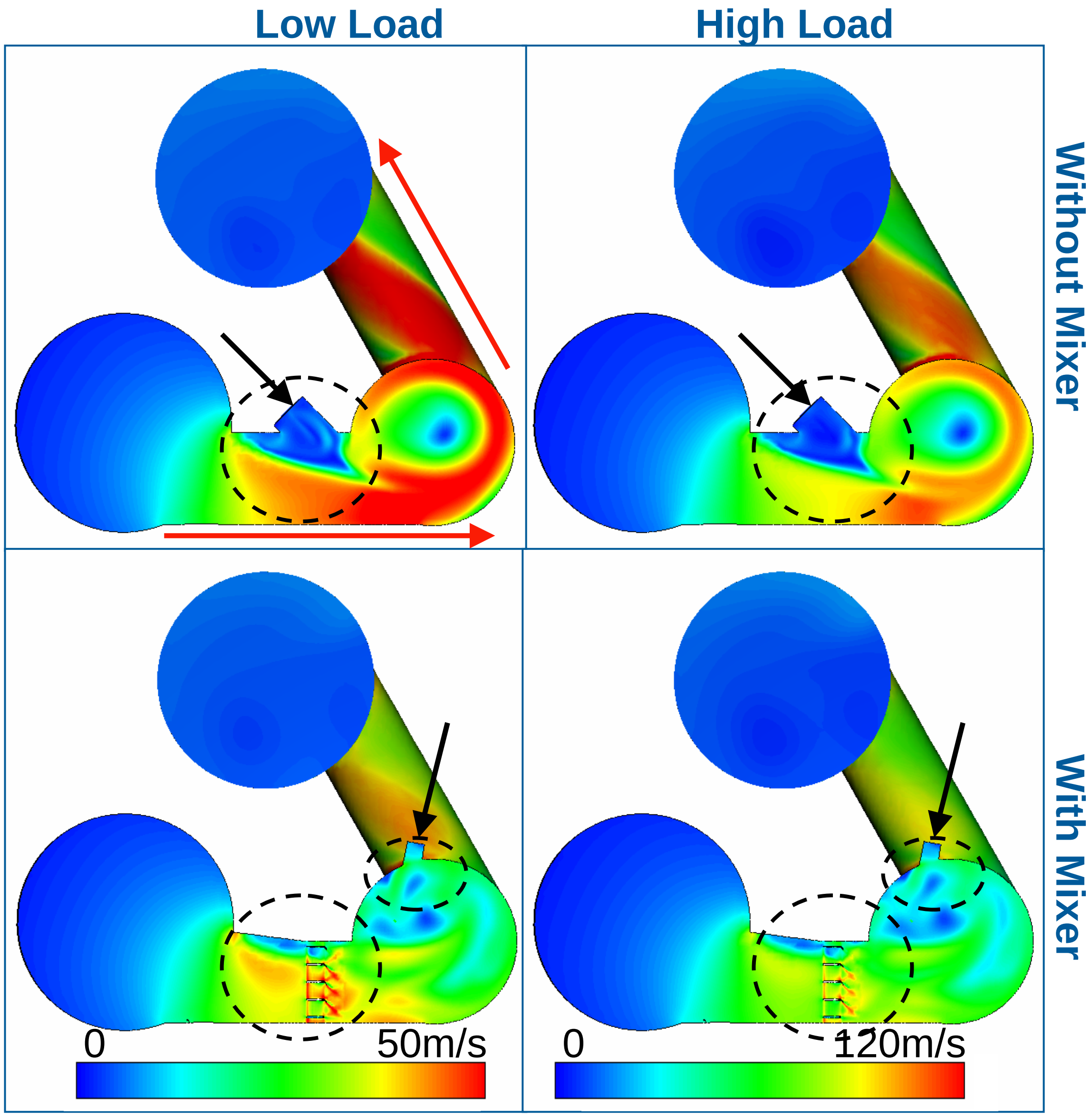
- Spray angle
- Droplet distribution
- Wall impingement as function of flow field





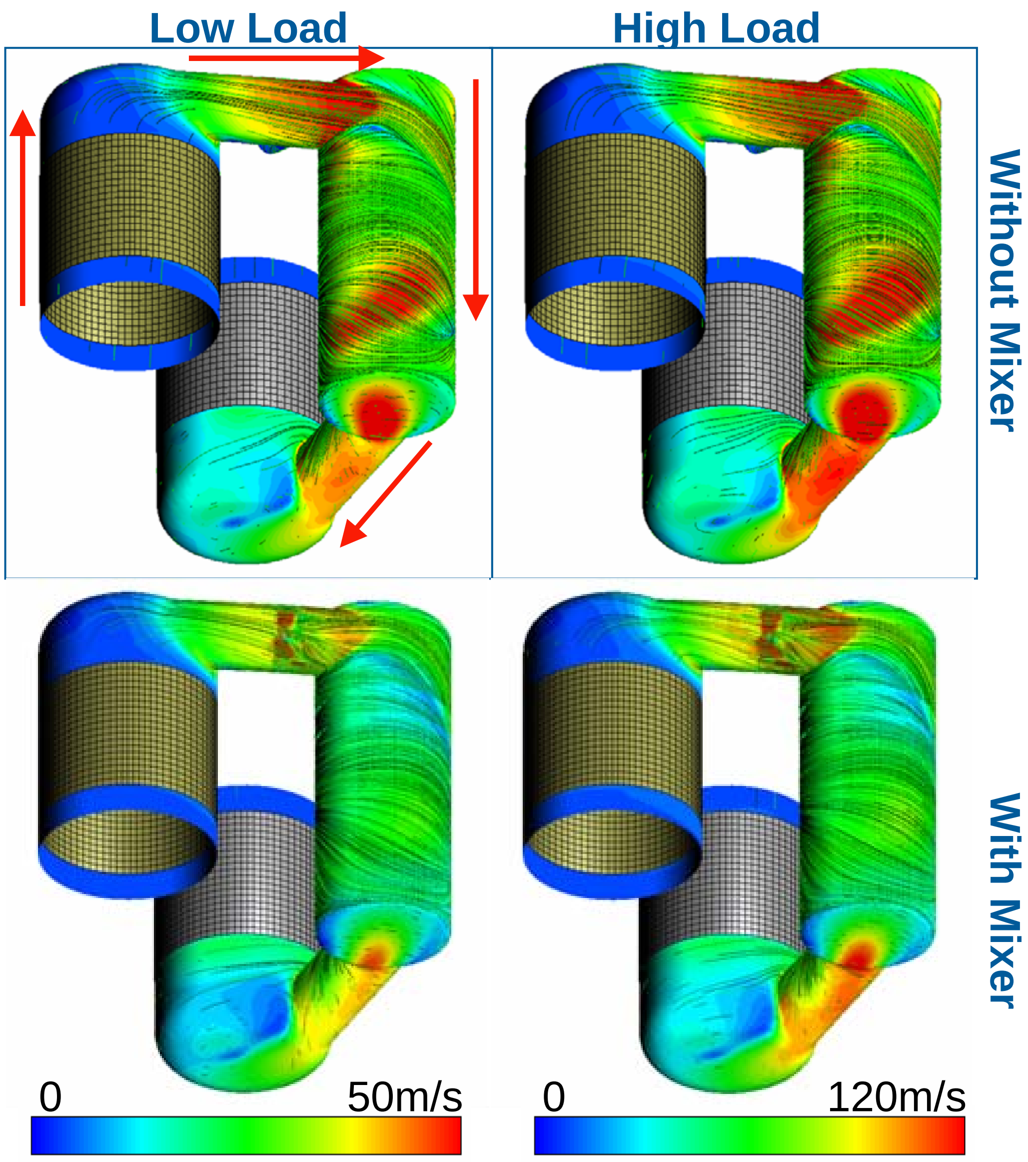
FLOW DISTRIBUTION, CUT PLANE THROUGH INJECTOR

- Characteristic stagnation zone around injection point of system without mixer can be observed
- Stagnation zone almost disappears for system with mixer
- High probability of wall wetting around the nozzle tip due to cross flow motions around it



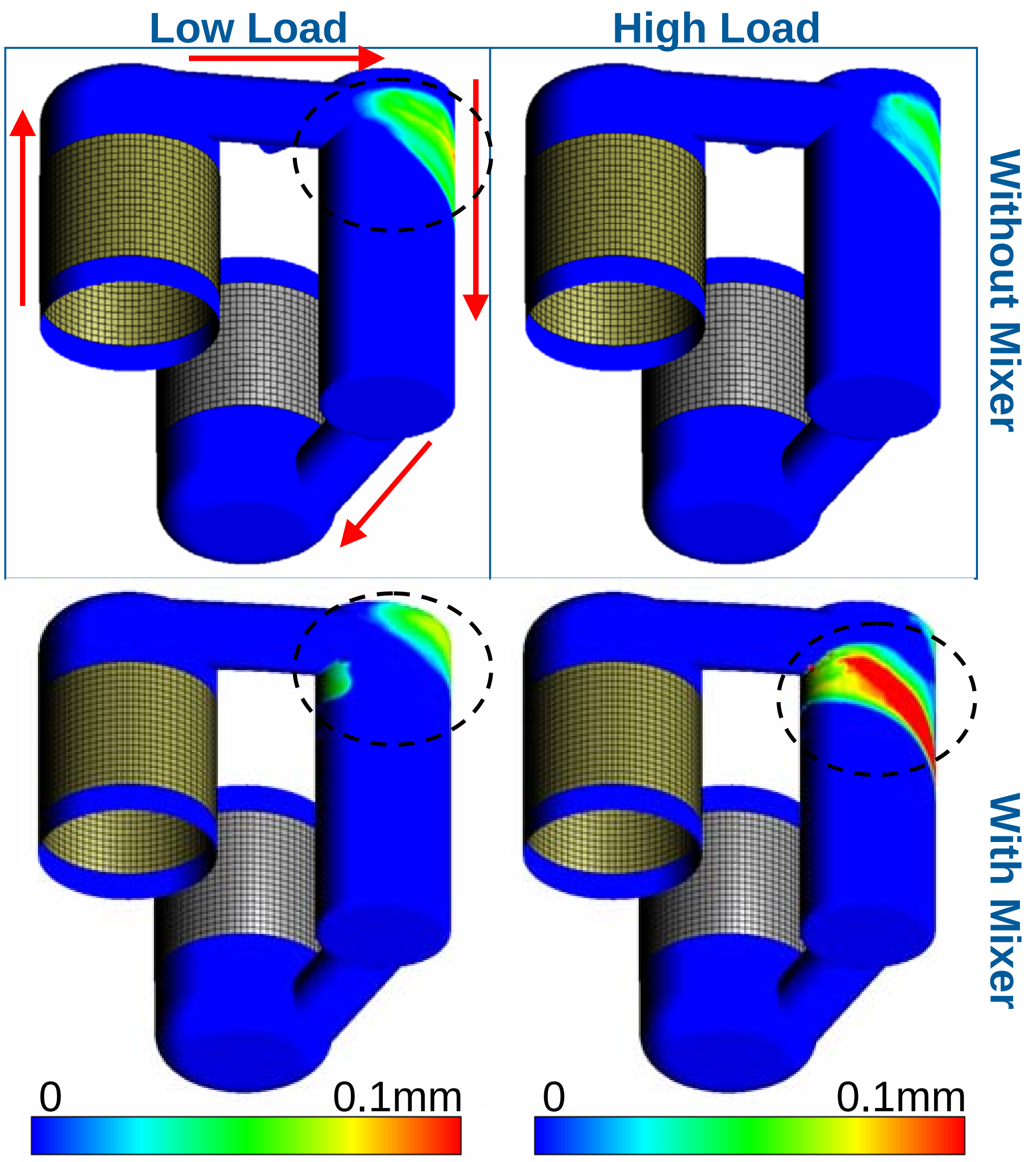
FLOW DISTRIBUTION, OVERALL SYSTEM

- Geometry of tangential connection pipes to mixing chamber leads to significant swirl motion→ support of evaporation and thermolysis
- Mixer disturbs flow pattern but does not overcome the basic swirl motion
- Mixer causes higher pressure losses in system → impact on engine performance



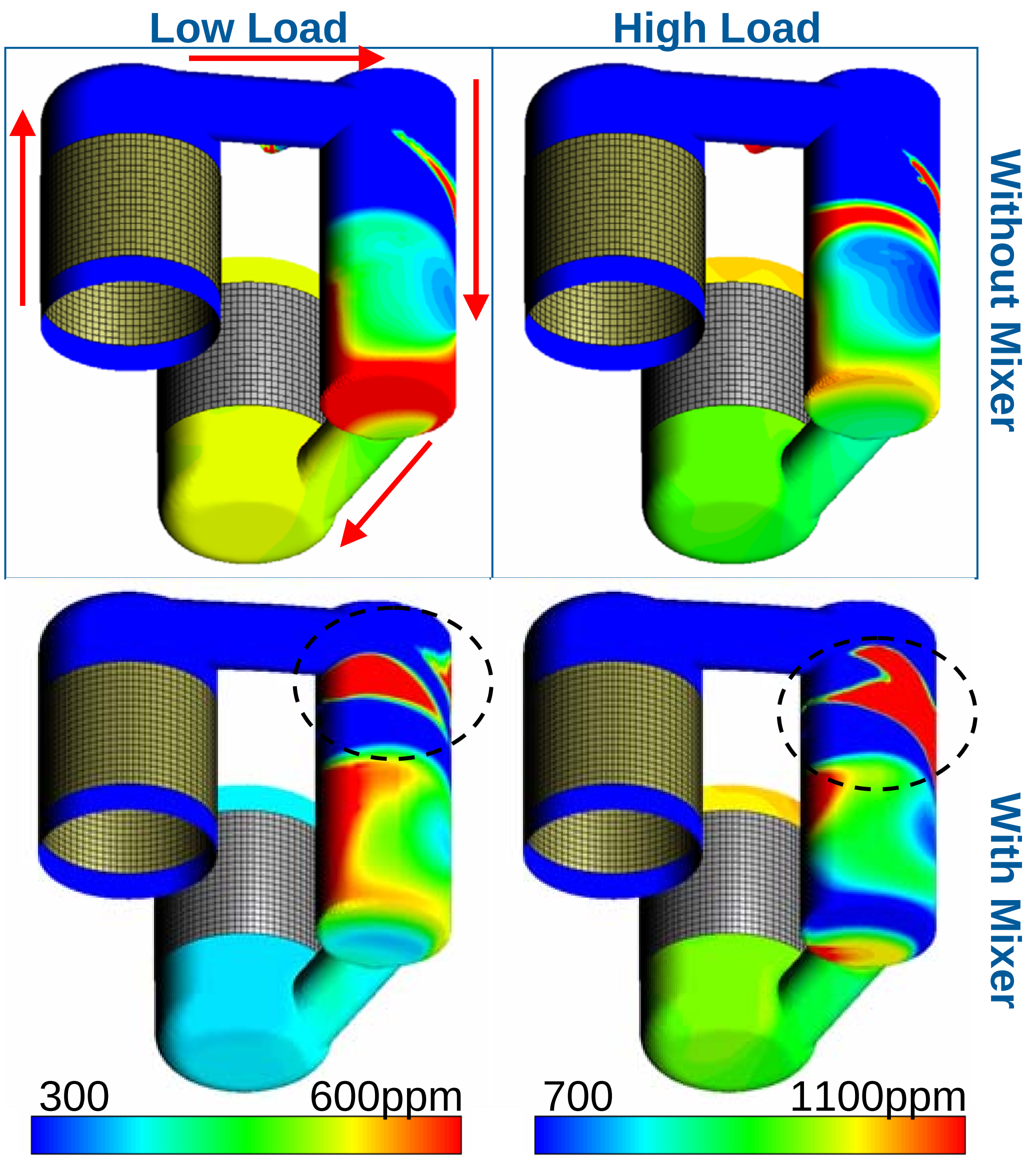
UREA/WATER WALL FILM THICKNESS, OVERALL SYSTEM

- Low load points show smaller film area compared to high load
- High load points show superior droplet break up and evaporation
- System with mixer at low load shows similar film area but smaller film mass
- System with mixer at high load shows significant film thickness in impingement region

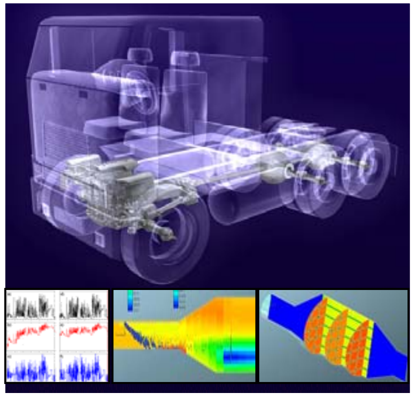


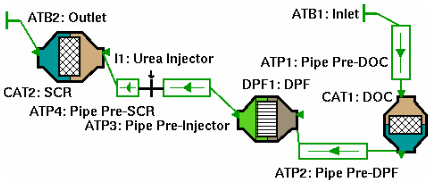
NH3 DISTRIBUTION, OVERALL SYSTEM

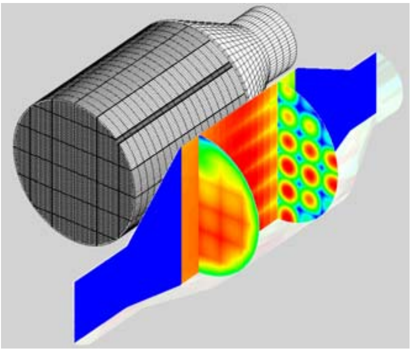
- System without mixer shows good NH3 preparation and high NH3 uniformity at SCR catalyst inlet
- Uniformity is mainly influenced by high swirl flow in the mixing chamber
- System with mixer shows for both load points a higher amount of NH3 is released from wall film



OUTLINE





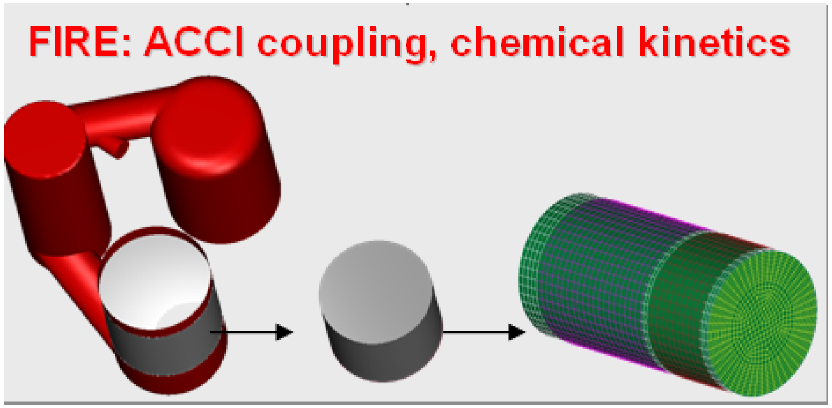


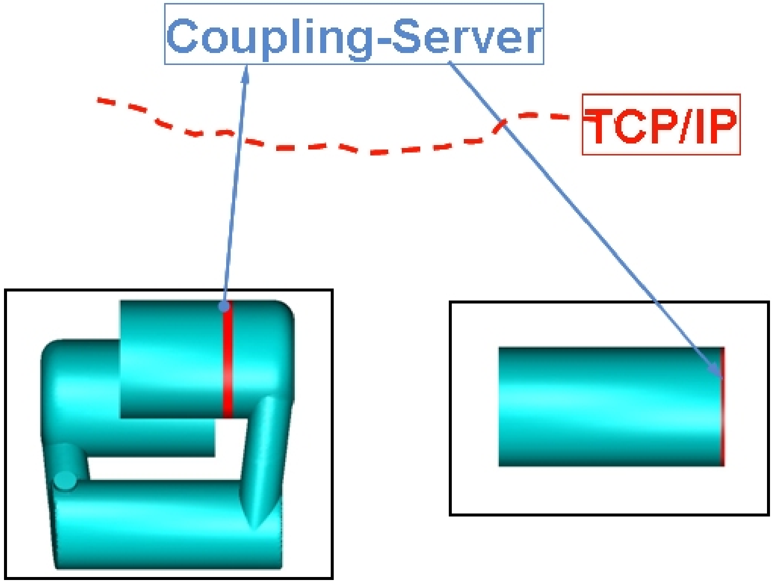
- EAS Simulation
- Models and Examples
  - Flow Uniformity
  - DPF
  - DPF, Mixer
  - Urea Injector
  - **SCR**
  - Overall System
- Summary

3D SCR SIMULATION

AVL Code Coupling Interface (ACCI)

- Performs mapping between chosen faces of simulation domains
- Decouples SCR converter simulation from urea formation simulation
- Maps profiles of velocity, temperature, species, TE,… from spray simulation to SCR catalyst conversion
- Allows spreading of simulation load to different hosts via TCP/IP coupling

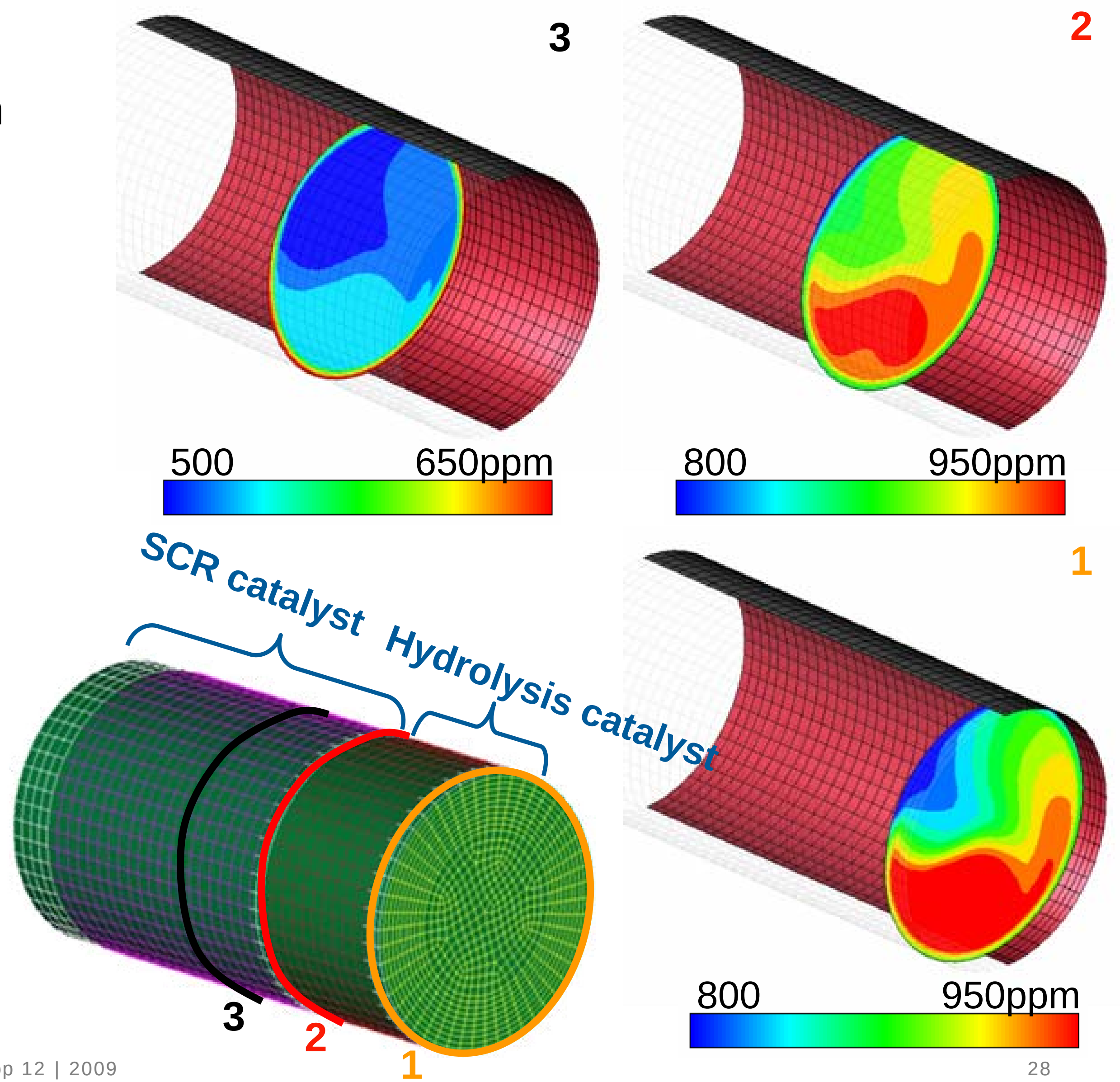




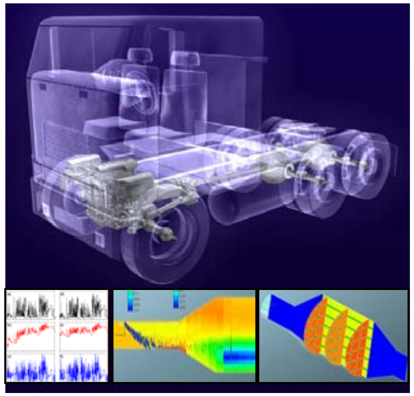
HYDROLYSIS AND SCR CATALYST

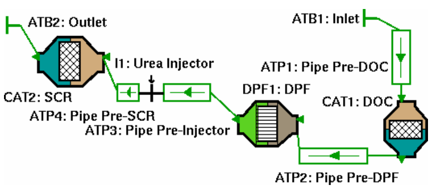
Radial NH3 distribution can be observed, but on a small absolute level:

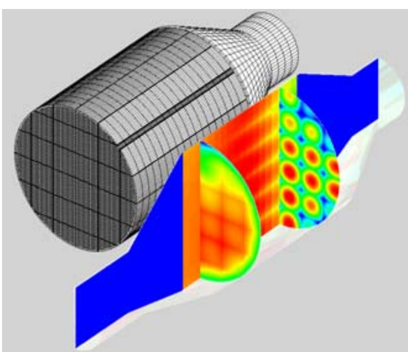
- This is caused by the high urea conversion performance of the injection system
- The SCR catalyst could also reasonably be investigated with simplifying 1D models



OUTLINE







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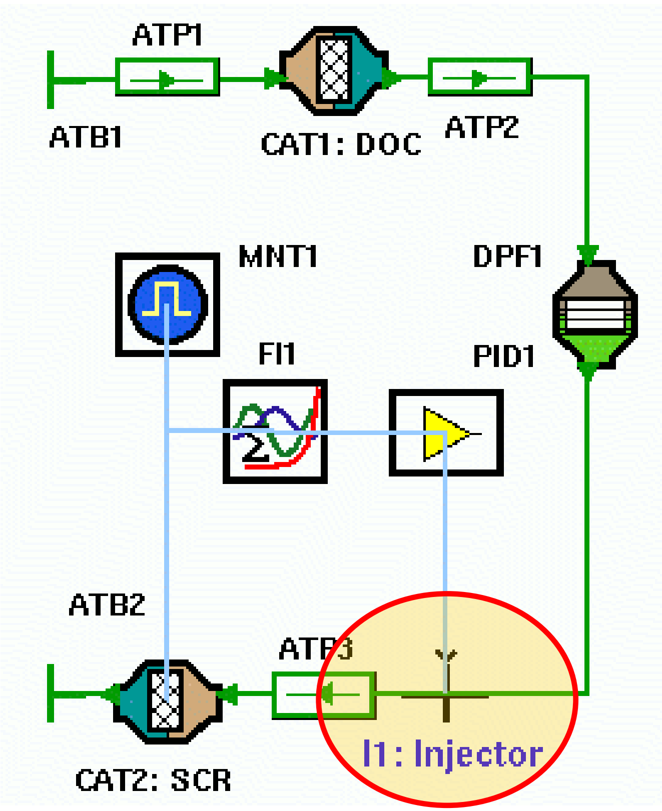
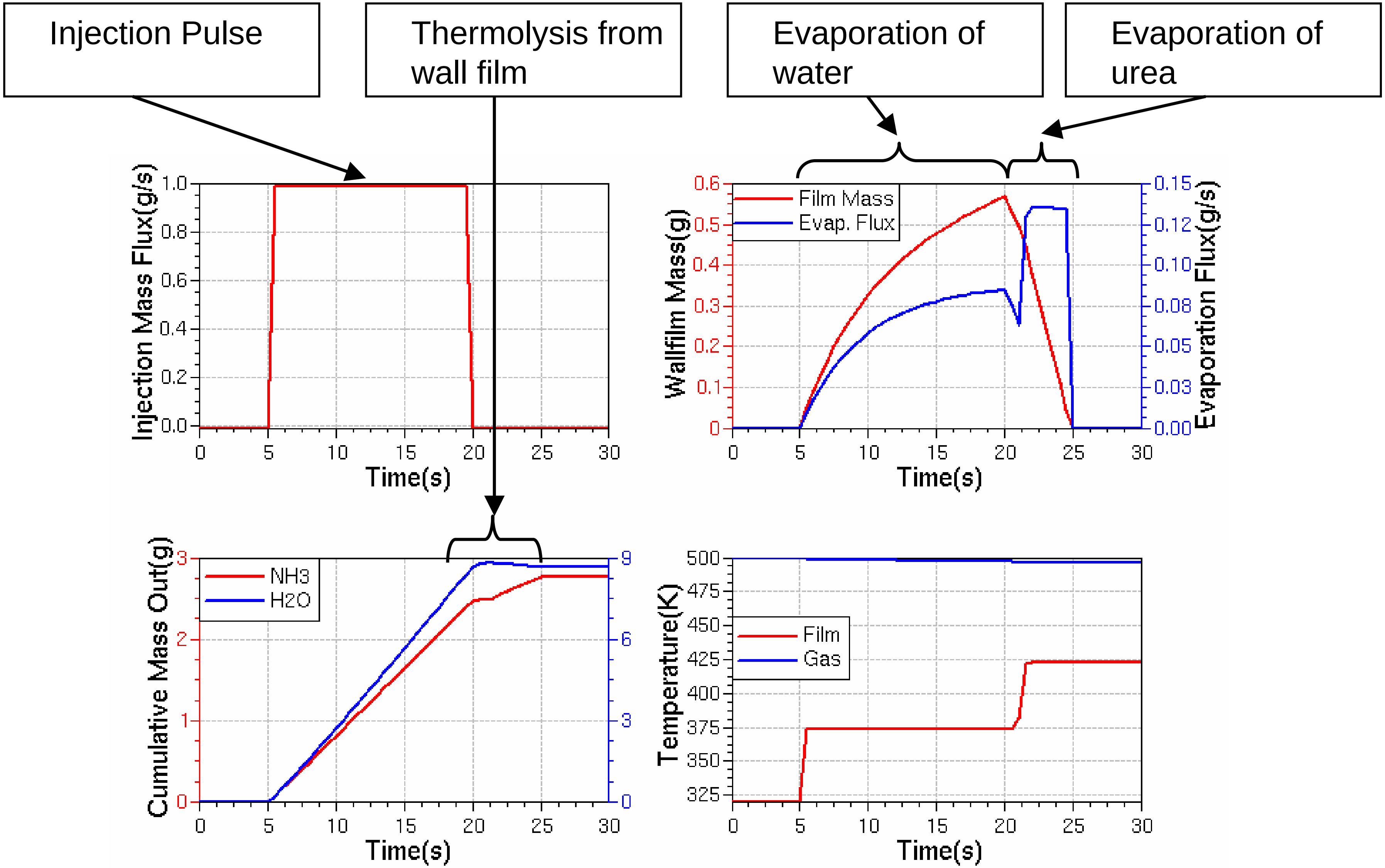
1D INJECTOR MODEL

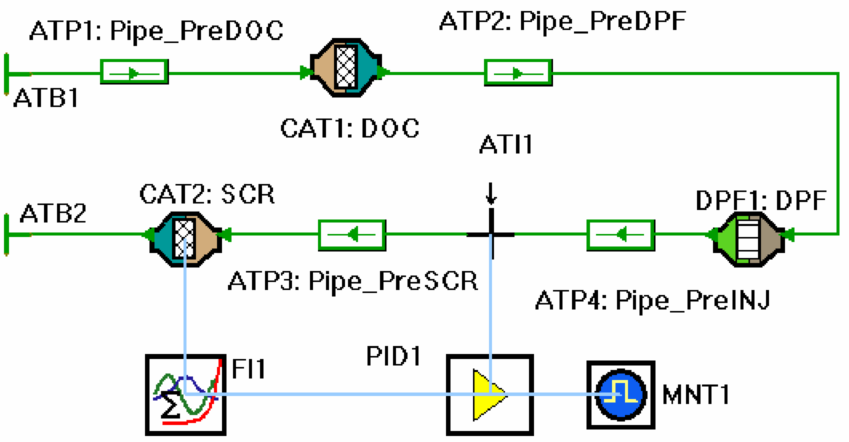


- Data base for pre-defined (adBlue, water, Diesel,…) and user-defined liquids
- Injection of arbitrary liquid and gas mixtures
- Pre-defined and user-defined break-up of liquids covering instantaneous evaporation and reactions (adBlue→ $2NH_3+CO_2+6H_2O$)
- User-defined build up of wall film
- Multi-component evaporation from wall film considering
  - film temperature driven evaporation pressure
  - component partial pressure in the gas phase
  - flow conditions
- Heat-transfer between wall, wall film and gas phase
- Dosing control modeling via
  - PID, Formula Interpreter elements
  - Simulink

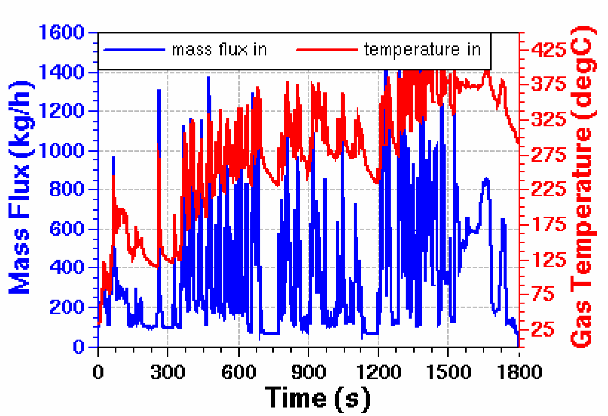
1D INJECTOR MODEL, WATER/UREA DOSING



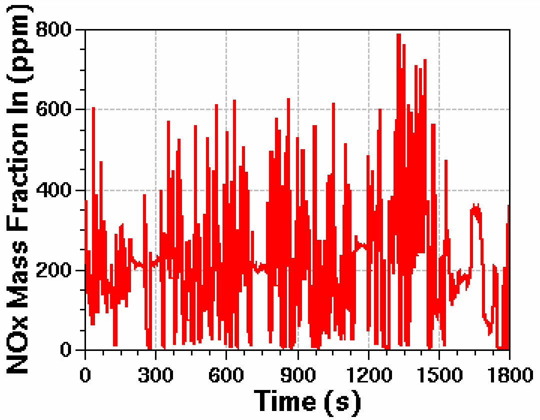
UREA INJECTION CONTROL DURING DRIVE CYCLE



- DOC: 20lt, 400/5
- DPF: 30lt, 200/12
- SCR: 35lt, 400/7
- Pipes: 10m/100mm, dual wall



- **Formula Interpreter:** Sensors NO and NO2 at SCR inlet and evaluates NOx level
- **PID:** Sensors NH3 at SCR inlet and steers injected Urea mass flow in order to meet alpha=1



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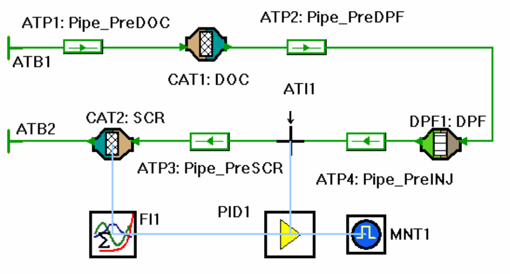
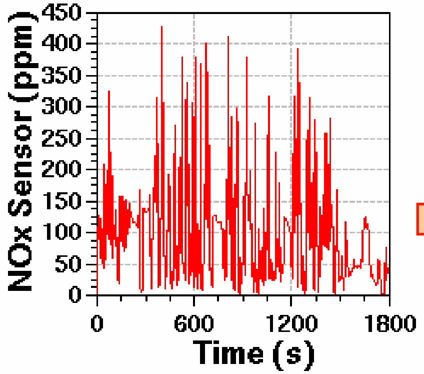
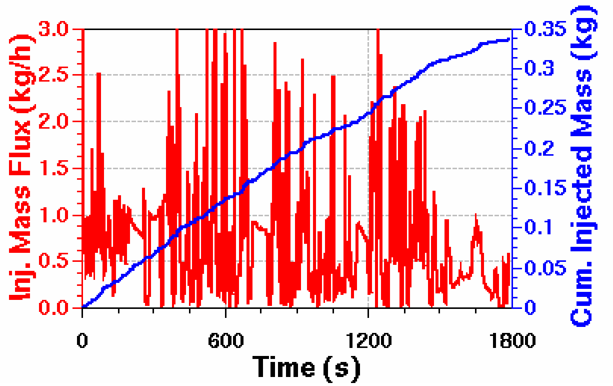
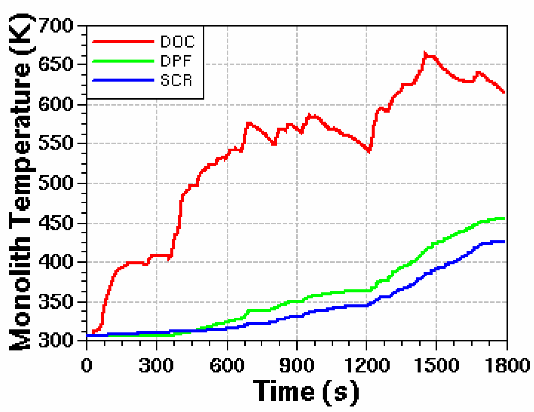
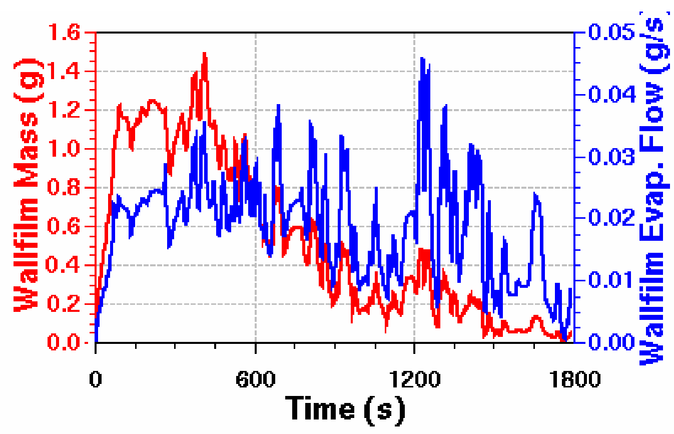




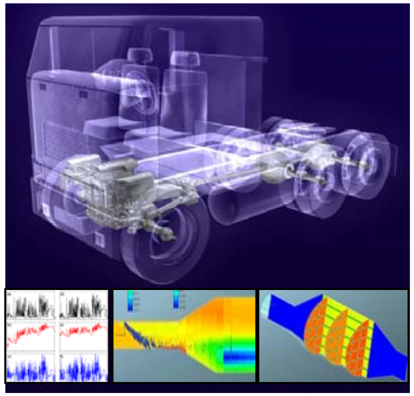
Urea Injection steered via NOx mass flow

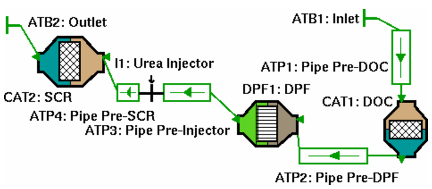


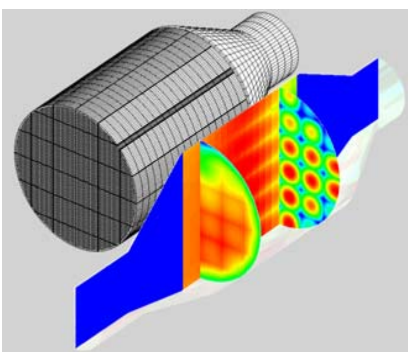




OUTLINE







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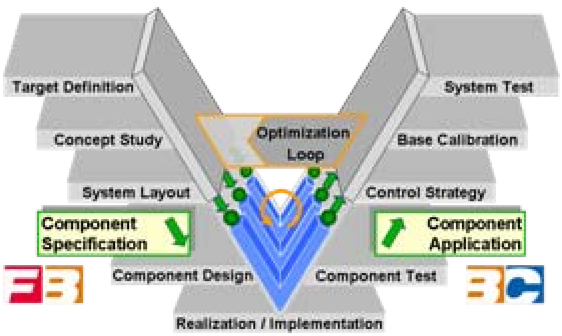
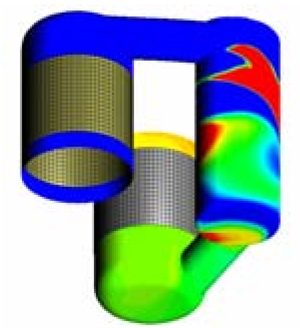
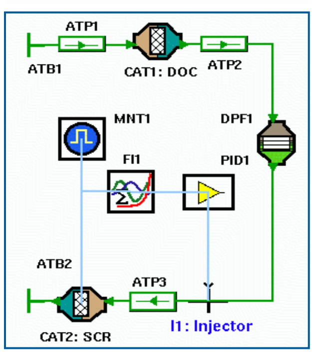
SUMMARY







The development of EAS is supported by an efficient and systematic simulation framework used from the early concept phase to the late calibration phase

- 1D is used to
  - Calibrate reaction models
  - Perform overall system design and analysis
  - Investigate control strategies
  - …
- 3D is used to
  - Calculate flow uniformity
  - Investigate adBlue dosing, spray and wall film
  - Investigate mixer performance
  - Predict temperature (gradients) during DPF regeneration
  - ...