Integrated EGR Systems: How To Optimize EGR Components In Regard To Performance And Packaging Requirements

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EGR (Exhaust Gas Recirculation)???

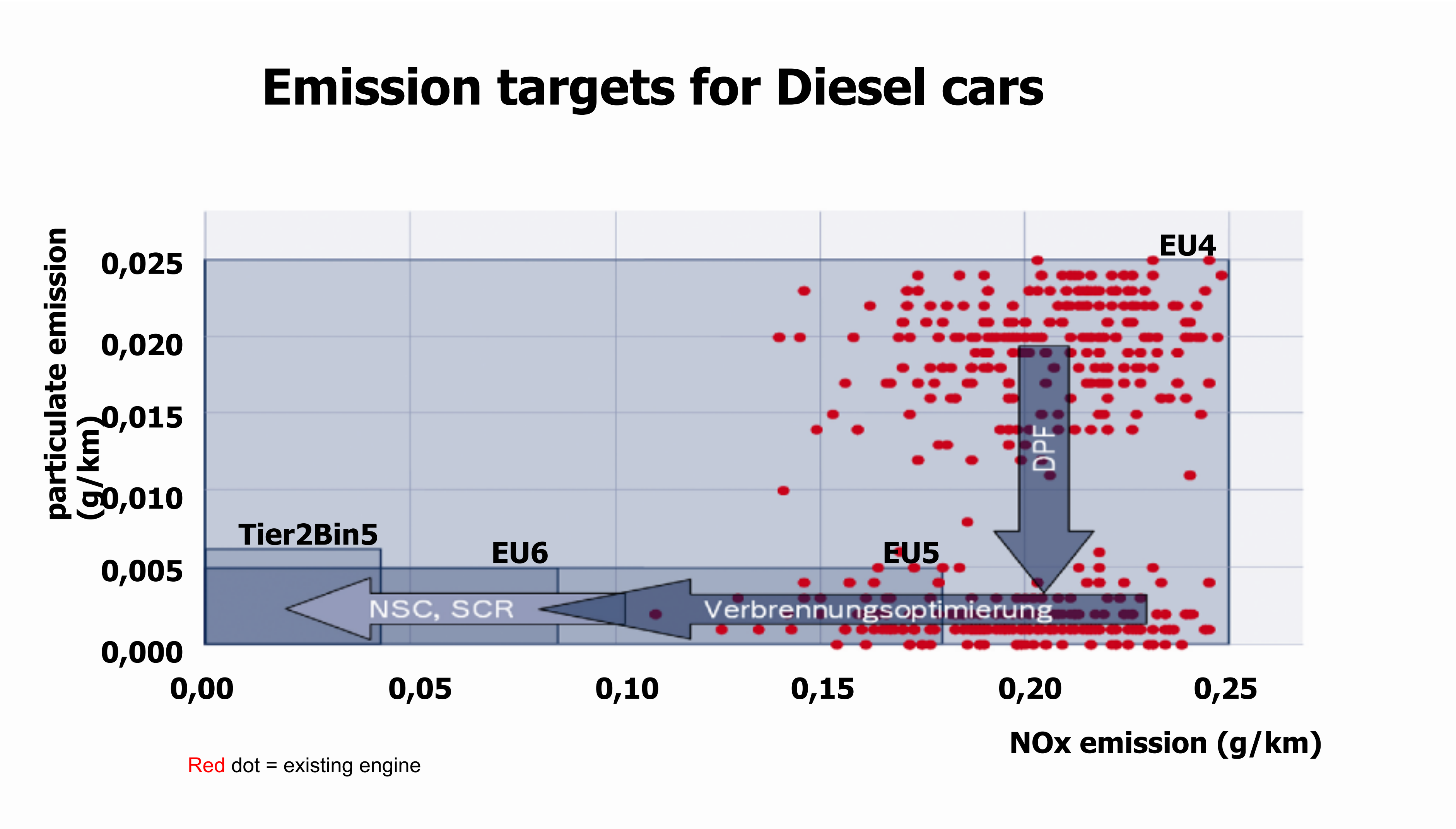
Why EGR is used:

- ✓ Global emission legislation is limiting NOx emissions to a significantly lower level
- ✓ EGR is most common process to reduce NOx emissions during the combustion process caused by pressure and temperature peaks
- ✓ EGR is one of the available NOx reduction systems like SCR or DeNOx-cat and can be used also in combination with one of these systems

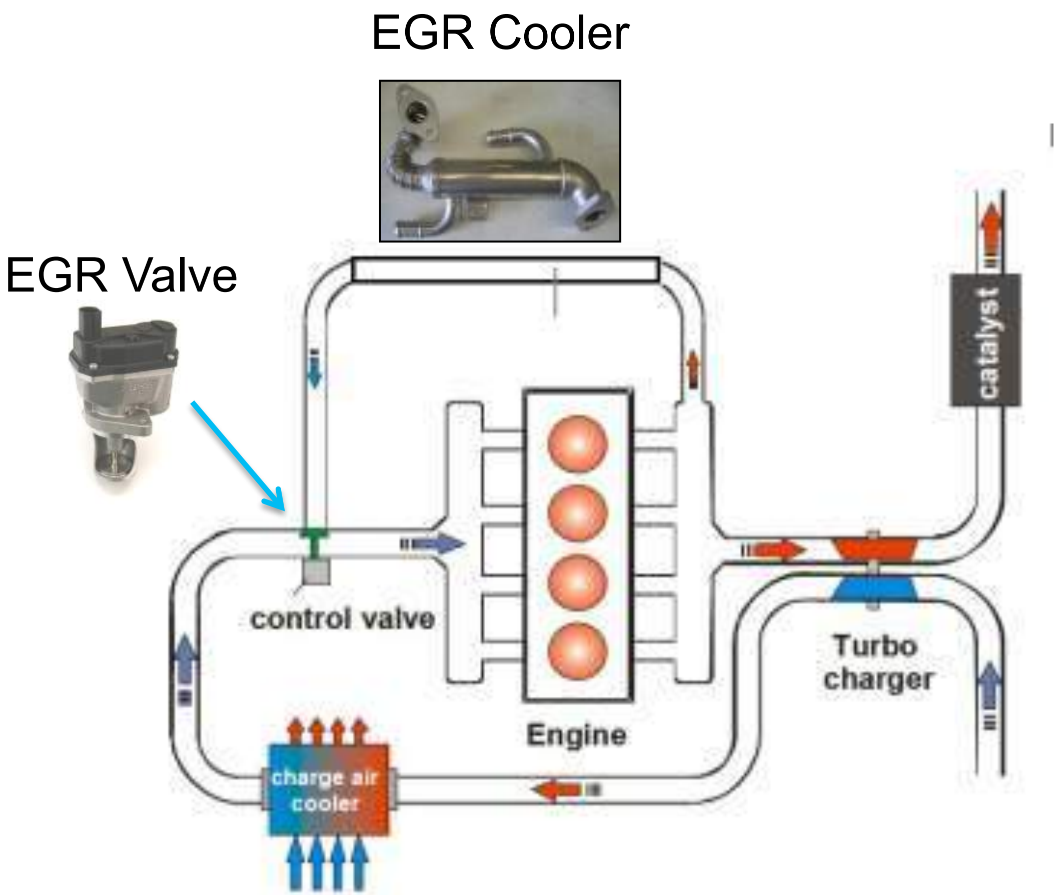
How EGR is working:

- ✓ EGR feeds inert exhaust gases after cooling back into intake system
- ✓ EGR substitutes air, which is not relevant for combustion process
- ✓ EGR increases the specific energy coefficient of the charge air inside the combustion chamber to reduce temperature of charge air during compression

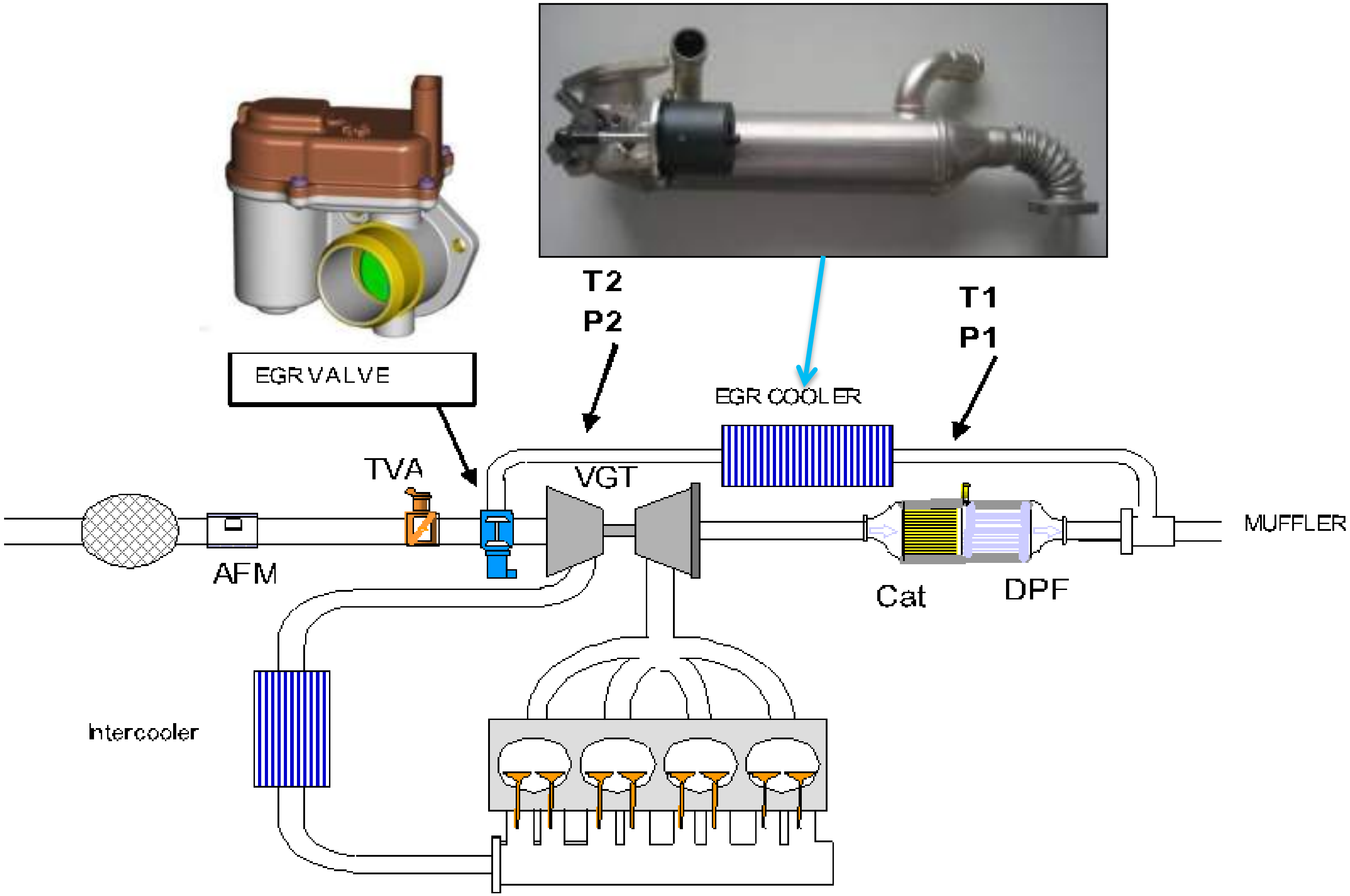
Emission Targets



Typical High Pressure EGR System

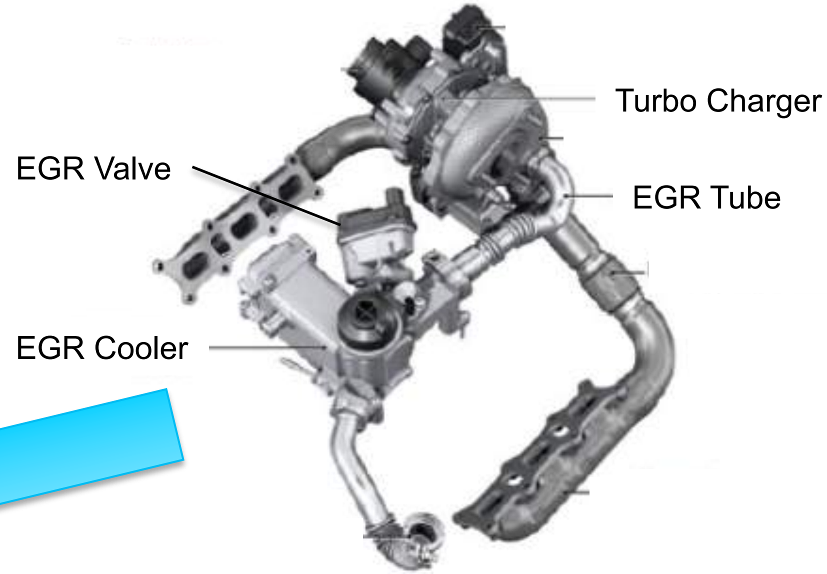


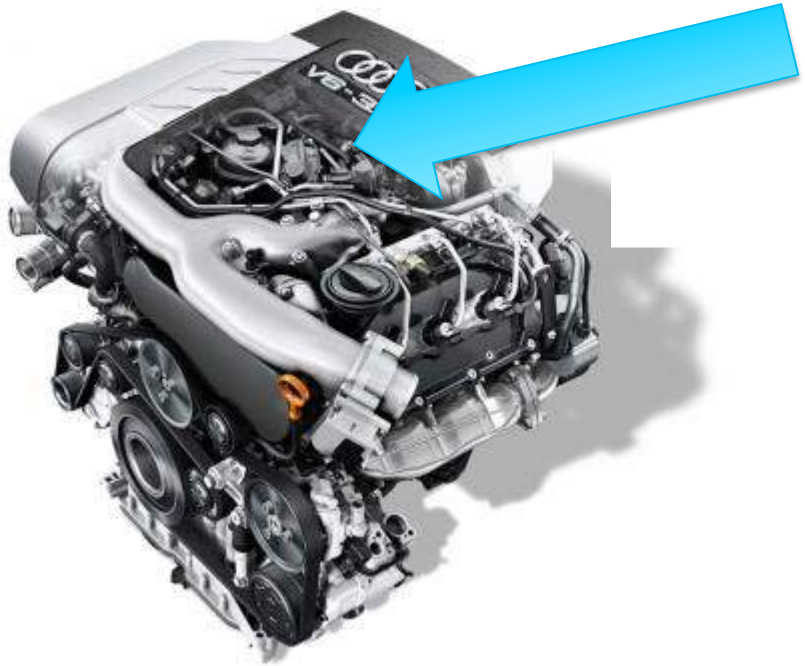
Next Level EGR Systems:
Low Pressure EGR System



EGR Components on Current Engines: Example Audi W36 V6 Diesel Engine (EU6 compatibel)

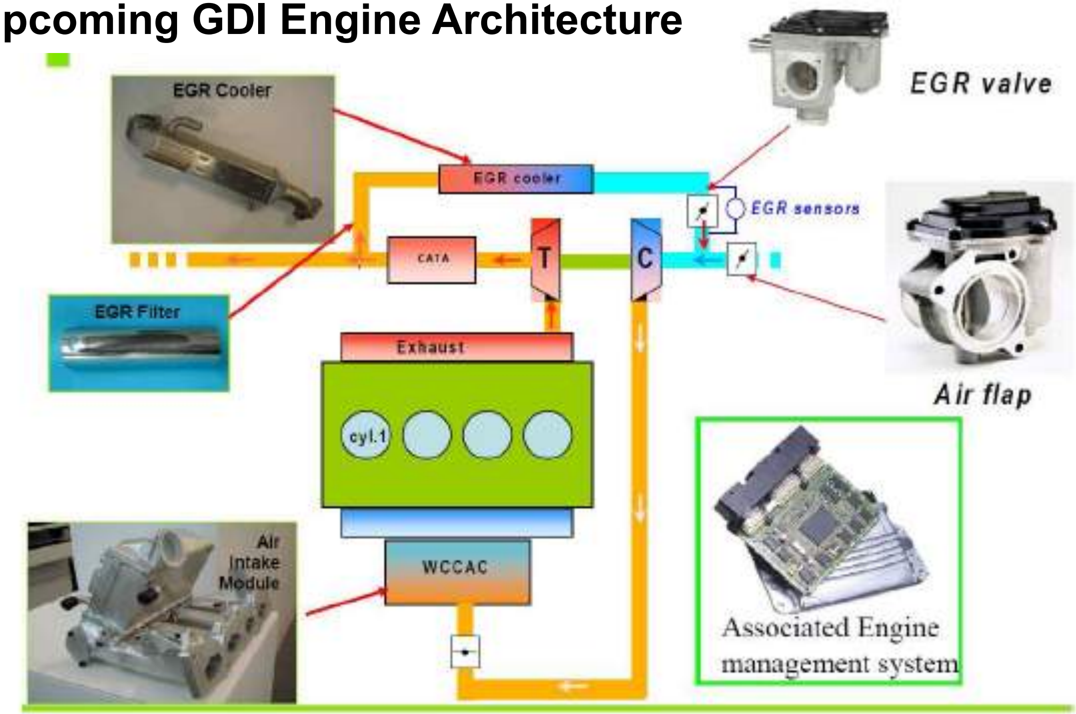
Engine uses High Pressure EGR System





Next Step in Technology: EGR at Gasoline GDI Engines

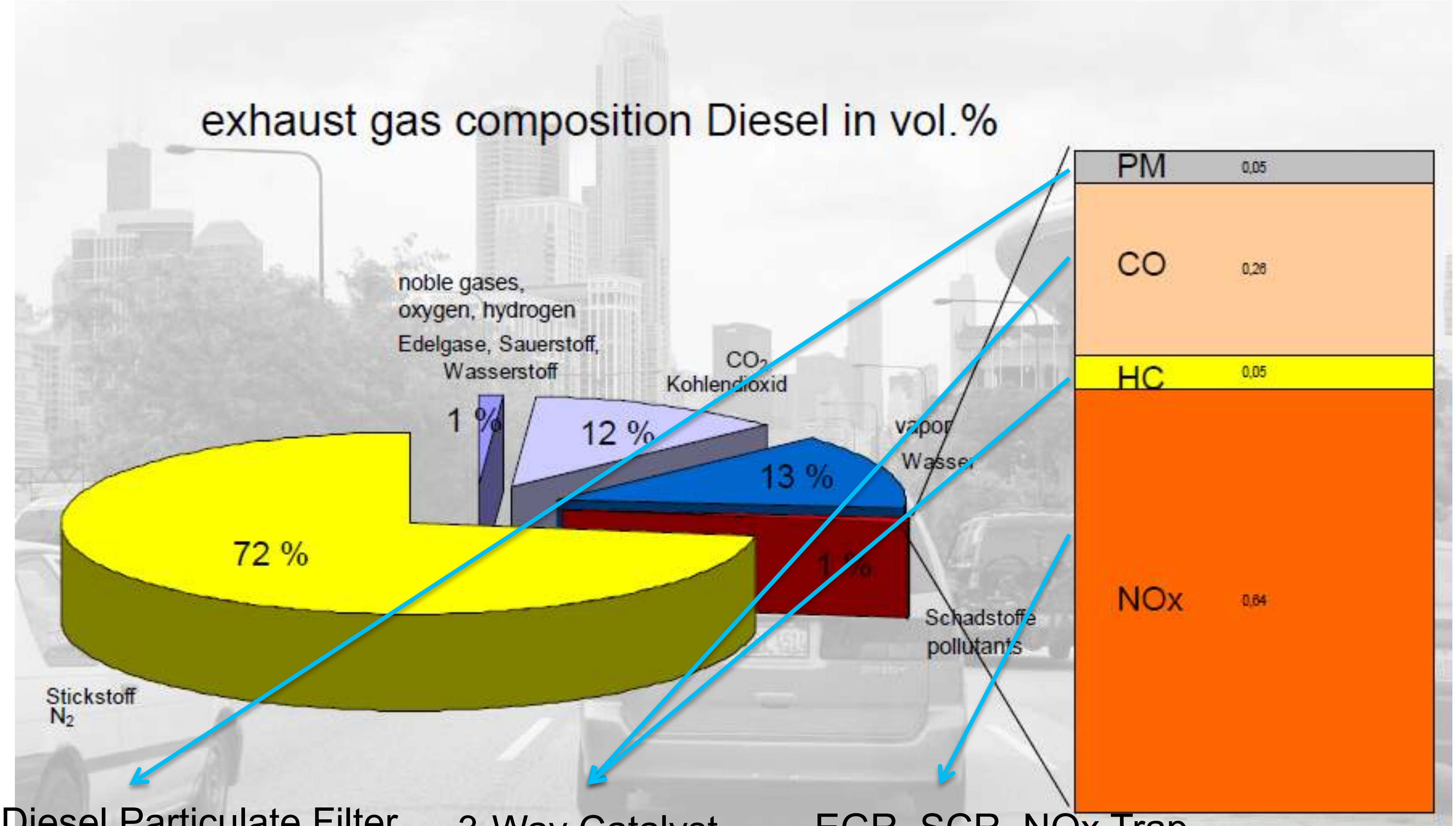
Upcoming GDI Engine Architecture



Upcoming highly efficient gasoline engine technology will use emission management technology from state of the art Diesel engines!

- Cooled EGR suppresses both pre-ignition and knocking
- Cooled EGR can lead to reduction of fuel consumption of appr. 9% at mid loads (if combined with water cooled charge air cooler)
- Downsizing and downspeeding of GDI engines will drive engine technology into same direction as Diesel engines

Diesel Exhaust Gas Composition

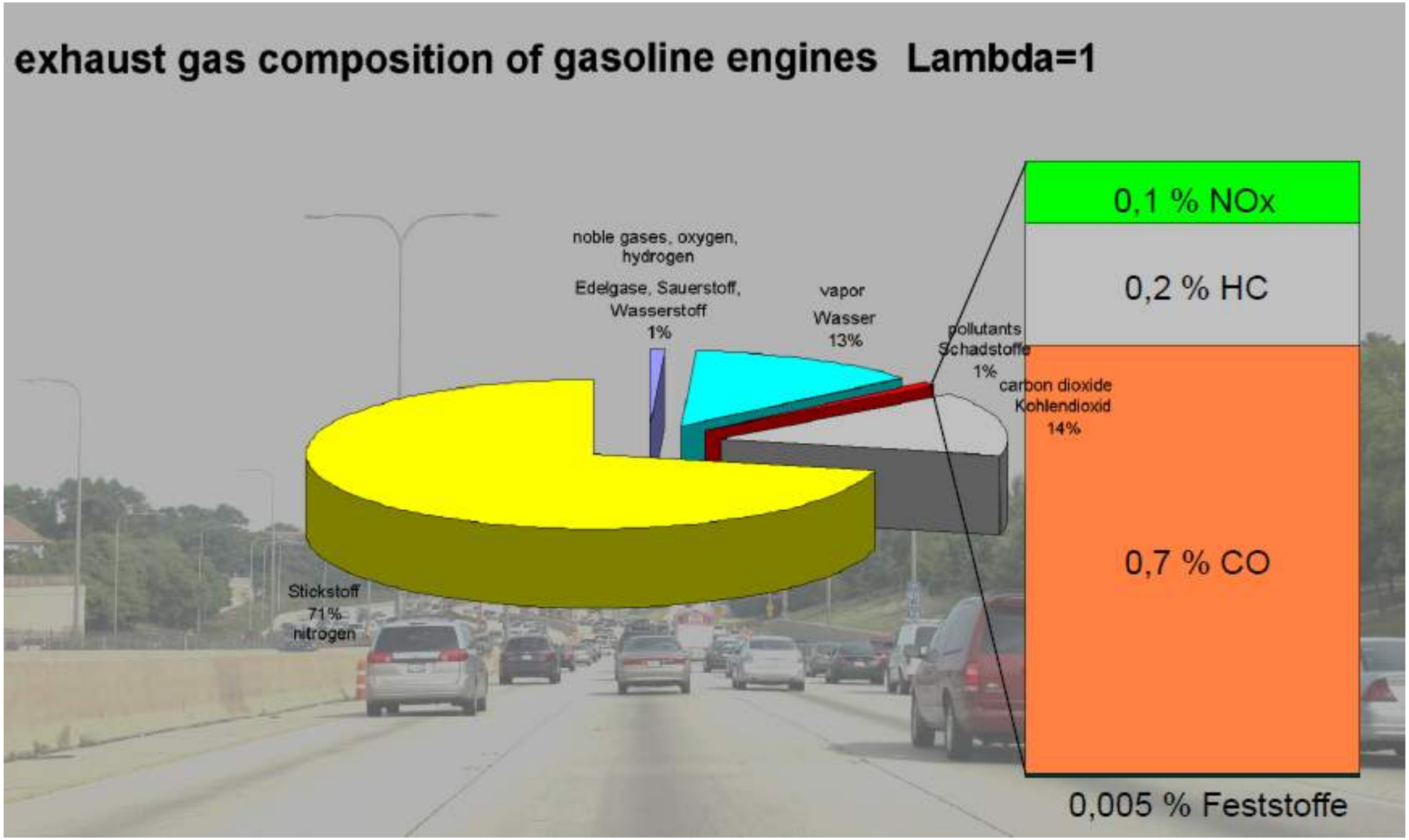


Diesel Particulate Filter

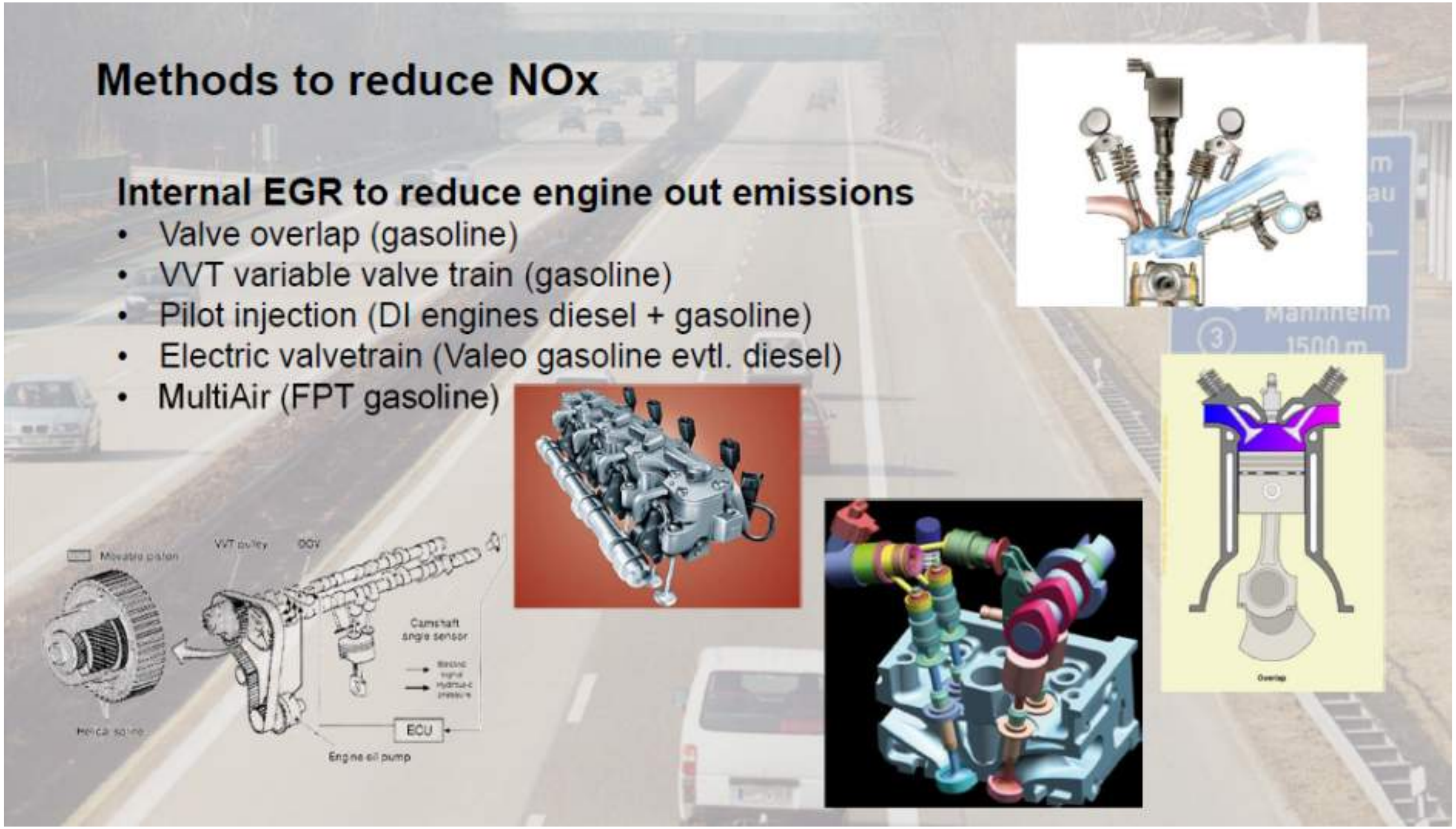
3-Way Catalyst

EGR, SCR, NOx Trap

Gasoline Exhaust Gas Composition



Titel



Methods to reduce NOx
Internal EGR to reduce engine out emissions
• Valve overlap (gasoline)
• VVT variable valve train (gasoline)
• Pilot injection (DI engines diesel + gasoline)
• Electric valvetrain (Valeo gasoline evtl. diesel)
• MultiAir (FPT gasoline)
VVT pulley
OCV
Camshaft angle sensor
ECU
Engine oil pump

EGR Components and Integration

- **Typical Components of a EGR System:**

➢ **EGR Valve**:
Regulates the amount of recirculated exhaust gas

➢ **EGR Cooler:**
Cooles the recirculated exhaust gas before engine intake

- **Critical Performance Elements:**

➢ Pressure Drop
➢ Heat Transfer
➢ Soot Resistance
➢ Smallest Possible Packaging

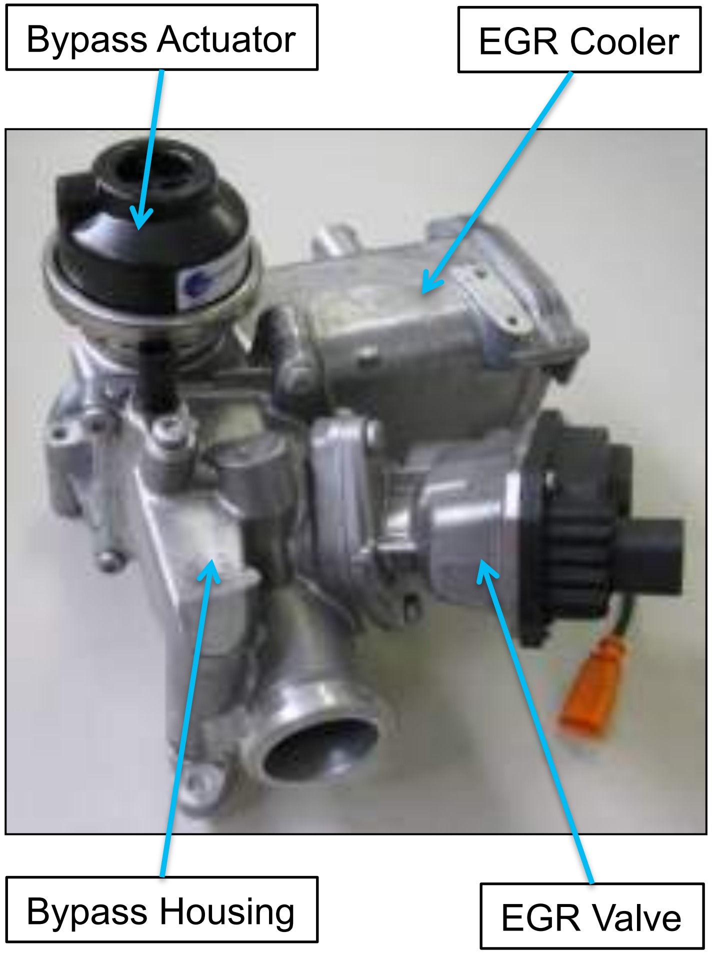
- **Integrated Systems** offer best potential for overall performance optimization!

Why Integrated Systems?

- CS Tests and Simulations have proven that pressure drop and thermal performance can be influenced significantly by smart design of the gas and water flow path

- To get to the optimal overall system performance the bypass actuator, the EGR valve, the bypass housing and the cooler itself need to be designed and adjusted „as a whole“ => the product/system is designed „around“ the gas flow to ensure lowest possible pressure drop, most efficient heat transfer and smallest possible packaging

Integrated EGR System:



Optimization of Performance and Packaging by Simulation and Testing

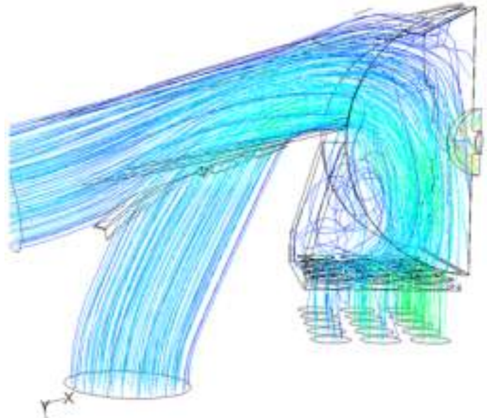
CooperStandard

Introduction to CFD with Ansys CFX

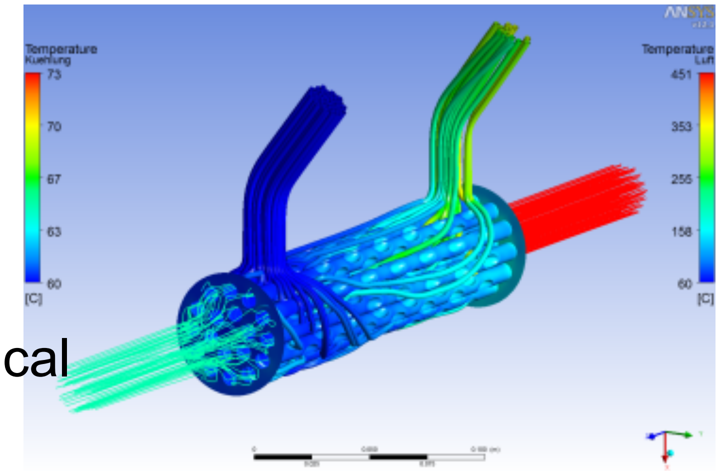
- = Numerical calculation process

  Analytical methods ⟷ CFD ⟷ Measurements

- minor steps to optimise design
  - pressure drop (Δp) in flow sections (intake, cooler tube,…)
  - Δp of entire cooler with variable density (from Excel tool)
- Virtual testing
  - Calculation covering entire systems ("conjugate heat transfer")
  - Temperature distribution in critical components (valves, seals…)



Flow lines in the intake area (2007)



Simultaneous calculation of gas and coolant (2010)

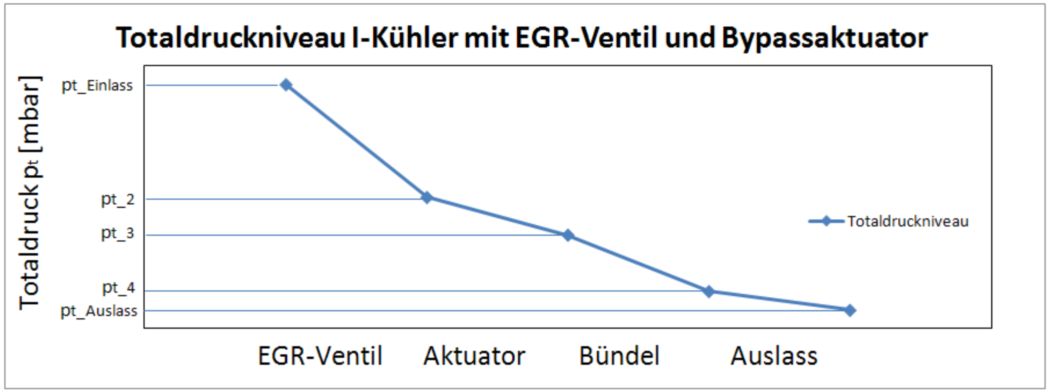
Use of CFD at Cooper Standard

CFD as part of development process
a. Tool in concept phase

- Initial orientation of components, modelling fluid-conveying surfaces (gas, coolant) in the available space
  - The data is used to generate first rough CFD model
  - Implementation of the cooler bundle (approximate values from Excel, calculation of individual tubes)
    - → Target specs (pressure drop, cooling capacity) as guide for dimensions
  - Calculation with heat exchange on surface of cooler bundle
    - → Draw total pressure distribution of the cooler/module

Using CFD to evaluate model changes for target specs

no



→Diagram highlights areas where optimisation would be most efficient

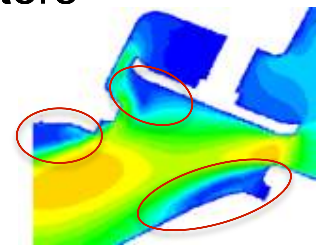
Diagram 1: Qualitative graph of the total pressure level of an I-cooler

- Target specs ±x% achieved? —yes→ Basic structure for cooler developed

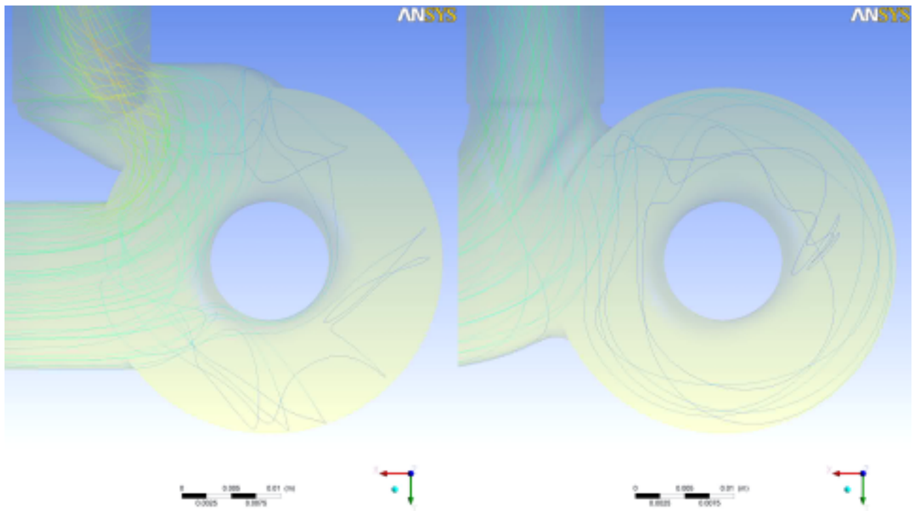
CFD as part of development process
b. Optimisation tool

- Defining sensitive parameters (radius, curvature)
  - detect dependencies, adapt geometry on basis of parameters
  - E.g.: 1. Contours downstream of valve/flap/actuator
    - → separations/back flows

    2. Contour at intake/deflection/outlet
    - → back pressure when flowing out of bundle (influences mass distribution because of feedback of subsonic flows)



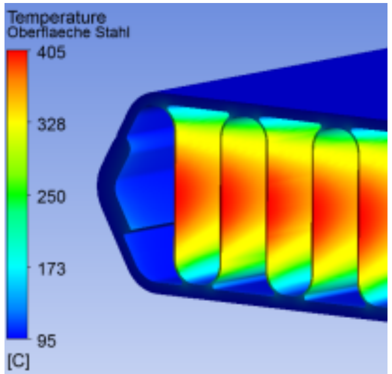
Velocity field downstream of valve seat



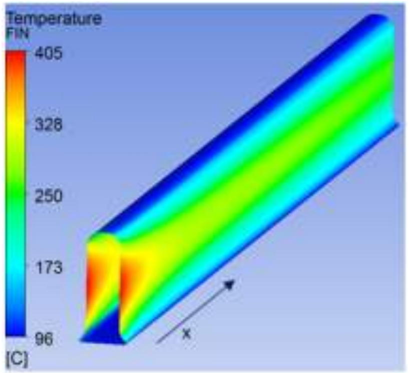
Position of bearing: Initial design (left); improved flow pattern (right)

CFD as part of development process
c. Component strength

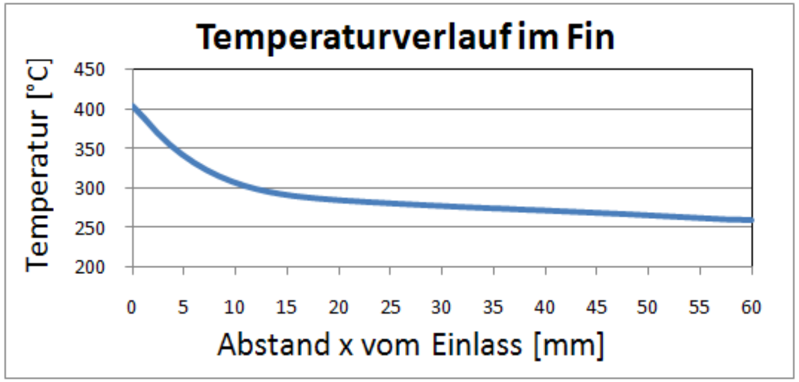
- Detailed views for temperature curves



Temperature distribution intake



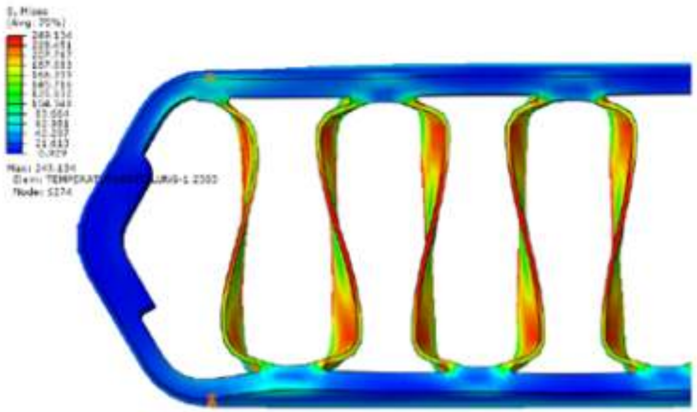
Temperature distribution fin



Temperature distribution along the x-axis

  - evaluation of critical areas with regard to boundary temperatures
  - input for calculating existing stresses (one-way FSI)

CFD → Temperature distribution (CFD) as boundary condition for FEM → FEM →



Stresses due to temperature load

Introduction to test cooler

- So far, EGR coolers with tubes for heat exchange have been manufactured at Cooper for applications from EU3 to EU6
- In order to broaden the field of application, however, other heat exchanger geometries are also studied and developed ready for series production
- Apart from numerical investigations, tests are also an important instrument in studying, comparing and validating these concepts
- The first question asked when customers come with enquiries usually relates to the cooling capacity and the pressure drop
- The fundamentals of EGR coolers with different heat exchanger elements therefore need to be investigated using test models:
    1. Tubular coolers with ø6 mm dimple tubes
    2. Flat-tube coolers with ø8 mm tubes
    3. Plate coolers (plate/fin)
- For this purpose, test coolers were produced using series components, e.g. the outer tube
- These test coolers and the results measured on the cooler test bed are presented below
- In order to make the measured data more directly comparable, the data were scaled to an identical jacket cross-section, which was filled out with the heat exchanger elements concerned

Survey of CSA cooler concepts

- **Flexfin tubes**
  - Good heat transfer, large pressure drop, good flexibility, long process times

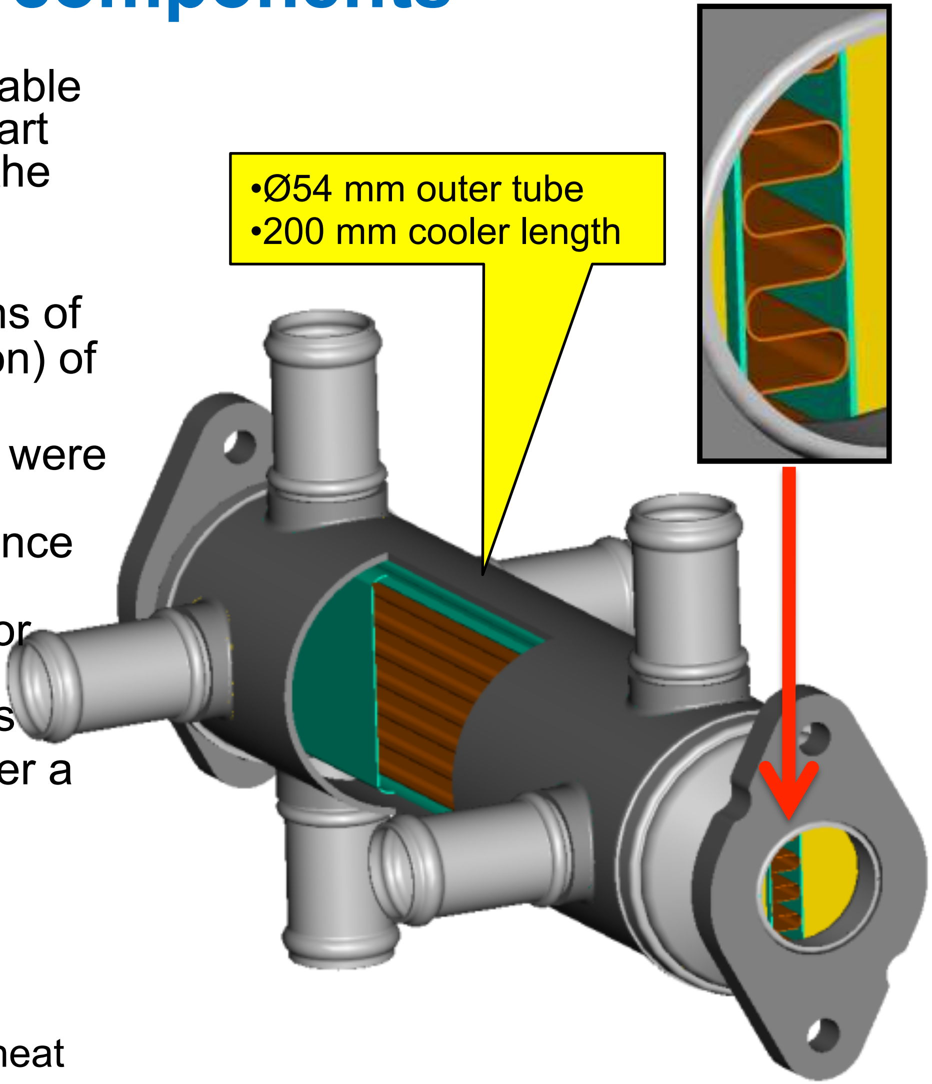
- **Dimple tubes**
  - Most flexible to arrange in cooler cross-sections
  - Diameter variable; smaller ones increase capacity and pressure drop, for example
  - Fine tuning of cooling capacity and pressure drop via geometry and distribution of dimples

- **Flat tubes**
  - E.g. made from ø8 mm tubes
  - Can be dimpled for fine tuning
  - Thanks to their low height, suitable for conditions where little or no sooting occurs
  - Primary use therefore in low-pressure EGRs

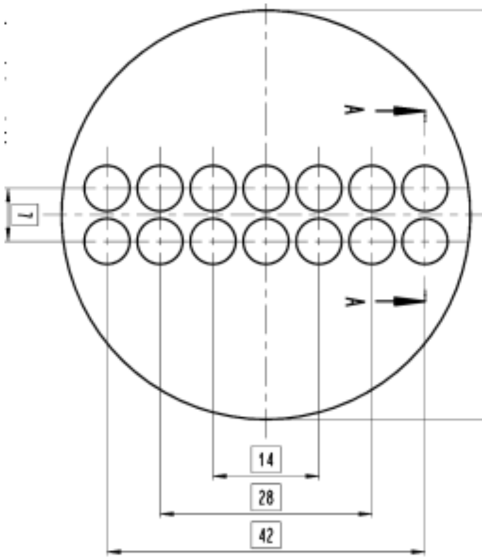
- **Plate with corrugated metal (plate/fin)**
  - Corrugated metal increases the heat transfer
  - Adapts the capacity and pressure drop via plate dimensions and corrugated metal geometry
  - Less flexibility over cooler cross-sections (rectangular)
  - Hot/cold structure intended to reduce sooting effects
  - Principle use therefore in high-pressure EGRs

Test coolers from series components

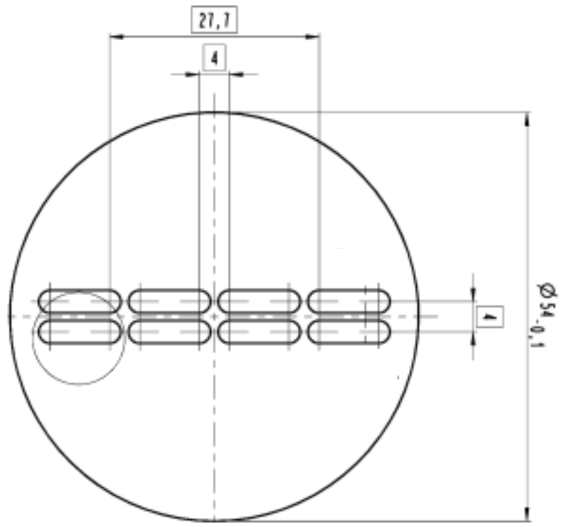
- In order to make test coolers readily available to validate the concept, components – apart from the perforated plates and of course the heat exchanger elements – from series production were used:
- To improve comparability, the tube portions of the round and flat-tube coolers (distribution) of the plate coolers were designed similarly
- Furthermore, additional water connectors were fitted in order to test the effect of different approach flow directions of the coolant, since the flat tubes
  and in particular the plate meant that major differences could be expected
  compared to the conventional round tubes
- In this way, systematic investigations under a variety of boundary conditions can be conducted:
  - Gas temperatures and mass flows
  - Coolant temperatures and volume flows
  - Counter-current, co-current principle
  - Different approach flow conditions for the heat exchanger elements



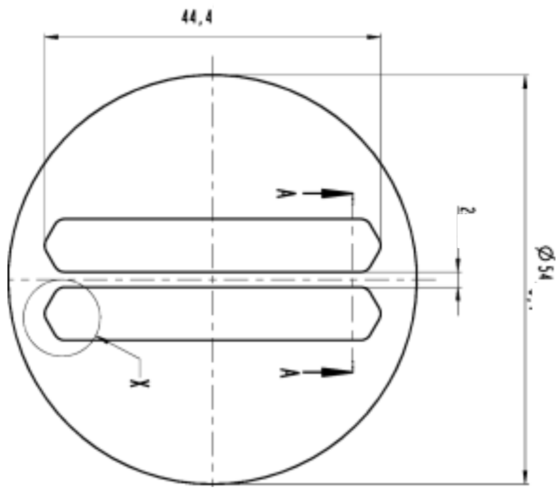
Cross-sections (perforated plates) of the test coolers



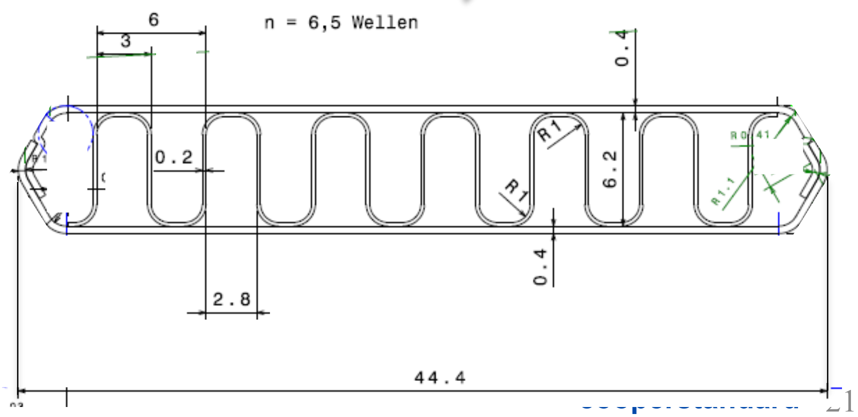
Round-tube cooler, test cooler with dimple tubes



Flat-tube cooler with dimples



Plate/fin cooler



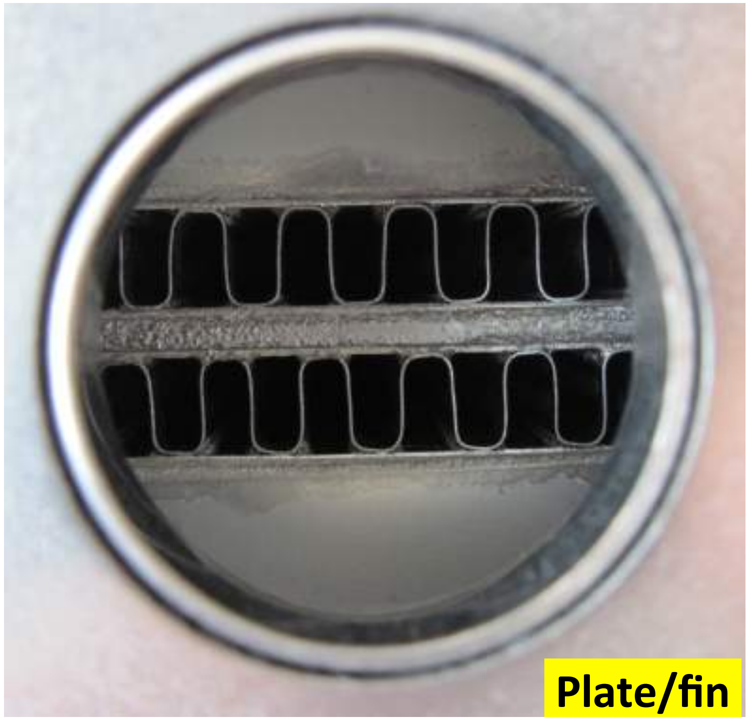
Cross-section through 2-walled plate element with straight corrugated metal (fins)

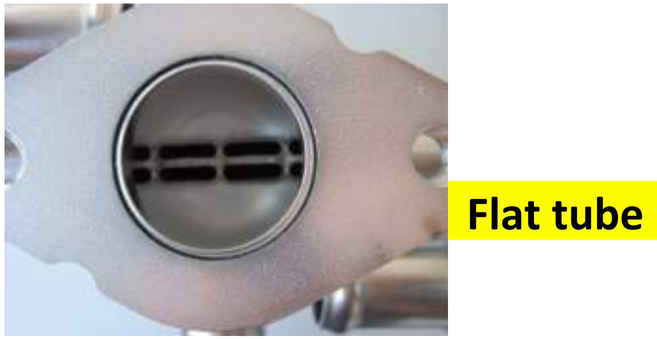
Geometry of the heat exchanger elements

- The table below shows the geometrical positions of the test coolers
- The tube/plate surfaces with coolant flowing directly around them, via which the heat exchange takes place, are almost identical in the flat-tube and plate coolers, but about 22% smaller than in the dimple-tube cooler
- Regarding the cross-sectional area through which the gas flows, the situation looks quite different: here, the cooler with plates has about 50% more flow cross-section available than the one with dimple tubes and about 150% more than the one with flat tubes
- Considerable differences in the results can therefore be expected, e.g. regarding the pressure drop, under identical boundary conditions
- Related parameters, such as the gas mass flow per flow cross-section, may also be useful for obtaining a better direct comparison between the coolers.

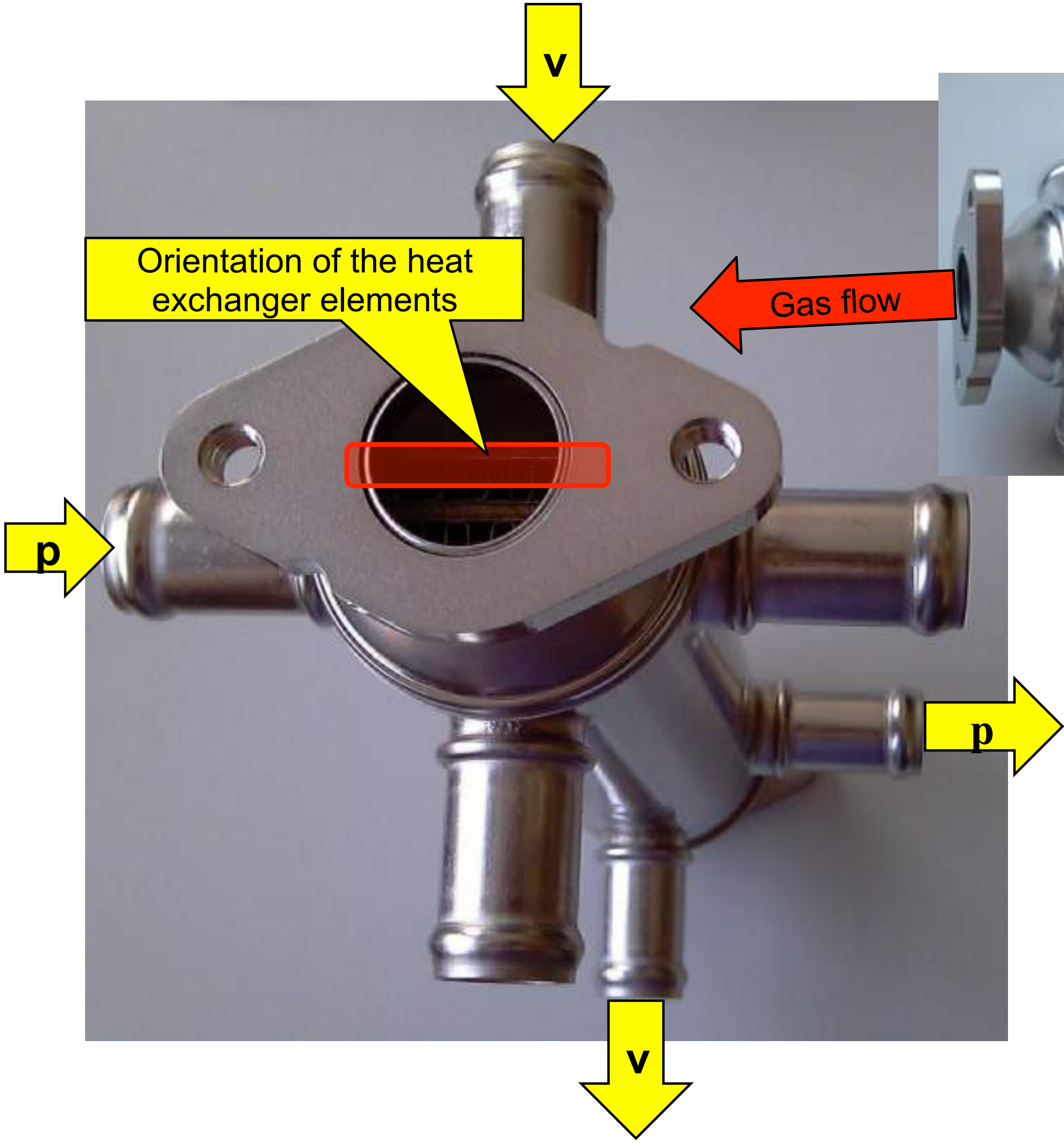
			Strömungsquerschnitte				Wärmeübertragungsfläche	
Kühlertyp	Bündel-länge [mm]	Rohre/ Platten [-]	pro Rohr bzw. Platte [mm²]	Verhältnis bez. auf Dimpelrohr [-]	Gesamt-querschnitt [mm²]	Verhältnis bez. auf Dimpelrohr [-]	Direkt gekühlte Innenfläche [mm²]	Verhältnis bez. auf Dimpelrohr [-]
Flachrohre	200	8	24,5	1,03	196	0,59	37686	0,78
ø6 mm Dimpelrohre	200	14	23,8	1,00	333	1,00	48381	1,00
Plate/Fin	200	2	245,5	10,33	491	1,48	37325	0,77

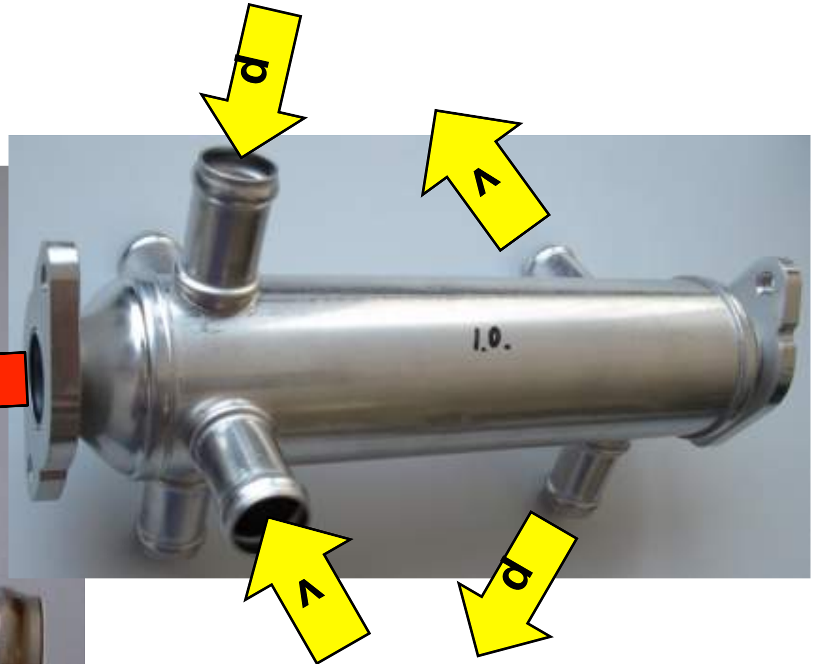
Test coolers





Coolant flow



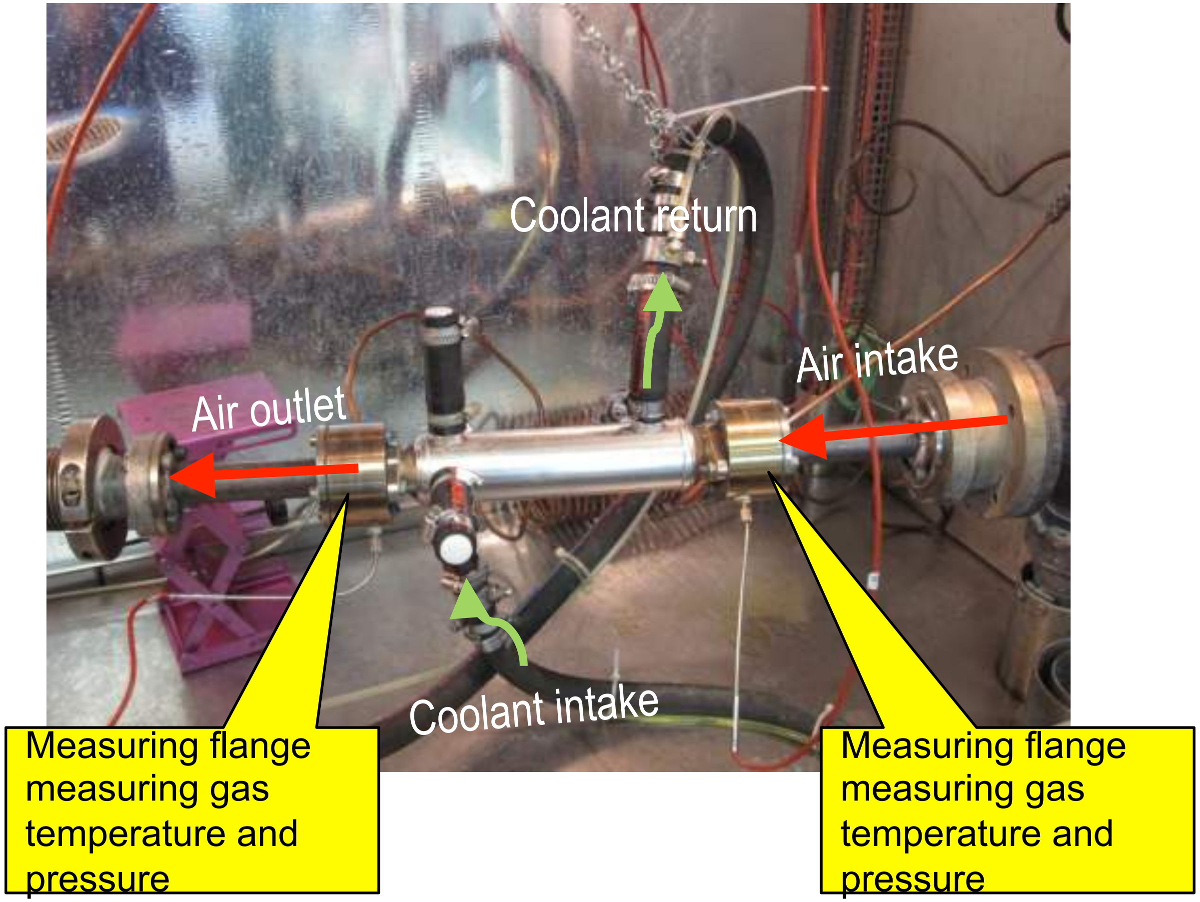


2 different flow paths for the coolant around the heat exchanger elements were investigated:

- **vertical** (**v**)
- **parallel (p)**

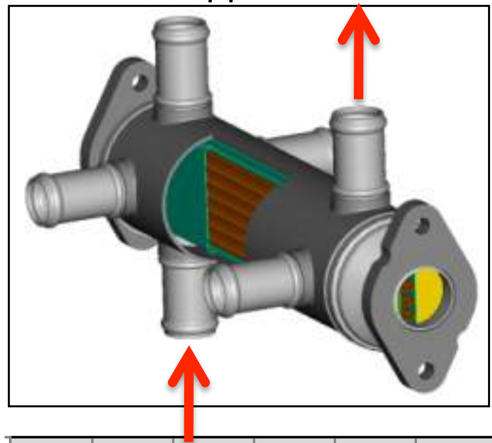
to the orientation of the heat exchanger elements

Experimental set-up in the cooler test bed



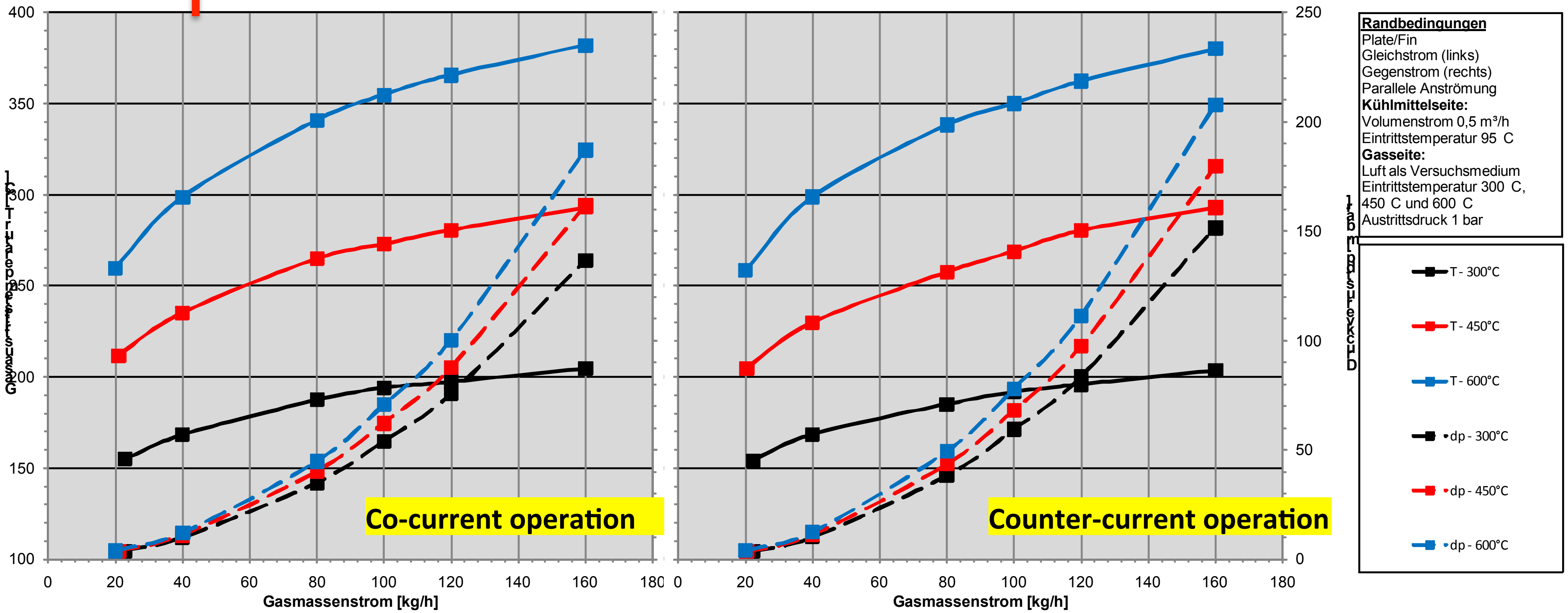
(1) Example of systematic investigations

Parallel approach flow to the rows with the heat exchanger elements

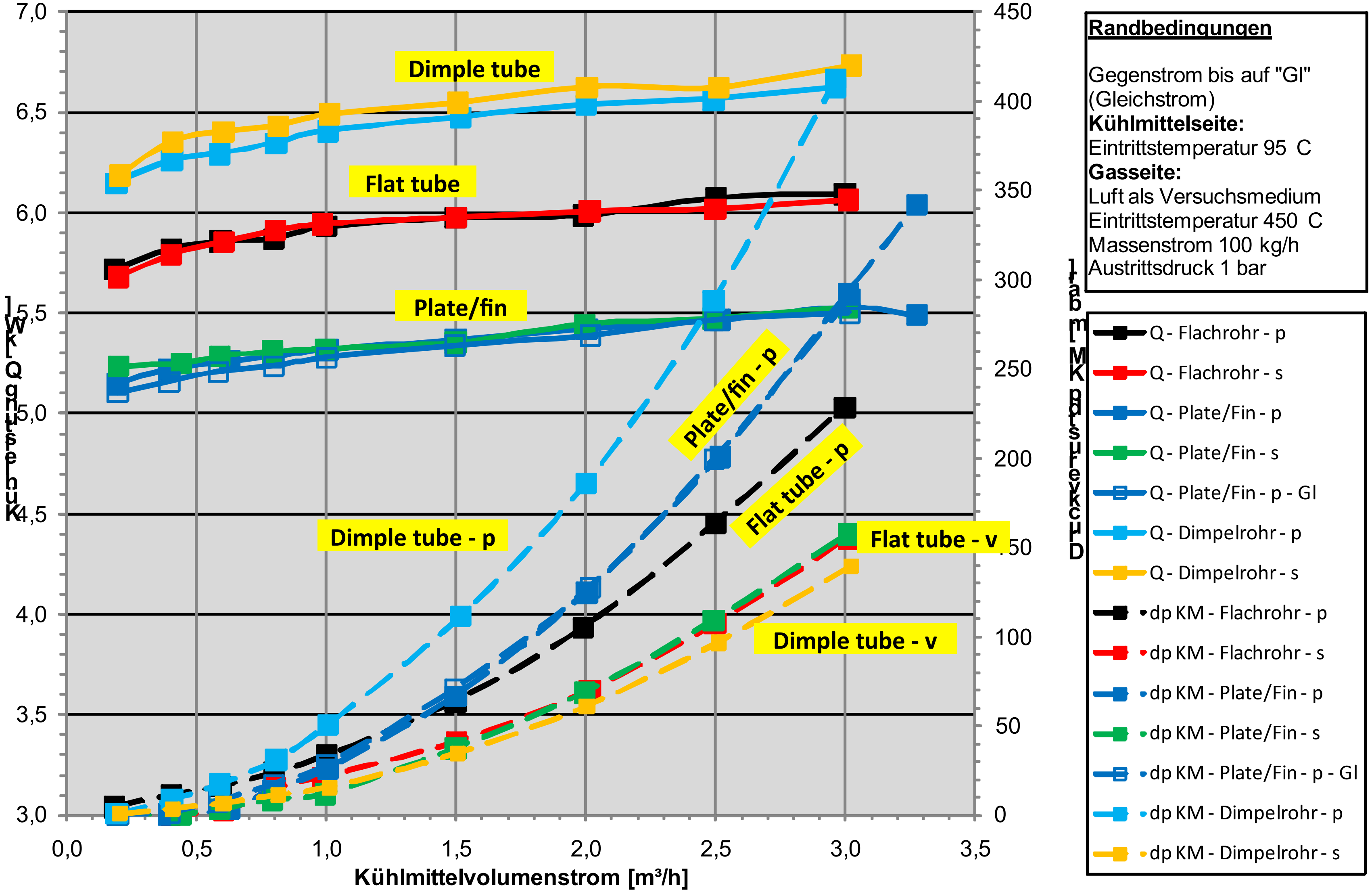


Variable operating conditions with test coolers, here:

- Different gas entry temperatures
- Co-current ⇔ counter-current:
    - No influence on the gas exit temperature



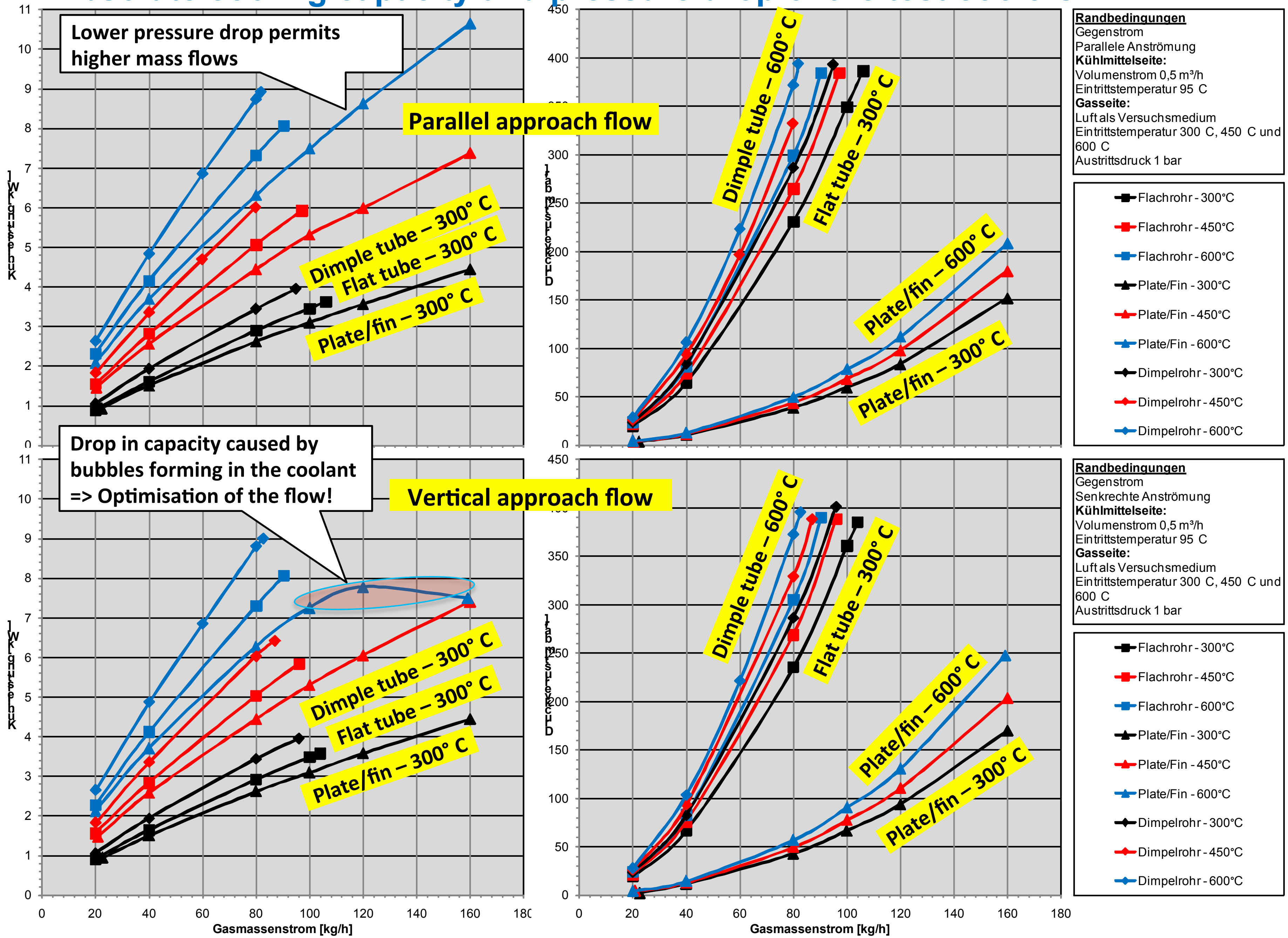
(2) Example of systematic investigations



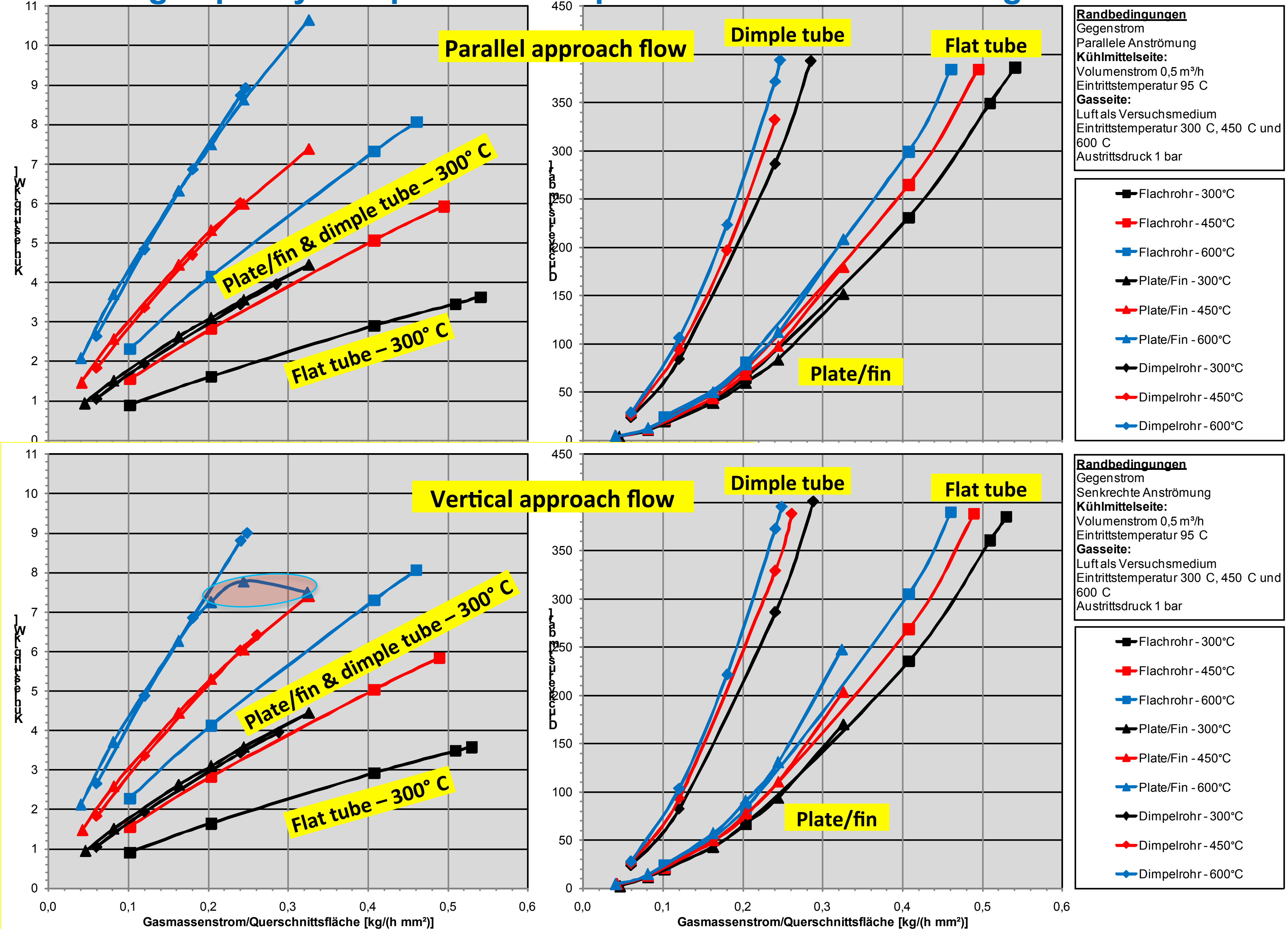
Randbedingungen

Gegenstrom bis auf "Gl" (Gleichstrom)
Kühlmittelseite:
Eintrittstemperatur 95 C
Gasseite:
Luft als Versuchsmedium
Eintrittstemperatur 450 C
Massenstrom 100 kg/h
Austrittsdruck 1 bar

Absolute cooling capacity and pressure drop of the test coolers

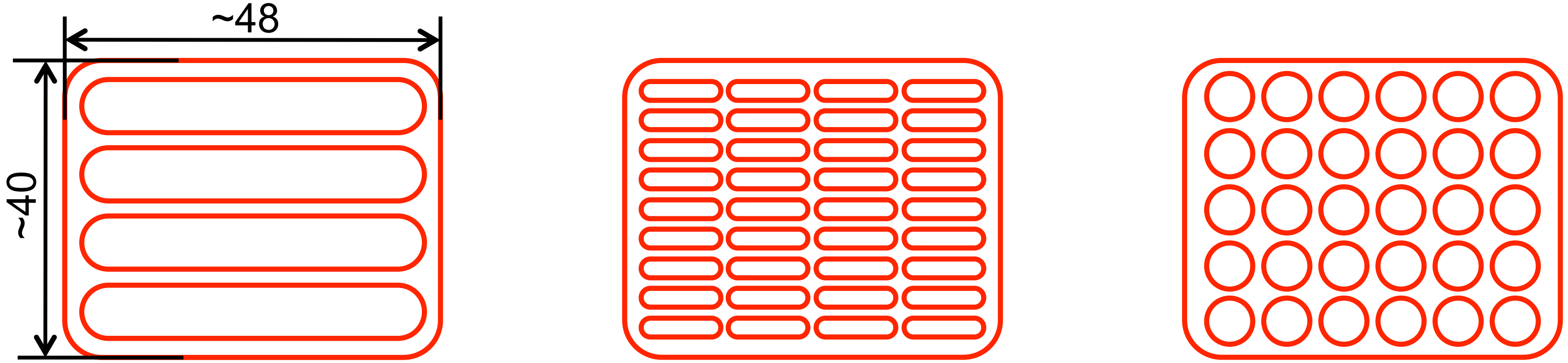


Cooling capacity and pressure drop of test coolers according to cross-section



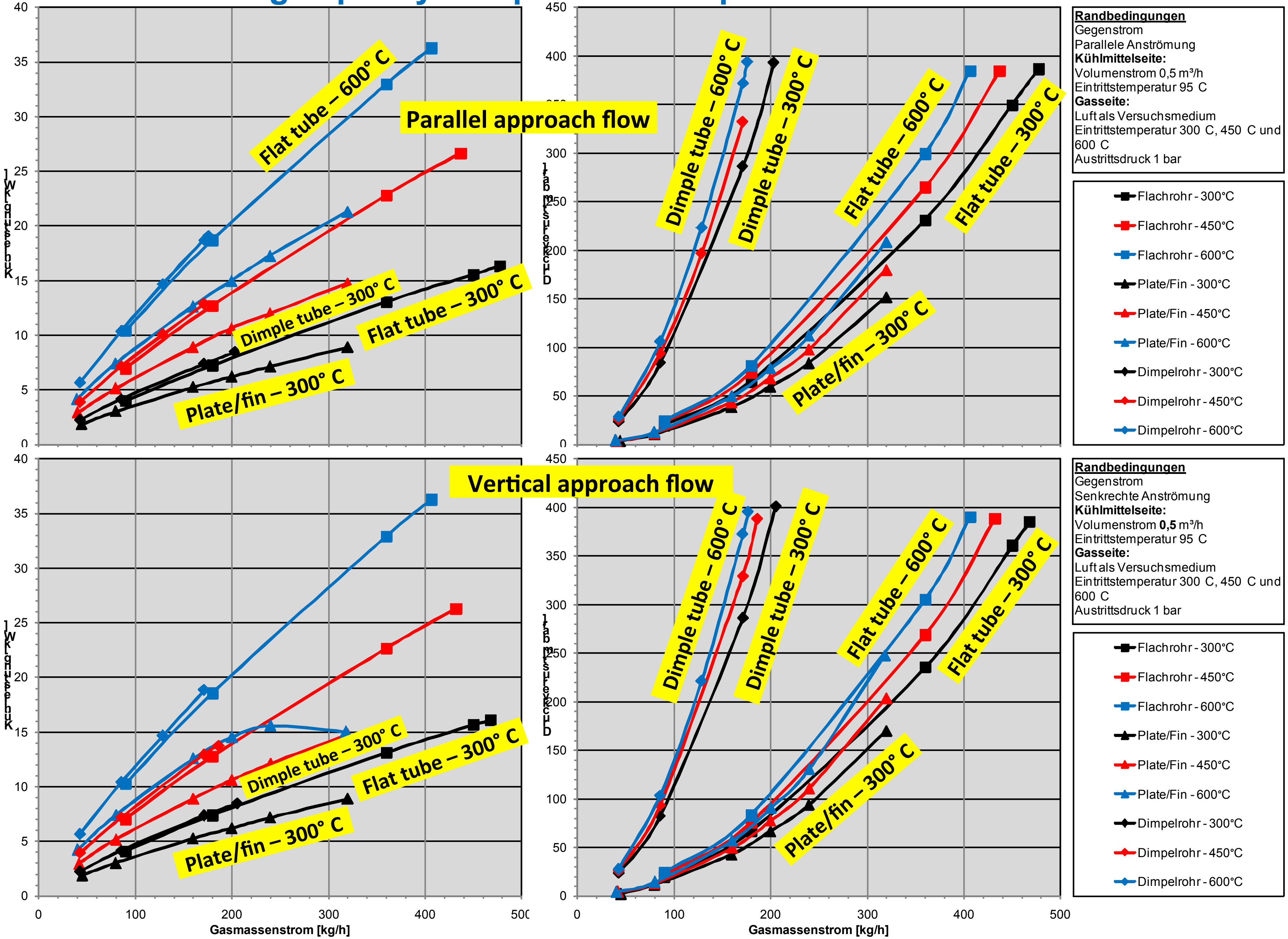
Scaling to identical cooler cross-sections

- The results measured (gas side) with the test coolers were now transferred to a rectangular cooler cross-section, which can be used well by all 3 heat exchanger elements
- Tubes, especially ones with a small diameter (here ø6 mm), can be adapted most easily to different cross-sections
- This results in the relationships shown in the table below



Kühlertyp	Bündel-länge [mm]	Rohre/ Platten [-]	Strömungsquerschnitte: pro Rohr bzw. Platte [mm²]	Strömungsquerschnitte: Verhältnis bez. auf Dimpelrohr [-]	Strömungsquerschnitte: Gesamt-querschnitt [mm²]	Strömungsquerschnitte: Verhältnis bez. auf Dimpelrohr [-]	Wärmeübertragungsfläche: Direkt gekühlte Innenfläche [mm²]	Wärmeübertragungsfläche: Verhältnis bez. auf Dimpelrohr [-]	Massen der Wärme-tauscher-elemente [g]
Flachrohre	200	36	24,5	1,03	883	1,24	169589	1,64	351
ø6 mm Dimpelrohre	200	30	23,8	1,00	713	1,00	103673	1,00	217
Plate/Fin	200	4	245,5	10,33	982	1,38	74651	0,72	371

Scaled cooling capacity and pressure drop

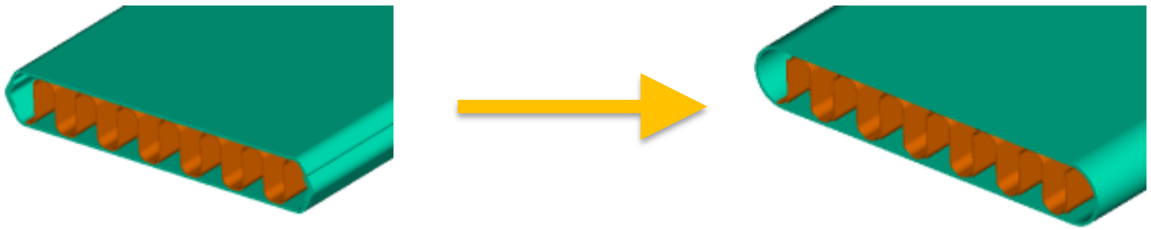


Summary Part B

- The smaller the cross-section of a heat exchanger element, the more variably, i.e. more ideally, a possible cooler cross-section can be exploited
- In the new flat-tube and plate coolers, it is for the most part possible to take over standard manufacturing and assembly technology - vacuum soldering, perforated plates, defined soldering gaps … -, thus minimising risks inherent in new technologies
- All 3 heat exchanger concepts can be adapted to specific capacity and pressure drop requirements, within certain limits, by means of variable geometries
- In the test coolers with round tubes, the dimples were well formed and therefore produced a good cooling capacity on a relatively high pressure drop level
- In the test cooler with the plate concept, a straight piece of corrugated metal was welded in; this produced the lowest pressure drop and a relatively low cooling capacity

Outlook

- Progress in the validation plan with test cooler
  - Vibration test, further typical cooler tests, “sooting test”
- Expansion of the existing data basis
  - Projects with dimple tubes for comparison with the new technologies
- Development of test cooler with wavy plate fins
- Conversion of prototype construction from two shells to robust flat tube (better soldering process)



Comparison of measurement and simulation

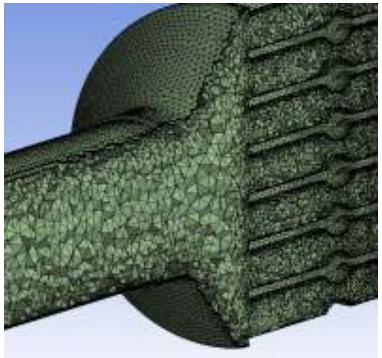
Next generation of coolers with CFD
a. CFD of an EGR cooler

- Calculation without heat transfer (isothermal)
- Calculation with heat transfer in the cooler bundle
- Extension of the model with heat transfer (free convection)
  - particular influence in the case of ribbed external geometry
- Implementation of cast metal/cooler bundle
  - more precise calculation of real surface temperatures
- Simultaneous solution of gas and liquid flow
- Gravity taken into account (Boussinesq approximation for coolant, only transiently possible)
  - heated coolant rises

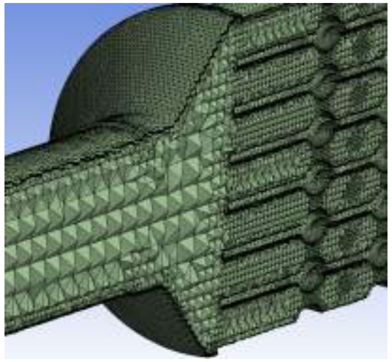
Complexity ↓
Efficiency ↑

Next generation of coolers with CFD
b. Comparison of CFD and measurement - dimple tube

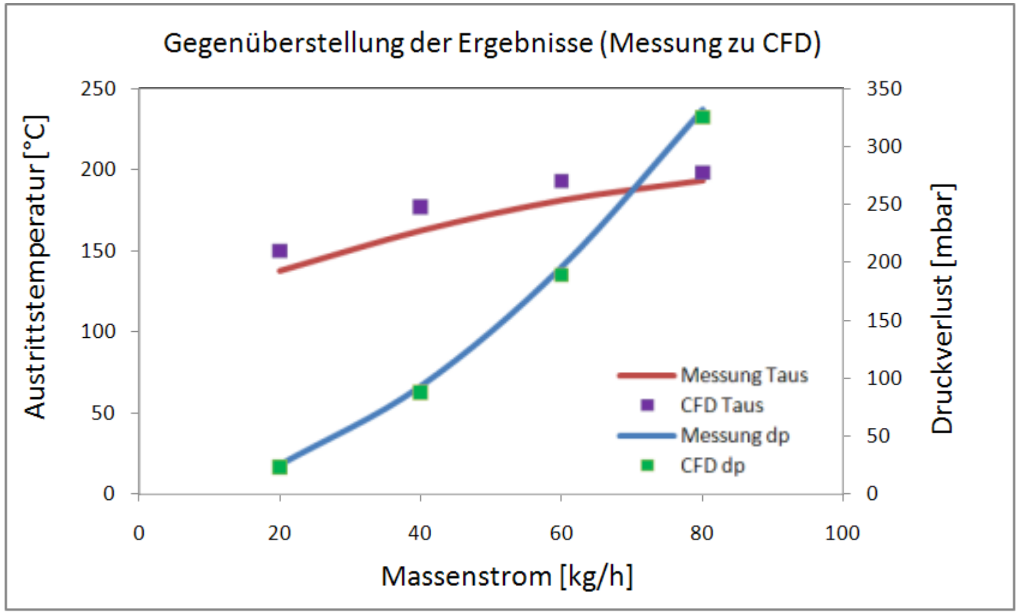
- Advantage of relatively small coolers is exploited in order to compare various meshing parameters
  - Meshing standard established (calibration with measured data)
    - → good match between the values
    - → better convergence with area-independent meshing



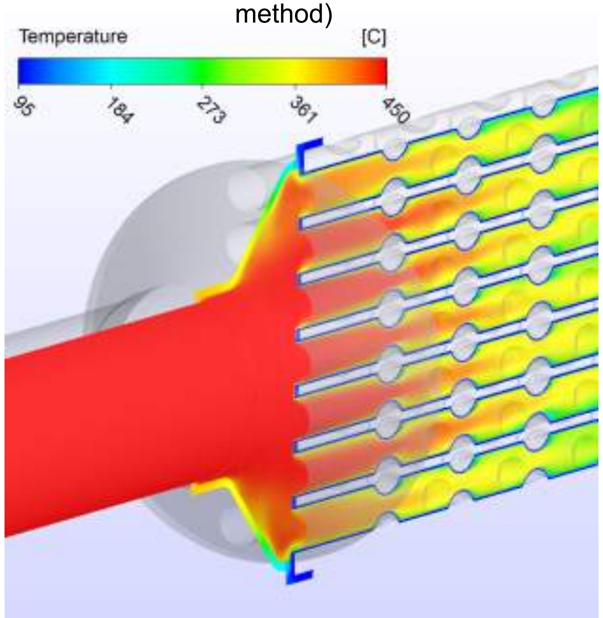
Area-dependent



Area-independent (ICEM CFD method)



Measured data: 450° C gas; 95° C coolant (constant)

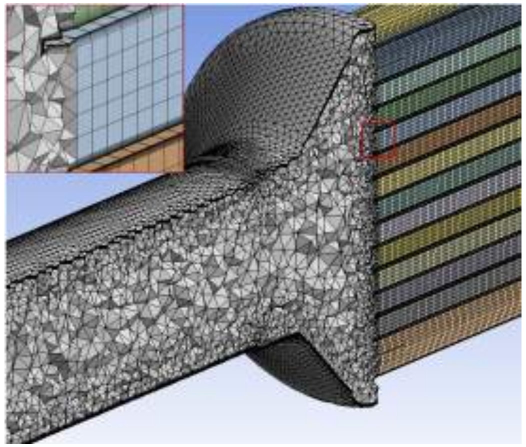


Temperature distribution in dimple tubes

Next generation of coolers with CFD
c. Comparison of CFD and measurement - fin, flat tube

- Regular geometry of fins
  permits further meshing techniques
  - Extruded meshes along the flow
    → No numerical diffusion

- Meshing with flat tubes (with dimples) same as with dimple tube



Area-dependent+multi-zone (hexahedron)

		Δp [mbar]	$T_{Austritt}$ [°C]	
Dimpelrohr	Messung	331	193	
	CFD (1.8)	325	198	
Flachrohr	Messung	265	234	
	CFD (ideal)	345	231	→ Calculation based on the ideal CAD data
	CFD (oval)	325	235	→ Calculation based on an oval cross-section
	CFD (ohne)	290	240	→ Calculation without dimples (extruded mesh possible)
Wellfin	Messung	44	257	
	CFD	53	257	→ Regular geometry (extruded mesh possible)

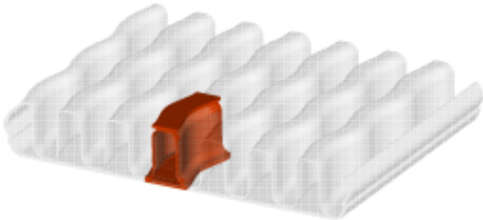
→ Better match between results with extruded meshes

→ Tendency towards excessively high pressure drop with flat tube and corrugated fin the same, despite matching outlet temperature

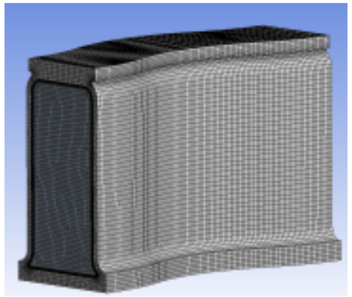
Next generation of coolers with CFD
d. Wavy plate fin – parametrised model

- What possibilities result to increase the cooling capacity?
  - Levers in the cooling tube are the choice of diameter, arrangement + depth of the dimples

- Creating a parametrised model in ProE
  - Detached “piece” from entire wavy plate fin

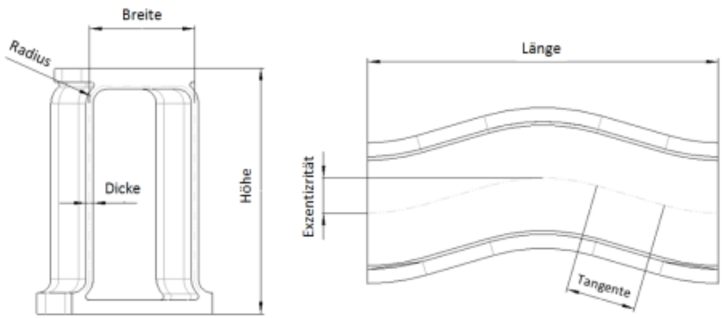


“Piece” of entire model



“Extruded mesh (multi-zone)

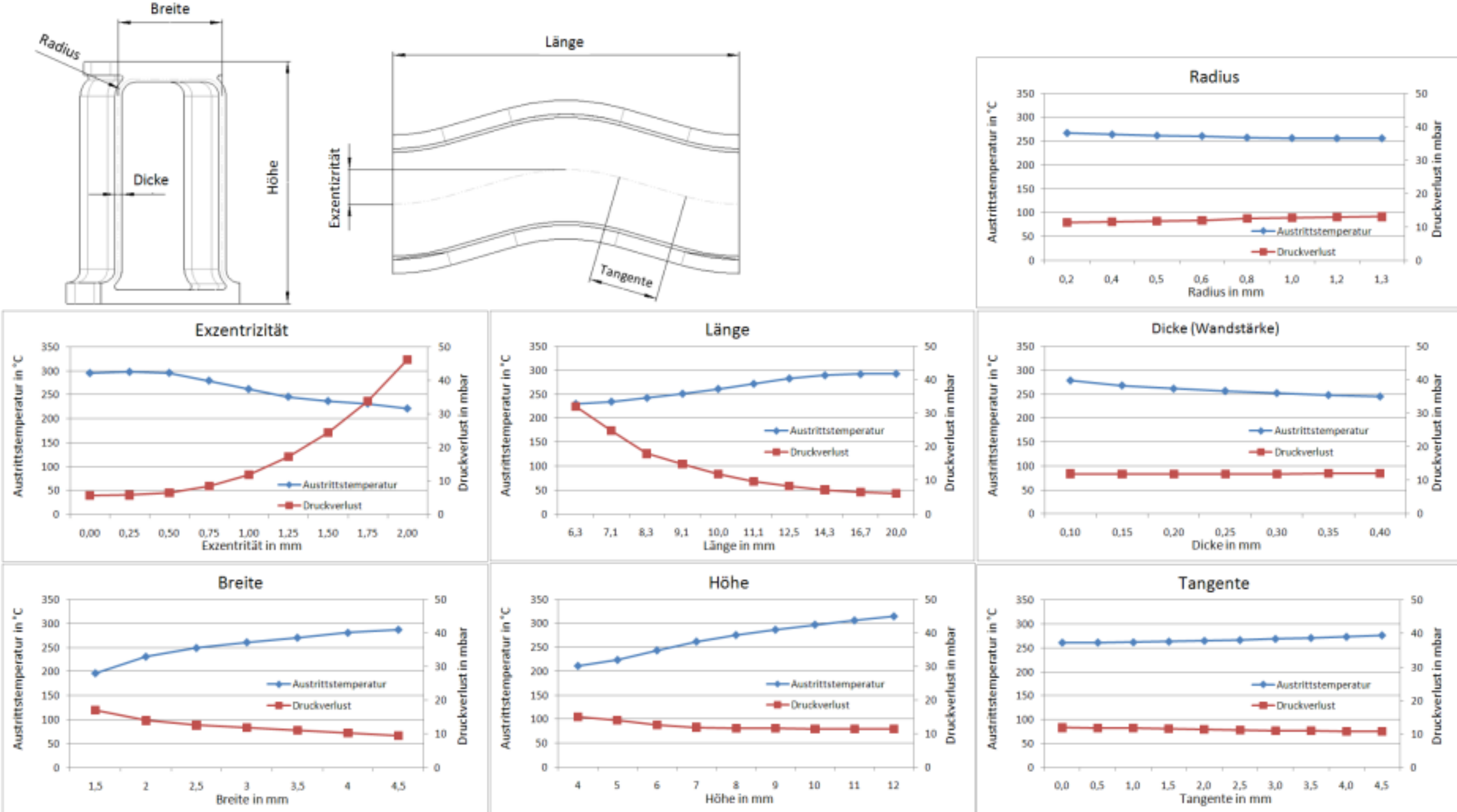
  - Defining seven parameters



Defining the parameters investigated

Next generation of coolers with CFD
d. Wavy plate fin – parametrised model

- From the parameters investigated, it was possible to obtain the following findings



Summary

- Development of the next generation of coolers (new projects, new technology) with sharp increase in use of simulations
  - Rapid increase in efficiency despite more complex problems
  - Virtual testing already a standard element in development

- Establishment of new cooler technologies at CooperStandard
  - Test coolers as technology demonstrators (assessment of manufacturability, difficulties in production)
  - Comparative measurements in the laboratory
  - Design tools expanded for EGR coolers

- Measured values and numerical calculations combined
  - Meshing standards defined
  - Simulations validated by good matches