State of the art cooling system development for automotive applications

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Introduction: Vehicle & Engine

Vehicle: Mercedes-AMG A45

Engine: M 133 DE 20 AL

Key facts

- World’s most powerful series compact sports car
- Highest specific output for series 4-cylinder engine
- Displacement: 1991 cm³
- Output: 280 kW / 381 hp
- Max. Torque: 475 Nm
- Acceleration 0-100 km/h: 4.2 s
- Max. speed: 270 km/h

→ Highest demands on cooling system
→ Heat input to cooling system up to ≈ 200 kW
→ Target system layout for race track
Evaluation of status quo

- How good are the applied heat exchangers in the competitive environment?
- Are the cooling circuits well balanced?
- Is there still room for improvement?

Approach technical and physical limits

- What can be achieved with current state-of-the-art technology?
- Which potential can be exploited with advanced technology?

Accelerate and improve efficiency of development process

- Provide viable component and system specifications at early design stage
- Support and monitor prototype phase to avoid useless development iterations
- Support supplier management and benchmark
Cooling system design and modelling

High temperature cooling circuit
• Engine and transmission cooling

Low temperature cooling circuit and charge air duct
• Coolant-cooled (indirect) charge air cooling

HVAC refrigerant circuit
• Complete model of AC system including condenser, evaporator, vehicle cabin model etc.

All circuits modelled in full detail to support transient cycle calculations.
Cooling system design and modelling

Cooling module (air side)

- Detailed Cool3D-representation of heat exchangers and underhood air flow path
- Reproduces total air mass flow rates as well as main features of flow and temperature distribution

- Electric fan
- HT main radiator
- AC condenser
- LT main radiator
- HT additional cooler

LT wheelhouse radiator
Model calibration and validation

Air mass flow rate and distribution calibration by detailed CFD underhood analysis

Comparison of total air mass flow rate

Comparison air flow distribution
Model calibration and validation

Validation example: Transient acceleration / deceleration cycle

Validation example: Passenger compartment hot cool down
Heat exchanger benchmarking: Overview

Hardware analysis
Design characteristics, materials, manufacturing quality, part details, ...

Caloric performance measurement
Determination of heat transfer and pressure drop maps

Competitive comparison
Performance benchmark for specific component sizes and operating conditions

Thermodynamic analysis
Determination of component heat transfer and pressure drop correlations
**HX benchmarking: Thermodynamic analysis**

**Thermodynamic modelling in heat exchanger development tool TheSim**

Break down overall HX performance to performance of the parts → convective heat transfer correlations for both sides (coolant tube / air fin), incl. heat balance control & optimization

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**Cooling system development for automotive applications**

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HX benchmarking: Competitive comparison

Performance comparison at reference conditions

- Scaling to reference sizes and performance calculation at reference operating conditions
- Starting point for potential analysis and pareto optimization

![Graph showing HT radiator performance vs. airside pressure drop]

- "high speed" operating point
- "high torque" operating point
Heat exchanger optimization: Core variations

1. Definition of characteristic operating points
   - System simulation in GT with original heat exchangers provides characteristic operation conditions (temperatures, mass flow rates) and reference performance for each heat exchanger at design operating points or transient cycles.

2. Virtual heat exchanger core variations
   - Alternative „virtual“ cores are generated in TheSim and evaluated at the same operating conditions. Miscellaneous options for variation are available, e.g.:
     - Macroscopic parameters: Core depth, fin height, fin pitch, tube height, material thickness, material type, ...
     - Microscopic parameters: fin louver length, louver angle, louver pitch, ...
     - Tube and fin technology: plain fins, louvered fins, lanced offset fin, ...
Heat exchanger core variations at characteristic operating point

- Example: HT radiator @ max. speed operating point

**HT radiator: Performance vs. airside pressure drop**

- Core parameter variation
- Original core

Selection of Pareto-optimal cores

- Only original core depth due to packaging
- Cores with acceptable coolant pressure drop
- Cores without “extreme” core parameters
Optimization of system performance

Evaluation of Pareto-optimal heat exchanger combinations in system model
- Example: Results at maximum speed operating point for HT/LT cooler combinations

![Graph showing charge air vs. HT coolant temperature with annotations for up to 5 K improvement for engine cooling and up to 4 K for CAC.](image-url)
Specifications and supplier management

Overall system performance
Repeat system performance for various operating points and transient cycles
→ Select HX with best overall performance

Heat exchanger target specification
Detailed performance and pressure drop target specification for HX
→ Viable development base from the start

Monitor development process
Do supplier developments step in the right direction? Target achievement realistic?
→ Avoid useless development iterations

Support supplier selection
Evaluate degree of target achievement and supplier support, performance benchmark
→ Technical base for supplier selection
Summary

GT model of vehicle cooling system
• Detailed GT model of the vehicle cooling system reproduces steady operating points and transient cycles to a high degree.
• This applies for 1-phase coolant circuits as well as for 2-phase refrigerant circuits.

Heat exchanger benchmark
• Detailed heat exchanger benchmark analysis shows component performance in a competitive environment.
• Provides starting point for optimization.

Heat exchanger and system optimization
• Extensive core variations reveal Pareto-optimal heat exchanger variants.
• System calculations show the overall best heat exchanger combinations for each operating point and enable the selection of the best candidates for overall performance.
• The results show a significant potential for improvement.

Support of supplier management
• Detailed and viable component specifications from the start are the base for an efficient and target-oriented development process.
• Continuous monitoring avoids unnecessary development iterations. A detailed component and supplier benchmark supports the supplier selection.
Thank you for your attention