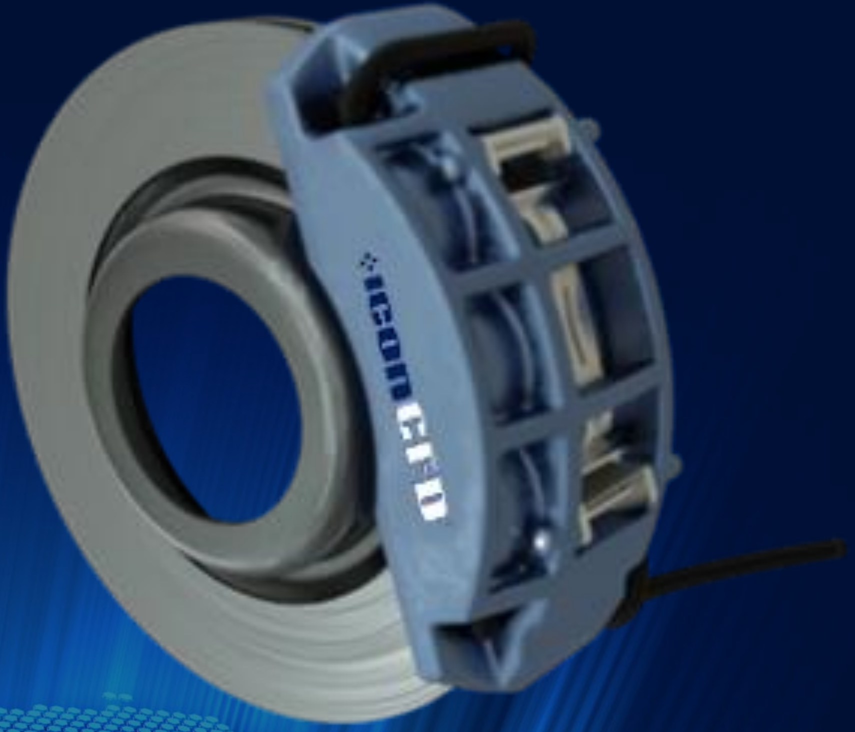
IDAJ Conference Online 2023

Advanced CHT Simulations for Brake Disc Cooling Applications Using iconCFD



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Agenda

- Motivation
- Thermal Models
- Impact of Physical Models
- Proof-of-Concept
- Results & Validation
- Conclusions

Motivation

Challenges in Brake System Thermal Analysis

- **Complex phenomena**
  - Transient Conjugate Heat Transfer (CHT).
  - Radiation.
  - Rotating parts.
  - Thin gaps.
- **Escalating simulation turnaround time**
  - Mesh size.
  - Rotating Mesh.
  - Long physical times with small time-steps.
  - Complicated setup.
- **ICON's solution**
  - Precise temperature predictions of the cool-down phase.
  - Simple (static mesh), fast (hours instead of days) yet accurate.
  - Supports full industrial complexity.

Image courtesy of AUDI AG

Brake Cooling Simulation

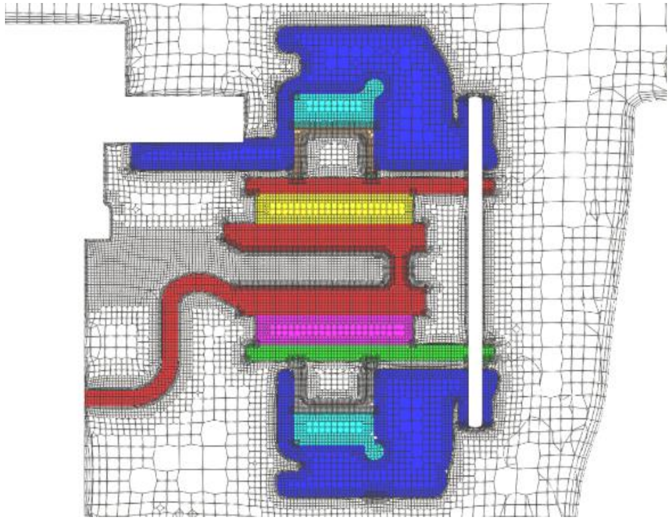
Methodology

Automatic CHT mesh generation

EA simulation
- RANS/DES
- MRF/AMI

Thermal simulation (HEAT UP)
- Fixed heat source applied at PAD/DISC interface

Thermal simulation (COOL DOWN)
- Residual heat load at PAD/DISC interface



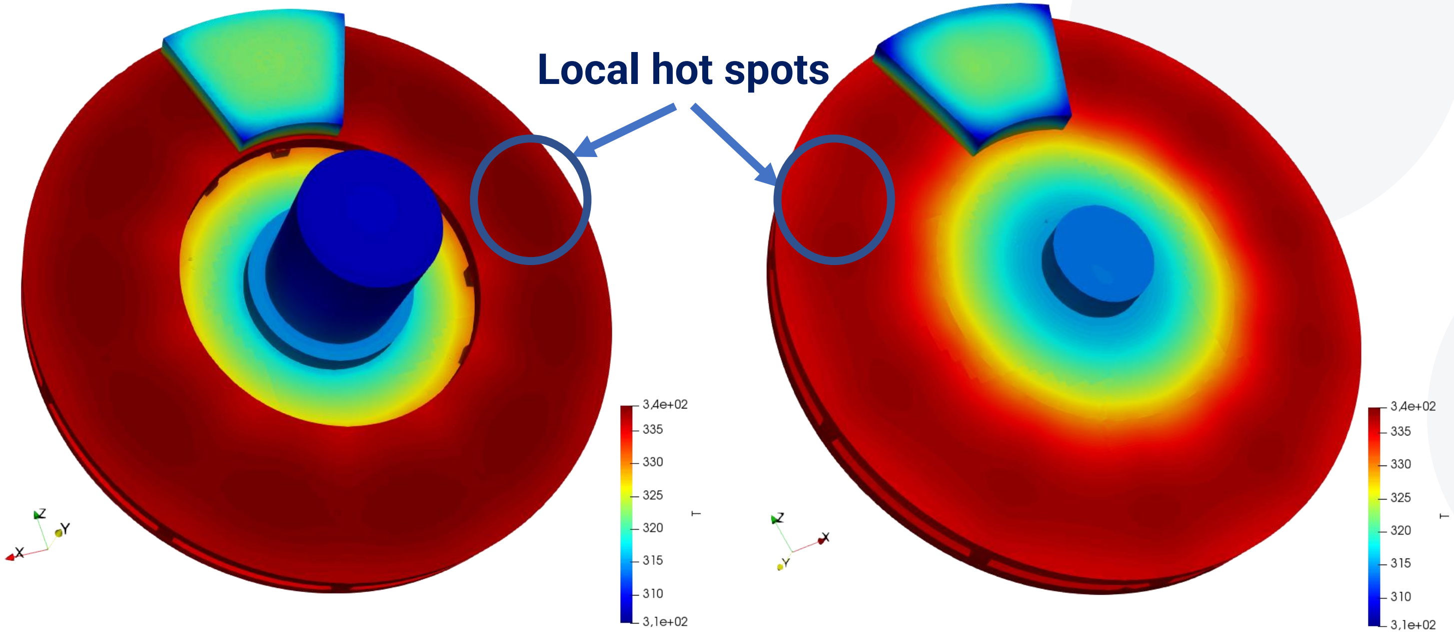
Slice through the mesh

- Thermal simulations use a frozen background airflow solution
  - Valid approach for low Mach airflow with negligible buoyancy effects
  - The heat-up simulation can be performed with a steady-state solver
  - Transient cool down is performed on a **static mesh**
  - **Band-Average-Flux approach (iconBAF) is used**

Thermal Model

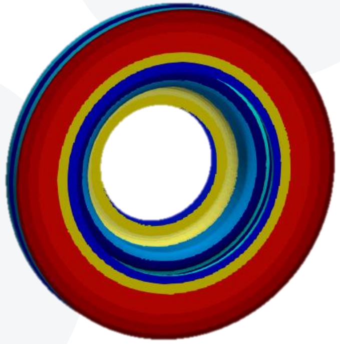
iconBAF

- Thermal diffusion time scale of the disc **>>** rotor revolution timescale ➔ iconBAF.
- The disk **is automatically split up in concentric bands,** on which the heat fluxes are balanced.
- Simulates a rotation without the need for a moving mesh!



Periodic patterns of temperature distributions obtained with the BAF model

Internal cooling patches split into bands by iconBAF boundary condition



Calculated heat fluxes per band

Impact of Physical Models

- Beyond iconBAF, **other modelling choices** are made
  - Flow compressibility.
  - Air thermal properties.
  - Radiative heat transfer.

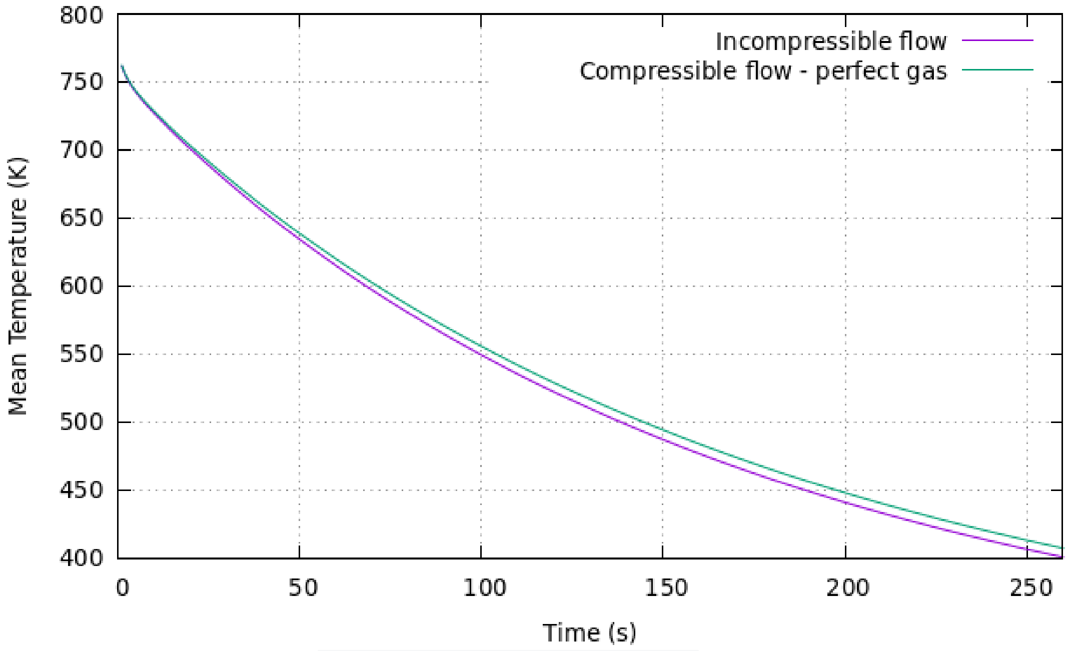
- We need to find the right balance between:
  - Turnaround time reduction.
  - Approximations.
  - Solution accuracy.

Impact of Physical Models

Flow Compressibility

- In typical industrial brake cooling simulations, the temperature range spans from **approximately 600°C down to 100°C**.
- If **air behaves as a perfect gas**, it is important to note that a **highly heated brake disc can significantly reduce air density** in its immediate vicinity.
- The **reduction in air density leads to a decrease in mass fluxes** in that specific region and this, in turn, affects heat convection near the disc's surface.
- **When the air's density is a function of temperature, the cooling rate of the disc is slower as expected**.
- Despite two extreme temperature conditions, their **impact on the cool-down curve is relatively small.**

→ The use of a **frozen airflow approach in the transient cool-down** phase is justified.



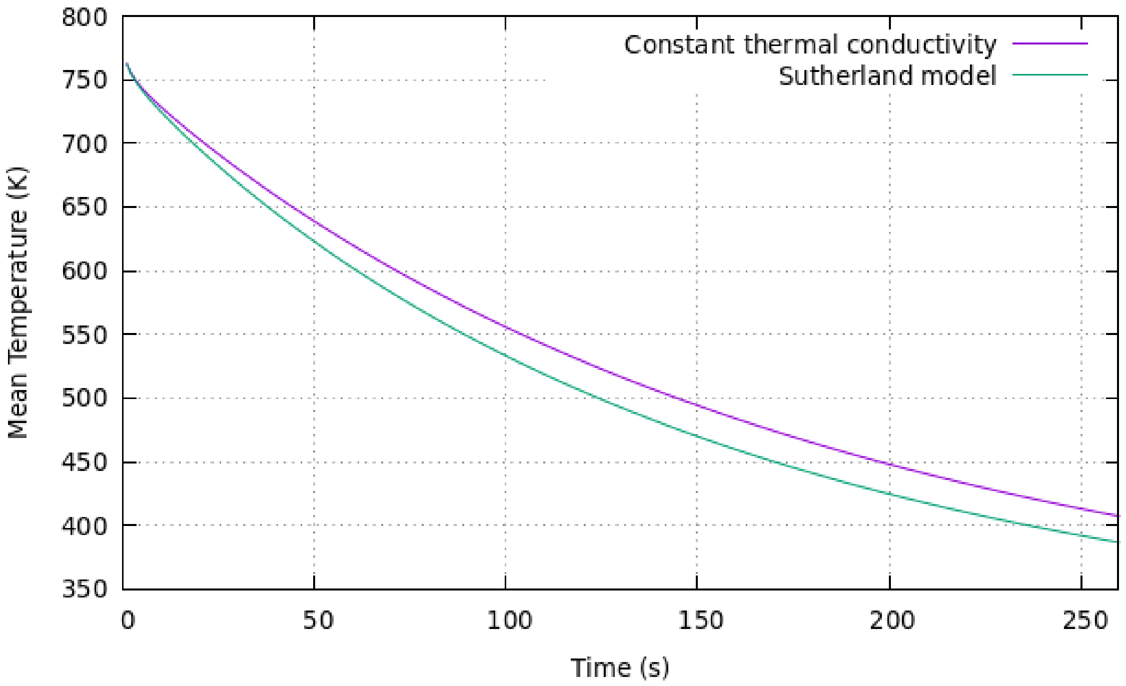
Impact of flow compressibility on brake disc cool-down rate

Impact of Physical Models

Air Properties

- **Air properties undergo temperature-dependent variations**, with certain properties being more responsive to temperature changes than others.
- Notably, **thermal conductivity** can go through a **considerable increase** as temperature rises.
- Taking this property into account with the **Sutherland model** can lead to significant modifications in the solution, particularly in areas where heat conduction is the predominant mode of heat transfer.
- Activating **the Sutherland model, at high temperatures the air thermal conductivity increases changing the graph slope** and **accelerating the cool-down rate** in that region.
- Naturally, at lower temperatures, the cool-down curves for both models once again run parallel to each other.

→ **The Sutherland model is retained.**



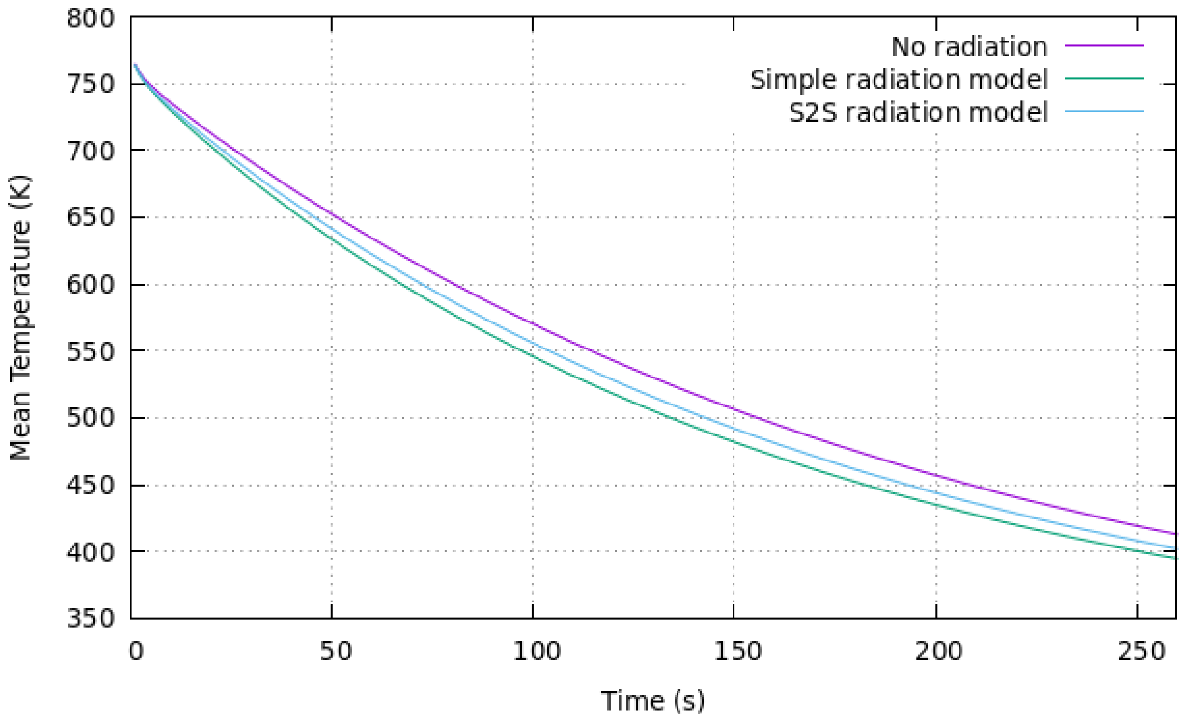
Contrasting brake disc cool-down rates using two distinct thermal conductivity models

Impact of Physical Models

Radiation

- While **convection remains the dominant mode of heat transfer**, it is essential to recognize that radiation also exerts a noteworthy influence on the disc's cooling rate.
- To emphasize the impact of radiative heat transfer, a transient cool-down simulation is conducted, comparing cases **with and without radiation effects**.
- Initially, a **simplified radiation model** is employed, which approximates radiation on the surface by using a **constant infinite reference temperature**.
- Furthermore, a more sophisticated **surface-to-surface (S2S) radiation model** based on view factors is utilized in order to assess the improvement in accuracy compared to the simplified radiation model.
- The results of this investigation clearly indicate **an important heat loss due to radiation**.

→ The **S2S model introduces lower radiation losses and is retained.**



Influence of radiation on brake disc cool-down rate

Proof-of-Concept

- ICON has applied the shown methodology to the **AeroSUV** geometry, **adopted with a simple brake system on the front axle.**
- The simulation methodology analyzes the **cooling performance of the disc** fitted within the boundaries of the vehicle.
  - Parameters like wheel dimensions, rim design, underhood flow exits, radiator exit temperatures, ride height, air deflectors, etc. are taken into account.
- A common methodology is to investigate the **cooling at a constant vehicle speed** which brings the advantage that the **flow solution can be solved in advance** and allows **relative easy comparisons with track testing**.
- This **neglects any input of buoyancy**, which due to the forced flow, is assumed to have low impact.

Zhang, C., Tanneberger, M., Kuthada, T., Wittmeier, F. et al., "Introduction of the AeroSUV-A New Generic SUV Model for Aerodynamic Research," SAE Technical Paper 2019-01-0646, 2019, https://doi.org/10.4271/2019-01-0646.

Proof-of-Concept

Workflow

- The **thermal simulation is split into 2 phases**.
  - In the first phase, the **brake is preconditioned by releasing a heat load** at the interface between pad and disc regions to heat up the materials and precondition the simulation for the cool down phase.
  - In the **cool down phase**, the heat release is removed and an air gap is modelled between pad and disc to prevent any direct heat conduction.
- For the **AeroSUV** test case 3 cooling configurations are looked at:

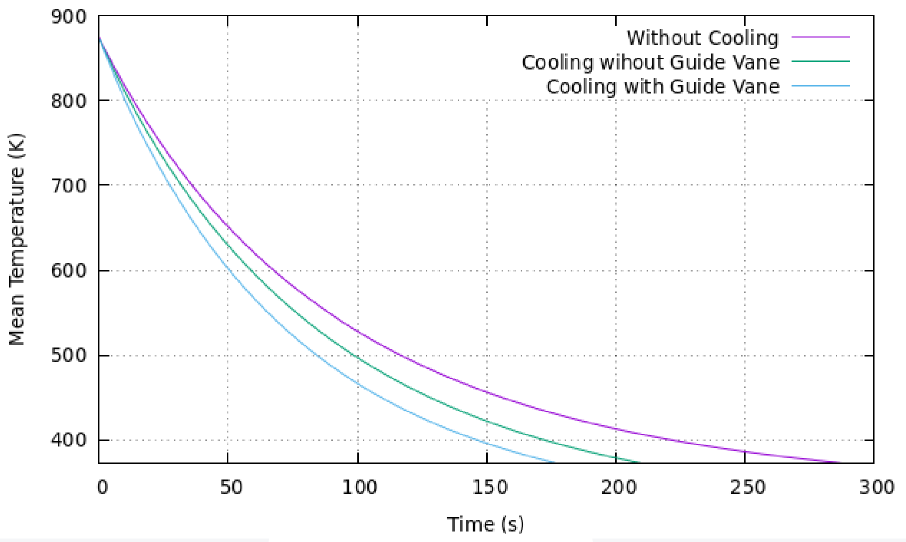
Without Cooling

Cooling without guide vane

Cooling with guide vane

Proof-of-Concept

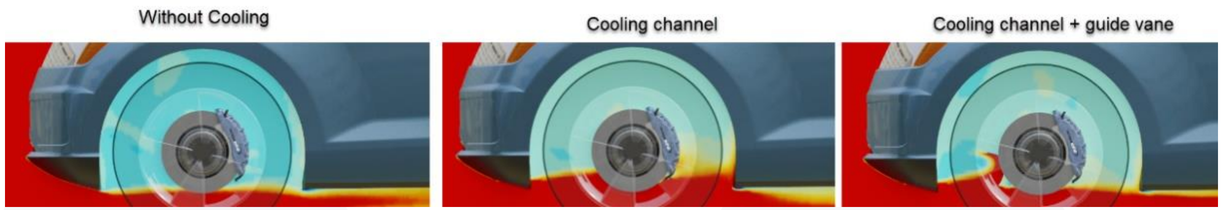
- The cooldown curves of the average material temperature in the disc rotor region are shown.
- **Reference** without any cooling the disc requires almost **5 min** to cool down from 600°C to 100°C at a constant 140kph vehicle speed.
- **Ventilating the wheel house** with cold air via the fitted ramp reduces this time by 1 min 20s.
- Adding the **guide vane** reduces time to cool down to 100°C to 3 min.



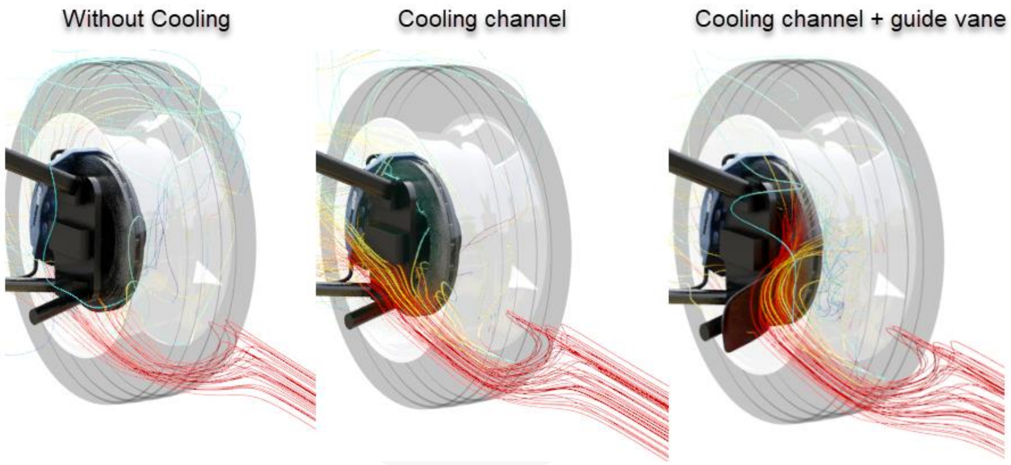
Mean brake disc rotor temperature during cooling phase

Proof-of-Concept

- Investigating the flowfield reveals that without any measure the flow passes the wheel house and the disc is **only cooled by the flow it can generate due to the pumping effects** of the rotating disc.
- With the **cooling channel** added, the airflow is being guided towards the brake.
  - Optimizing the ramp contours can allow to push air into the brake and thus increase the mass flow throughput and consequently increase cooling efficiency.
- With the **guide vane** added the flow can now be turned into axial direction towards the brake and further increase the mass flow throughput.



Cross-section of fluid volume with total pressure visualization



Flow streamlines with total pressure visualization

Industrial Validation

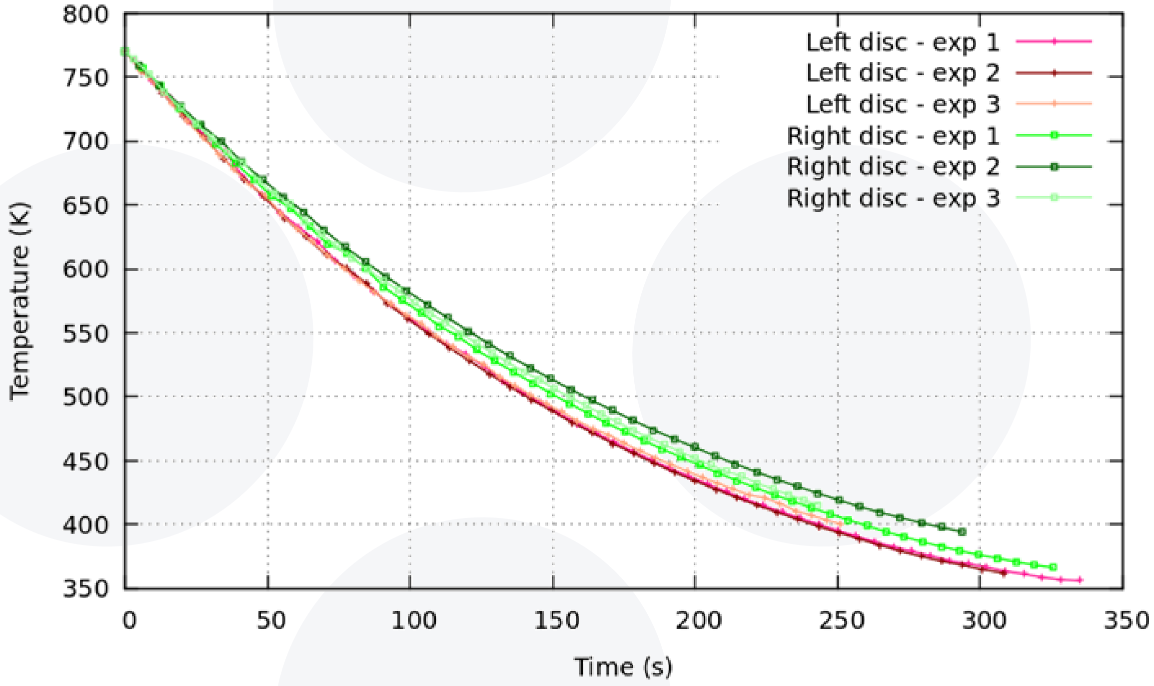
- An **Audi SUV** is used for validation.
- CHT mesh of **93 million cells** capturing all details of vehicle in the same setup as performed on track experiments.
  - 14 solid regions for the brake assembly and 1 fluid region for air.
- The airflow solution is calculated using the steady-state **SIMPLEC** solver.
- The utilized turbulence model is **two-layer realizable k-epsilon** and rotating walls are modelled by the **MRF** approach.
- The **experimental data have been acquired using embedded thermocouples** placed in the brake discs during on-track testing.

Example SUV – image courtesy AUDI AG

Industrial Validation

Experimental Data

- It is important to note that the nature of on-track testing, as opposed to more controlled wind tunnel experiments, introduces inherently higher variability of experimental data.
- **On-track testing conditions are less controlled and repeatable** due to external factors such as variations in road surfaces, fluctuations in ambient weather conditions, and the influence of various vehicle operational characteristics.
- While the Front Left Disc shows consistent behaviour, the Front Right Disc is showing much more variations on 3 repeated test runs.

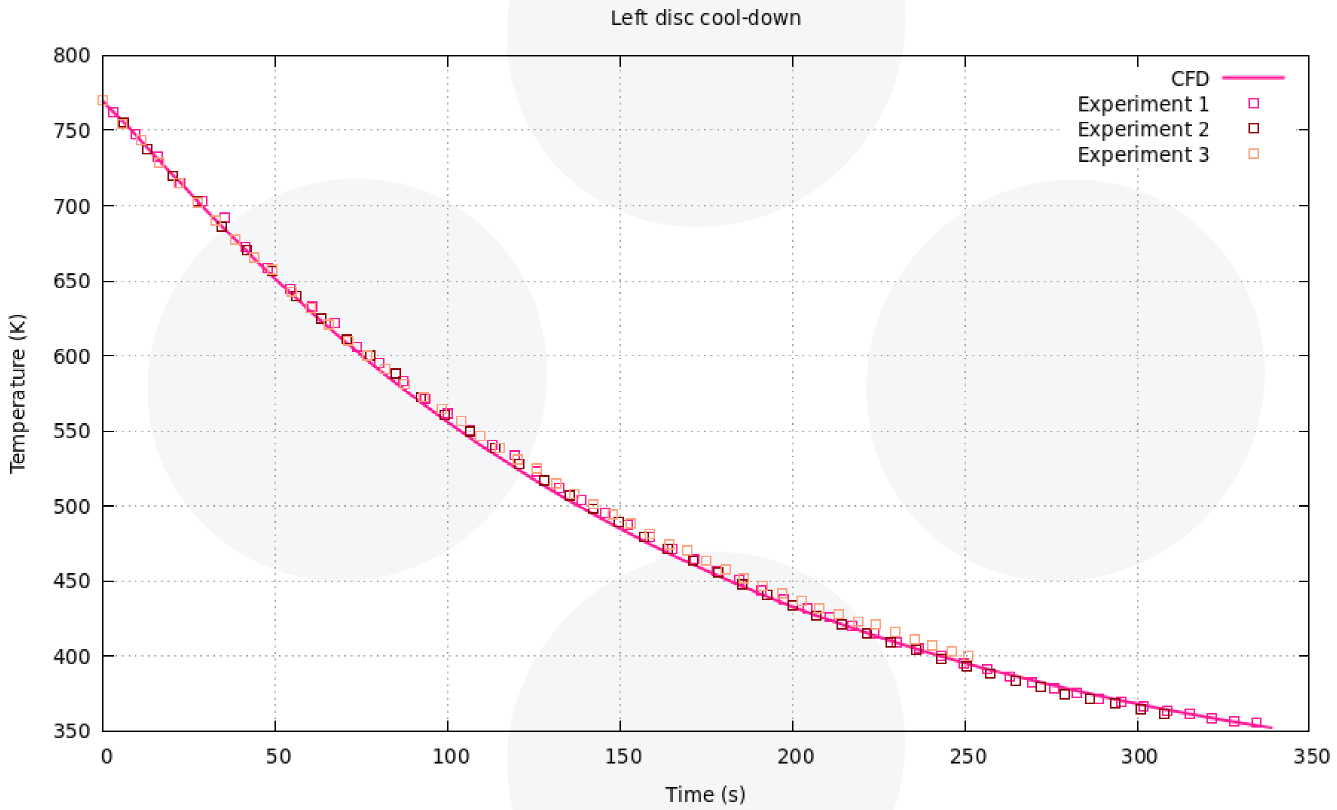


Experimental measurements of cool-down rates for front left and right brake discs

Industrial Validation

AUDI Validation Case – Front Left

- Using the **BAF method** in conjunction with the **S2S radiation model** and the **Sutherland conductivity** model, the computational results **accurately predict the cool-down behaviour for the left disc.**

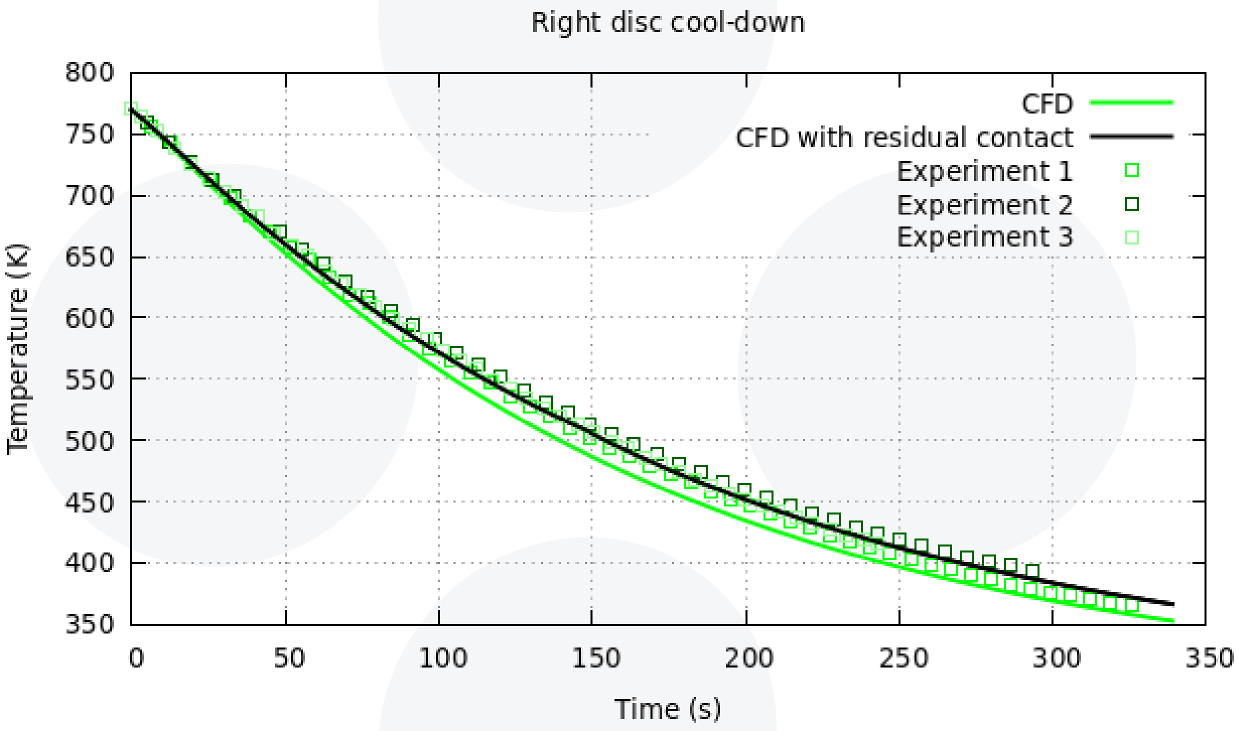


Comparison of cool-down rates for the front left disc

Industrial Validation

AUDI Validation Case – Front Right

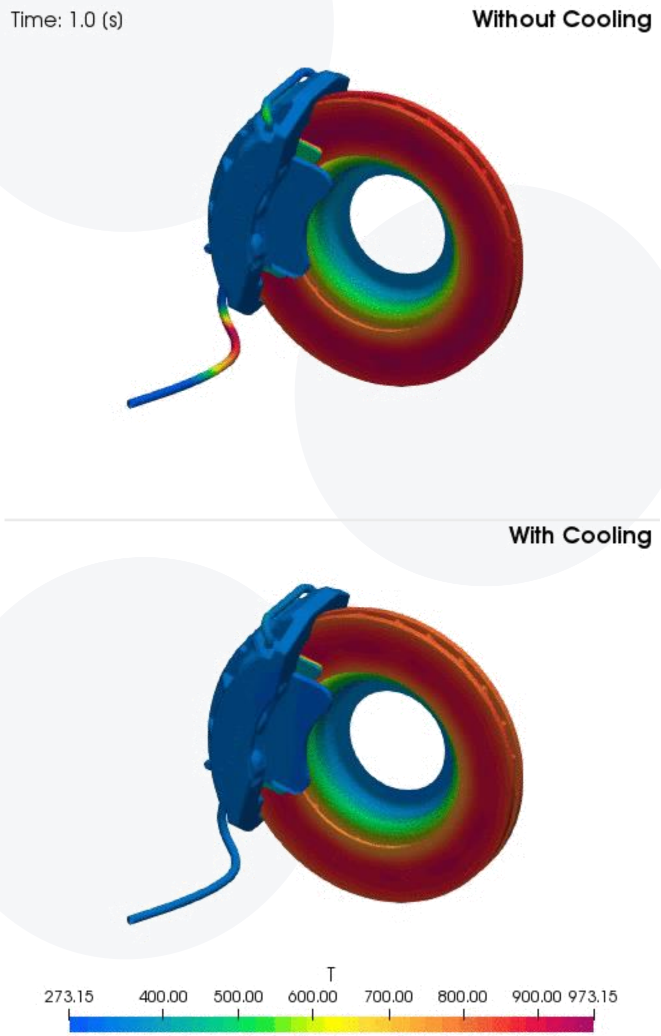
- The **collected data reveals a notable difference** in the experimental cool-down rates between the left and right brake discs, this is **not replicated** in the CFD results.
- **Potential cause A:**
  - **Sensitive transient physical phenomenon in the right wheel arch**, which is not captured by a steady-state airflow solver.
  - **Different modelling approaches** (e.g. transient DES) for the airflow prediction could be further investigated to help resolve this unknown.
- **Potential cause B:**
  - A **residual contact between the pad and the disc.**
  - In this experiment**, the pull-back mechanism** of the caliper esp. on the front right was not always functioning properly, and thus potentially resulting in residual contact of the pad/disc.
  - Modelling the **residual contact** in the CFD results in a **better correlation.**



Comparison of cool-down rates for the front right disc

Conclusions

- **Innovative simulation**
  - Efficient exploration of brake cooling designs.
  - Fully automated and reduced complexity (static mesh).
- **Practical impact**
  - Clearly reveals the effects of the cooling devices on the brake performance.
- **Joint efforts with AUDI AG**
  - Proven accuracy validated with real-world track data.
  - Reliability of the method.
  - Used in the early design process when no prototypes are available yet.
- **Efficiency**
  - Only 50% more CPU time than “basic” (steady-state) EA simulation.



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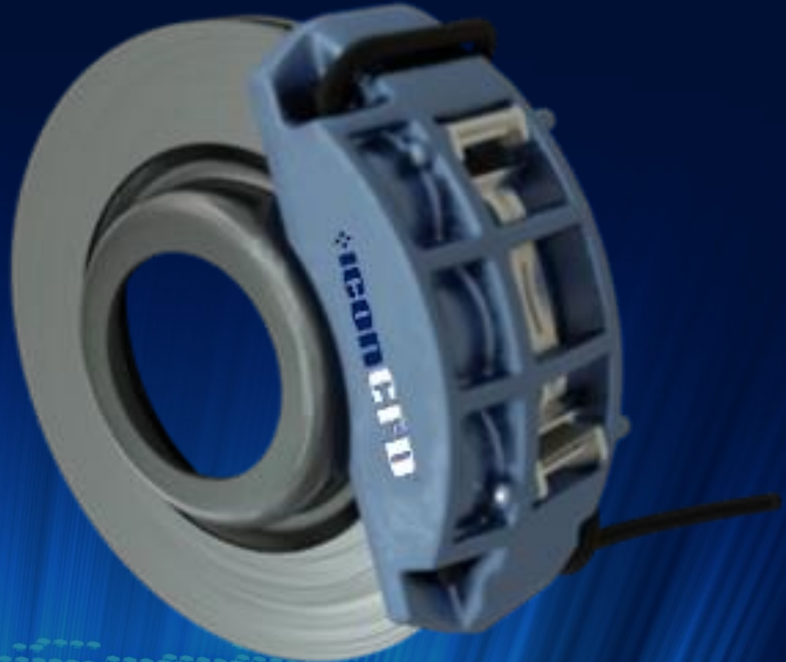

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