# Appendix T

## Validation of a Method to transfer Heat Transfer Coefficents from a Computational Fluid Dynamics Simulation to a Lumped Parameter Thermal Mathematical Model

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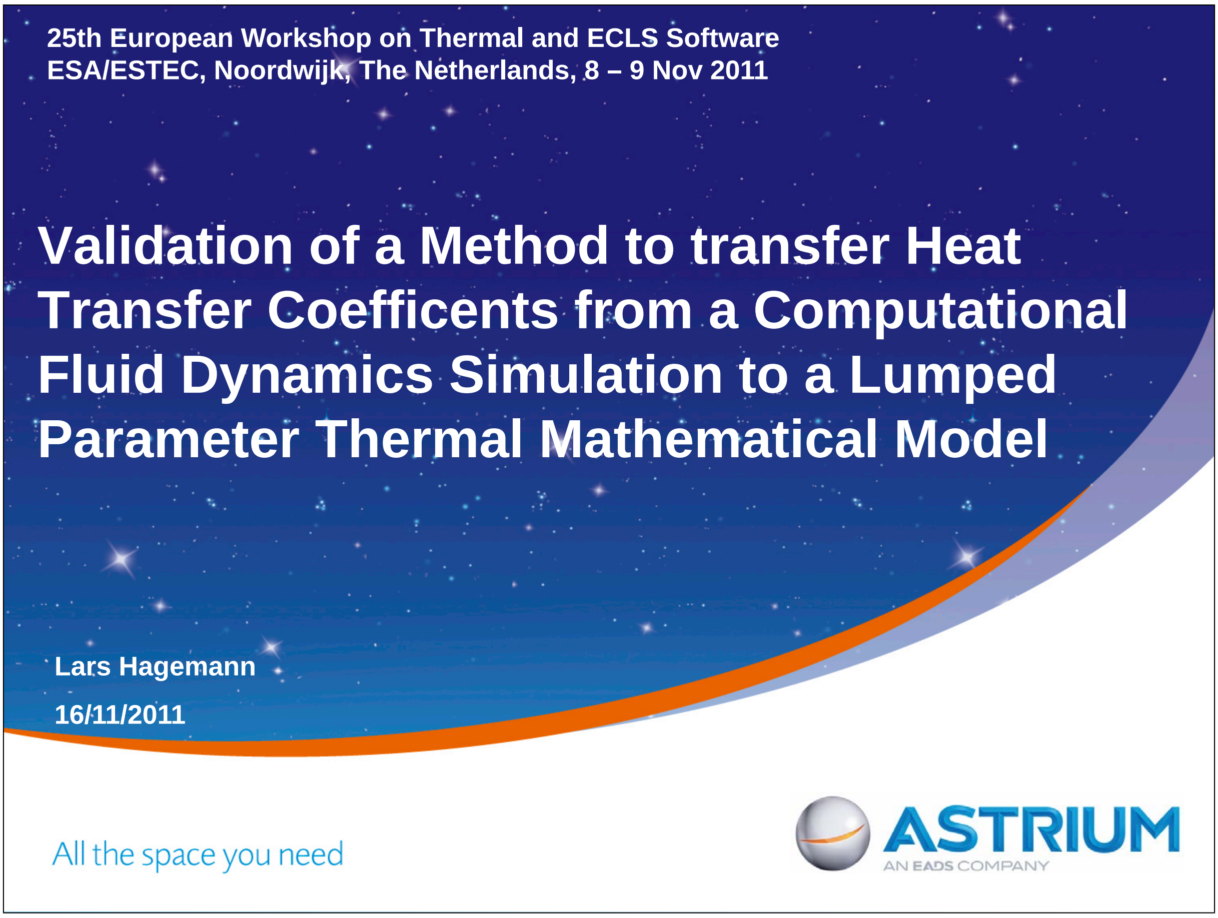
## Abstract

The thermal behavior of the cryogenic upper stage of the Ariane 5 launcher is simulated on system level with an overall thermal mathematical model (TMM) in ESATAN.
The stage mainly consists of the tanks which are surrounded by sub-systems and further structure. Cavities between the components are vented with inert gas. During ground phase, convection in the cavities plays a major role in the thermal budget of the stage. This convection is mostly predominated by buoyancy forces, because of large temperature gradients appearing in the vicinity of the cryogenic tanks. The flow regime is typically in transition or full turbulent regime.
To simulate the flow in the cavity computation fluid dynamics (CFD) simulation is used. The heat flows are transferred to the TMM by calculating the thermal conductor values from the results of the CFD simulation.

In this presentation the validation of this method is explained. A test setup representing a simplified typical upper stage configuration was developed and realized. In order to achieve the requested flow similarity, two temperature controlled walls were part of this test cavity: one cooled with liquid nitrogen, the other one heated with a water conditioned heat exchanger. Temperature measurements attached to other walls of the cavity as well as gas temperature measurements were used for validation of the CFD simulation.
The test setup was modeled with the CFD code Ansys/FLUENT. Good agreement between test and CFD simulation was achieved. The steady state solutions of these fluid dynamic calculations are used to determine heat transfer coefficients, which are introduced into the related ESATAN model. The wall heat transfer coefficients are calculated on an area-weighted basis of wall heat fluxes and refer to mean gas temperatures within the cavity in the same way as implemented in the ESATAN code.
A simplified system level model of the test setup was established in ESATAN, where the heat transfer coefficients from the results of the CFD simulation were implemented.
Little differences in the resulting temperatures between CFD and TMM show the validity of this engineering method.


25th European Workshop on Thermal and ECLS Software
ESA/ESTEC, Noordwijk, The Netherlands, 8 – 9 Nov 2011
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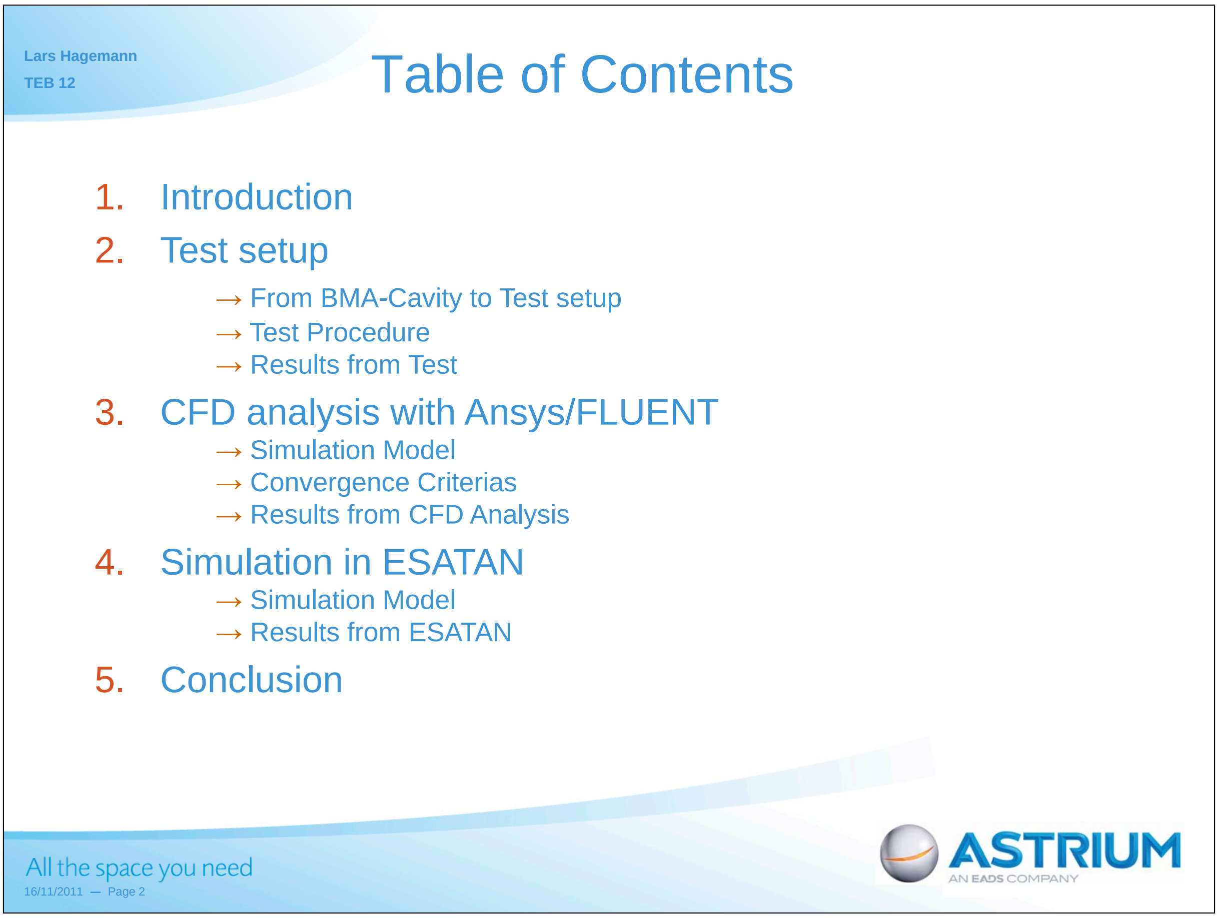
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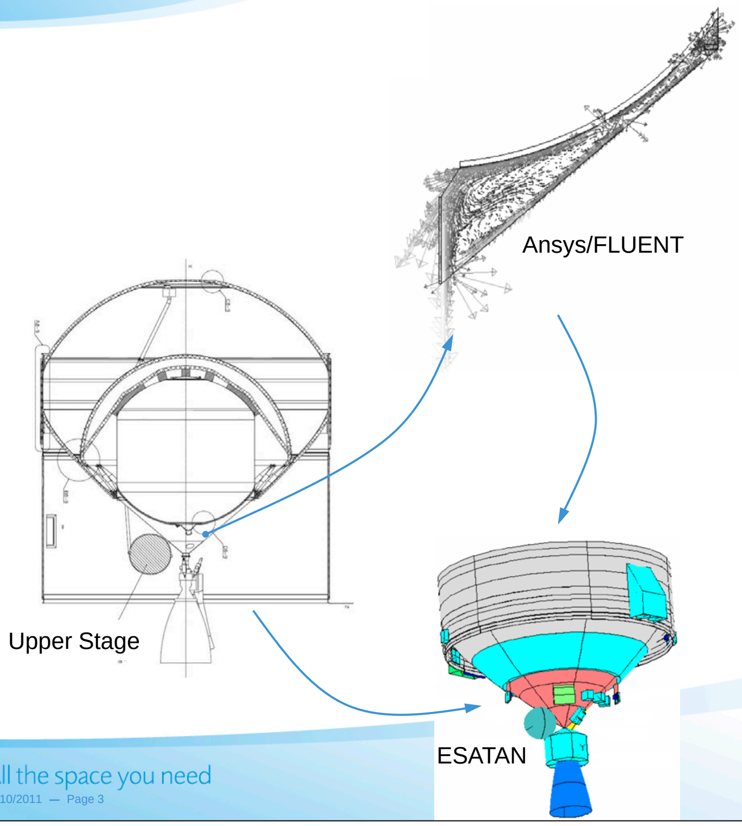
# Introduction




- Simulation of upper stage on system level with a thermal mathematical model (TMM) in ESATAN
- Mostly turbulent flow in cavities, due to high temperature gradients in the vincinity of cryogenic tanks
- Computational Fluid dynamics simulation of the flow in Ansys/FLUENT. Delivering heat flows, temperatures and heat transfer coefficients
- Implementation of heat transfer coefficients into the TMM via linear thermal conductor values

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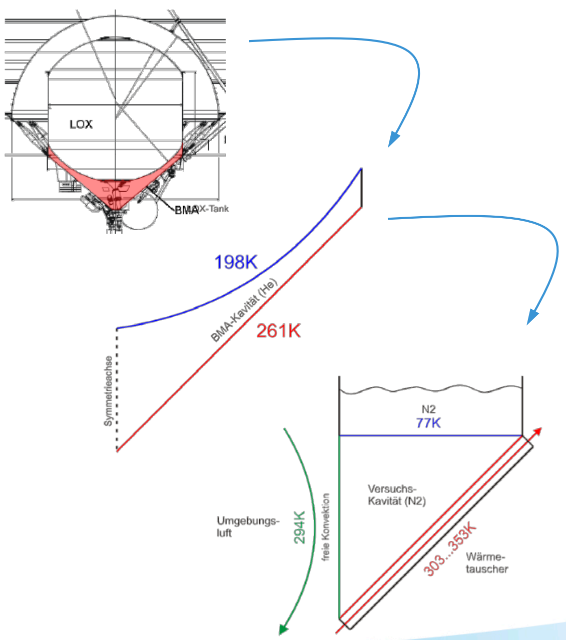
# Test Setup

From BMA-Cavity to Test Setup




- Estimation of the flow regime inside the BMA-Cavity
  - → Venting gas Helium
  - → Characteristic length 1.8 m
  - → Rayleigh-Number $Ra=1.06 \cdot 10^9$
  - → Turbulent flow regime
- Estimation of the required temperature gradient inside the test setup
  - → Venting gas Nitrogen
  - → Characteristic length 0.707 m
  - → Required minimum Rayleigh-Number $Ra=1.06 \cdot 10^9$
  - → With a Nitrogen cooled (77K) wall on the top side of the cavity the minimum temperature on heated wall is 303K to reach a turbulent flow regime.

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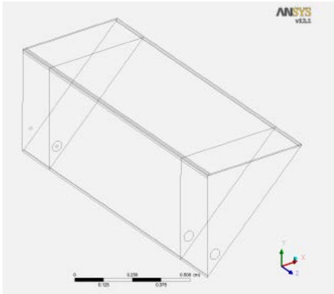
## Test Setup

Test configuration and procedure

- Configuration of the cavity
  - → Three compartments for decoupling the measuring section from impact of the noninsulated walls at the beginning and end of the cavity.
- Convection Test Procedure
  - → The test cavity is vented with a small Nitrogen mass flow rate. Due to the hot and cold wall a natural convection flow develops and produces an temperature distribution on the vertical wall. Together with the gas temperature this data is recorded.




- Positions of thermocouples on vertical wall for recording the temperature distribution:

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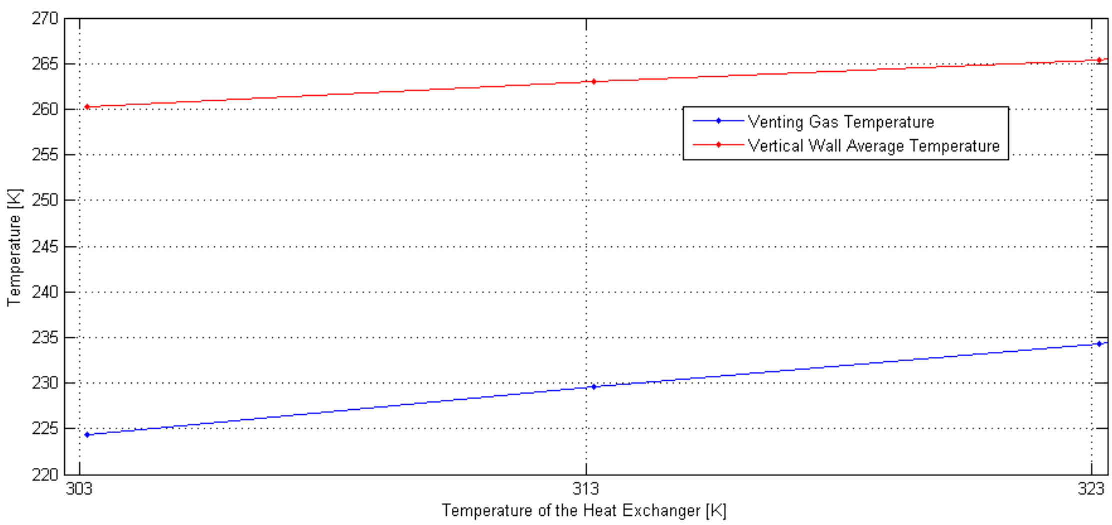
## Test Setup

Results from convection test




- By varying the temperatur of the hot wall the evolution of the resulting temperatures is evaluated

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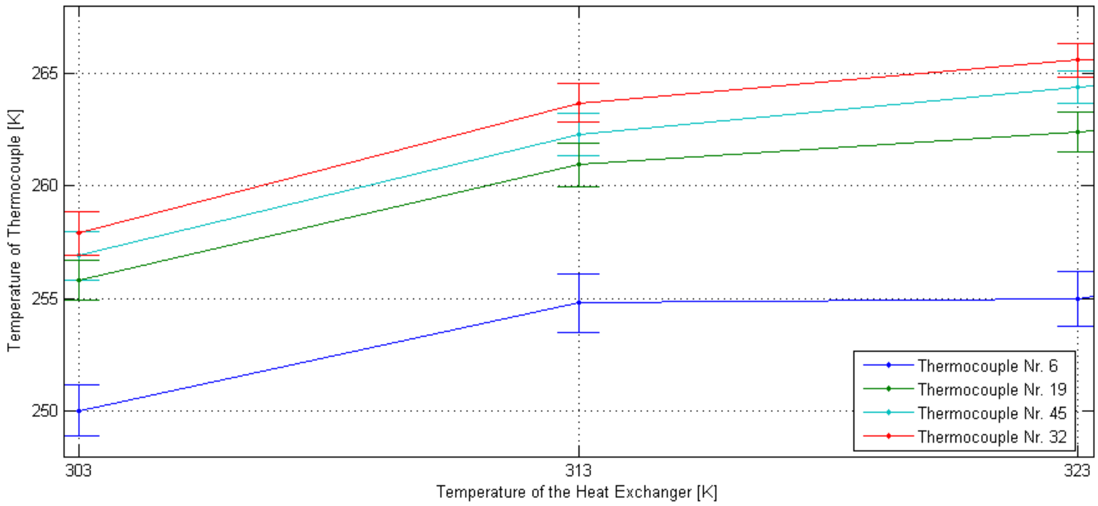
# Test Setup

Vertical Wall Temperatures of selected Thermocouples




- Like the average Temperature of the vertical Wall the Temperature of selected Thermocouples increases with rising heat input from heat exchanger

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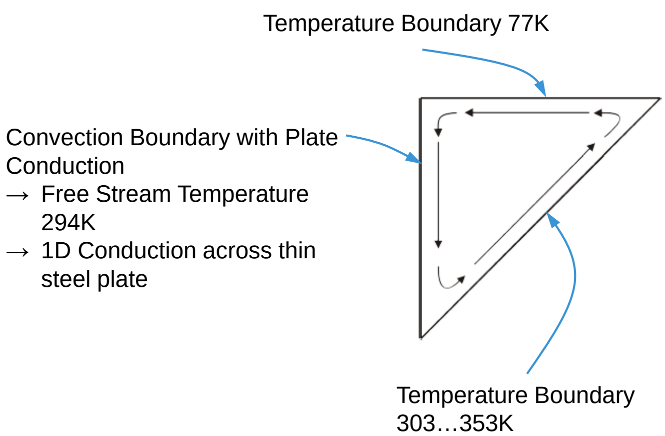
# CFD analysis with Ansys/FLUENT

Simulation Model




- Three-dimensional mesh respecting the venting holes
- Turbulence modeling with realizable k- ε
- Density approximation via Boussinesq-Approach
- Radiation considered
- Venting modeled via mass flow inlet and pressure outlet
- Stady state
- 700000 Cells

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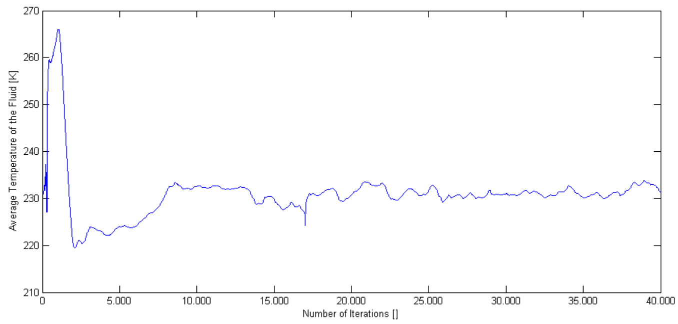
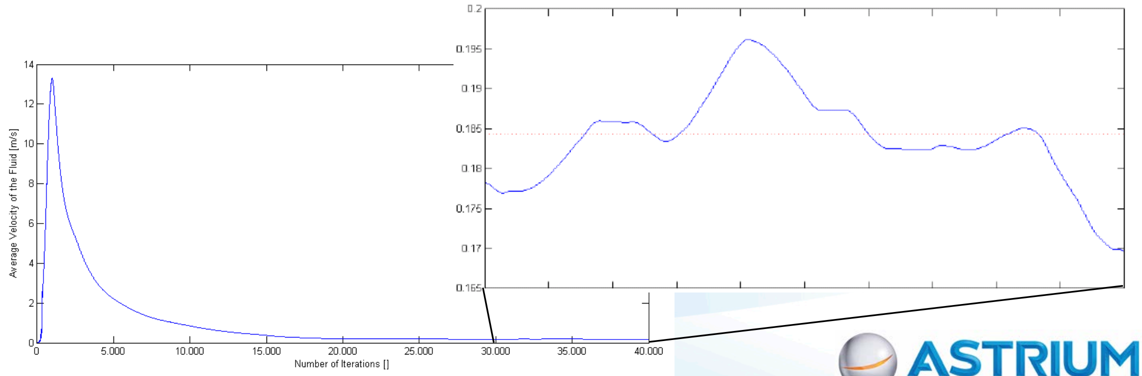
## CFD analysis with Ansys/FLUENT

Indicators for Convergence

- The residuals in a CFD simulation with a bouyancy driven flow are not significant. Therefore other indicators for convergence are used:
  - → Total heat flux across the model
  - → Average speed of the fluid
  - → Average temperature of the fluid

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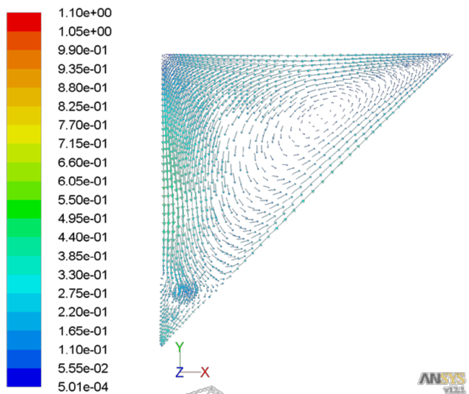
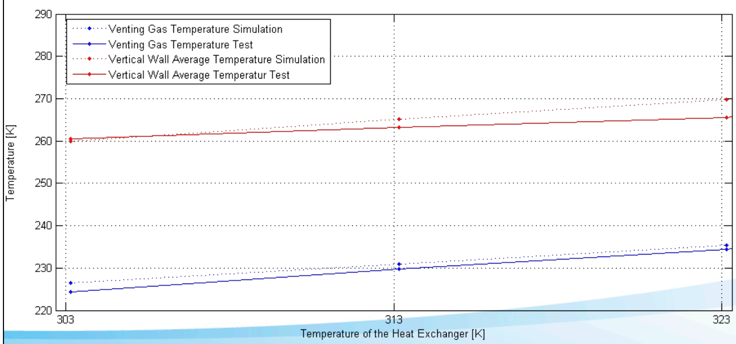
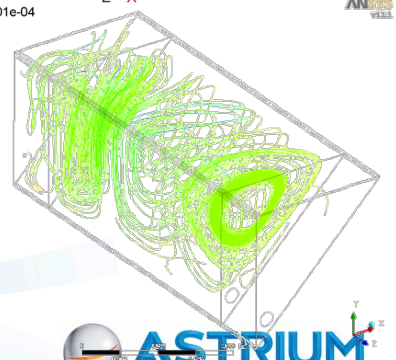
## CFD analysis with Ansys/FLUENT

Results from CFD simulation

- Good agreement between test and simulation for heat exchanger temperatures between 303K and 323K
- Mainly circulating flow inside the cavity
- Divergence in upper temperature level. Fluid flow is unstable due to higher energy level inside the cavity





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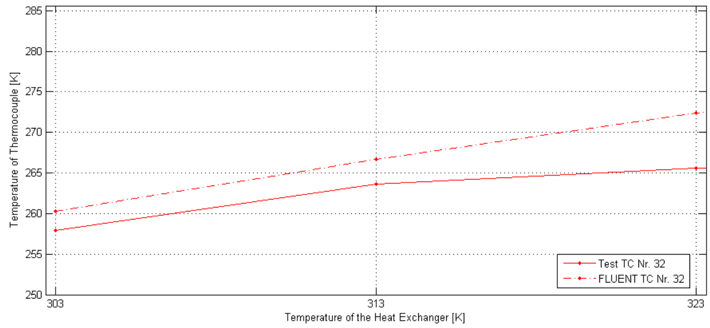
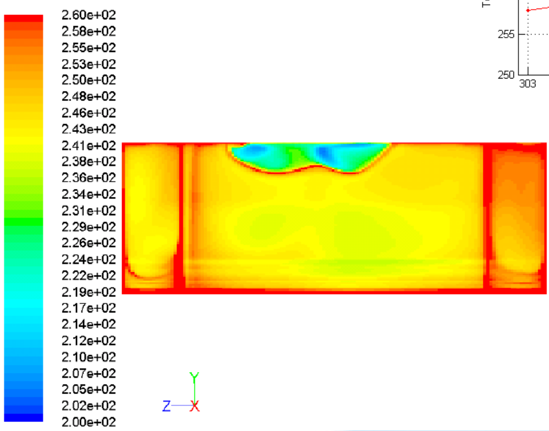
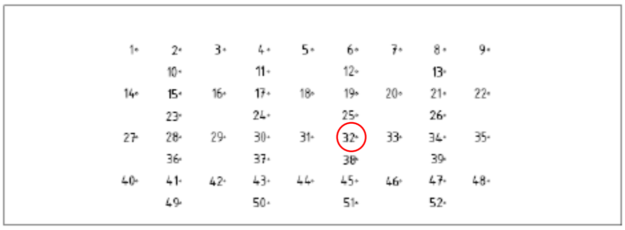
# CFD analysis with Ansys/FLUENT

Results from CFD simulation

- Divergence in upper temperature level occurs. similar to average temperatures.
- High gradients in temperatures at some areas





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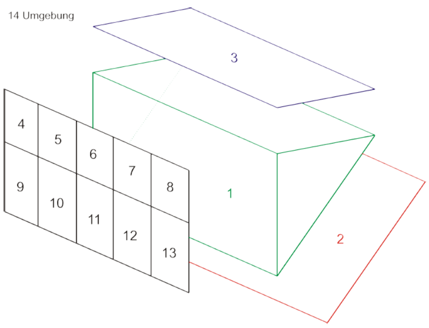
# Simulation in ESATAN

Simulation Model

- Modeling the test cavity with 14 thermal nodes
- One gaseous node representing the fluid in the middle section
- Subdevision of vertical wall for temperature distribution
- Linear conductors representing the convection between walls and fluid

$$GL_{i,j} = \alpha \cdot A = \frac{\dot{Q}}{T_j - T_i}$$

- Due to no significant impact the venting and the heat transfer via the walls at beginning and end are neglected



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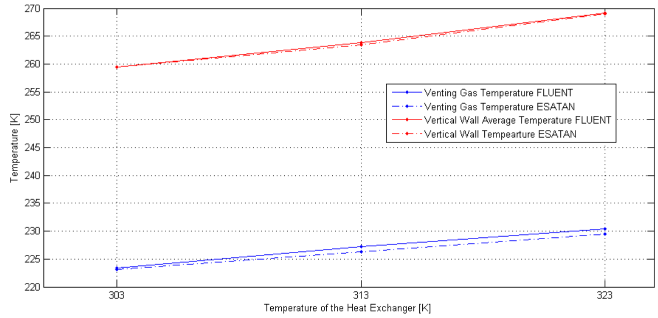
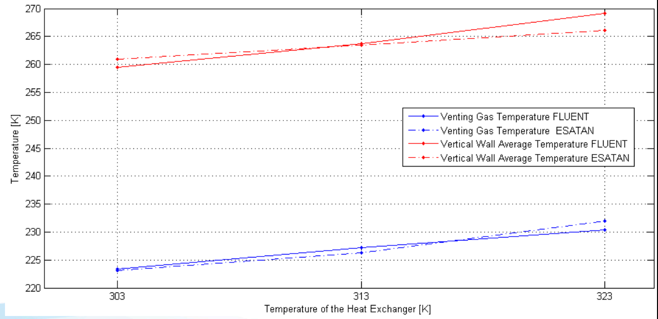
# Simulation in ESATAN

Results

- Comparison CFD and test results
  - → Little differences between CFD and test results
  - → Good agreement of linear conductors representing the convection




- Linear Conductors valid over a wide domain (see lower diagram)
  - → Linear conductor values of the heat exchanger temperature 313K is used to calculate the other cases with higher or lower temperature

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# Conclusion

- Validity of the method to transfer Heat Transfer Coefficents from a Computational Fluid Dynamics Simulation to a Lumped Parameter Thermal Mathematical Model is affirmed
- Good agreement between test results and CFD results
- Good overall agreement between CFD results and Lumped Parameter TMM

- Future outlook
  - → Further studies on flow instabilities
  - → Extension to multiple gaseous nodes and implemeting of Heat transfer between gaseous nodes in TMM

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Questions ?
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