Flow and thermal performance prediction for automotive accessory units and their integration into underhood CFD flow analysis with multi thermal systems

G. SEIDER, F. BET
InDesA GmbH, Germany

ABSTRACT

Simulation techniques are reviewed for three-dimensional vehicle underhood flow analyses with integrated thermal systems such as the engine structure with intake air and exhaust system as well as the complete coolant system. Multi thermal systems simulation is capable to predict transient warm-up or cool-down behaviour of the engine and engine compartment.

To enhance the fidelity of such complex analyses it is recommended to test the simulation models of accessory components like pumps, fans and heat exchangers on virtual test benches before they are integrated into the overall vehicle thermal underhood model. The latest advances of InDesA's virtual test bench suite for accessory components are presented and discussed with respect to simulation techniques, prediction accuracy and their potential for direct integration into thermal underhood simulation models.

1 INTRODUCTION

CFD underhood thermal and flow simulation is widely adopted in the virtual vehicle creation process for a wide variety of automotive platforms and it has proofed to be a valuable design tool for over a decade [1]. As CFD software packages have developed towards multi-physics capabilities and computer cluster become more powerful it is feasible and efficient to directly couple different thermal systems and functionalities, such as the underhood flow with the complete coolant circuit or the exhaust system including heat transfer from the exhaust gas.

As the degree of system coupling is increasing it becomes harder to oversee the fidelity of the integrated simulation models for auxiliary devices like coolant pumps, thermostats, cooling fans, and heat exchangers. Those components are essential to power fluid and flow systems as well as to manage heat transfer. To enhance the simulation quality for such accessory units, InDesA has build up a virtual test rigs suite where auxiliary components can be efficiently tested before they are integrated into complex vehicle models.

In addition virtual test rigs for components have proved to be faster, more flexible and more cost efficient in comparison with traditional physical testing. Virtual testing therefore supports the development on component level, where the performance of pumps, fans and heat exchangers can be verified or further optimized.

2 UNDERHOOD SIMULATION WITH MULTI THERMAL SYSTEMS

Not yet common practice but feasible as demonstrated in [2] and [3] classical CFD underhood analysis for the prediction of cooling performance can be extended to the simulation of thermal reliability/protection for various underhood components such as engine mounts, sensors, plastic parts and covers. The extended analysis must include not only all thermal transport phenomena as convection, conduction and radiation but also all solid materials and fluids participating in the process of thermal transport.

Other than for cooling performance analysis thermal reliability prediction is often concerned with transient cool down processes over several minutes. This has been demonstrated in [2] for a vehicle after high speed operation cooling down in parking position. As the hot end of the exhaust systems radiates heat into the engine compartment peripheral components can be thermally damaged over a period of up to 20 minutes which is a challenge for the CFD simulation in terms of compute time.

As structural parts are commonly included in a thermal analysis it is advisable to add the conjugate heat transfer (CHT) functionality most CFD codes offer to account for heat conduction in solid materials. That way the analysis can be embedded in one CAE tool which usually leads to a more efficient model handling.

For thermal underhood analysis the dominant heat source is the combustion engine, releasing heat directly to the engine structure and to the exhaust gas. This is where the simulation process must start. It is advisable to use transient, but averaged boundary conditions with respect to the engine cycle at the combustion chamber walls for gas temperatures and heat transfer coefficients. Those boundary conditions should be derived from a one-dimensional engine performance analysis like GT-POWER. Besides the 1D analysis will provide inflow boundary conditions for the 3D flow analysis of the exhaust system starting at the exhaust manifold inlet.

The three-dimensional CFD/CHT model for underhood thermal reliability/protection analysis usually consists of the engine structure, i.e. the oil pan, engine block, cylinder head, and cover with as many internal components that significantly can store and release thermal energy, e.g. crank shaft or cam drive. The coolant water jacket and the entire coolant circuit with water pump, thermostat and heat exchangers should be included as well as the engine lubrication system. There is no need to simulate the return oil flow within the engine. This can be handled by boundary conditions for the oil temperature and heat transfer coefficient derived from a 1D oil circuit analysis.

For completeness the intake and exhaust system must be included in the 3D analysis and finally the vehicle body to simulate the aerodynamics and the flow through the engine compartment. Figure 1 shows the different systems which can be integrated into one analysis model for the thermal underhood analysis with respect to transient engine/vehicle operation.

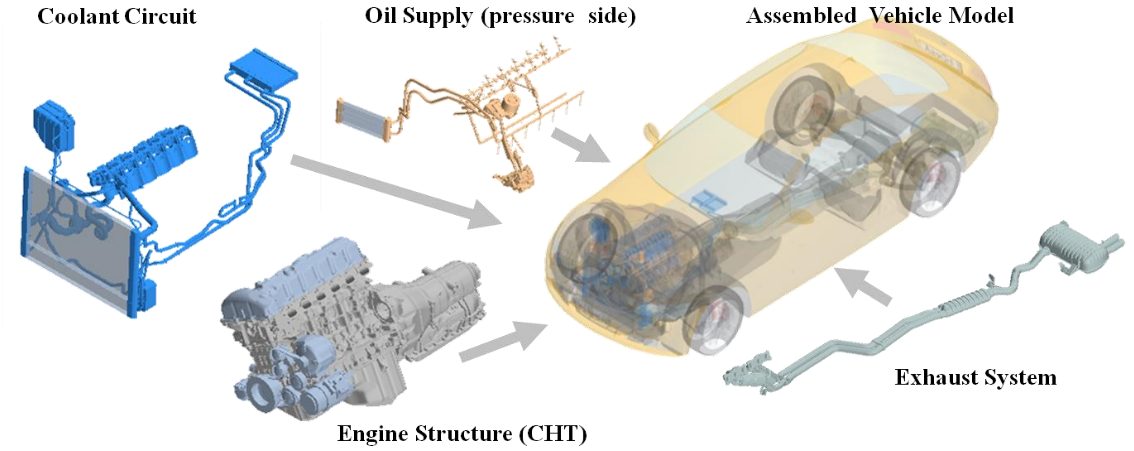


Figure 1: Integration of thermal systems into the underhood environment

The model set-up is not only restricted to vehicle underhoodanalysis but can be carried over to the analysis of motor bikes as well (Figure 2).

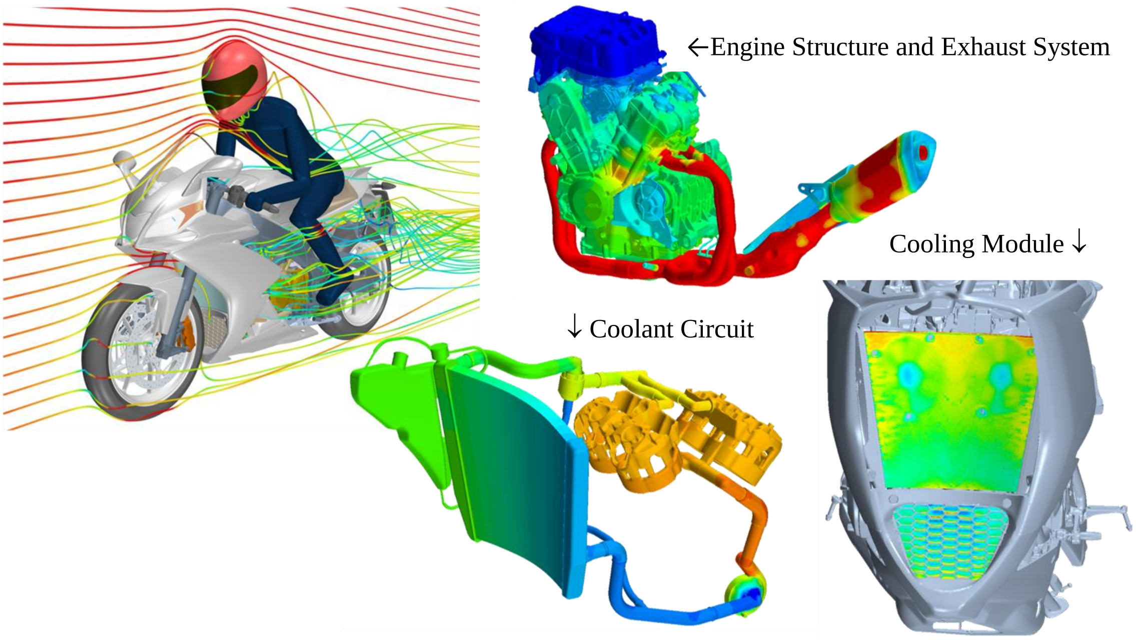


Figure 2: Thermal analysis of a motor bike

It is important to note that vehicle thermal systems are powered and managed by a number of different supplier components, such as water and oil pumps, heat exchangers, thermostats and valves. However, the final integration into the vehicle is done by the OEM. Therefore the thermal analysis of the complete system is performed at the OEM where all components need to be assembled in one CAE model.

In general the OEM receives the supplier components as CAD parts which need to be included in the vehicle thermal underhood model. The risk is high that the meshing and modelling strategies applied to the overall simulation model do not meet the requirements for the components. As an example, a water pump running into cavitation at high speeds will need two-phase flow treatment to predict the correct mass flow rate. If two-phase flow is neglected for the coolant circuit the mass flow rate will be higher than in reality with incorrect heat transfer for the whole thermal system.

Another problem can arise, if the underhood package does not leave enough space to apply proper mesh interfaces for the flow in or out of components. For example, if a radiator is placed so close in front of a cooling fan that the meshing interface for the fan's reference frame is too close to the fan, the predicted flow rate can be too low resulting in incorrect heat transfer for the overall system.

To improve the overall quality of thermal underhood simulation it is advisable to investigate and test supplier components on a virtual test bench before being integrated into larger systems. InDesA has developed a concept, where virtual testing becomes part of the virtual creation process and serves multi thermal systems simulation at the same time.

3 THE CONCEPT OF VIRTUAL BENCH TESTING FOR ACCESSORY COMPONENTS

The virtual creation process for vehicles and components has generated a growing demand for a highly optimized virtual test environment that is fast, flexible and cost efficient in comparison with traditional physical testing. Such virtual test facilities can be standardized especially for automotive accessory units, generating performance maps for fans, pumps, compressors and heat exchangers. InDesA has therefore started to build up its virtual test facility center several years ago [4] and has gained knowledge and experience on how to accurately simulate accessory units. Lessons learnt from other comprehensive studies [5],[6] have been integrated as well. This knowledge is consequently transferred to thermal underhood simulation.

The simulation of performance maps whether for pumps, compressor or heat exchangers requires the simulation of several operating points. One advantage of virtual testing over physical testing is that different operating points can be run parallel instead of sequential. However, the speed up through parallel testing is limited by the available compute resources. For the present study a parallel computer unit with 112 nodes, high performance switch and integrated storage area network was used. Besides, the architecture of the cluster was optimized for the use of the STAR-CCM+ software.

Virtual testing requires boundary conditions which can more easily and more accurately applied to the investigated unit in comparison to physical bench testing. For example, inlet mass flow rates and temperatures to feed a heat exchanger can be simply prescribed in the pre-processor, while sophisticated controllers must stabilize those quantities at the physical test bench.

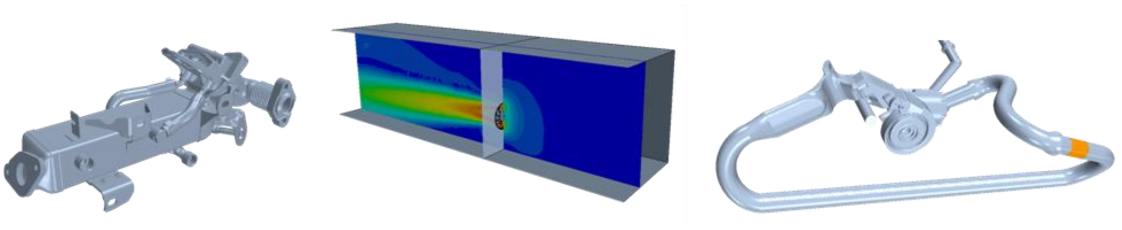
Bench testing is commonly used to confirm performance data for a defined set of operating points. To transfer those results to other operating points with different boundary conditions, it is useful to derive more general data with the help of similarity solutions. For heat exchangers a Nu-correlation can be derived from the test data, requiring a post-processing which is in this case accomplished within the GT-SUITE software package. Thus performance data can be produced for operating points that may be needed later for a thermal underhood analysis.

InDesA's virtual test benches can be classified into three categories. Test benches of type A are characterized by a simple set-up, where the investigated unit is isolated and fed by simple inlet and outlet flow ducts and within a clearly defined or adiabatic environment. Most heat exchangers fall into this category.

Type B test benches are similar to physical test cells, where a special but standardized environment is designed to investigate the performance of a component. Wind tunnels or two-chamber test cells to investigate cooling fans will fall into this category.

Finally, category C includes all test bench setups where a component is located in a unique environment that influences the performance of the investigated unit. For example, the performance of mechanical driven water pumps can change for different group assemblies where inflow and outflow conditions are affected. Figure 3 gives an overview over the three virtual test bench categories. In the following, an A-type test bench for an EGR heat exchanger module will be discussed in more detail followed up by examples for B and C-type test benches.

Typ A **Typ B** **Typ C**



Typ A

- isolated component in isolated test environment;
- no interaction with other components

Example:
EGR cooler module

Typ B

- standardized test environment,
- interaction with other components

Example:
two-chamber test cell

Typ C

- unique test environment,
- interaction with other components

Example:
Water pump assembly

Figure 3: Test cell categories for InDesA's virtual test bench suite

4 TEST BENCH FOR AN EGR COOLER MODULE (A-TYPE)

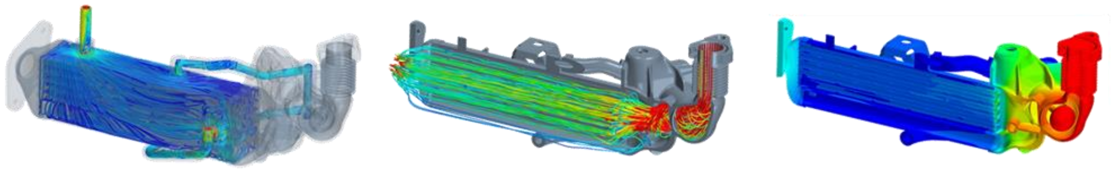
The virtual test bench for an EGR (exhaust gas recirculation) cooler module is classified as a category A test bench for its simple setup with connecting inlet and outlet pipes for the exhaust gas and the coolant. The outer housing surface can be encapsulated with adiabatic boundary conditions. In general constant gas flow rates at constant gas temperatures are used to verify heat exchanger performance although the EGR cooler will in reality be charged by pulsing flow from the exhaust system. As flaps and valves are integrated into most EGR cooler modules, their positions must be defined as well.

The EGR cooler is one of the most sophisticated heat exchangers also with respect to operation, as it links the air intake system with the exhaust system as well as the coolant systems. Besides, flaps and valves are controlled and actuated by the ECU causing dynamic response of the system. This becomes especially challenging when integrated into a thermal underhood analysis.

The CFD model is set up in STAR-CCM+ with one-to-one nodal connectivity, i.e. the exhaust gas, the structure, and the coolant space is meshed in one piece without mesh discontinuities at the surface interfaces. Thermal conduction is simulated by use of the conjugate heat transfer functionality of STAR-CCM+. Special care is taken with respect to flow leakage around the bypass flap by enhancing the mesh resolution in the vicinity of the flap hinge. For the sake of publishing, an own dimple or tooth design was created for the heat exchanger pipes to enhance turbulence and heat transfer. The resulting computational mesh contained about 14 million cells.

The simulation results are shown in Figure 4 : the outlet temperature and pressure loss of the coolant can be predicted, as well as the areas where boiling is likely to occur. Further, the volume flow rates for valve seat cooling can be determined and flow uniformity be assessed. For the exhaust gas, the most important result is the prediction of the outlet temperature and the pressure loss. It is also meaningful to calculate the force on the bypass flap for different opening angles, or flow leakage if heat transfer targets are not fully met. Structural temperatures can be computed everywhere - and most importantly in the valve seat area - to enable structural stress/strain analyses to gain some insight into fatigue problems. Finally, the heat flux is computed from the exhaust gas through the structure to the coolant.

Coolant | **Exhaust** | **Structure**



Coolant
- temperatures
- pressure loss
- onset of boiling
- volume flow rates
- flow uniformity

Exhaust
- outlet temperature
- pressure loss
- force on flap
- flow leakage

Structure
- temperatures, esp. for valve seat
- heat transfer

Figure 4: Simulation results from the EGR test bench

The virtual test bench reveals comprehensive information that is important for the virtual creation process of a heat exchanger. But it is not feasible to integrate such a highly resolved model into a multi thermal system underhood analysis. As for most heat exchangers a dual-stream porosity approach with coupled heat sources and sinks and prescribed heat transfer is more appropriate to use. However, the virtual test bench can be used to create the needed heat transfer map. Moreover a Nusselt correlation can be derived so that arbitrary boundary conditions can be retrieved by applying similarity solutions and be fed to the thermal underhood analysis.

To derive a thermal performance map of a heat exchange and consequently a Nusselt correlation, at least 16 operating points must be simulated. The simulation can be run in parallel in about one day on the above described computer cluster. One advantage of virtual testing over physical testing is that heat transfer can be accurately determined also for low mass flow rates. That is one of the reasons why the regression accuracy for the Nusselt correlation is very high (Figure 5). For the regression the GT-SUITE pre-processor is used, which must be fed by the 16 data points and characteristic dimensions of the heat exchanger.

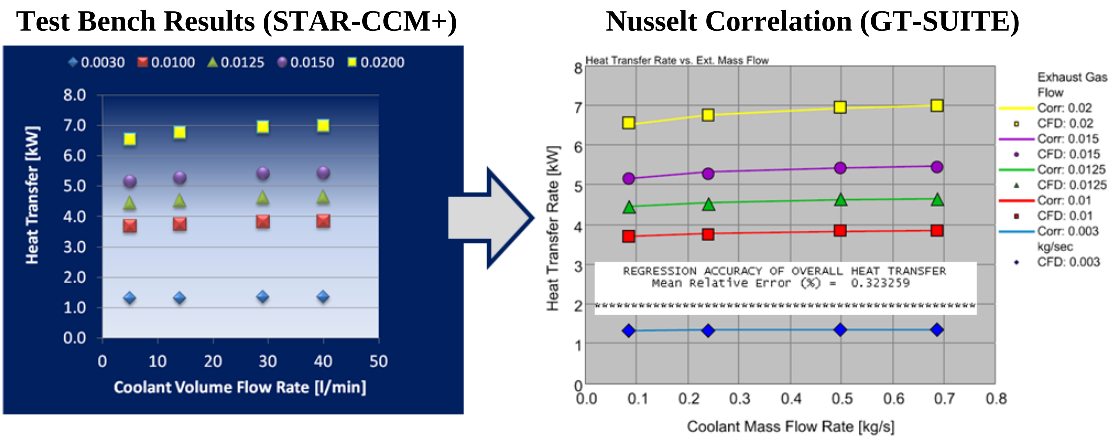


Figure 5: Derived Nusselt-correlation for an EGR cooler

Heat exchangers which are integrated into the intake air or the exhaust gas system are exposed to pulsing gas flow which generally leads to enhanced heat transfer. To predict the heat transfer enhancement, pulsing boundary conditions were used for the simulation of one operating point. The boundary conditions were derived from a GT-POWER engine performance model. For the current EGR cooler the heat transfer enhancement was 8%. This result can be integrated as heat transfer enhancement factor into the Nusselt correlation [7].

5 TYPE B AND TYPE C VIRTUAL TESTBECNHES

To recall, type B virtual test bench setups are similar to standardized physical test cells while for type C a component is located in a unique testing environment, often a component assembly. In the following a virtual two-chamber test cell will be described to evaluate the performance of cooling fans (type B) and a test bench setup for a mechanical water-pump as a representative of a type C test bench.

5.1 Test Bench for Performance Prediction of Cooling Fans (type B)

Cooling fans are one of the dominant accessory components for underhood thermal management. Unfortunately fan performance is significantly downgraded by tight front-end package conditions. This is especially crucial for high performance sports cars with high cooling requirements.

Therefore it is not sufficient to compare fans on test benches with undisturbed inflow and outflow phenomena as the blade design of fans accounts already for typical underhood flow conditions. For the comparison of cooling fans it is meaningful to compare the designs for different in- and outflow conditions. InDesA therefore uses a two-chamber virtual test cell starting with undisturbed in- and outflow conditions adding up a cascade of standardized obstacles to account for typical underhood flow phenomena. In order to standardize those obstacles the geometry is kept simple and is scaled according to the fan dimensions. As an example a baffle is placed downstream of the fan with variable distance from the fan. This baffle accounts roughly for the flow deflection through the engine. To form a more realistic underhood environment further baffles are added to represent the hood, the underfloor panels, and wheelhouses. The arrangement of those panels is scaled according to the target vehicle class.

Upstream of the fan the cooling module acts as a flow straightener, which is simulated with a honeycomb-like structure as known from wind-tunnel design. Further panels can be added to account for the flow duct from the front-end openings to the fan. The different panels can be added in consecutive steps during the simulation to analyze the expected downgrade in fan performance through the vehicle package conditions (Figure 6).

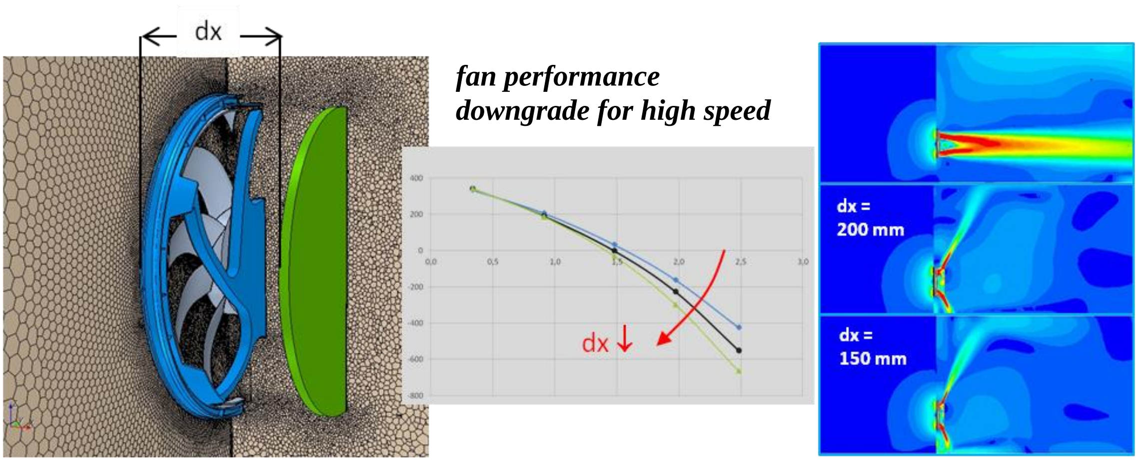


Figure 6: Virtual test bench for a cooling fan

The virtual test bench is also used to find the best CFD modelling strategy for the fan. Most commonly used for underhood simulation is the MRF (multiple reference frame) approach where the fan is simulated stationary in an rotating reference frame but does not physically rotate with reference to its shroud and the test bench. This is causing flow uniformities downstream of the fan. More accurate results can be obtained by using sliding meshes for the fan, where the fan is rotating with reference to the adjacent parts. The use of sliding meshes requires more compute time since the flow is truly transient.

What is common to both methods: the fan has its own frame, whether it is stationary or rotating. If the interfaces between the frames are placed too close to the fan blades the accuracy of the solution can be adversely affected. This is often the case for underhood simulation as the frame interfaces must be placed between the fan and the adjacent parts, namely the heat exchanger in upstream direction and the shroud struts in downstream direction. So virtual bench testing is also used to assess the placement of frame interfaces which are likely to be used in the underhood simulation model.

5.2 Test Bench for Mechanical Coolant Pumps (type C)

Mechanical coolant pumps are often directly integrated into the engine block or chain case with unique inflow and outflow conditions. Also thermostat valves and flaps may be important to include as they influence inflow conditions. As mechanical water pumps often run into cavitation at high speeds the correct pressure at the connecting pipe to the expansion tank must be specified as well. Outside the water pump assembly the coolant circuit can be simplified (Figure 7). At the InDesA test center the analysis is run in a closed circuit with a porous region to account for the system flow resistance.

Similar to the simulation of fans the impeller of the water pump can be modelled by use of the MRF approach or sliding meshes. However, as cavitation is a local and transient phenomenon starting to occur at the blade tips (Figure 7), the transient approach with sliding meshes and cavitation modelling is mandatory. Again this simulation approach is important for the virtual creation process of coolant pump assemblies to determine pump performance, but it is not the appropriate approach for multi thermal system underhood analysis. In that case it is recommended to use the MRF approach if the water pump operates outside the cavitation zone. If cavitation occurs at high impeller speeds a body force model approach should be used populated with the results from the transient sliding analysis.

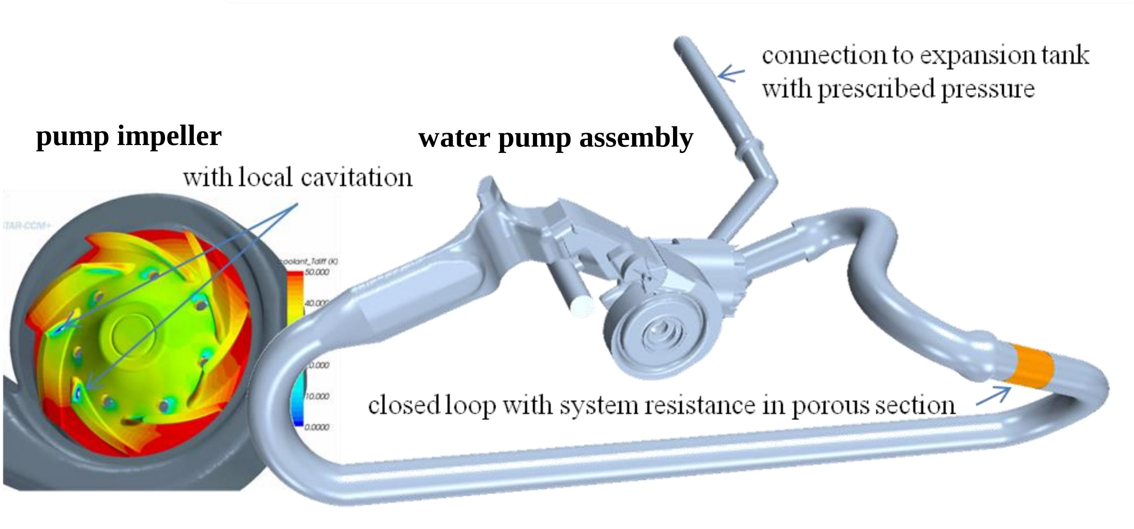


Figure 7: Virtual test bench for a coolant pump assembly

6 CONCLUSION

InDesA has developed a virtual test bench suite for accessory components that serves the virtual product creation process at the supplier's site as well as multi thermal systems simulation in the OEM's development environment.

Virtual bench testing of accessory units has proved to be beneficial to the simulation of complex thermal and flow systems, such as thermal underhood analysis, as simulation approaches can be tested and verified on component level before being integrated into larger systems.

Standardized testing procedures take into account that components change their performance characteristics as they interact with other components in modules or assemblies. In consequence performance downgrades of components due to tight underhood package situations can be assessed beforehand. Thus, virtual bench testing on component level enhances the overall fidelity of complex system simulation and allows for performance forecasts in the early development stage.

7 REFERENCE LIST

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