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Using virtual testing to improve heat rejection predictions in combustion engines

Executive summary

InDesA GmbH (Integrated Design Analysis) has developed a new method to predict heat rejection early in engine development. This method provides higher fidelity and confidence than bench testing alone using software-based virtual testing that is backed up by data from physical tests. With further development, InDesA believes this methodology has the potential to replace physical prototype heat rejection testing altogether.

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Introduction

Engine designers are under pressure to design more efficient engines to decrease emissions and fuel consumption. To achieve these design goals, the trend is pointing toward engine downsizing and higher compression ratios in order to increase power output. Increasing the power output, in turn, creates higher demand on thermal heat management. The high thermal loads will generate thermal stresses that can lead to shorter engine life, or failure. In addition to meeting new, challenging government regulations, engineers are working on shorter development cycles to more quickly introduce superior products to the market.

Combustion engines generate heat by fuel combustion and the friction created by moving engine parts in relative motion. A key phase of engine and vehicle development is designing the various technologies to manage and dissipate this heat, collectively termed heat rejection. Well-considered engineering of heat rejection is essential for peak engine performance at high operating temperatures, and also for optimizing engine behavior during warmup. Combustion engines are significantly less efficient when starting cold than at steady-state operating temperatures, so an important objective of engine development is to reduce energy losses by ensuring that systems and components reach their intended operating temperature range as rapidly as possible.

Conventionally, predicting heat rejection is done using physical engine prototypes and special-purpose heat rejection test benches. The problem is that once a physical prototype has been built, it is expensive to make changes and optimize the engine design. Ideally, issues with heat rejection need to be identified early in the design cycle, before the first hardware has been built.

The shortcomings of physical prototype testing for heat rejection

InDesA has developed a new method to predict heat rejection using software-based virtual testing that is backed up by data from physical tests. InDesA is a consulting and engineering services firm specializing in simulation and analysis of complex fluid flow and heat transfer systems based north of Munich, Germany. InDesA's approach is built around a detailed Simcenter STAR-CCM+™ software engine model embedded in a virtual underhood environment. Simcenter STAR-CCM+ is part of Siemens' Simcenter™ portfolio. Combustion and exhaust temperatures are derived from 1D engine process simulation, while friction heat is measured in physical testing.

The conventional approach to measuring heat rejection has been to use an early development stage physical engine prototype. To begin, the engine is instrumented with pressure indicators in the cylinder head. This gives a measure called indicated mean effective pressure (IMEP) and another called brake mean effective pressure (BMEP), representing the torque at the flywheel. The two measures are used to derive the friction for the complete engine, called friction mean effective pressure (FMEP). A specially cast and equipped cylinder head must be fitted to the engine to obtain these measurements, adding to the complexity and cost. The prototype engine is also instrumented with temperature sensors (thermocouples) to monitor engine temperatures. This is important in order not to damage the engine as it is exercised on the test bench. A related complication is the special test bench required: Heat rejection testing requires the bench to have conditioning appliances for engine oil and coolant, which are not present on ordinary engine test benches.

Early-stage prototype engines typically have built-in performance limits to safeguard the engine during testing. These can include restrictions on speed and torque, and an enrichment of combustion mix-all designed to protect the engine by keeping temperatures lower than a series engine, with significant impact on heat rejection. The dilemma is that heat rejection needs to be understood early in development, but the engine's combustion and exhaust characteristics are often not mature enough at this stage for accurate evaluation of heat rejection based on physical testing.

Supplementing physical with virtual testing

To remedy these shortcomings, InDesA developed a new approach that uses standard physical test procedures to calibrate simulation models based on 1D and 3D representation of fluid flow and heat transfer, shown in figure 1. The simulation is then used to obtain complementary information so the user can overcome the uncertainties and lack of accuracy caused by the immaturity of early-stage physical engine builds.

Physical testing provides comprehensive information about the engine, such as combustion pressure, temperatures, friction (tear-down measurements) and fuel consumption, whereas thermal maps of integrated heat exchangers should be tested on separate virtual or physical test benches. These measurements are used to populate and calibrate various 1D engine models. The resulting 1D simulations yield predictions for fuel consumption, basic engine operating parameters, mass-flow rates, pressure and temperature in the air induction and exhaust systems, and in the coolant and lubrication circuit. This 1D simulation output then provides the boundary conditions for a Simcenter STAR-CCM+ model of the engine as well as the underhood and full-vehicle environment. This is used to calculate heat exchange inside the engine and through the exhaust and cooling systems, and heat rejection to the ambient environment.

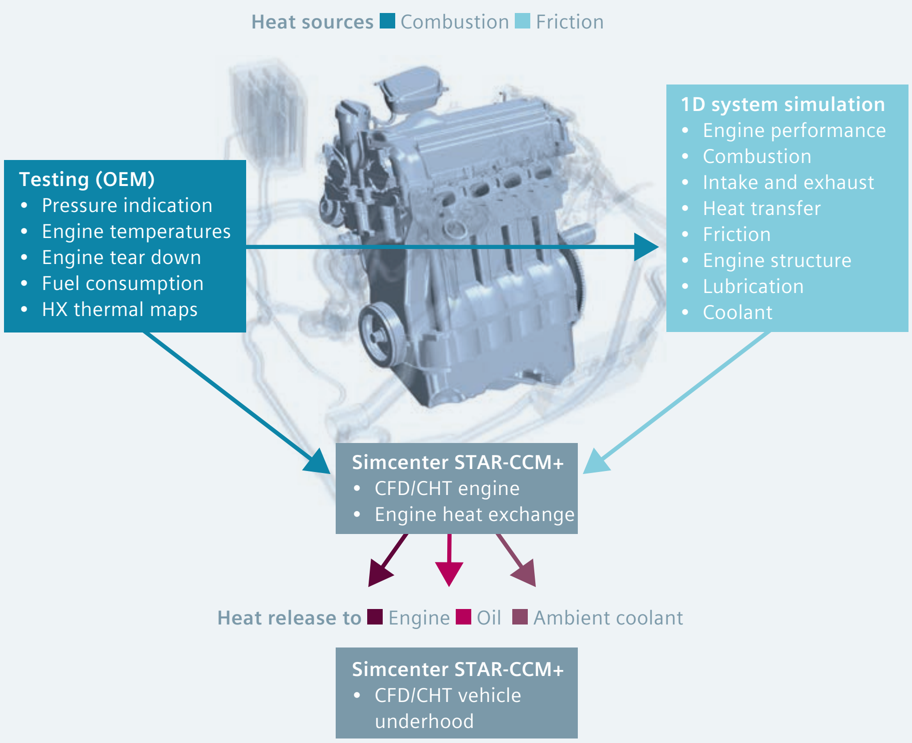

Figure 1: InDesA's approach to engine and vehicle underhood thermal simulation.

Replacing the physical test cell with a virtual underhood environment

Engine heat rejection is controlled with thermal management technologies embedded in the engine thermal design, exhaust, cooling and lubrication system design and underhood environment. To virtualize all of these, InDesA used Simcenter STAR-CCM+ to model a virtual engine. The model was designed to demonstrate thermal simulation techniques with options for different thermal management technologies: split cooling, water-cooled exhaust manifold, engine oil cooler and thermal encapsulation.

The virtual engine is brought to life with 1D simulation data for engine performance, combustion with air intake and exhaust, heat transfer to the engine structure, lubrication and coolant circuit (shown in figure 2). Then to improve on the traditional physical test cell, InDesA used Simcenter STAR-CCM+ to develop a virtual car with underhood and full-vehicle environment that brings together computational fluid dynamics (CFD) and conjugate heat transfer (CHT) models.

InDesA's virtual concept car is named Pandora. Given the negative connotations of Pandora's Box, it is highly unlikely an automotive original equipment manufacturer (OEM) would take this name for a production car model. On the other hand, in Greek mythology Pandora was a most beautiful woman created by gods, and hence the name was considered to be suitable.

The Pandora virtual car model is used to simulate engine thermal performance with heat transfer to the engine compartment and ambient environment, demonstrated in figure 3. The Pandora model includes the engine and a simplified engine compartment, with air induction, exhaust and coolant systems and a frontend heat exchanger module. The goal is to provide greater fidelity together with a wider range of operating conditions than a physical test cell typically operated at decent test cell temperatures (see figure 4).

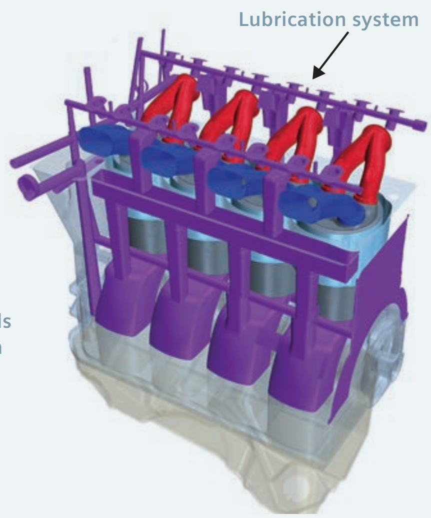

Figure 2: The virtual engine is brought to life with data from 1D simulation.

Figure 3: Pandora is a virtual concept car with underhood and full-vehicle environment that was modeled with Simcenter STAR-CCM+ to simulate engine thermal performance with heat transfer to the ambient environment.

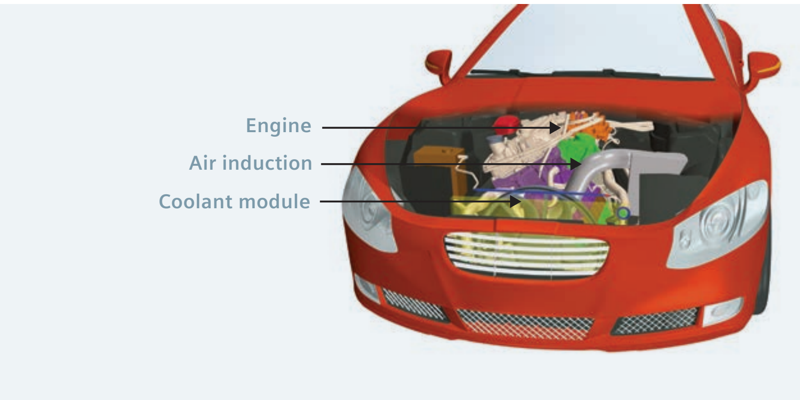

Figure 4: Engine installation of InDesA's virtual concept car Pandora.

Air flow through the engine compartment is modeled in accordance with vehicle speed and cooling fan performance. Air temperature is also modeled in accordance with heat release from the radiator module in front of the engine. The 1D vehicle model, which includes a drive train, road model and ambient environment, is used for transient simulation. Hence, boundary conditions for any driving cycle from warmup to race-track operation can be provided.

The engine model is detailed down to a level suitable for thermal stress analysis (see figure 5), with heat flux going from combustion into the liner, piston, flame deck and exhaust ports. In addition, dissipated frictional heat is added to the engine liner. This allows the user to calculate internal heat flux; for example, the heat exchange between the engine structure, coolant and engine oil.

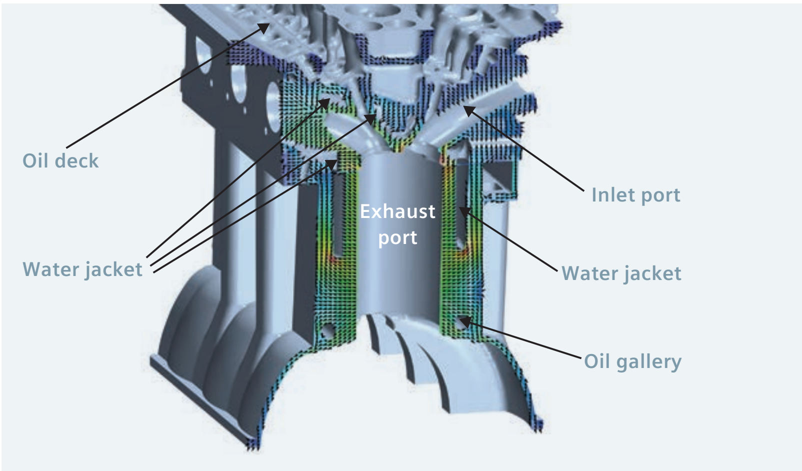

Figure 5: Heat flux vectors in the engine structure.

Counting on Simcenter STAR-CCM+

Based on these heat exchanges and 1D simulation models, a unified vehicle model of between 100 to 150 million cells is created in Simcenter STAR-CCM+, which is used to calculate the heat flux from the engine to the coolant and lubrication system; from there it is transported to the heat exchanger pack in the frontend (see figures 6 and 7). There the heat is released to the cooling air passing through the heat exchanger and cooling fan, shown in figure 8. Therefore, the engine receives the correct underhood air temperature and flow conditions, which is significantly different from conventional test cell testing.

This integrated Simcenter STAR-CCM+ simulation model allows the various heat sources to be quantified precisely; the breakdown of each is shown in figure 9. In the example for a vehicle speed of 240 kilometers per hour (KPH) with 135 kilowatt (kW) engine brake power, 51 percent of the total combustion heat comes from the combustion chamber, 37 percent from the water-cooled exhaust manifold and 12 percent from engine friction. It must be noted the latter quantity is an input from physical testing. The model also reveals heat release to the coolant (79.6 percent), engine oil (14 percent) and ambient environment through the engine surface (5.8 percent). InDesA notes that due to internal heat fluxes and redistribution, the values revealed by simulation differ from what might be expected based on engineering intuition. The simulation also gives temperature for the coolant, oil in the oil gallery and air downstream of the heat exchanger.

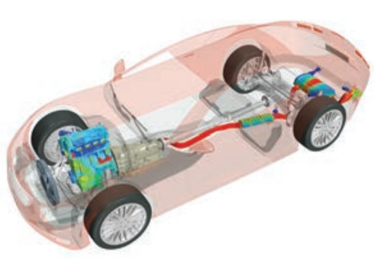

Figure 6: Heat flux from engine surface to ambient environment at 240 KPH and 135 kW.

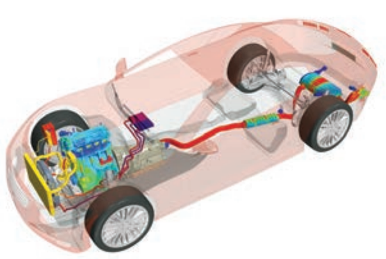

Figure 7: Heat rejection of the engine combined with the cooling system at 240 KPH.

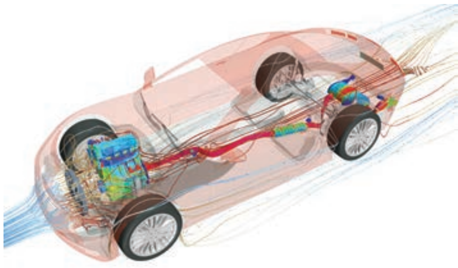

Figure 8: Streamlines through engine compartment for 240 KPH at 135 kW.

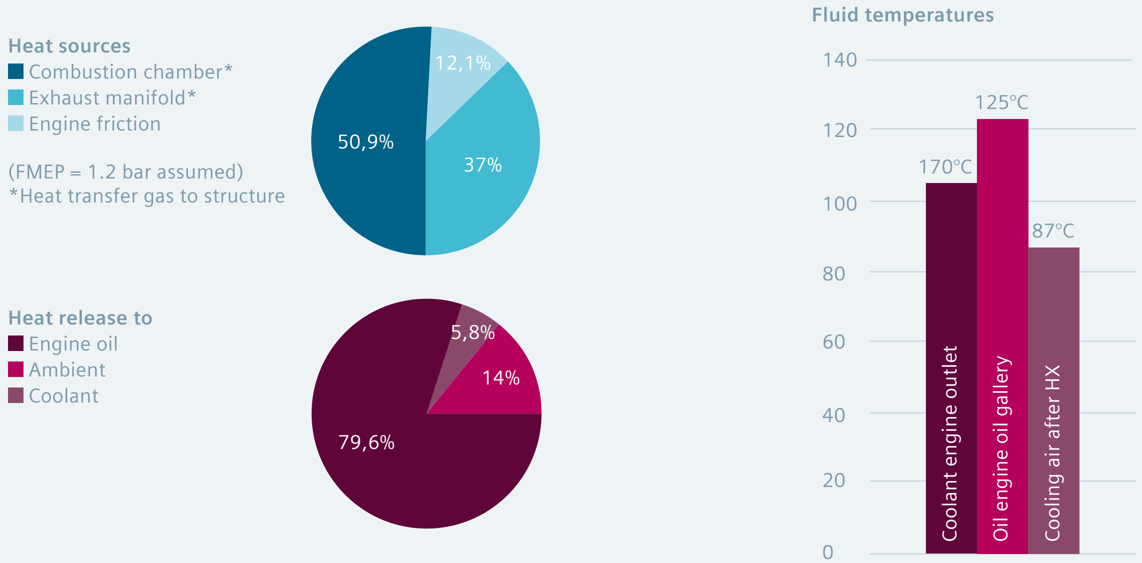

Figure 9: Breakdown of heat sources and where the heat is released in the Pandora model.

Conclusion

Used in combination with bench testing of physical prototypes, InDesA's virtual approach can be used to predict heat rejection early in engine development with higher fidelity and confidence than bench testing alone. With further development, InDesA believes this methodology has the potential to replace physical prototype heat rejection testing altogether.

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