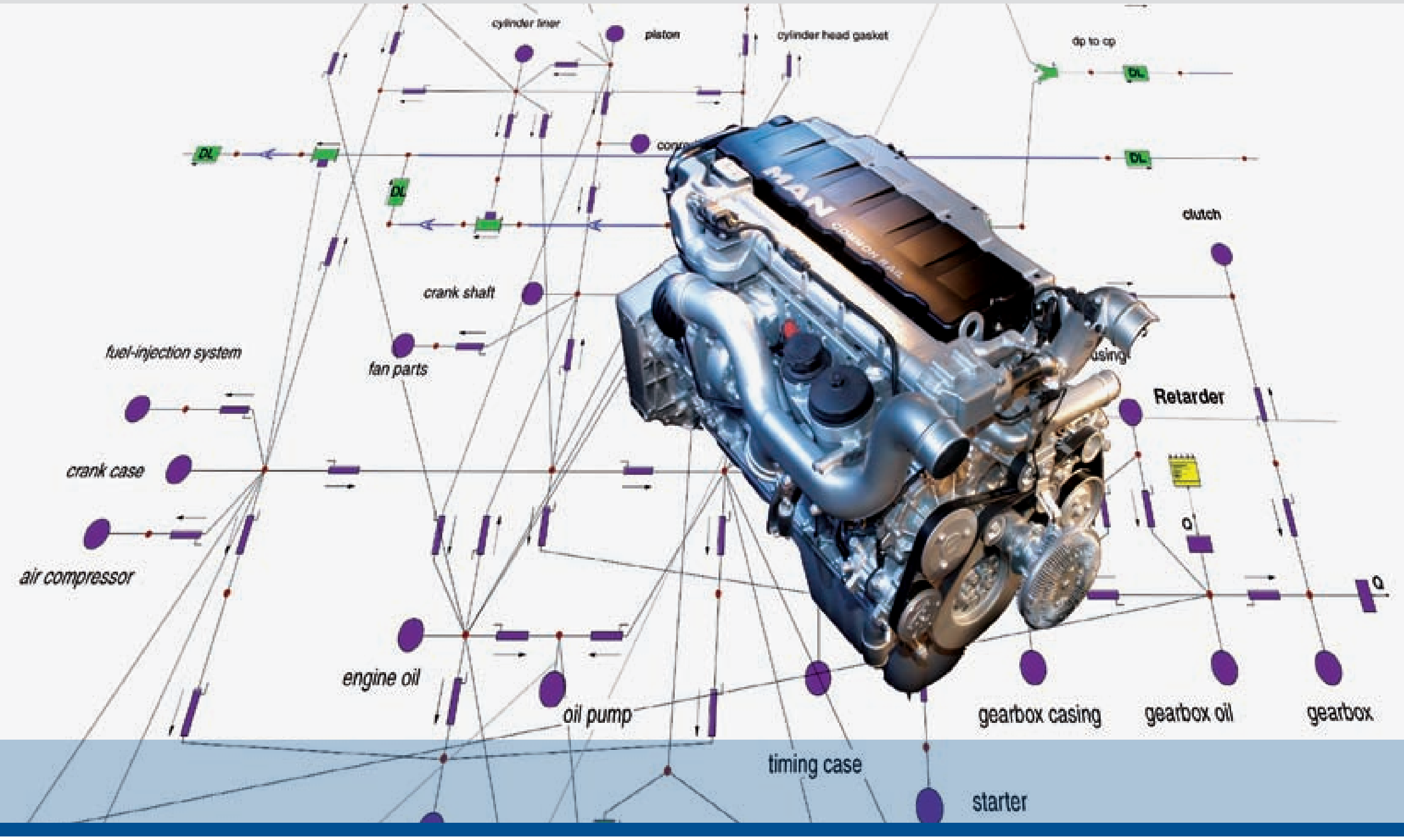

CFD Simulation for the Cooling Circuit of a Truck Diesel Engine

The field thermal management, the optimization of the heat balance in vehicles, is an essential factor to reduce fuel consumption and emissions. Like many other units in internal combustion engine R&D, computer based simulation systems are used more and more. At MAN Nutzfahrzeuge AG one developed a simulation system called FasiFlow, based on Flowmaster, to create the CFD simulation model of a cooling circuit in a truck diesel engine. By combining different calculation programs like the tool Flowmaster the system enables entire and precise simulation of hydraulic and thermal processes.

1 Introduction

Increasing demands on time and costs, ever more complex vehicles and the growing concern for environmental factors have forced manufacturers to introduce more efficient methods for the development and the optimization of new diesel engines. For many years, computer based simulation has been an inherent part of the engine and vehicle development at MAN Nutzfahrzeuge AG. The reasons for this trend are complex; the analysis of different variants, reduced effort for tests and prototyping, and the deep insight into interrelations, which previously were only possible with cost intensive testing. This not only improves product quality but can help to reduce development times and costs significantly.

2 The Simulation System FasiFlow

MAN developed FasiFlow specifically for the simulation of cooling circuits in internal combustion engines. It concerns a superordinate instance, with which the co-simulation of the fluid simulation system Flowmaster in addition to the length dynamic simulation Fasimat was realised. This tool is an in-house simulation system based on Mathlab/Simulink and it is used respectively for transient determination of fuel consumption and power needs of drive trains during any driving cycles.

With FasiFlow it is possible to analyse quickly different concepts and variants. The detailed investigation of interactions between different reference circles and parts of that and of fan, viscous fan clutch, thermostat valve and coolant pump allow tighter focused system improvements in the pre-development phase, **Figure 1**.

To get a possible high correspondence with reality, one worked closely together with the testing department during the system development to calibrate by cross-referencing with existing test data. For every development step, the calculation model was adjusted and validated on the base of the test results, **Figure 2**. The following objectives were formulated concrete:

- Gain a detailed view of the power requirements for the coolant pump, cooler fan and viscous fan clutch
- Assess temperatures within the engine and coolant
- Investigate the warm-up phase
- Understand the influence of the ambient temperature on warm-up, cooling power and retardation
- Understand the influence of the static head (pressure and temperature) on the cooling system and the engine output

FasiFlow work is divided into preprocessing, where all data for the char-

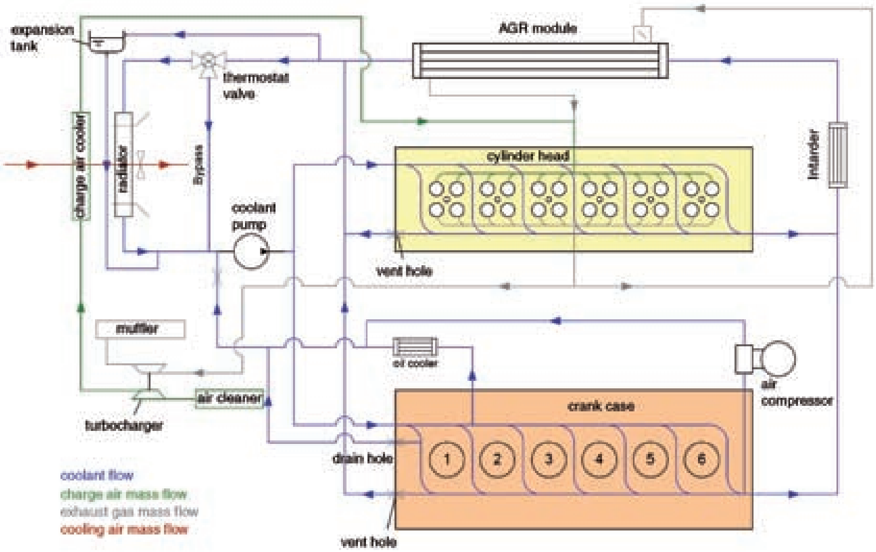

Figure 1: Simulated material flows in the combustion engine

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acteristic diagrams and starting conditions for the start of the simulation are calculated, the calculation itself using Fasimat and Flowmaster and the analysis of the results using Simulink and Diadem, **Figure 3**.

Primarily, during pre-processing two Matlab scripts were executed. First, all necessary characteristic diagrams (for example heat flow into the coolant as a function of engine speed and engine load, exhaust gas recirculation (EGR) rate, efficiency of turbine and compressor) were calculated and stored. Furthermore before each new simulation the starting conditions were calculated, which can vary in accordance to the drive cycle data or the vehicle itself (among other things vehicle speed, used gear, actual condition of the clutch, ambient pressure and temperature).

3 Fluid Simulation with Flowmaster

The Flowmaster model includes all systems necessary for the calculation of the flow in the cooling circuit, charge air and path of the cooling air as well as for the temperature distribution and the heat flow in the complete engine system, **Figure 4**. The calculation requires input values, which were transferred from Matlab/Simulink to Flowmaster by using the "FlowmasterLink for Matlab" interface.

Flowmaster is an analytical-empirical program for the solution of one-dimensional internal flows. It enables the modelling of piping systems for the calculation of the volumetric flow distribution, pressure losses, pressure waves and the heat transfer into fluids and solids.

The fluid system simulation works with schematic models or networks created from a library of predefined components. For each component, curves and characteristic diagrams are provided in the software which can simply be used directly or the user can modify these predefined curves or input their own. The user must also define the parameters for the simulation, for example lengths, diameters or altitudes. In this way, even for complex networks the modelling effort is manageable.

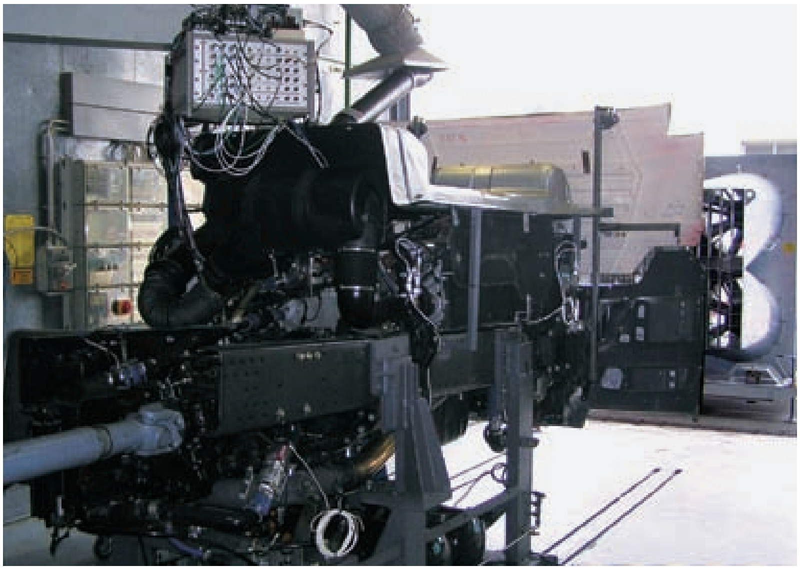

Figure 2: Test bed structure of the powertrain with air stream fan

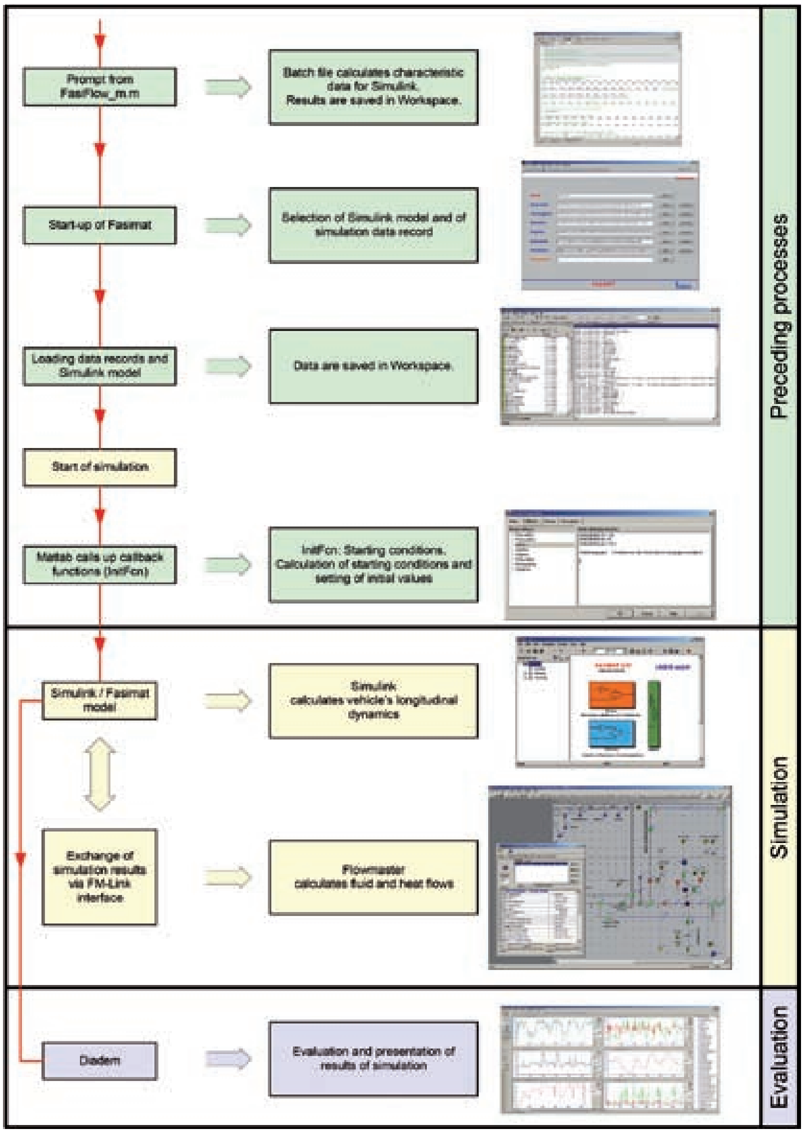

Figure 3: Flow diagram of the process of FasiFlow simulation

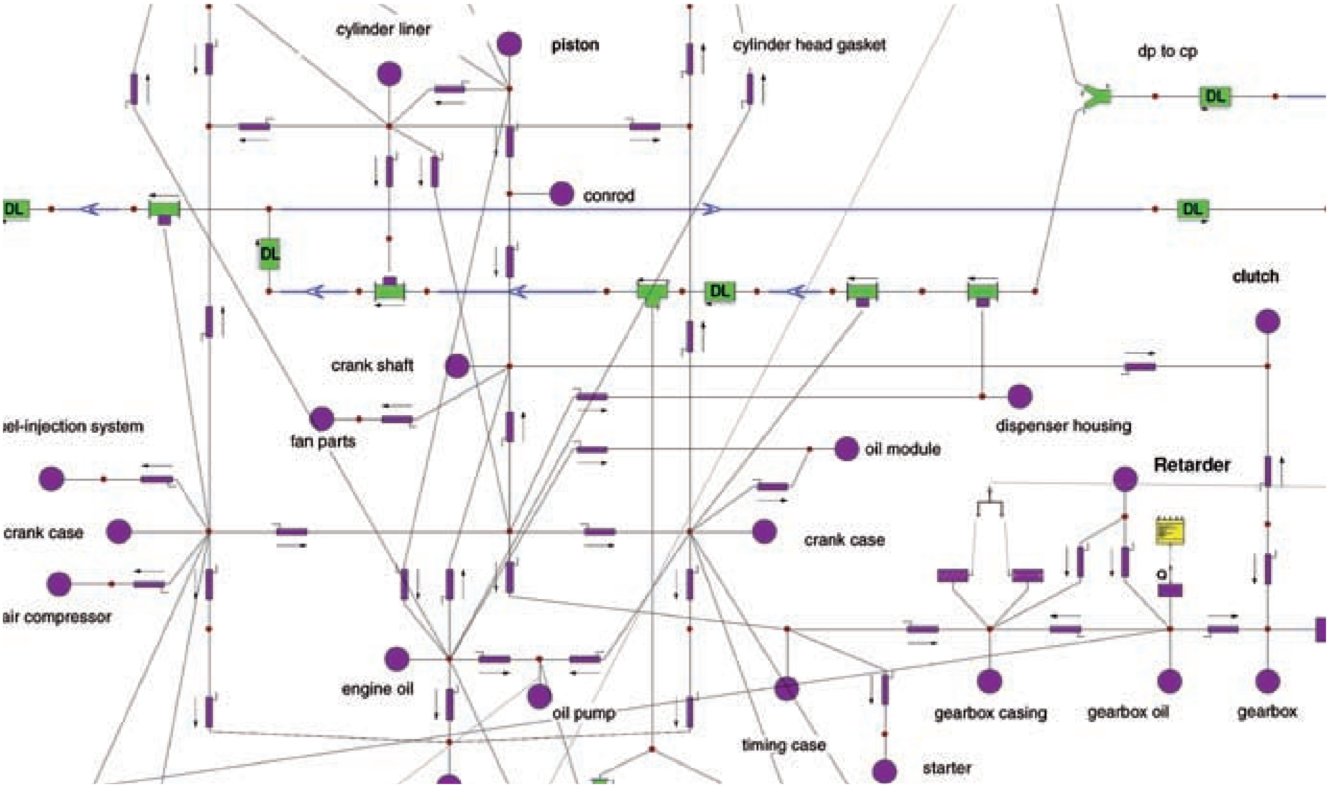

Figure 4: Cut of the Flowmaster calculation model for crankcase and additional components

4 Hydraulic Model

In order to understand the hydraulic power, the heat flow in the cooling system and the power consumption of the coolant pump and the fan, it is necessary to know the volumetric flow in all circuits of the internal combustion engine.

For FasiFlow all circuits of the engine and ancillary components (coolant pump, cylinder head, crankcase, EGR-heat exchanger, thermostat, coolant cooler and surge tank) were modelled. Also the pressure losses in the coolant circuit (pipes, retarder etc.), air flow (for example bumper, charge air cooler, radiator) and charge air (air filter, compressor, charge air cooler, turbine and exhaust system) have to be taken into account.

To reduce simulation times, system detail was kept to a minimum. Feeder pipes for components consisting of a number of pipes, pipe elbows and restrictions were combined into a single component, representing the hydraulic resistance characteristics of the parts.

5 Influence of the Static Head

Pressure and temperature of the ambient air influences the drag and engine output of a vehicle as well as the capacity of the whole cooling system. Whereas the heat transfer in a cooler, besides the mass flow, primarily depends on the cooling air temperature, the drag is influenced by the air density.

Almost independent from the air pressure, the fan conveys a constant speed and therefore a constant volumetric flow. If the air density decreases, the cooling air flow decreases and the capacity of the cooling system declines.

If the decrease in cooling air flow is offset through an increase in the fan peed, the power requirement of the ventilator increases gradually up to an elevation of 2000 m. At the same elevation an increase in ambient air temperature results in the cooling capacity of the cooling system decreasing. As a result average power consumption increases, because the temperature difference between coolant and cooling air decreases.

At a static head of 1030 m, starting on 0 m, the drag decreases by 10 %. To get the same reduction of drag at the same elevation by changing the temperature, the ambient temperature has to be raised by 30.5 K.

6 Viscous Fan Clutch, Cooler Fan and Coolant Pump as Consumers

By calculating the combined air consumption of the above components an accurate power requirement could be determined for them. The coolant pump, viscous fan clutch and cooler fan are not powered by the engine; therefore the measurement from a consumption map resulting from an engine on a test bed is not sufficient to determine their power consumption. During simulation the power of these consumers has to be assigned to other consumers. To map the coolant pump as a consumer, the power requirement has to be deducted from the measured consumption map. To determine the consumption share, all losses in the powertrain and traction resistances must be bal-

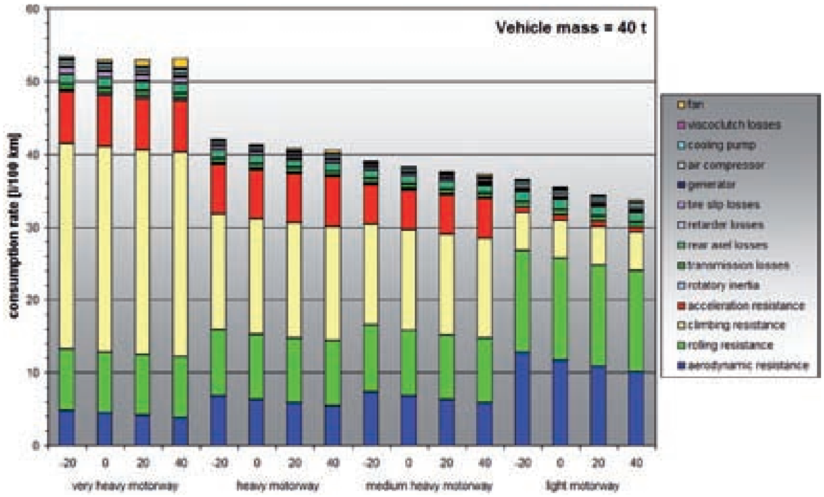

Figure 5: Consumption shares, calculated with FasiFlow for different difficult Autobahn

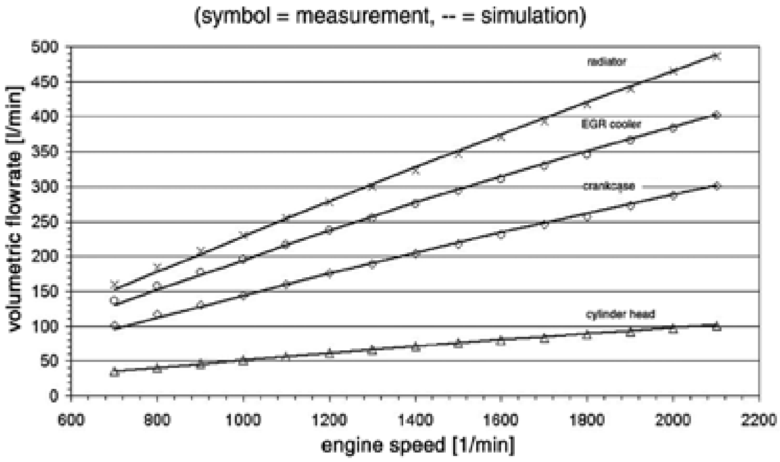

Figure 6: Volumetric flows through coolant cooler, EGR-heat exchanger, crankcase and cylinder head at opened thermostat

anced, **Figure 5**. The integrated energy requirement of a consumer cannot be set in relation to the engine, because the power requirement of a component is not necessarily directly proportional to that of the engine.

An example is to clarify this: On a flat road the air stream is sufficient for engine cooling. If the cooler fan does not work, the consumption share and energy requirements are zero. On an incline the retarder and cooler fan will engage. The energy requirement of the fan over time will increase, but not the consumption share, because the energy is gained from the change in the potential energy of the vehicle. The consumption share of the fan will be zero, because with a trailing throttle no fuel will be injected.

7 Comparison of the Volumetric Flows

The mass flow in sub-circuits influence the transferred heat flows as well as the coolant temperature. The coolant flow rates in sub-circuits were measured independently of the engine speed and the position of the thermostat valve. By means of the measured flow rates the pressure loss coefficient in all relevant sub-circuits can be calculated. Altogether three series of measurements were determined (opened, closed, and the transition from opened to closed thermostat valve).

The simulation model of the coolant circuit was adapted to the system behaviour of the engine by adjusting the pressure loss coefficients of the sub-circuits or components to the measured values. Using the Flowmaster model, valves were installed at the measuring points, at which the flow rate was calculated. In addition, the coolant temperatures in the sub-circuits, the speed of the coolant pump and the pressure in the surge tank were adjusted to the corresponding measured values.

By using the fluid data in correlation with the Reynolds number for a defined flow diameter, the pressure loss coefficients were calculated and a database for the Flowmaster components was provided. In the Flowmaster model the valves were replaced by discrete losses with corresponding ξ-curves of the flow resistances. A check calculation was made on the base of the predominant constrains during the measurement. A good correlation was achieved for both the opened and closed thermostat valve, **Figure 6**.

8 Hydraulic Power Requirements

The hydraulic power requirement of the sub-circuits and the mechanical input power of the coolant pump were explored for different coolant temperatures and for the water/glycol mixing ratios. Calculations were run for the engine at warm standby using the following boundary conditions:

- fluid: water/glycol mixture (50:50), temperature: 85 °C
- no additional heat transfer into the cooling system, except for hydraulic losses
- thermostat: opened
- pump speeds (engine speeds):
  1100 rpm (600 rpm, idle)
  2450 rpm (1340 rpm, corresponds with 85 km/h)
  3477 rpm (1900 rpm, corresponds nominal speed).

Significant fractions of the hydraulic power requirement come from the sub-circuit leading to the EGR cooler (4.4 %) and the cooler itself (24.7 %). The power requirement for the through-flow of the cylinder head (3.0 %) and the crankcase (3.7 %) is relatively small. It has to be taken into account that for the thermostat valve and its case (16.2 %) a fraction of the hydraulic power requirement is already enclosed in the return flow of cylinder head and air compressor. The **Table** shows the power for the through-flow of the cooling system. Based on an average power requirement for an engine of 100 kW for a 40-t truck on a plane at a velocity of 85 km/h and an engine speed of 1340 rpm, it results in a consumption share for the coolant pump of 1.8 %, which is correspondent to a fuel consumption of 0.53 l per 100 km.

9 Different Coolant Temperatures

For incompressible flow media like coolants the hydraulic power requirement is a product of volumetric flow and pressure generation. By an increasing dynamical viscosity of the coolant, the flow conditions and hydraulic power requirements in the sub-circuits change at very low temperatures. Accordingly, the power requirement becomes smaller with a decreasing coolant temperature.

Between +10 and −10 °C a significant decline of the hydraulic as well as the mechanical power requirement can be noticed. At high coolant temperatures (> 50 °C) there is nearly no change of the power requirement. To reduce friction inside the engine and to raise thermal efficiency in the coolant cooler, an increase in coolant temperature at part load does not have a major impact on the hydraulic and mechanical power requirement of the coolant pump.

10 Evaluation of Different Mixing Ratios

The viscosity of the coolant depends on the water/glycol mixing ratio, which depends vice versa on the coolant temperature. The mechanical power requirements only rise slightly when increasing mixing ratios at operating temperature (85 °C), due to an increase of both mixture ratio and pump efficiency.

For the engine at warm standby the influence of the mixing ratio on the mechanical power requirement of the coolant pump can be disregarded. At lower coolant temperatures the power input of the coolant pump will be reduced with a higher glycol fraction of the coolant, **Figure 7**.

Table: Power requirements for the flow-through of the cooling system
(* efficiency V ribbed belt drive with 96 %; KMP = coolant pump)

n_{Motor} in rpm	n_{KMP} in rpm	P_{hydr} in W	η_{KMP} in W	$P_{mechKMP}$ in W	$P_{Anteil\text{-}Motor}^{*}$ in W
600	1098	77,6	48,8	160	167
1340	2452	864	47,9	1803	1878
1900	3477	3103	47,8	6492	6763

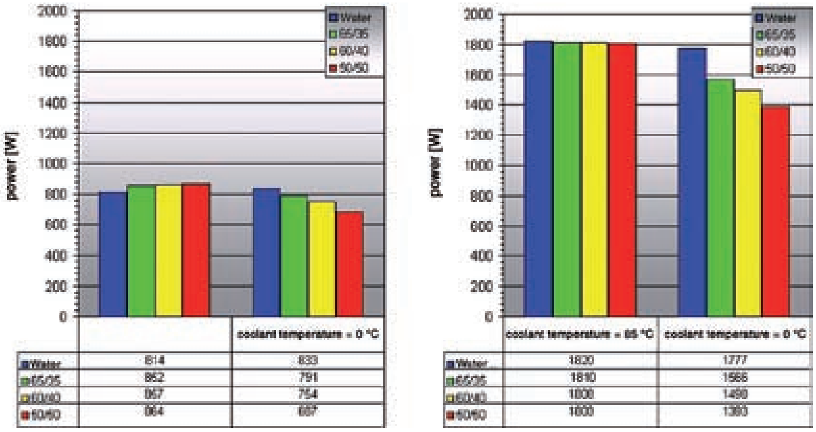

Figure 7: Hydraulic (left) and mechanical (right) power requirements of the coolant pump at different mixture ratios and temperatures of the coolant

11 Evaluation of Thermal Lags

In the Flowmaster model, also thermal lags are considered for the description of thermal flows in both engine and additional components. They are based on the existence of a mass (fluids or solids) and its specific heat capacity and have a major impact on the temperature of components and coolant. For the calculation of thermal flows between solids with different temperatures; the mass, the specific heat capacity, the transfer surface and the heat transfer coefficient have to be specified.

On the solid side the engine and its additional components, clutch, transmission and retarder were considered. As Flowmaster does not display 3D temperature distributions in solids, the engine and attaching components were fragmented into a number of point masses, which were linked together by thermal resistances.

The thermal lag of the coolant in the sub-circuits was realized with cylindrical pipes, because only this components allow different temperature distributions of a fluid in a component and the description of realistic system behaviour. The flow profile was adjusted for each sub-volume. The length of the pipe did not have an impact on the temperature distribution in a fluid. To keep the pressure loss small, lengths were set to 1 mm. The pressure loss curves in the sub-circuits were stored in discrete losses without a fluid volume.

12 Determination of the Thermostat Position

The thermostat valve unit changes its position depending on the coolant temperature and works like a 3/2-way valve. The volumetric flow is reduced by the bypass at increasing temperature and is enlarged through the coolant cooler at the same time.

The pressure loss coefficient in the bypass was calculated based on the measurements of the volumetric flows in the sub-circuits at a closed thermostat valve. That way the standardized ratio of “volumetric flow through bypass” and “volumetric flow through coolant cooler” could be calculated and displayed.

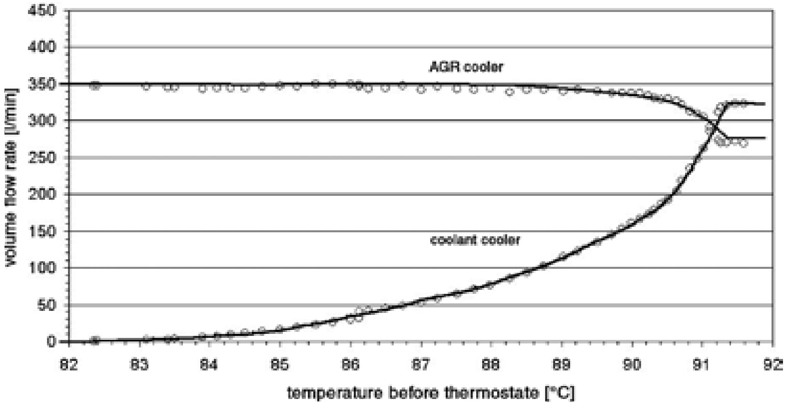

Figure 8: Volumetric flows through coolant cooler and EGR cooler when opening the thermostat valve (o = measured, – = simulated)

The hydraulic model was adjusted using the measurement results. In the Flowmaster model the thermostat valve was represented by two ball valves; their pressure loss coefficients came from the Flowmaster database.

The Simulink model shows a valve position under provision for the thermal lags dependent on the coolant temperature of a measured thermostat unit. For adjusting the system behaviour to the real ratio of volumetric flows, a translation matrix was defined in the Simulink-model. The matrix shows where the valve position in the Flowmaster model needs to be to get the same volumetric flow ratios as at the candidate.

Finally, the system behaviour of the FasiFlow model was tested by a comparison to the measurements. The volumetric flows through the coolant cooler were compared to those through the EGR cooler, **Figure 8**.

13 Determination of the Exhaust Gas Temperature

The exhaust gas temperature is required for the calculation of the turbine rating and in the EGR cooler. It influences the heat transfer between exhaust gas and coolant cooler significantly and therefore indirectly the power requirement of the cooler fan. It is defined by the thermal flow transferred into the fluid and the specific heat capacity. The temperature of the exhaust gas in the cylinder results from the following points: the injected fuel, the cooled charge air temperature, the fuel temperature and the EGR rate. In the EGR cooler it is mainly formed by the EGR rate, the coolant temperature and the efficiency of the coolant cooler.

During each iteration of the simulation the specific heat capacity of the exhaust gas is newly calculated by determining the stochiometric consistence of the exhaust gas from the molar mass fractions. With the aid of the molar mass flow ratios of the reacting gases the volume fractions (ξ values) were determined. With these ξ values and the temperature dependent specific heat capacity of the reacting gases the specific heat capacity of the exhaust gas is calculated.

The specific heat capacity changes in dependency on the exhaust gas temperature and the air/fuel ratio η. In the simulation the values for the specific heat capacity were between 1.025 and

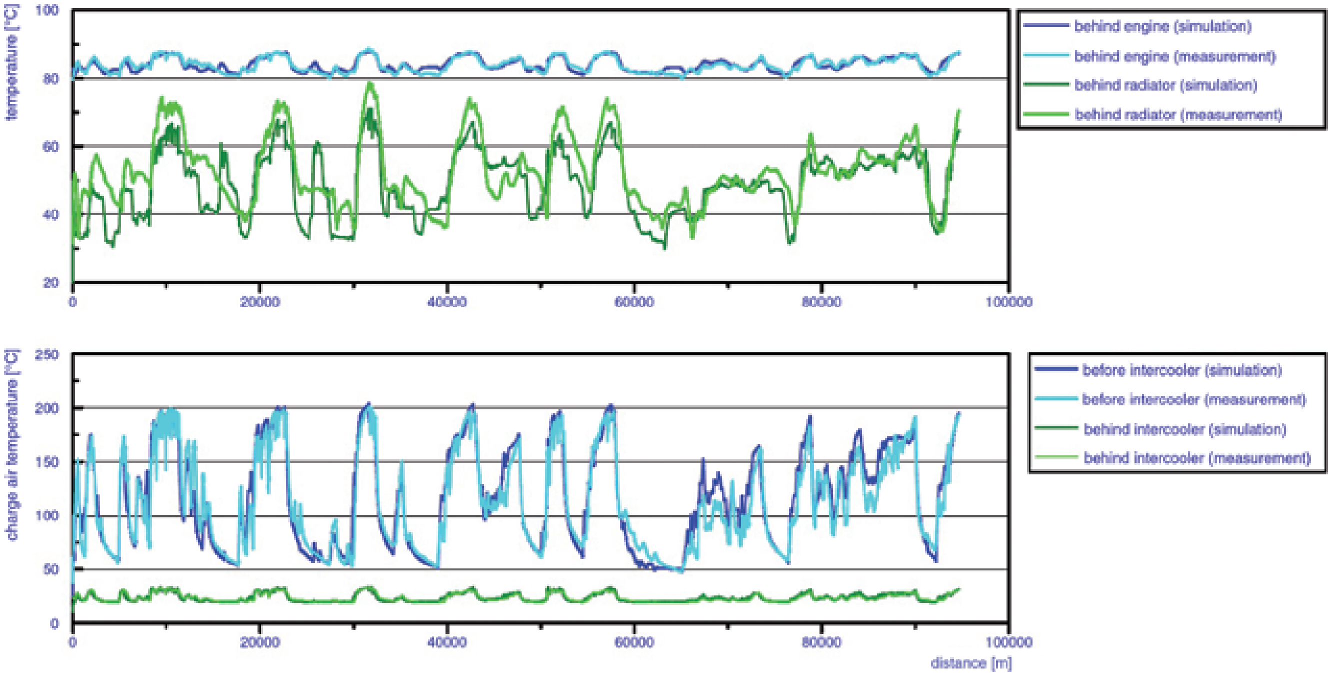

Figure 9: Comparison of measurement with simulation for coolant temperature after coolant cooler, and charge air temperature before and after charge air cooler

1.17 kJ/(kgK), which corresponds to a change rate of more than 12 %.

14 Results and Outlook

Although the FasiFlow model is not verified in every detail, the correlation between simulation and measurement has already reached a very high standard, **Figure 9**. The quality of the predictions is sufficient enough to construct and optimize cooling circuits with a high degree of accuracy.

In addition the model allows a deep insight into the complex interactions inside the cooling circuit, which are very hard to analyse empirically. Further advantages of the simulation system are the reproducibility of results, an increasing understanding of the system and a reduction of prototyping costs.

Advanced research is necessary for more detailed submodels as well as for the component based acquisition and identification of parameters. In the future it is necessary to have a stronger support of the measurement department in the early development phase, to develop and optimize new cooling systems with a significantly higher amount of virtual design techniques.

With the available simulation system it is possible to research for example extreme climatic situations or to test new components or alternative control strategies with much lower effort. Most important goals are the reduction of fuel consumption and emissions as well as better heat removal to the ambient environment. This point is critical, as raising engine power and sanctions for the reduction of exhaust gas emissions increases with limited interior space in modern trucks.

15 Summary

The field thermal management, the optimization of the heat balance in vehicles, is an essential factor to reduce fuel consumption and emissions. Like many other units in internal combustion engine R&D, computer based simulation systems are used more and more. At MAN Nutzfahrzeuge AG one developed a simulation system called FasiFlow, based on Flowmaster, to create the CFD simulation model of a cooling circuit in a truck diesel engine. The system makes it possible by combination of different calculation programs like the tool Flowmaster to do entire and precise simulation of hydraulic and thermal processes. ■

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