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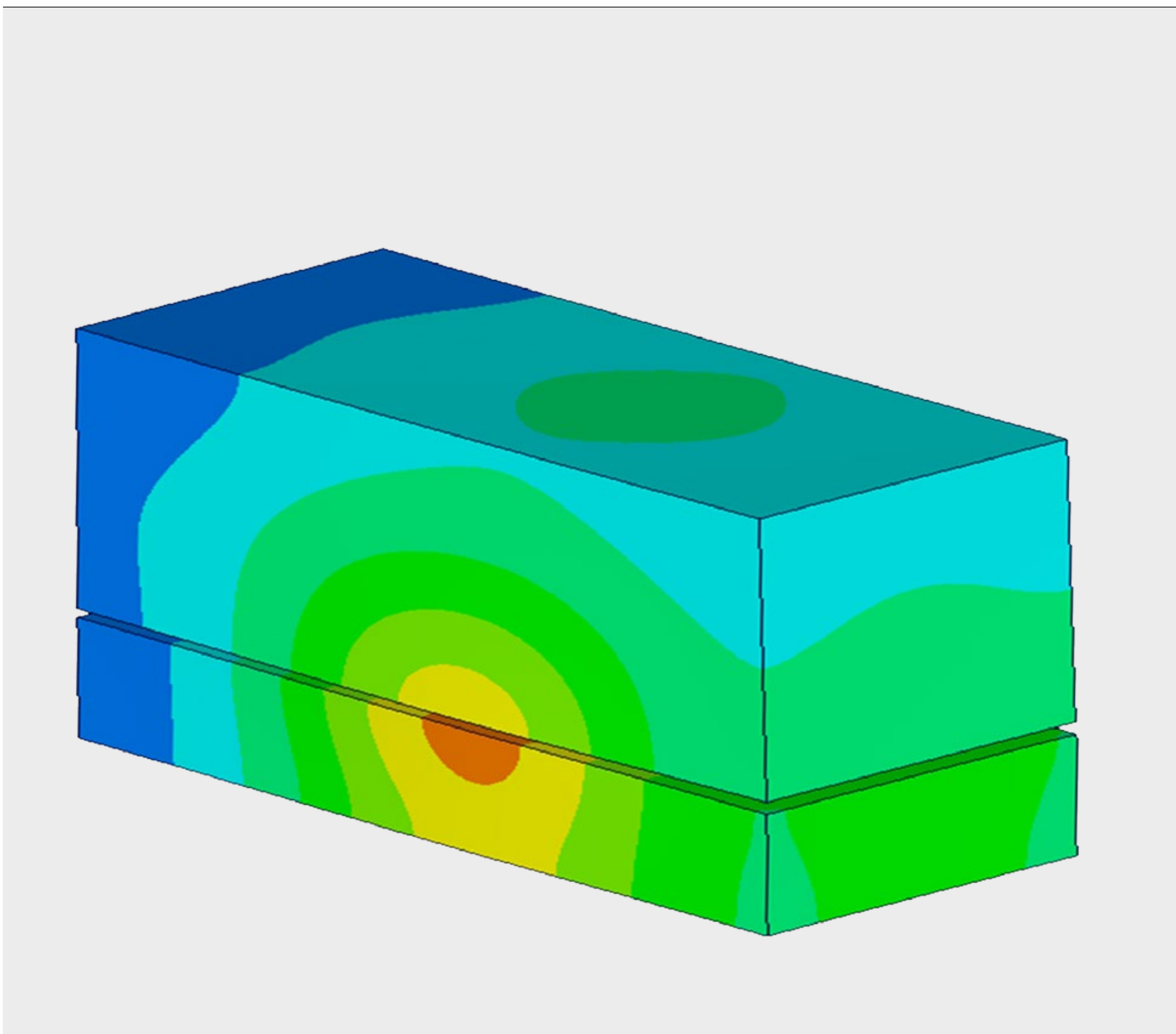
Thermo-elastohydrodynamics of the Piston-Cylinder Contact in High-pressure Pumps

An increase of the rail pressure in common-rail systems from currently 2500 to 3000 bar is to be expected due to stronger emission laws. Within the FVV research project Diesel 3000 bar, at the University of Kassel and the RWTH Aachen University the basics for the design of the piston-cylinder contact of common-rail pumps at high pressures were developed. For this purpose, measurements of pressure and temperature were performed in a flat gap and compared with the results of a thermo-elastohydrodynamic simulation model.



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1 MOTIVATION

Compliance with the stronger emission limits, the ambition to raise the rail pressure in common-rail systems to 3000 bar is given. This will allow a fine atomization of the fuel and therefore a more efficient combustion. Within the technical system of the high-pressure pump, the design of the piston-cylinder contact gets critical when the rail pressure increases [1]. A pressure drop from such a high level causes high temperature gradients due to dissipation of the energy in pressure. For a detailed examination of these effects, the critical piston-cylinder contact has been investigated in a FVV research project in an abstracted test bench with a flat gap without relative movement of the contacting surfaces with measurements and simulation. The evidence of the valid functionality of the Thermo-elastohydrodynamic Lubrication (TEHL) model and the test bench at an operation pressure of 1000 bar is the subject matter of this article.

2 MICRO GAP TEST BENCH

The micro gap test bench is intended to describe the geometry of the piston-cylinder contact as accurate and reliable as possible and allow to measure local pressures and temperatures as well as the leakage in the tribological contact at the same time. The difficulty is to adjust the typical gap heights of only few micrometers and the high pressure of up to 3000 bar. The piston-cylinder contact of a real high-pressure injection pump is a round gap. The manufacturing of such a round gap and the installation of measuring sensors of temperature and pressure can hardly be achieved. An allowed alternative solution is to unroll the round gap to a flat gap which has been developed in this project. With a length of 21 mm and a width of 3 mm, edge effects are negligible and the knowledge gained can be transferred to the round gap.

FIGURE 1 (left) shows schematically the round gap of a high-pressure pump and the unrolling of the round gap to the flat gap, **FIGURE 1** (right). Along the gap length, pressures and temperatures are measured at three positions. The pressure and the temperature at position A is measured 1.5 mm after gap inlet, position B is placed 10.5 mm after inlet and measurement position C is 19.5 mm after inlet, symmetrical to position A. Strain gauge pressure sensors and thermocouples are used in the test bench. With that, it is possible to measure the main effects in the gap. Furthermore, the volume flow which flows through the gap, is measured in the outlet. Moreover, pressure and temperature are measured in the inlet and additionally, the temperature is measured in the outlet. These measured sizes are also used as boundary conditions in the simulation calculation. For the investigations, the SRS Calibration Fluid CV [2] was used.

3 SIMULATION

For the valuation of the micro gap test bench system behavior, it is necessary to consider the interaction between the structure of the case and the fluid film. According to the built up micro gap test bench, a thermo-elastohydrodynamic simulation model

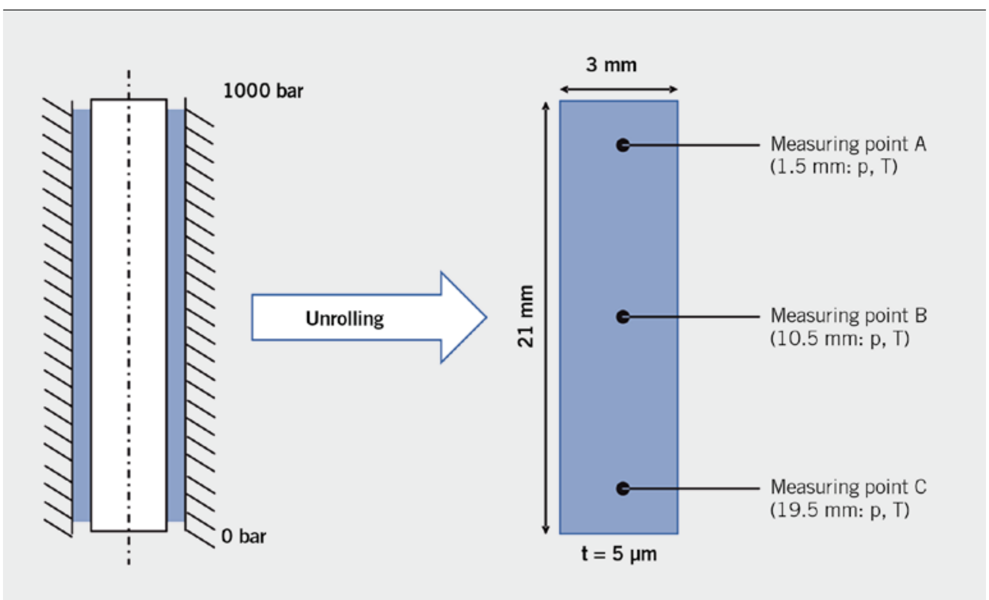

FIGURE 1 Functional principle of the flat gap with measurement positions along the gap (© University of Kassel)

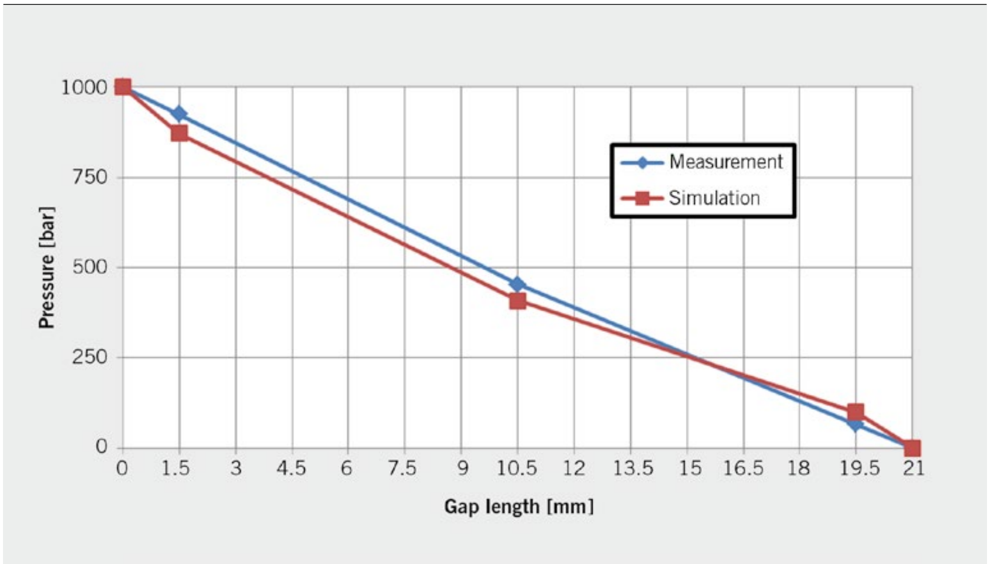

FIGURE 2 Pressure distribution over the gap length (© University of Kassel)

was created with the program First at the Institute for Drive and Vehicle Technology which is able to point out the structure dynamic effects as well as the hydrodynamic effects. For the hydrodynamic calculation in the gap, the Reynolds differential equation is used and it allows to describe the flow in narrow gaps two-dimensionally. Elastic gap changes due to hydrodynamic pressure is considered as well as the backlash on the pressure calculation. When the pressure releases over the gap length, a high dissipation energy occurs which leads to high temperatures in the fluid film and in the surrounding solids. So, it is necessary to consider the effect of the temperature in the whole system of the micro gap test bench. For this, apart from the Reynolds equation, the energy equation is being solved in the fluid film and it can describe the thermal balance in the whole system [3]. In addition to the heating of the fluid film due to the dissipation energy, the simulation also considers the heat conduction in the solids with thermal deformation effects (thermo-elastohydrodynamic lubrication). The most relevant fluid property is the viscosity which is being considered as a function of the temperature within the TEHL simulation. Because the fluid behavior was investigated at high pressures, the dependence of the viscosity on the pressure was also considered within the TEHL simulation. To determine the pressure gradient over the gap length and the thermal level in the fluid film, the inlet pressure and inlet temperature but also the outlet pressure were set as boundary conditions in the hydrodynamic simulation. Because the direct gap inlet temperature was unknown, inverse parameter identification techniques were used to reach a best match between measurement and simulation.

FIGURE 2 shows the comparison between the measured and calculated pressures at the measurement positions of the micro gap test bench for an inlet pressure of 1000 bar. With a maximum deviation of 53.6 bar at the position of 1.5 mm in the gap, there is a very good match of the pressures.

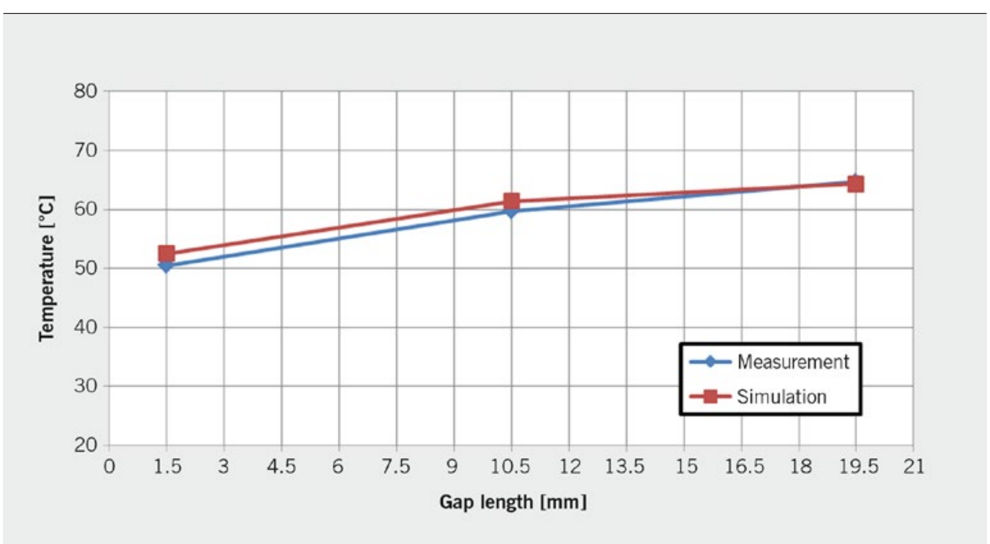

FIGURE 3 Temperature distribution over the gap length (© University of Kassel)

Similarly, **FIGURE 3** shows the comparison between the measured and calculated temperatures over the gap length. Due to the dissipation energy in the fluid, the test bench heats up and reaches the highest temperature of 64.68 °C near the gap outlet at the 19.5 mm. With a maximum deviation of 1.96 °C near the gap inlet, there is also a very good match between the measured and simulated temperatures.

The leakage calculated with the TEHL simulation model is 0.044 l/min and deviates from the measured leakage by only 1.17 %. Furthermore, a EHL simulation with a constant viscosity for the inlet temperature was performed and here, the calculated leakage deviates from the measurement by 28.85 %. This comparison makes the need of the temperature effects in the tribological contact clear.

4 SUMMARY AND OUTLOOK

Within the FVV research project Diesel 3000 bar, a micro gap test bench was built up to investigate the piston-cylinder contact of common-rail high-pressure pumps at high pressures in an abstracted form of a flat gap. With a wide range of sensors, the recording of local pressures and temperatures along the gap and the leakage was possible. To show the effects in the gap in a site- and time-resolved way, a TEHL simulation model of the micro gap test bench was built up and the results were compared with the measurements. These simulation results show a very good accordance of the pressures, temperatures and of the leakage and they also outline the need of consideration of temperature effects in the simulation of tribological contacts at high pressures.

Hereafter, more publications of measurements on the micro gap test bench at extremely high pressures up to 3000 bar are in work. Especially, the comparison of the complex TEHL simulation with the experiment is expected to be discussed. The detailed description of the design and construction of the basically oriented micro gap test bench will also be shown in a further article.

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