Setting up a Measurement Device for Tribological Studies in the Piston Assembly

- FVV-Project Piston Ring Oil Transport -

Georg Wachtmeister ¹⁾ Claus Kirner ¹⁾ Benedict Uhlig ¹⁾ Andreas Behn ²⁾ Matthias Feindt ²⁾

1) Institute of Internal Combustion Engines, Technical University of Munich
Schrägenhofstraße 31, 80992 Munich, Germany

2) Institute of Measurement Technology, Hamburg University of Technology
Harburger Schloßstraße 20, 21079 Hamburg, Germany

Received on July 12, 2016

ABSTRACT: Within the FVV-Project Piston Ring Oil Transport a novel research engine was developed for the investigation of the lubricating oil management in the piston assembly. The various measurement techniques are applied for detailed studies of the lubricating oil film thickness, oil transport, and the complex movements, and pressure conditions at the system piston assembly.

KEY WORDS: heat engine, spark ignition engine, lubricating oil, tribology [A1]

1. Introduction

Aim of this research project was the design of measurement techniques for tribological studies in the piston ring area. This implies the examination of the whole piston ring pack, in particular of the lubricating oil film thickness between piston and liner as well as the oil distribution in the piston ring grooves. Particularly for the application of the measurement instrumentation a single-cylinder petrol engine has been developed (Fig. 1). Measurement techniques can be applied throughout the operating range of the engine to research the general process of oil transport and its determining factors. ⁽¹⁾

Fig. 1 Research engine

2. Research Engine

Measurements are carried out using the developed single-cylinder gasoline engine. The engine data are shown in Table 1. Piston, piston rings and conrod are series production parts of a gasoline engine with a cylinder capacity of 2.0 liter. The cylinder liner design is close to the production engine. This design ensures that all results are transferable to series production engines.

Table 1 Engine data

Engine data	value
Bore x stroke	82.5 mm x 92.8 mm
Series production parts	Piston, conrod
Timing drive	2 inlet valves, 2 exhaust valves
Max. peak pressure	110 bar
Compression ratio	9.5 : 1
Max. engine speed	6500 rpm (with mechanical linkage 4000 rpm)
Flywheel mass	1.5 kgm ²
Mass balancing	1. and 2. engine order

3. Measurement technology

3.1 Mechanical linkage system

In this project different measurement pistons were designed to acquire tribological data at the moving pistons. Therefore cables and optical fibers must be routed from the piston to the stationary data acquisition system. For the realization a mechanical linkage system was built, as shown in Fig. 2.

Fig. 2 Mechanical linkage system, acc. to ^(1,9)

Similar systems were already used in previous projects ⁽²⁻⁸⁾. The built system consists of a coupling arm and a swing arm. The coupling arm is pivoted mounted on the connecting rod and the swing arm is attached to the crankcase. The kinematics are designed so that the deflection angle in the joints is as low as possible. The sensor cables and optical fibers are routed through the joints in order to twist them instead of bending, which ensures

a long life. In addition, the mechanical linkage system must have a space for at least 30 sensor cables, 8 optical fibers, and 8 capillary tubes. According to calculations of the piston side force with and without the mechanical linkage system it has a negligible effect on the piston secondary movement up to an engine speed of 3000 1/min.

3.2 Measurement pistons

The developed measurement pistons are used for recording piston secondary movement, piston ring movement, ring land pressures, oil film thickness, and oil transport. Other published measurements on the piston assembly since 1997 can be found in ^(3, 5, 10-16). Owing to the various measurement techniques and high amount of sensors, two measurement pistons with different objectives were built up, like Fig. 3 indicates. Measurement piston 1 is specially equipped for the measurement of piston secondary motion and ring land pressures. Measurement piston 2 has a focus on oil film thickness, oil transport and temperature measurements.

Fig. 3 Measurement pistons, acc. to ^(1,9)

3.3 Optical setup

Oil film thickness measurements are conducted using laser-induced fluorescence (LIF). Publications on this topic since 1997 can be found in ^(2, 17-27).

Fig. 4 shows the optical setup for measuring oil film thickness by means of LIF, which contains sixteen synchronous points of measurement. One single beam path of the optical setup is highlighted. Monochromatic laser-light excites at (a.) and is divided by a cascade of beam-splitters (b.) into sixteen optical paths. With the help of two mirrors (c.) and a dichroic mirror (d) the beam can be coupled into a optical fiber (e.). At the liner of the research engine the laser light exits the fiber directly into the oil film and induces fluorescence. Fig. 4 shows that the continuous-wave laser with a wavelength of 473 nm leads to an adequate excitation of fluorescence because the added dye can absorb the laser light. The emission spectrum of the dye is located at higher wavelengths due to the Stokes-shift, with a maximum around 500 nm. The fluorescence light returns through the same fiber and is conducted via the dichroic mirror (d.), a filter, and convex lens (f.) to a photodiode. There, the fluorescence light is measured for intensity. For thin oil films the fluorescence intensity can be linearly related to an oil film thickness. A calibration experiment allows to put the fluorescent intensity in relation to absolute oil

film thicknesses values. This experiment was conducted directly on the research engine which allows to calibrate the optical path, the placement conditions, and reflections. Therefore precision foils were clamped between a piston ring and the liner. By increasing the thickness of the foils a linear correlation between oil film thickness and fluorescence could be measured and applied. Similar experimental setups were built up in (2, 20, 26). Fig. 8 and Fig. 9 show the qualitative signals since the calibration was only conducted for the first piston ring. As a result this calibration is not valid for the remaining piston assembly parts.

Fig. 4 Optical setup, acc. to (1, 9, 28)

3.4 Piston ring rotation

The piston ring gap circumferential position can be recorded using a radioisotope-based method. Two different radioactive samples (^{60}Co and $^{110\text{m}}\text{Ag}$) were mounted within the piston ring 1 and piston ring 2, respectively, whereby the position of the probe is close to the ring gap. Two scintillation counters are arranged in a rectangular angle outside the engine for detection of incident gamma radiation, as Fig. 5 points out. The number of incident gamma quants is dependent on the distance between probe and scintillation counter. By means of the two scintillation counters it is possible to measure the circumferential position as Fig. 5 shows for a weak ^{60}Co probe within piston ring 2.

Fig. 5 setup ring gap position measurement, acc. to (1, 9)

The graph indicates the measured counting rate versus the piston ring angle to the anti-thrust side for both detectors. Only in the area between 40° and 130° to the anti-thrust side (ATS) there is a low precision in determining the position of the probe. Because of the different photopeaks of ^{60}Co (1173 keV and

1332 keV) and $^{110\text{m}}\text{Ag}$ (657.8 keV and 884.7 keV), it is possible to differ between the piston ring gap position of the piston ring 1 and piston ring 2.

3.5 Oil sampling and tracer injection

To draw conclusions about the gas content of the lubricant-gas mixture in the piston ring grooves, the content of capillary tubes is visually analyzed using a microscope camera. Therefore a vacuum pump and a piezo valve extracts the mixture from the piston ring grooves via the capillary tubes. Software controls the sampling and evaluates the capillary fill level. The analysis is based on the brightness at the surface of the inner diameter of the capillary, which is a result of the different refractive index of air and oil on the glass surface. This setup is also used to pump a oil-dye mixture into the piston ring grooves for analyzing the transport velocity of the oil within the piston assembly. Optical fibers besides the capillary tubes detect the emission of the oil-dye mixture from the capillary tube. The other optical fibers within the piston assembly measure the shifting of the oil, as soon as the oil-dye mixture can be detected by the optical setup.

Fig. 6 Oil sampling setup, acc. to (1, 9)

4. Results

4.1 Ring land pressure

Fig. 7 features the measured combustion chamber pressures and ring land pressures for different engine operating points. One specialty is that the ring land pressure 2 is higher for motored condition and 5 bar IMEP than for 7.5 bar and 10 bar IMEP. This circumstance is due to the better sealing of piston ring 1 in case of higher combustion chamber pressures. The pressure conditions are summarized in Table 2. The ring land pressure 1 amounts to 13–15 percent of the combustion chamber pressure in fired engine operation, and up to 27 percent in motored condition. On the ring land 2 pressures are 2.9–3.5 percent of the combustion chamber pressure for the operating point 10 and 7.5 bar IMEP. For 5 bar IMEP the value is 10 percent, and for motored operation 19 percent.

Table 2 combustion chamber and ring land pressures, acc to ⁽¹⁾

	Combustion chamber [bar]	Ring land 1 [bar]	Ring land 2 [bar]
motored	9	2.5	1.7
5 bar IMEP	22	3	2.2
7.5 bar IMEP	42	5.5	1.5
10 bar IMEP	52	8	1.5

Fig. 7 Ring land pressures, acc. to ⁽¹⁾

4.2 Oil film thicknesses

Fig. 8 Oil film thickness, acc. to ^(1,9)

Fig. 8 shows a sectional view of the liner (left side). Within the cylinder-housing there are nine points for oil film thickness measurements. The optical fibers are glued in stainless steel ferrules for polishing and are mounted flush to the liner surface inside LIF-probes. The LIF-probes are sealed with radial caulking o-rings against the water cooling between cylinder-housing and liner. Fig. 8 visualizes the upward and downward moving piston for one working cycle. The moving piston edges are visualized as black lines, the piston rings are colored as blue areas, and the piston skirt is colored in gray. The LIF signals are plotted on horizontal lines where the measuring points are placed. The graph shows 4 different operating points. As the signals point out the oil film rises when the piston runs over the measuring points. The signals are low for piston position below the measuring points, and higher for the piston above the measuring points because the

cooling jet splashes fresh oil on the liner. Investigations showed that the engine speed has a less significant influence on the oil film thickness compared to the engine load. Therefore the following results show the oil film thicknesses for different loads.

Fig. 9 visualizes the measured oil film thicknesses at half stroke of the piston skirt in the power cycle. The bottom edge of the piston skirt and the oil scraper ring pushes a lot of oil in front of it. When the piston rings 2 and 1 pass the measuring point the signal level decreases down to 1.6 to 3.4 μm . Moreover the oil content between the piston rings declines with rising load. The reason for this phenomenon is that blow-by gases due to higher combustion chamber pressures increase and higher contact pressures between piston, piston rings and liner squeeze oil out.

Fig. 9 Oil film thickness at 1/2 stroke piston skirt, acc. to ^(1,9)

4.3 Piston ring gap position

The measurement principle was tested in fired engine operation, by varying engine speed (I), and load (II). Using the measured counting rates on both detectors, (III), the angular position of the sample, (IV), was calculated. The piston ring gap 2 starts at 135° angle to the anti-thrust side, marked as position X. From 150 to 500 s the ring gap of piston ring 2 turned slowly to the thrust side and moved back toward the anti-thrust side at 550 s. The resolution in this area is low due to the high distance of the sample position to the scintillation counters. From 850 s on a higher counting rate was acquired on the ATS scintillation counter again. The sample reached the anti-thrust side and turned further in direction of the cam-drive (1250 s). In this area the piston ring gap remains until the end of the measurement.

Fig. 10 Piston ring gap position, acc. to ^(1,9)

4.4 Oil transport

For detecting the oil transport velocity within the piston assembly, oil with fluorescence tracer was injected through the capillary tubes into the piston ring grooves of piston ring 1. The engine is operated at a speed of 1000 1/min and with 5 bar IMEP for this measurement. The analysis is based on the detector signal of the optical fiber in the piston ring groove 2. Fig. 11 shows the start of the injection of the oil-dye mixture into the piston ring groove 1 which had a duration of 10 s. After a delay of 50 cycles the fluorescence signal at the optical fiber in piston ring groove 2 rises. A signal maximum is detected for a crank angle from 380° to 450°. After the injection the signal level at the optical fiber decreases slowly until the end of the measurement.

Fig. 11: Oil transport, acc. to (1,9)

5. Conclusion

Using this research engine and the applied measurement technologies many tribological phenomena in the piston assembly can be observed. Moreover the influence of changes in the piston ring pack with respect to the oil supply can be explained. This will help to provide input data for better future simulation models of the oil transport and to improve engines concerning the oil consumption. Therefore on the research engine also blow-by, ring land pressure, piston and piston ring movements are measured to obtain a detailed knowledge of the tribology in the piston assembly. A future target is the calibration of the LIF-measurement technique for the purpose of showing absolute oil film thicknesses for all piston rings and the piston skirt instead of qualitative results. Another important field of research is to measure the relationship between the oil content in the piston ring grooves and the lubricating oil consumption.

This paper is written based on a proceeding presented at JSAE 2016 Annual Congress.

Acknowledgment

The research project (IGF-no. 17553) was encouraged by the Federal Ministry for Economic Affairs and Energy on the orders of the German Bundestag with the help of the German Federation of Industrial Research Associations e. V. (AIF) and the Research Association for Combustion Engines e. V. (FVV). The authors thank for the allowance and for the support of the user committee,

which was lead by chairman Dr.-Ing. A. Robota (Federal Mogul Burscheid GmbH). Furthermore, the authors thank Prof. Dr.-Ing. Georg Wachtmeister (Institute of Internal Combustion Engines, Technische Universität München) and Prof. Dr.-Ing. Gerhard Matz (Institute of Measurement Technology, Technische Universität Hamburg-Harburg) for their support, as well as Dr. rer. nat. Heiko Gerstenberg of the research neutron source Heinz Maier-Leibnitz (FRM II) for consulting and providing the radioactive samples.

References

- (1) Kirner, C., Uhlig, B., Behn, A., and Feindt M., "Kolbenring-Öltransport: Öltransport durch die Kolbenringe," Vorhaben Nr. 1124, FVV Abschlussberichte Heft 1072, (2015).
- (2) Weimar, H.-J., "Entwicklung eines laser-optischen Messsystems zur kurbelwinkelaufgelösten Bestimmung der Ölfilmdicke zwischen Kolbenring und Zylinderwand in einem Ottomotor," Dissertation, Universität Karlsruhe, Karlsruhe, (2002).
- (3) Knörr, M.G., "Reduzierung der Verlustleistungsströme am System Kolben/Kolbenringe/Zylinderlaufbahn," Dissertation, Technische Universität München, München, (2013).
- (4) Kuhn, T., "Messung der Zylinderverformung von Aluminiumkurbelgehäusen für Dieselmotoren," Dissertation, Universität Hannover, Hannover, (2001).
- (5) Ito, A., Mochiduki, K., Kikuhara, K., Inui, M. et al., "A Study on Measurement of Conformability of the Piston Oil Ring on the Cylinder Bore Under Engine Operating Condition by Laser Induced Fluorescence Method Using Optical Fiber," J. Eng. Gas Turbines Power, Vol. 136, No. 12: p. 121503, (2014), doi:10.1115/1.4027808.
- (6) Mufti, R.A. and Priest, M., "Experimental Evaluation of Piston-Assembly Friction Under Motored and Fired Conditions in a Gasoline Engine," J. Tribol., Vol. 127, No. 4: p. 826, (2005), doi:10.1115/1.1924459.
- (7) Golloch, R., "Untersuchungen zur Tribologie eines Dieselmotors im Bereich Kolbenring/Zylinderlaufbuchse," in: Fortschritt-Berichte VDI, Reihe 12, VDI-Verlag, Düsseldorf, (2001).
- (8) Werner, M., "Entwicklung eines Motorprüfstands zur Untersuchung der Kolbengruppenreibung und deren Haupteinflussgrößen," Dissertation, Technische Universität München, Garching, (2014).
- (9) Uhlig, B., Kirner, C., Behn, A., and Feindt, M., "Investigation of the Lubricating Oil Management on the Piston Assembly," MTZ Worldw, Vol. 77, No. 4: pp. 62–69, (2016), doi:10.1007/s38313-016-0019-0.
- (10) Nakayama, K., Yasutake, Y., Takiguti, M., and Furuhashi, S., "Effect of Piston Motion on Piston Skirt Friction of a Gasoline Engine," SAE Paper 970839, (1997), doi:10.4271/970839.
- (11) Taylor, R.I. and Evans, P.G., "In-situ piston measurements," Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, Vol. 218, No. 3: pp. 185–200, (2004), doi:10.1243/1350650041323386.

- (12) Teraguchi, S., Suzuki, W., Takiguchi, M., and Sato, D., "Effects of Lubricating Oil Supply on Reductions of Piston Slap Vibration and Piston Friction," SAE Paper 2001-01-0566, (2001), doi:[10.4271/2001-01-0566](https://doi.org/10.4271/2001-01-0566).
- (13) Tamminen, J., Sandström, C.-E., and Nurmi, H., "Influence of the Piston Inter-ring Pressure on the Ring Pack Behaviour in a Medium Speed Diesel Engine," SAE Paper 2005-01-3847, (2005), doi:[10.4271/2005-01-3847](https://doi.org/10.4271/2005-01-3847).
- (14) Tamminen, J., Sandström, C.-E., and Andersson, P., "Influence of load on the tribological conditions in piston ring and cylinder liner contacts in a medium-speed diesel engine," Tribology International, Vol. 39, No. 12: pp. 1643–1652, (2006), doi:[10.1016/j.triboint.2006.04.003](https://doi.org/10.1016/j.triboint.2006.04.003).
- (15) Madden, D., Kim, K., and Takiguchi, M., "Part 1: Piston Friction and Noise Study of Three Different Piston Architectures for an Automotive Gasoline Engine," SAE Paper 2006-01-0427, (2006), doi:[10.4271/2006-01-0427](https://doi.org/10.4271/2006-01-0427).
- (16) Mittler, R., Mierbach, A., and Richardson, D., "Understanding the Fundamentals of Piston Ring Axial Motion and Twist and the Effects on Blow-By," ASME Internal Combustion Engine Division Spring Technical Conference, No. ICES2009-76080: pp. 721–735, (2009), doi:[10.1115/ICES2009-76080](https://doi.org/10.1115/ICES2009-76080).
- (17) Nakayama, K., Seki, T., Takiguchi, M., Someya, T. et al., "The Effect of Oil Ring Geometry on Oil Film Thickness in the Circumferential Direction of the Cylinder," SAE Paper 982578, (1998), doi:[10.4271/982578](https://doi.org/10.4271/982578).
- (18) Hentschel, W., Grote, A., and Langer, O., "Measurement of wall film thickness in the intake manifold of a standard production SI engine by a spectroscopic technique," SAE Paper No. 972832, (1997), doi:[10.4271/972832](https://doi.org/10.4271/972832).
- (19) Park, S. and Ghandhi, J.B., "Fuel Film Temperature and Thickness Measurements on the Piston Crown of a Direct-Injection Spark-Ignition Engine," SAE Paper. 2005-01-0649, (2005), doi:[10.4271/2005-01-0649](https://doi.org/10.4271/2005-01-0649).
- (20) Stein, C., Budde, M., Krause, S., Brandt, S. et al., "Schmierölemission und Gemischbildung: Beeinflussung der Schmierölemission durch die Gemischbildung im Brennraum von Verbrennungsmotoren," Vorhaben Nr. 933, FVV Abschlussberichte Heft 901, (2010).
- (21) Inagaki, H., Saito, A., Murakami, M., and Konomi, T., "Measurement of Oil Film Thickness Distribution on Piston Surface Using the Fluorescence Method. (Development of Measurement System)," JSME international journal. Ser. B, Fluids and thermal engineering, Vol. 40, No. 3: pp. 487–493, (1997), doi:[10.1299/jsmeb.40.487](https://doi.org/10.1299/jsmeb.40.487).
- (22) Thirouard, B., "Characterization and modeling of the fundamental aspects of oil transport in the piston ring pack of internal combustion engines," Ph.D. Thesis, Massachusetts Institute of Technology, Massachusetts, (2001).
- (23) Przesmitzki, S., "Characterization of oil transport in the power cylinder of internal combustion engines during steady state and transient operation," Ph.D. Thesis, Massachusetts Institute of Technology, Massachusetts, (2008).
- (24) Senzer, E., "Oil transport inside the oil control ring groove and its interaction with surrounding areas in internal combustion engines," Ph.D. Thesis, Massachusetts Institute of Technology, Massachusetts, (2012).
- (25) Baba, Y., Suzuki, H., Sakai, Y., Teck Wei, D.L. et al., "PIV/LIF measurements of oil film behavior on the piston in I. C. engine," SAE Paper 2007-24-0001, (2007), doi:[10.4271/2007-24-0001](https://doi.org/10.4271/2007-24-0001).
- (26) Wigger, S., "Charakterisierung von Öl- und Kraftstoffschichten in der Kolbengruppe mittels laserinduzierter Fluoreszenz," Dissertation, Universität Duisburg-Essen, Duisburg-Essen, (2014).
- (27) Kim, K.-s., Godward, T., Takiguchi, M., and Aoki, S., "Part 2: The Effects of Lubricating Oil Film Thickness Distribution on Gasoline Engine Piston Friction," SAE Paper 2007-01-1247, (2007), doi:[10.4271/2007-01-1247](https://doi.org/10.4271/2007-01-1247).
- (28) Kirner, C., Halbhauer, J., Uhlig, B., Oliva, A. et al., "Experimental and simulative research advances in the piston assembly of an internal combustion engine," Tribology International, Vol. 99: pp. 159–168, (2016), doi:[10.1016/j.triboint.2016.03.005](https://doi.org/10.1016/j.triboint.2016.03.005).