Heat-transfer augmentation techniques to improve seal life

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This article looks at several heat-transfer augmentation technologies that have been developed at Louisiana State University's Center for Rotating Machinery. Aimed at reducing interfacial heat in mechanical seals, they include the design of seal rings with an internal heat exchanger, surface texturing techniques to improve heat transfer, and the design of a new generation of seals with a heat pipe.

Industry spends huge sums of money on pump repair every year. It is estimated that 80% of the repair costs is dedicated to seals and bearings.

The most influential factors identified for being responsible for seal failure are:

- high interfacial temperature and associated thermal distortion between the rotating and mating seal rings;
- thermo-elastic instability; and
- excessive non-uniform wear.

The process is governed by viscous heating of the fluid as it is sheared between ring faces and cooling is provided by the flush fluid.

Water can easily reach its boiling point and cause damage by flashing across the faces. When low-viscosity hydrocarbon liquids, such as liquid butane are used, the heat generation is also affected by the rubbing friction between surfaces.

Furthermore, if the operating speed exceeds a certain critical value, then thermo-elastic instability – leading to the formation of macroscopic hot spots on the seal faces – can occur, depending on the contact pressure, surface finish and material properties.

Thus, the reduction of interface temperature to prolong the seal's service life calls for the implementation of appropriate heat-transfer augmentation techniques.

This article presents several heat-transfer augmentation technologies that have been developed recently at the Center for Rotating Machinery (CeRoM), Department of Mechanical and Industrial Engineering, Louisiana State University (LSU).

Developed to reduce interfacial heat in mechanical seals, they include the design of seal rings with an internal heat exchanger, surface texturing techniques to improve heat transfer, and the design of a new generation of seals with a heat pipe.

Seal design

The design of mechanical seals is quite intricate, even though they have a seemingly simple structural configuration.

The key components of a mechanical seal are two rings: one is stationary and the other is attached to the shaft, with which it rotates (**Figure 1**).The rotating ring is often called the primary ring and the stationary one is its mating ring.

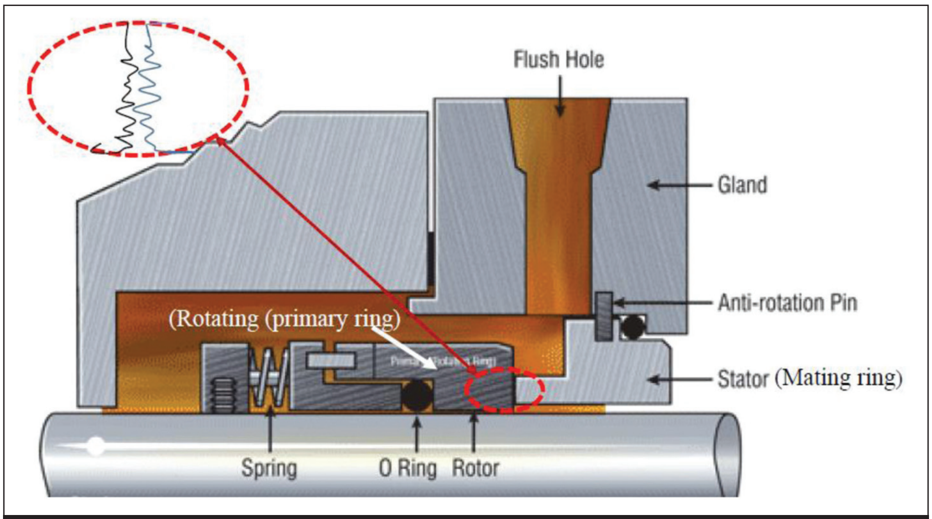

Figure 1. Schematic of a mechanical face seal (Khonsari and Bosser, 2008 and 2017).

The process fluid, which is to be contained, provides a thin film of fluid – typically on the order of a few micrometres thick – in the gap between the two rings. This very small film thickness protects the surface from direct rubbing contact by providing lubrication to avoid excessive interfacial heat. Nevertheless, a great majority of seals fail because of the effect of heat and, in fact, many seals fail long before the seal faces wear out.

If the interfacial temperature is too high, the lubricating film can flash, vaporise and significantly damage the faces.

Another heat-related issue is the non-uniformity of temperature across the faces that causes thermal distortion, affects the surface finish and results in wear with an unacceptable leakage rate that constitutes failure. Hydrocarbon pump seals are particularly susceptible to this type of failure wherein thermally-induced distortion dominates the mechanical distortion caused by pressure.

Still another form of failure caused by the effect of heat is so-called thermo-elastic instability (TEI). TEI is a phenomenon that manifests itself in the form of local hot spots on the surfaces that can be seen by the naked eye if the operating speed exceeds a certain critical threshold (Jang & Khonsari, 2003, 2004 and 2013; and Peng *et al.*, 2003).

Therefore, it follows that by providing mechanisms to improve heat-transfer augmentation, one can improve mechanical performance, reduce wear and extend seal service life to a great extent.

The sections that follow provide an overview of some of the research and development that has been done at the LSU's CeRoM, which focuses on thermal management of mechanical face seals. The details of these studies are available in various publications and patents referenced in the text.

Heat transfer consideration

The source of the interfacial heat generation is the friction between the contacting bodies and the relative sliding speed.

Assuming that the pressure is uniform over the face of the mating ring, the heat generation is given be **Equation** 1.

$$Q_g = P_m V A_f f \qquad (1)$$

where P_m is the mean pressure between the rings; V is the mean velocity of the rotating ring; A_f is the seal's face area; and f is the coefficient of friction in between the rubbing parts.

This heat is then conducted into the primary and mating rings and carried away by the cooling fluid (process fluid or barrier fluid) by means of convection.

Understanding the nature of heat transfer and the fluid–solid interaction requires detailed calculation of the flow and energy consideration. Progress towards this objective was made by Luan and Khonsari (2006, 2007a and 2008) by simultaneous treatment of the energy and Navier–Stokes equations, taking into account the laminar and turbulent nature of the flow field around the rotating and stationary rings.

Heat-transfer correlations, in terms of the Nusselt number as a function of the Prandtl and Reynolds number for both the rotating and stationary rings are provided. Using these, one can conveniently estimate the convective heat-transfer coefficient. The interface temperature can be then predicted using procedures developed in studies by Luan & Khonsari (2007b) and Khonsari & Booser (2008 & 2017).

This, of course, depends on the properties of the seal's materials, operating conditions and the flush plan arrangement. The appropriate course of action then must be taken if the surface temperature exceeds a certain threshold. This may involve consideration of an appropriate heat-transfer augmentation technique.

A review of innovative developments leading to patents is given by Xiao & Khonsari (2013 & 2015). In what follows, a brief overview is provided of some of the recent designs developed by CeRoM researchers.

Mating rings with internal cooling channel

The first idea to discuss is the design of an internal heat exchanging system, within the mating, to remove the interfacial heat generated between the mating ring and rotating ring.

An effective heat exchanger would require having close proximity to the seal surface. This was achieved by designing a so-called double-tier mating ring made from two half rings (male and female) that form an internal flow channel when combined (Somanchi & Khonsari, 2005).

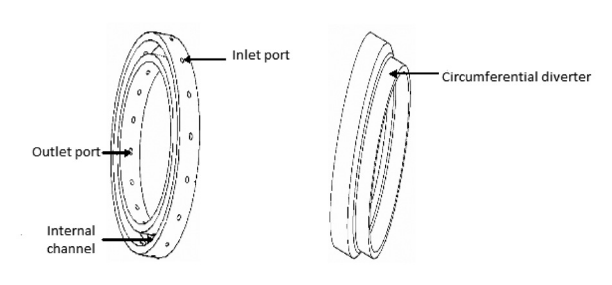

Figure 2. The female and male sections of a double-tier seal (Khonsari & Somanchi, 2005).

Designed into the female section are a groove-channel and a series of radial holes that extend from its outer diameter to the inner diameter, to form coolant inlet and outlet ports (**Figure 2**).

The male section has a circumferential diverter to direct the coolant towards the interior surface area of the seal face. Different prototypes of this design were made and the rings were either shrink fitted or thread fitted to form a single mating-ring unit with an internal structure, hence the name double-tier seal (DTS) mating ring.

This design provides an effective internal route for cooling fluid (gas or liquid) into the mating ring and diverts it towards the surface to provide cooling.

Note that the use of this approach requires modifying the gland design to allow the cooling fluid to enter and exit, as shown in **Figure 3** (Khonsari and Somanchi, 2005). Laboratory test results (using air and water as the cooling fluid) presented in this article reveal that this design has superior thermal performance compared with conventional seals.

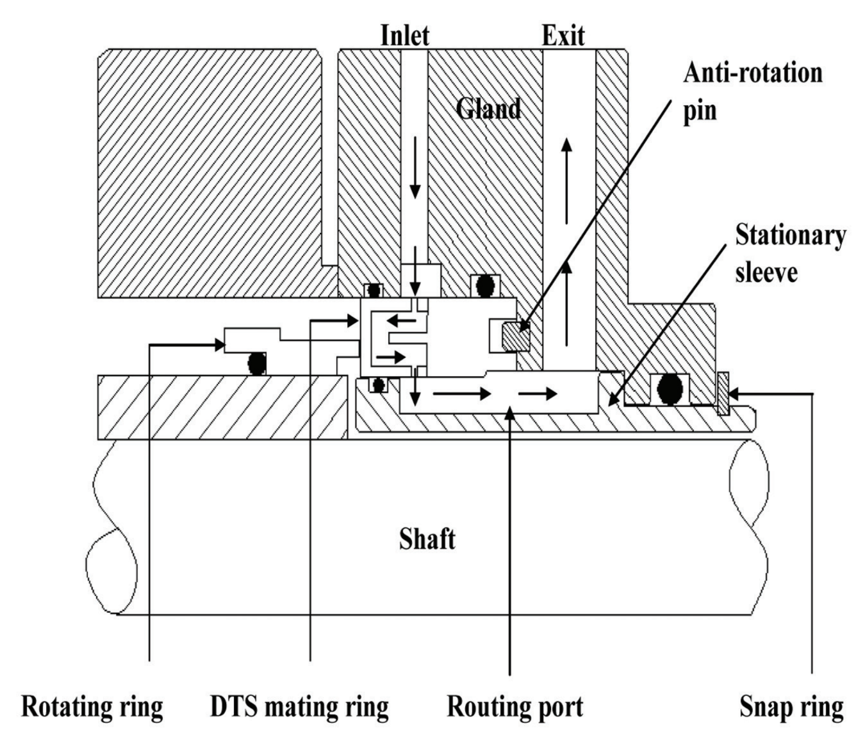

Figure 3. Design of the modified gland (Khonsari and Somanchi, 2005).

Another version of the mating ring design is shown in **Figure 4**. In this design, the stationary seal ring is a single-piece structure containing a series of through-channels (Khonsari and Somanchi 2007). Relatively large radial slots on the stationary ring minimise clogging – in case the coolant contains debris.

Laboratory tests revealed that this design is also very effective in removing heat. Subsequently, a prototype cartridge design of this seal was built, installed and field-tested in a local refinery in Louisiana with remarkable success over a very long period.

Mating rings with textured sidewall

Surface texturing, using a laser, has emerged as a viable technology for enhancing the performance of tribological components.

Textures in the form of "dimples" are primarily implemented directly into the lubricated surfaces to reduce friction and increase load-carrying capacity. This concept has

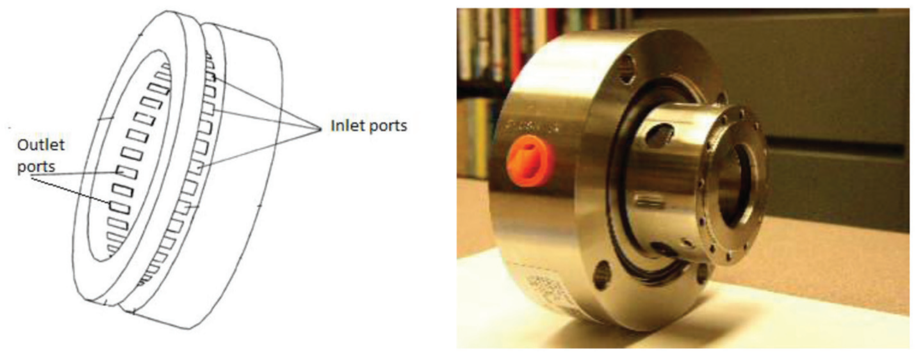

Figure 4. Schematic of the single-piece perforated mating ring design (*left*) (Khonsari and Somanchi, 2007) and the field-tested cartridge prototype (*right*).

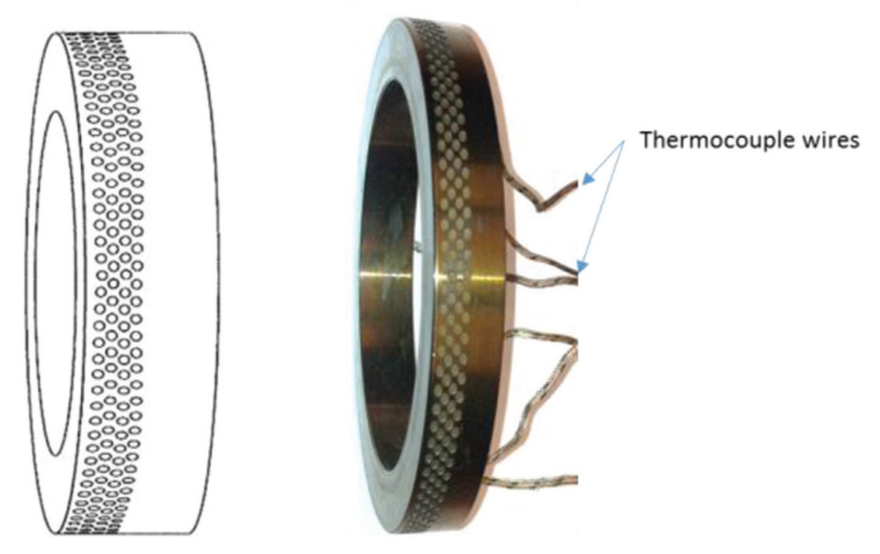

Figure 5. Schematic of a mating ring with textured side wall and a prototype with thermocouple wires for laboratory test (Xia and Khonsari, 2013 and 2014).

attracted worldwide attention from different points of view.

Within our group at the CeRoM, we have concentrated on modelling aspects associated with cavitation effects and the examination of lubrication regimes (Qiu & Khonsari, 2009; 2011a, b & c; and 2012) and optimisation of load-carrying capacity (Fesanghary & Khonsari, 2011, 2012; and 2013; Shen & Khonsari, 2013). All of these studies concentrated on texturing the lubricated seal faces.

This section examines a different application of surface texturing with the primary objective of improving heat transfer performance. For this purpose, Khonsari and Xiao (2012) designed a stationary ring with dimples fabricated onto its sidewall, as illustrated in **Figure 5**, along with a prototype.

This design has several rows of micro-dimples – etched by a laser – around the circumference of the mating ring. Six thermocouples were installed at different locations to monitor the temperature in real time.

A series of laboratory tests were performed at the CeRoM with a seal testing apparatus to investigate the performance of the textured seal.

Both conventional (plain mating ring) and dimpled surface rings were tested under identical operating conditions for comparison purposes (Xia and Khonsari, 2013).

The tests were run at shaft rotating speeds of 1800 rpm and 2700 rpm, with diluted propylene glycol as the working fluid. Temperatures were recorded for further analysis.

Comparison of the dimpled versus plain mating ring revealed that by appropriately texturing the sidewall, the interface temperature can be reduced by approximately 10%. The practical implications of this approach are that by lowering the interface temperature, one can minimise thermally-induced distortion and reduce wear. In addition to laboratory experiments, computational fluid dynamics (CFD) simulations were performed to visualise the flow field and to extend the range of operating conditions beyond what could be achieved in a laboratory setting.

Good agreement between theory and experiments attests to the usefulness and practicality of this approach. Note that this particular design requires no additional changes to flush arrangements or gland design, making this simple design attractive for implementation in an industrial setting.

Mating rings with a built-in heat pipe

The effectiveness of heat removal is directly related to the thermal conductivity of the mating ring.

Xiao & Khonsari (2015) reported the development of a mating ring with a built-in heat pipe with very high "effective thermal conductivity" to enhance transmission of heat away from the interface. The increased thermal capacity results from the phase change of a working fluid in the heat pipe.

A heat pipe has an evaporator section within which the working fluid vaporises by absorbing the heat input coming from the outside source, that is, the interfacial heat source. As a result of vaporisation, pressure increases and the vapour flows from the high-temperature region to the low-temperature end. The vapour then condenses on the inner surface of a wick inserted into the cavity of the mating ring and releases heat to the surroundings. The working fluid then returns to the high-temperature region by virtue of the wick's capillary action (**Figure 6**).

Laboratory tests, using a mating ring with a built-in heat pipe, revealed remarkable heat removal capacity compared with the conventional ring.

Specifically, at 1800 rpm, the measured interface temperature was approximately 47°C in this design, compared with 64°C in a conventional seal. At 2700 rpm, the heat-pipe ring's temperature was only 51°C, compared with 77°C in the plain ring without the built-in heat pipe.

Tribological measurements

In previous sections, different methodologies for improving heat transfer in mechanical seals were presented.

This section focuses on laboratory tests used to evaluate tribological performance. In particular, the results of a recent study by Xia & Khonsari (2015) are summarised.

The seal rings were made of heat-treated stainless steel (17-4 PH) with and without a built-in heat pipe rubbing against a rotating disk-shaped element made of the same material. The rubbing faces of both disks were polished to 1–2 helium light bands, which is typical in mechanical seals, and tested using a tribometer.

The disks were immersed in SAE engine oil for lubrication and the tests involved measuring temperature, the coefficient of friction and

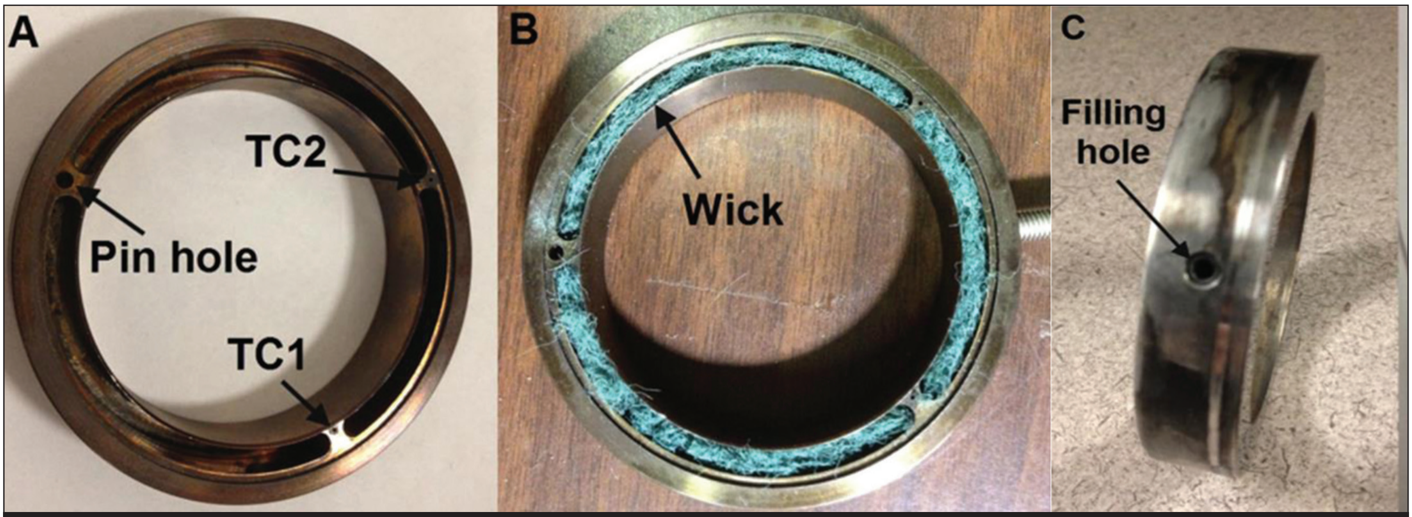

Figure 6. Photographs of a mating ring with a built-in heat pipe within its housing without wick (*A*); with wick (*B*); and the side view, showing the location of the filling hole (*C*), (Xiao and Khonsari, 2015).

wear. The operating speed was varied from 500 rpm to 1100 rpm.

Interestingly, the conventional design failed at 1100 rpm under the load of 133.5 N. In contrast, the ring with the built-in heat pump continued to operate at the same speed up to a 311.5 N load. Overall, the design with the heat pipe had a lower temperature and a more uniform temperature distribution.

A more uniform temperature field results in less thermal stress and damage, lower wear and longer service life. Furthermore, the coefficient of friction of the conventional design was about 0.15 before boundary contact, but was reduced to about 0.1 for the heat-pipe design.

Simple calculations showed that the film thickness of the heat-pipe design had been roughly 2.3–2.8 times greater than that of the conventional design – improving tribological performance by protecting the surfaces from rubbing.

Conclusions

This article has provided a brief overview of development work, by the research team at the LSU's CeRoM, relevant to improving the performance of mechanical seals.

Particular emphasis was placed on improving thermal performance. It shows that a variety of design options are available, which can reduce wear and improve seal service life in an effective manner, and can be put to use in an industrial setting.

Acknowledgements

The author wishes to thank his collaborators (Mr Somanchi, and Drs Jang, Luan, Peng, Pascovici, Qiu, Shen, Xia and Fesanghary) whose joint papers are used as the basis of this presentation.

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This feature article is based on a keynote paper entitled '*Heat transfer augmentation techniques to improve seal life*' that was presented at the 15th EDF–Pprime workshop, which was held in Futuroscope Chasseneuil, France, on 6 October 2016.

For further information on this conference, contact: 15th EDF–Pprime workshop:
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Recently Published Papers

- A. Rajendiran, Department of Chemistry, Annamalai University, Annamalai Nagar, India, and Bharat Petroleum Corp Ltd, Mumbai, India; A. Sumathi, K.Krishnasamy and S.Kabilan, Department of Chemistry, Annamalai University, Annamalai Nagar, India; and D. Ganguli, Bharat Petroleum Corp Ltd, Mumbai, India: 'Antiwear study on petroleum base oils with esters', *Tribology International*, Volume 99, July 2016, pages 47–56. Petroleum-based mineral oils are used for manufacturing lubricants for industrial applications. However, because of concerns of environmental pollution, the trend is to attempt to migrate to environment-friendly and biodegradable lubricants, by using vegetable oils and synthetic esters, as these too can function as lubricants. According to the authors of this study, substantial reduction in friction and wear can be achieved by mixing various proportions of mineral base oils and esters, without adding any conventional anti-wear additives. Also, this research reveals the optimum dosage of esters used for the reduction of wear and friction. This study is a useful tool for development of lubricants for industrial applications, say the authors.
- L. Galda, J. Sep and S. Prucnal, Faculty of Mechanical Engineering and Aeronautics, Rzeszow University of Technology, Rzeszów, Poland: 'The effect of dimples geometry in the sliding surface on the tribological properties under starved lubrication conditions', *Tribology International*, Volume 99, July 2016, pages 77–84. Surface topography should be constructed adequately according to the operating condition of the tribological system. Although there are many sophisticated lubrication systems that deliver lubricant to the sliding elements, during exploitational conditions co-acting elements also operate under starved lubrication. For example, whilst starting and stopping a machine, certain parts are exposed to wear or failure. This article presents the results of research work that examines sliding pairs in material matching of steel–steel. The tests were conducted using a pin-on-disc tribology tester, with modified sliding-pair geometry. The ball surface was subjected to grinding to obtain uniform contact of approximately 10 mm^2 with a co-acting disc. The disc surface was subjected to burnishing in order to produce dimples in various dimensions. The values of the coefficient of friction were measured and compared with all examined elements with pits and without depressions. It was established that the presence of dimples improved the tribological characteristics under starved lubrication conditions, at low sliding speeds. The positive effect of the dimple presence was more significant at a lower load. The dimensions of the depressions in the surface also influenced the tribological characteristics. The decrease in the coefficient of friction values was substantial where the dimples were shallow and the area density of the "oil pockets" was small.
- C. Kirner, J. Halbhuber, B. Uhlig, A. Oliva, S. Graf and G. Wachtmeister, Institute of Internal Combustion Engines, Technical University of Munich, Germany: 'Experimental and simulative research advances in the piston assembly of an internal combustion engine', *Tribology International*, Volume 99, July 2016, pages 159–168. The piston assembly is the most complex tribological system within an internal combustion engine. In order to fully exploit its optimisation potential, it is necessary to gain a deep understanding of this system. Therefore, in this paper experimental studies of two single-cylinder engines are combined with a simulation of the piston-ring pack, using computational fluid dynamics (CFD). The introduced measurement and simulation techniques enable a holistic approach to the investigation of the tribological conditions of the piston assembly, say the authors of this study. The results – like