Developing active lift technology to improve seal reliability for high viscosity oil services
Développement de la technologie « active lift » pour améliorer la fiabilité avec des huiles à haute viscosité

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Sealing high viscosity oils remained a challenge for plain face seals operating at high speeds. There is considerable heat generated at the sealing interface and a risk of dry running for very thin films. Hard face material combinations are preferred because there are concerns of blistering type face damage for carbon materials. But hard face material combinations need to operate with a much thicker film because there is no tolerance for dry running contacts, and this generally results in excessive leakages.

By controlling the pressure distribution and flow at the sealing interface, recent active lift technologies have been engineered on face seals in the aim to provide a stable hydrodynamic film with comparative leakages to plain face seals. This was achieved with the aid of computational design tools and a comprehensive set of test data for validation purposes. A methodology of acquiring accurate seal performance data including the sealing interface gap provided a full understanding on how the face seal operates. Tests were conducted on a number of plain face seals and face seals with active lift technologies to demonstrate their concepts.

L'étanchéité des huiles à haute viscosité reste un défi pour les faces conventionnelles fonctionnant à des vitesses élevées. Il y a beaucoup de chaleur générée à l'interface et un risque de fonctionnement à sec pour des films très minces. Un couple de matériaux durs est préférable, car les carbones peuvent cloquer. Mais les couples de matériaux durs ont besoin de fonctionner avec un film beaucoup plus épais parce qu'il n'y a aucune tolérance pour les fonctionnements à secs, et il en résulte généralement des fuites excessives.

En contrôlant les gradients de pression et de débit à l'interface, la technologie « active lift » a été mise en place sur les faces dans le but de fournir un film hydrodynamique stable avec des fuites comparables aux faces conventionnelles.

Ceci a été réalisé à l'aide de logiciels de calcul et des données d'essai à des fins de validation. Une méthodologie d'acquisition sur la performance d'étanchéité, y compris l'épaisseur de film interface, fourni une bonne compréhension du comportement de la face. Des tests ont été effectués sur un certain nombre de faces conventionelles et de faces avec technologie « active lift » pour démontrer leurs concepts.

1 Introduction

Plain face mechanical seals serve well on a majority of sealing applications. However, for some applications like for sealing high viscosity fluids at high pressures and speeds conventional plain face seal technology are limited. Associated with this type of sealing applications is considerable heat generated at the seal interface and a risk of dry running with mixed or even boundary fluid film lubrication. Furthermore, when cooling is unavailable, the temperature of the sealing interface could exceed the temperature limit of the sealed fluid.

In such application hard, ceramic seal face materials are preferred to overcome concerns of excessive distortions and blistering type of seal face damage often observed with soft, carbon seal face materials. Because of the limited tolerance for dry running contact of hard face material combinations, these seal need to operate with a considerable face gap. This is often achieved with the application of active lift technology (grooves or slots) to the sealing interface to enhance hydrodynamic, interfacial pressure generation. This hydrodynamic pressure enables the mechanical seal to operate with a stable, non-contacting gap and hence operate with lower power consumption and seal component wear. However, mechanical seals simply operating with such thick fluid film gaps will result in high, often unacceptable leakage levels. The challenge is to design an active lift feature for face seals that will generate hydrodynamic pressure and produce acceptable levels of leakage. Recent active lift technologies are close to achieving this by controlling the level of interfacial fluid film cavitation and reverse flow pumping effect with the use of geometric patterns and grooves [1-2].

Theoretical models are always limited by the availability of comprehensive test data for validation purposes [3]. Temperature and leakage measurements have served well in validating wet seal models but accurate film thickness measurements have always been the biggest challenge. Recent development of ultrasound technology in measuring liquid film gaps of "wet" seals has provided a solution to accurate measurements of the sealing interface gap [4].

This paper describes the application of ultrasound technology in measuring the interface gap of a purpose designed test seal to achieve a comprehensive set of seal performance results. Test results are presented for seals that operate with mixed lubrication and for seals with active lift technologies operating with full fluid film that are developed specifically for high viscosity oil applications.

2 Test seal and instrumentations

2.1 Compliant face seal concept

A typical mechanical face seal, shown in figure 1, would consist of a primary ring and a mating ring, one of which would be rotating and the other stationary with a fluid interface gap between the two opposing faces. The performance of the mechanical seal is therefore largely dependent on the characteristic of the sealing interface gap.

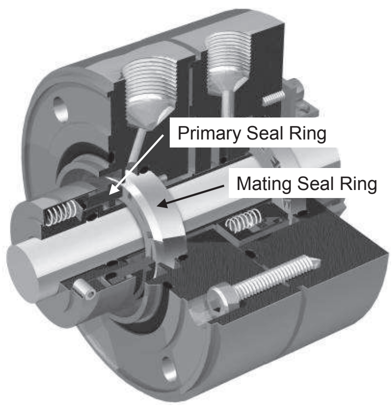

Fig 1 – Typical mechanical pusher cartridge seal, API arrangement 2

Typical face seals will operate with a non-parallel interface gap that changes with speed, pressure and temperature. In practice, the gap is engineered to control the leakage, performance and longevity of the seal. But for this study, it was important to obtain a consistent interface gap to obtain comparative and accurate results. A test seal was developed with a compliant primary face ring that provides a consistent fluid film gap with minimal face distortions. The sealing rings consist of a hard vs hard combination of SiC vs SiC. The test seal was designed to operate with a film thickness taper variation of less than 0.4 light bands across a 20 bar pressure range in comparison to the typical mechanical face seal that has up to 3 light bands of face curvature over the same duty range.

2.2 Film thickness measurements

Early work of fluid film research of mechanical seals and the development of metrology to measure the fluid film directly resulted in comprehensive computational mechanical seals models. These models based on empirical formulation of the hydrodynamic fluid film [5] were obtained using capacitance proximity probes embedded in the stationary seal ring component. This intrusive method of measuring the seal interface fluid film gap, where the tip of the capacitance probe needed to be flush with the sealing interface, may have produce inaccuracies and uncertainties in the measurements, in particular of those for high speeds and high viscosity fluids.

A recent developed technology of applying ultrasound in the measurements of thin fluid films was found to be successful for a number of applications including mechanical face seals [4]. This technique applies a semi-intrusive method where no disruption in the fluid film was imposed and hence the technology can be applied to standard seal components. Figure 2 shows the instrumented stationary mating ring used in the test seals. Two ultrasound sensors were bonded on the rear of the mating ring and centralised to target measure the thickness of the fluid film interface. Thermocouples are placed at the back of the seal ring component and are embedded as close as 1 mm from the sealing interface in order to measure the component and interface temperature.

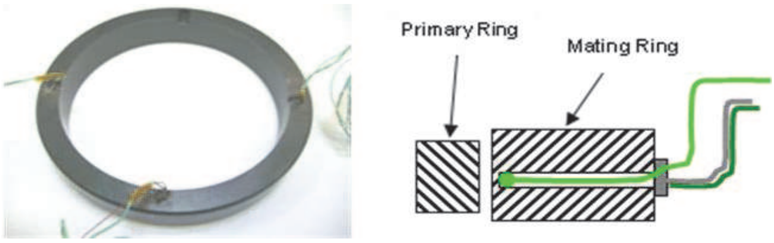

Fig 2 – Instrumentation of mating ring with ultrasound sensors and thermocouples

Figure 3 shows examples of the film thickness obtained with plain face seals of different surface roughness. Good cyclic repeatability of the film thickness would demonstrate a steady running seal. In this example, the difference in the surface roughness of the satin and matte lapped plain face component can be observed by the measured film thickness profiles.

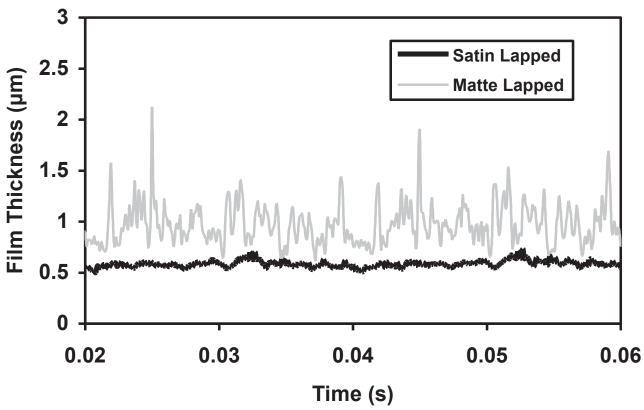

Fig 3 – Typical film thickness profiles with different primary ring finishes

Calibration of the measurement system was achieved by equipping the test seal with a polished primary ring with four shallow surface features of varying depths.

To ensure good comparative results, tests were conducted using a common instrumented mating ring, while any interface features or texturing was applied to the rotating primary seal ring. This minimized the variability in the sealing ring components and ensures small calibration errors of the ultrasound sensors.

2.3 Test rig and test procedures

Testing was conducted on a test rig dedicated to this project (see figure 4). The test rig is facilitated with data logging facility for speed, torque, temperatures and vibration. The test seal was also equipped with a condition monitoring system that uses externally mounted acoustic emission (AE) sensors used to detect severe seal face contacts and prevent catastrophic seal failures.

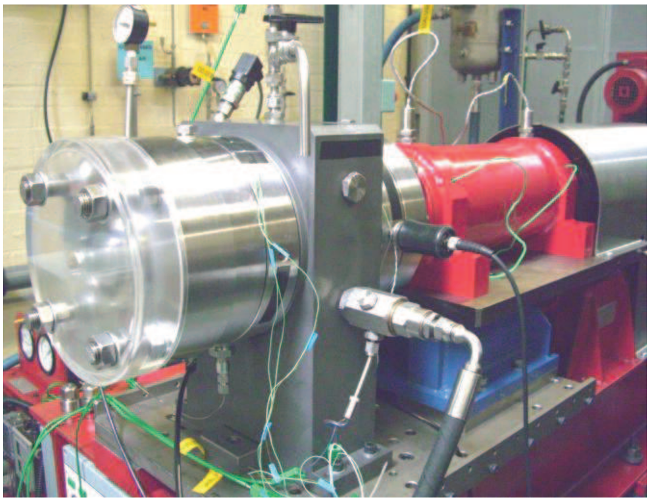

Fig 4 – Test rig

The seal performance was established by varying speed and pressure at set fluid supply conditions, mainly flow rate and temperature. Tests were conducted in a speed range from 0 rpm to 4500 rpm and a pressure range from 5 bar-g to 20 bar-g. Each pressure and temperature point was held for several minutes until steady state was reached before the film thickness was recorded.

Further tests were conducted to connect the film thickness at a specific speed and pressure condition with seal leakage. As seal leakage is found to be extremely sensitive to small changes in the fluid film gap, leakage was therefore continuously measured and logged over an extended running period and averaged for each operational point.

3 Test results

The following shows a selection of test results from testing seals with conventional face technology and seals with active lift technology.

In order to gain a better appreciation of the hydrodynamic fluid film gap, the fluid film thickness is normalised with the combined surface roughness of the sealing components, see equation 1.

$$H = \frac{h}{\sigma} \qquad [1]$$

where h is the film thickness
σ is the combined surface roughness of the sealing faces (typically 0.02 -0.2 μm Ra)

Given the above, the resting gap or static gap of a mechanical seal is generally just below 3 times the combined RMS of the surface roughness. Assuming a Gaussian distribution of the peak to valley of the surface asperities density, in practical terms, full fluid film lubrication is considered for H > 3 and mixed lubrication for H < 3 [6].

3.1 Conventional plain face seals

Hard vs hard seal material combinations have limited dry running capacity. The seal components generally use a surface finish combining a polished component running against a component with controlled coarse surface finish to provide sufficient lubrication at the sealing interface.

Figure 5 shows an example of a conventional plain face seal operated with incorrectly lapped and polished seal components. The seal failed due to oil starvation shortly after start-up. Although, the seal was able to run for a short period of time with considerable high interface temperatures, one sudden hard asperity contact was enough to start a continuous deterioration of the seals performance. This was captured by the erratic fluctuation of the fluid film gap and accompanied by increased acoustic emission (AE) and torque readings.

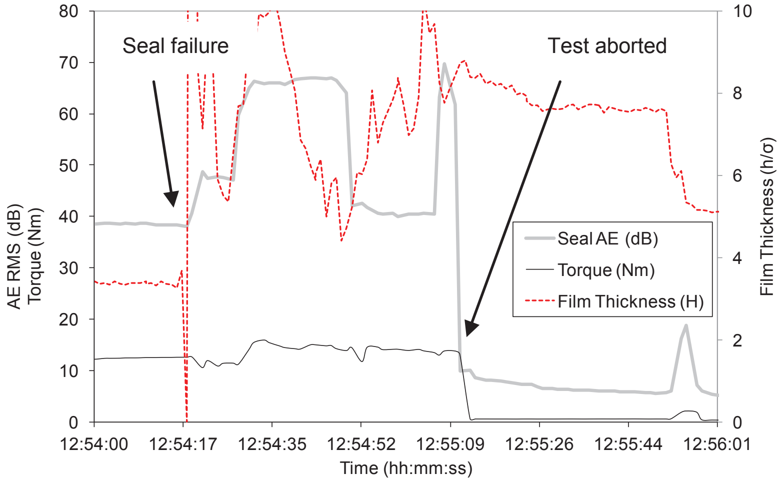

Fig 5 – Seal failure from dry running with plain face seal, 5 bar-g, 1500 rpm

Figure 6 shows an example of a conventional seal with correctly finished seal face components. For low pressure conditions, similar to the previous example in figure 5, the seal establishes stable full fluid film lubrication already from 1000 rpm. However, pressure shows a significant effect on the film thickness and the ability of the seal to maintain a full fluid film gap. For high pressures, full hydrodynamic film was only achieved for speeds above 3000 rpm (H > 3). Above 3500 rpm the gap is steadily increasing with speed, which resulted in a reduction of the interface temperature shown in section 3.3, figure 9.

The results confirm that a plain face seal has minimal hydrodynamic lift capacity supporting a stable full fluid film. For low speed and/or high pressure, it would be typical for a plain face seal to run with a degree of mixed or even boundary fluid film lubrication.

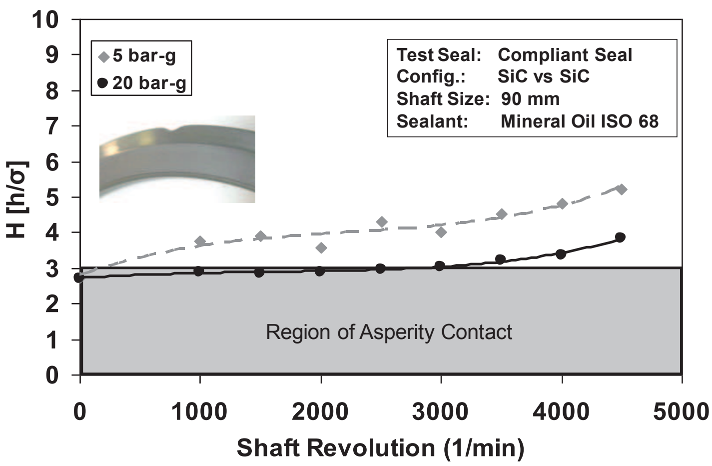

Fig 6 – Interface gap for conventional plain face seal

For application where interface lubrication is minimal or critical, improvements can be expected by adding slots or grooves, also known as "Hydropads", to the sealing interface [1]. Hydropads are grooves or cut-outs of up to a millimetre depth on the pressure facing diameter of the sealing ring, which in effect reduces the hydrostatic net closing force at the sealing interface. Furthermore, the thermal and pressure distortions created by the deep grooves generates a circumferential wavy pattern that is sufficient to improve the hydrodynamic fluid film generation.

The hydrodynamic lift generated by the hydropads can be seen in figure 7. In comparison to the plain face seal, the hydropad seal operates with a full fluid film that increases linearly with speed. The pressure showed little influence on the dynamic film thickness, which is an indication of the film stiffness or stability. As a result of this, the seal operated with a significantly lower temperature than the plain face seal (section 3.3, figure 9). However, the larger hydrodynamic film gap generated by the hydropads, particular at higher speeds, will inevitably result in greater seal leakage.

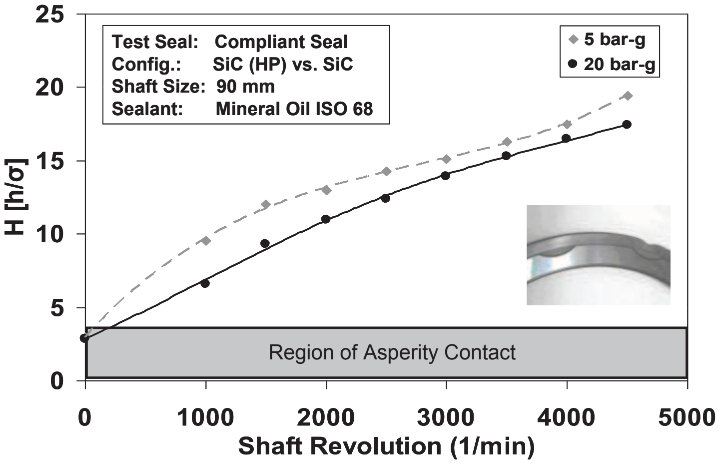

Fig 7 – Interface gap for Hydropad seal

3.2 Application of advanced active lift technology

Advanced active lift technology, in the context of this paper, is understood to use surface patterns or grooves of only a few micrometers depth [1]. The grooves generate a strong hydrodynamic interface pressure and establish a non-contacting fluid film gap. They also include a mechanism to reduce the interface leakage to a minimum (reverse pumping mechanism). Such groove designs, in theory, could achieve zero leakages at full fluid film lubrication by maximising and tuning the efficiency of the reverse pumping feature.

The Y-spiral groove is an example of such advanced active lift technology developed for high viscosity oil applications. This groove combines a conventional OD spiral groove with a return pumping groove. The groove is designed to generate hydrodynamic lift as well as reducing seal leakage. The performance of the test seal employing the Y-spiral groove is presented in figure 8. Test results show that the groove generated a strong and stable hydrodynamic film across the speed range. The efficiency of the return pumping grooves improves with speed, also resulted in a minor reduction in the fluid film gap.

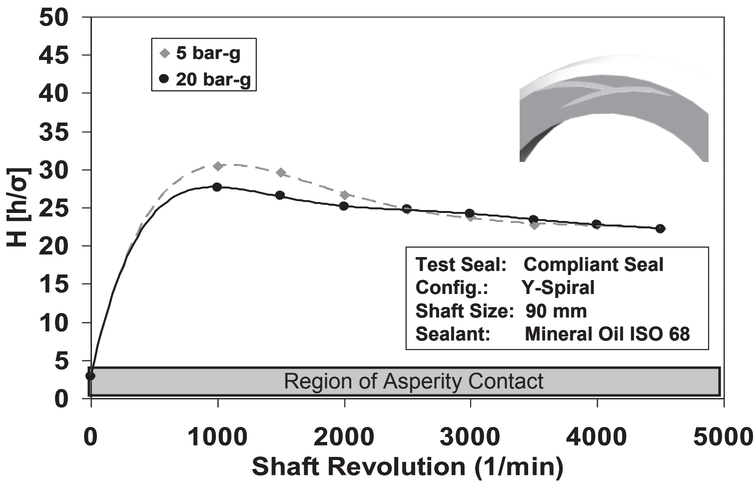

Fig 8 – Interface gap for seal with Y-Spiral groove technology

3.3 Seal performance comparison for high viscosity oil seals

Up to this point the paper presented a comparison of performance based on the fluid film thickness achieved by different seal interface technologies. In the following, a comparison of the key seal performance parameters relevant to the application of mechanical seals, seal interface temperature and leakage, is given.

The benefit of active lift technology can be seen in figure 9. The hydrodynamic films generated by the Y-spiral groove or the hydropads result in a significant reduction of seal interface temperature compared to the conventional plain face seal. For high speeds, the Y-spiral groove and hydropads showed similar interface temperatures, which is an indication of similar fluid film thickness gaps. However, at "low" speeds, a shallow groove, such as the Y-spiral groove, has an advantage over the deep hydropad in generating a large, stable fluid film gap. This is not only evident in the measured fluid film gaps for hydropad and Y-spiral groove (figure 7 - 8) but also in the lower face temperature shown in figure 9.

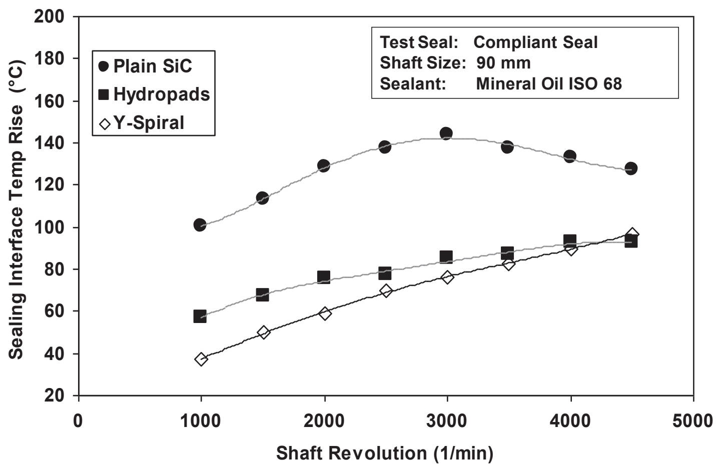

Fig 9 – Comparison of maximum interface temperature, 10 bar-g

Figure 10 shows the measured leakage performance of the test seals. The leakage of the plain face seal was mainly governed by the low fluid film gap, operating mostly in the mixed lubrication regime.

The leakage of the hydropad seal increases significantly with speed, which is in good agreement with the hydrodynamic theory of a wavy-face seal.

Unlike the "conventional" seal face technologies, the leakage characteristics of the Y-spiral groove seal showed reduced leakage with speed. The reduction is not only explained by the slightly reduced interface film thickness with increasing shaft speed (figure 8) but foremost the reverse pumping action by the groove. At 4500 rpm the leakage of the Y-spiral groove is comparable to that of the plain face seal but operates with sealing gap that is 4 times greater. Compared to a hydropad seal, the Y-spiral groove operates with a similar fluid film gap but significantly reduced leakage at higher shaft speeds, the target condition for this groove design.

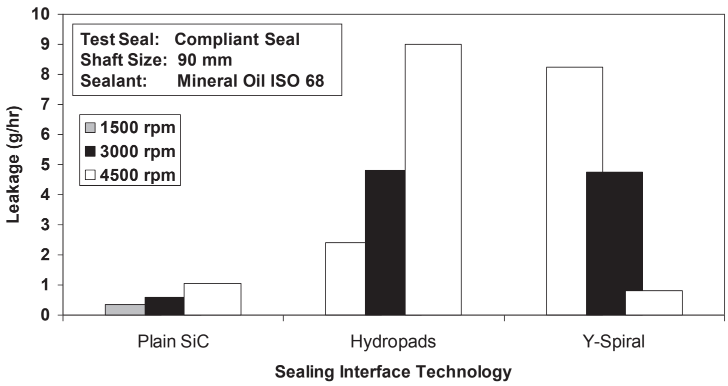

Fig 10 – Comparison of seal leakage, 10 bar-g

4 Conclusions

The application of ultrasound sound technology in obtaining accurate film thickness measurements was shown to provide valuable test results to further the understanding of the hydrodynamic fluid film gap for seals with target application of high viscosity, high speed oil sealing.

The investigation confirmed that conventional plain face seals operate mainly in mixed lubrication regime, which limits the selection of seal face materials best suited for high viscosity oil sealing.

The conventional solution of enhancing interface lubrication by the mean of hydropads proven to be successful but limitations exist for low speed gaps and high speed leakage.

For the target application of high viscosity, high speed oil sealing a Y-spiral groove appears to be very successful, providing a strong, stable fluid film and low level of seal leakage.

5 References

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