NOVEL TESTING OF FLUID LUBRICANTS FOR SPACE APPLICATIONS AT LOW TEMPERATURES

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ABSTRACT

The results of the first vacuum mini traction machine tests of fluid lubricants are presented herein. These tests characterise the performance of 4 vacuum lubricants from room temperature down to -80°C. Several lubricants, including common space fluids Fomblin Z25, Nye 2001a, and Braycote 601EF, have been tested to study how the fluid lubricant behaviour changes based on the test conditions, in particular at reduced temperature.

Overall, temperature was found to have a significant impact on the performance of all the fluids tested. At low temperatures, unique insights into the behaviour of the fluid-lubricated contacts have been found, as traction properties vary as temperature decreases and lubricant properties transition from a liquid to more solid state. The observations, gathered at a tribological level for the first time, were found to be unique to the fluid under test and test conditions, hence may be used in future to inform lubricant selection.

For oils the traction generally increases as temperature decreases and the behaviour shifts towards the hydrodynamic lubrication regime. This shows that the viscosity is increasing, and the fluid thickening and solidifying, with a reduction in temperature.

Grease behaviour appears more complex, with traction inconsistently increasing as temperature decreases and a transitional behaviour at moderately low temperatures. This transitional behaviour is suggested to result from, and varies due to, the fundamental product formulation.

Testing near, or below, the manufacturer reported pour point or minimum application temperature was shown to be potentially problematic. High, unsystematic traction behaviour can be observed.

The first interferometric studies of a Fomblin Z25 fluid film, under thermal-vacuum conditions, are presented. These first analysed results of the film thickness are observed to give comparable trends to those taken in ambient, room temperature, conditions in the literature.

Further analysis of this data is ongoing, it is expected that the VMTM will provide more comprehensive data that can be used to model mechanism contacts and connect fundamental lubricant properties to component traction.

1 INTRODUCTION

The tribological performances of fluid lubricants used in spacecraft components, are of critical importance to ensure the success of a spacecraft mechanism during flight. However, much of the focus of testing fluid lubricants is at relatively high temperatures (≥-20°C) and many upcoming missions will involve considerable operation in much lower temperature environments. Testing in lower temperature vacuum environments is often onerous to perform, both due to the investment in an appropriate test setup and support equipment, and the continuous critical control of the test temperature.

As a result, data to support the selection of fluid lubricants when operating at more extreme cold temperatures is restricted. There is a significant interest in identifying methods to characterise, rapidly and effectively, fluid lubricants, particularly for low temperature vacuum applications. Such methods are needed for many reasons from optimising the lubricant selection in application-relevant contact conditions to ensuring factors such as increased viscous losses at low temperatures are within the application design parameters.

This paper introduces a new system to rapidly characterise the lubrication properties of fluid products, a vacuum mini traction machine: the VMTM. The VMTM is an evolution of terrestrial devices that can rapidly study the tribological properties of a contact under a range of conditions by varying speed, load, temperature, and slide-roll ratio.

2 BACKGROUND

Terrestrial traction instruments come in various forms and sizes, with the VMTM evolved from smaller laboratory instruments such as PCS instruments commercial MTM version 2 [1] or a Wedeven Associates Machine (WAM) [2].

These commercial machines are designed, and have proven to be useful in being able, to test across a range of application conditions (speed, load, SRR etc) in order to understand the likely application behaviour of a lubricant in a system. Primarily such testing involves the generation of Stribeck curve(s). However, there are a number of other methods and uses for such instruments, particularly when combined with an optical interferometry technique: not only can tractional behaviour of lubricants be measured but also the role of tribo-films formed at the contacts (either due to the presence of additives within the lubricant or because of tribo-degradation) can be observed and measured.

3 EQUIPMENT

The internal design of the VMTM consists of two mechanical assemblies: rotating disc and ball motor assembles comparable to many commercial machines. Unlike commercial machines that operate within ambient air, these assemblies are located in a large box vacuum chamber fitted with a standard pump system. The chamber is designed to allow studies to be conducted in air, vacuum and in controlled gas environments. The sub-assemblies within the chamber are mounted to a base plate to allow for the complete traction assembly to be removed, shown in Fig. 1 below.

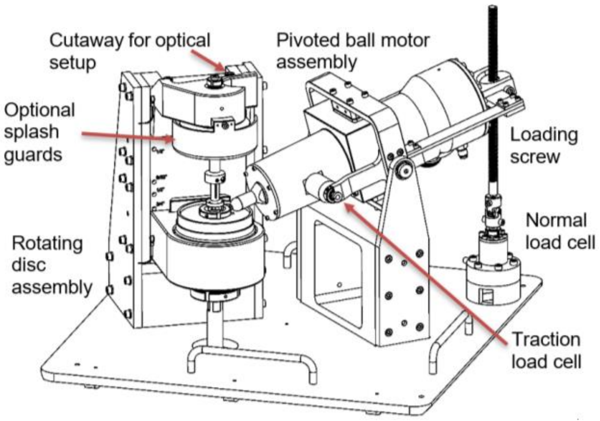

Figure 1: Diagram showing key parts of the VMTM.

The rotating disc assembly can accommodate a lower disc (traction) and an upper disc (optical). Both the upper and lower shafts of the two bearing housings contain electric heaters, heat exchanger piping and temperature sensors in close proximity, so that the sample temperature can be monitored and controlled. The VMTM can run at temperatures from -100°C to +100°C. VMTM operation within a thermal-vacuum environment ensures the traction data gathered is directly applicable to the needs of the space industry. The VMTM is believed to be unique in its ability to study a wide range of environmental conditions, well beyond the capabilities of other commercial traction machines.

A cutaway exists within the top disc sub-assembly to allow the interferometric optics (see Fig. 2) access to view the contact. The VMTM incorporates an optical interferometry system used to directly view and measure the films generated within the contact.

The second mechanical assembly contains the motor sub-assembly, to drive the ball, attached to a pivoted frame to enable a loading screw to vary the pitch of the motor housing; which positions and loads the ball against the traction or optical disc. Movement of the ball on the sample disc, parallel to the surface, is guided by a pair of flex-pivots connected to the motor housing and constrained with the traction load cell on one side.

One critical factor in the design of these systems is the lubrication. As space mechanisms are often minimally lubricated, a pot or lubricant pump was not developed on the VMTM as it would have been unrepresentative.

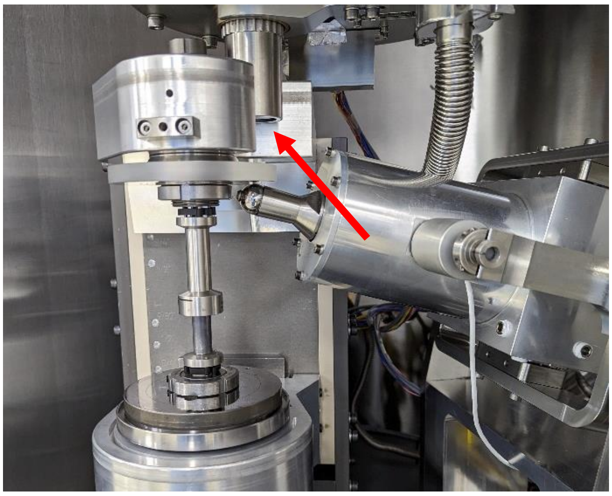

Figure 2: Image showing the optical disc measurement setup with the lens (arrowed) protruding into the cutaway.

4 MEASUREMENTS

The primary aim of traction machines is to gather traction data as a function of speed. When an appropriate range of speeds is selected, Stribeck curves, as shown in Fig. 3, can be used to characterise the contact.

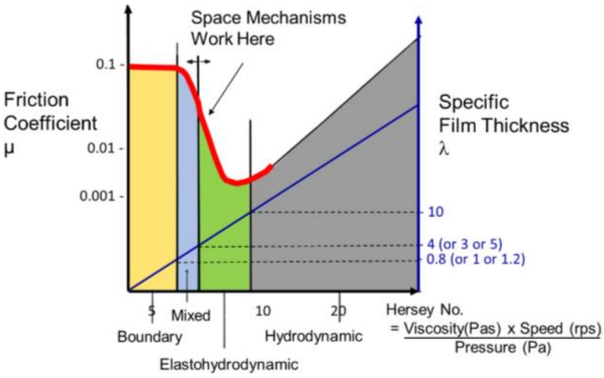

Figure 3: A typical Stribeck curve (taken from [3]).

4.1 Key Parameters

To define the traction conditions of a contact there are a number of variables to be considered. The most important parameters to understand when studying traction are the slide-to-roll ratio (SRR) and entrainment speed (U). Entrainment speed is effectively the average surface speed of the contacts. Analogous to entrainment speed is sliding speed (u_S), which is the difference between the two surface speeds. SRR is the ratio of the sliding to entrainment speed, often expressed as a percentage.

These parameters can be defined in terms of the two fundamental speeds of the system, the disc speed (u_D, in mm/s) and ball speed (u_B, in mm/s), using equations 1 to 3 below.

$$U = \frac{u_D + u_B}{2} \quad (1)$$

$$u_S = u_D - u_B \quad (2)$$

$$SRR = \frac{u_S}{U} \times 100 = \frac{u_D - u_B}{u_D + u_B} \times 200 \quad (3)$$

To achieve the relevant entrainment speed the ball can either be under or over rotated relative to the disc. The traction data reported here is in terms of the characteristic coefficient of traction (CoT) calculated using:

$$CoT = \frac{T_D - T_B}{2N} \quad (4)$$

Where N is the normal force and, T_D and T_B are the traction forces measured when the disc and ball, respectively, are moving faster than the entrainment speed. Hence, although CoT is reported in terms of a single, positive percentage SRR, it is calculated from the traction produced from both positive and negative SRRs.

4.2 Test Parameters

The SRR and speed can be set to be relevant to a particular application. Tests were run at two SRRs representative of bearing applications and gear applications.

In previous work [4] an envelope of applicable VMTM traction conditions were modelled in the CABARET ball bearing analysis software. Based on this a 0.5% SRR at 1.5 GPa was selected to be representative of a bearing application and was within the capabilities of the existing instrument setup.

To define an appropriate SRR and running conditions for gears, the contact of a space-relevant spur gear was modelled at ESTL. Although the data cannot be fully disclosed herein, it was found that for a typical spur gear the SRR can vary between -60% to +40% depending on the point in the contact. The range is not symmetrical due to the different radii of the pinion and gear components. In other applications, particularly heavily sliding applications such as worm gears and lead screw applications, the range of SRR will vary and likely will approach 200% SRR. Hence, a decision was made to base the VMTM testing on the maximum, symmetrical, representative SRR i.e. 40% SRR. The loading of gears can vary significantly, and it was decided that an SRR of 40% at 1 GPa would be sufficiently relevant to gear applications.

As the aim in traction tests (and indeed general Stribeck testing) is to cover a wide range of speeds a logarithmic-based scale must be used. A preferred number scale for the VMTM characterisation tests was used. The preliminary speeds outline the pattern used: 10, 12.5, 16, 20, 25, 31.5, 40, 50, 63, 80 and 100 mm/s. This range was then studied, reviewed and extended in order to ensure an appropriate range of data was collected. In many cases, a full range of 1 to 500 mm/s was used. Tests were not run beyond ~500 mm/s as this proved to be problematic for the lubricant retention.

The speed of the test defines the time for each test. As a minimum each test is run for twice the minimum time to complete 2 revolutions of the ball or disc or 10 s, whichever is longer.

Similarly optical testing can be accomplished using a similar, logarithmically scaled speed range. However due to the time needed to ensure appropriate images are taken the duration of each step is extended to 30s.

Traction testing was run down-to or just below the manufacturer stated application and pour point temperatures to fully understand the fluid behaviour at low temperatures. All tests were run under a vacuum, less than 5 x 10^{-6} mbar.

5 METHOD

5.1 Samples and Lubrication

To measure traction the VMTM runs a through-hole drilled ¾ inch ball against a 100 mm outer diameter (32 mm inner diameter) disc both made of 440C steel, as standard. VMTM discs are specifically finished to a high polish <0.030 µm Ra, to replicate the expected finish of bearing surfaces.

In oil tests a syringe is used to apply fluid of sufficient volume to as far as possible allow the contact to be fully flooded. In traction tests oil then readily spreads across the surface, due to the low surface tension. In optical tests the process is less rapid and often leads to dripping, making testing time sensitive.

Grease is similarly applied directly to the disc with a syringe or spatula, in excess, then redistributed around the contact during run-in.

5.2 Traction Testing

A series of tests were conducted covering the range of temperatures and both SRRs, with the speed ramps being performed for each test. The ball and disc were only changed when evidence of wear became apparent. For each SRR temperature was varied from +20°C to -80°C in 10°C increments.

5.3 Optical Testing

Testing was undertaken against the optical disc at a low SRR, 0.5%, and low load (10 N) to avoid damage to the optical coating. Temperature was controlled at -40°C, with work ongoing to gather data as a function of temperature and optimise the measurement and analysis procedure. Optical images were taken manually throughout each test step and analysed after testing. Thus far, measurements of the fluid film properties have only been made using Fomblin Z25.

5.4 Fluids

The results from testing four lubricants are reported herein:

- Fomblin Z25 – Z-type perfluoropolyether (PFPE) molecules are widely used as oils, and in greases, for the space industry and have a long heritage, [5]. Hence Z25 provides a key baseline of vacuum oil behaviour for traction testing and the first optical tests.
- Nye 2001a – A pure multiply alkylated cyclopentane (MAC) oil commonly used, with a wide application heritage. The oil has a much higher minimum application temperature (-45°C) than the PFPE fluids (typically -75°C).
- Braycote 601 EF – a PFPE oil and PTFE particulate grease commonly used in the space industry, with a long and extensive heritage.
- Uniflor 8971 – a PFPE oil and PTFE particulate grease reported to contain a lighter, lower viscosity "Z15" type, potentially best suited to lower temperature applications.

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6 RESULTS

6.1 Oil Traction Testing

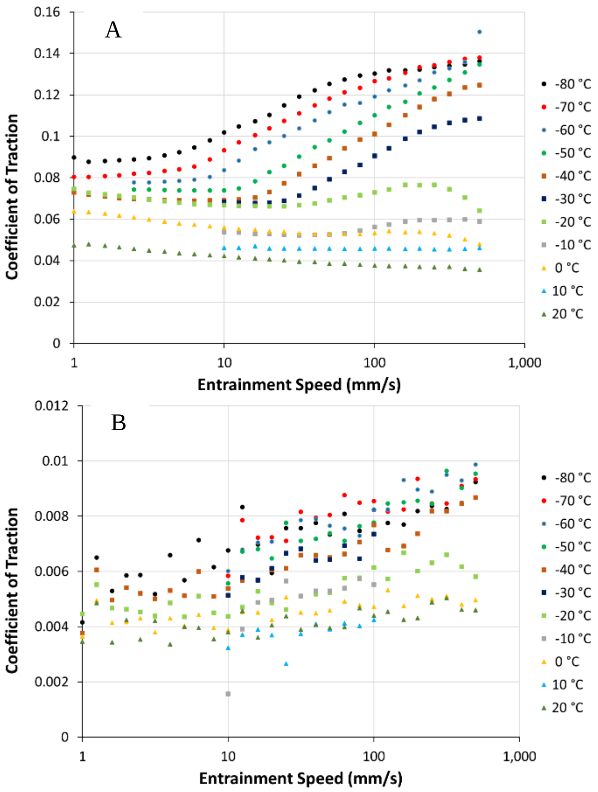

Figure 4: CoT, obtained over a range of temperatures at (A) 40% and (B) 0.5% SRR for Fomblin Z25.

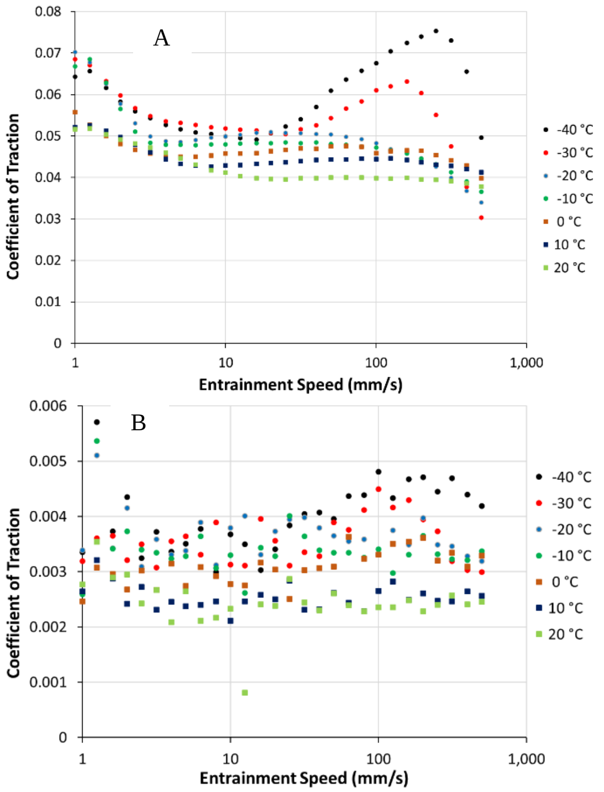

Figure 5: CoT, obtained over a range of temperatures at (A) 40% and (B) 0.5% SRR for Nye 2001a.

The measured CoT for Fomblin Z25 at 40% and 0.5% SRR are shown in Fig 4 A and B respectively. There is a clear temperature dependence in the data with traction increasing as temperature decreases. The 0.5% SRR data is noisier, even at a higher load, due to the low traction forces being measured.

It is apparent that as temperature decreases the gradient in the curve increases at high-speed, indicating a progression from mixed towards hydrodynamic lubrication. This trend can be assumed to be due to an increase in viscosity. Particularly below -20 °C the high-speed behaviour becomes more hydrodynamic in nature, perhaps due to a much higher viscosity in the oil.

Although there is some literature data on the viscosity of space fluids as a function of temperature [6], it was not possible to successfully collapse the data to create a simplified trend using this reference data. This suggests differences between features of the methodologies, the impact of localised high stresses or tribological heating.

CoT for Nye 2001a at 40% and 0.5% SRR are shown in Fig. 5 A and B respectively. Traction clearly increases as temperature decreases. It is also apparent in Fig. 5 that as temperature decreases gradient of the curve at high-speed increases: a progression towards hydrodynamic lubrication, due to an increase in viscosity.

The 40% SRR CoT data at -30°C and -40°C, is significantly higher and shows more strongly a hydrodynamic lift and even a mixed “U-shape” trend indicating a significantly higher viscosity as the pour point of the fluid is approached. At very high-speed traction reduces, an indication of starvation of the contact.

6.2 Grease Traction Testing

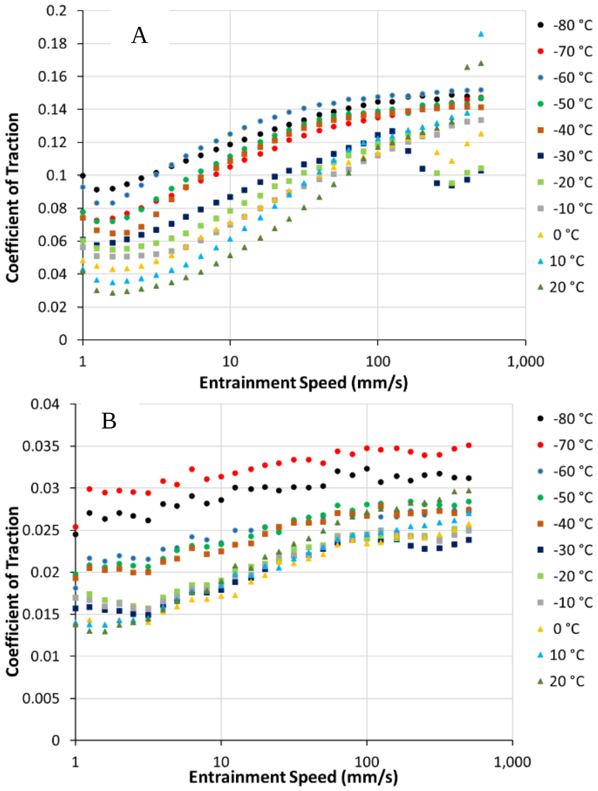

Figure 6: CoT, obtained over a range of temperatures at (A) 40% and (B) 0.5% SRR for Braycote 601 EF

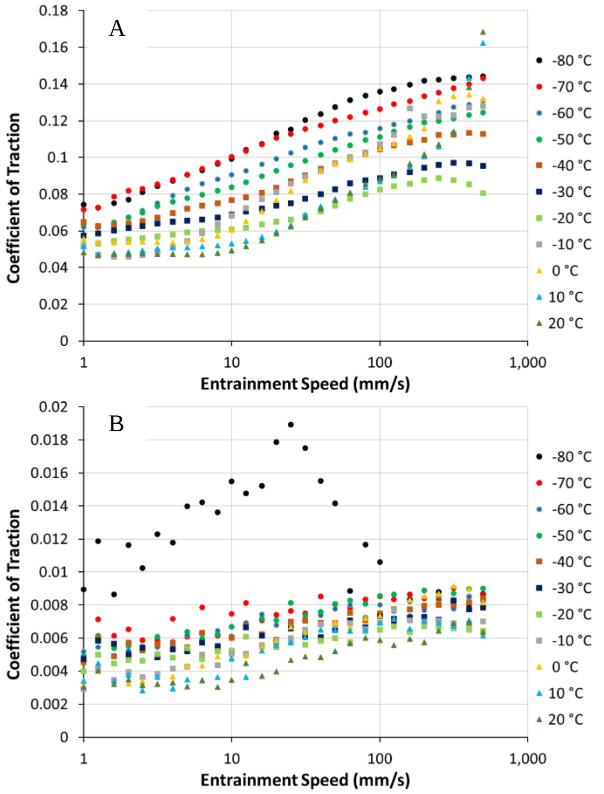

Figure 7: CoT, obtained over a range of temperatures at (A) 40% and (B) 0.5% SRR for Uniflor 8971

CoT for Braycote 601 EF at 40% and 0.5% SRR are shown in Fig. 6 A and B respectively. As seen in base oils, there is a clear general temperature dependence in the data with traction increasing as temperature decreases.

As shown in Fig. 6 A, 40% SRR, the temperature dependence may be less straight forward than for oil samples. As temperature decreases some curves appear “out of order” for example the highest curve is -60°C which is above the -80°C curve. Similarly in Fig 6 B the trend may not be in the expected order (for example -70°C tests give a higher traction than -80°C).

Interestingly, there appears to be 3 data groups in Fig 6 B: -70°C to -80°C; -40°C to -60°C; and -30°C to 20°C. It is also interesting to note that although the overall traction increases as temperature decreases the gradient appears to decrease. There is a clear hydrodynamic trend, albeit with data at high, >-30 °C, temperature appearing to present some mixed behaviour at low speeds.

However, it appears there is a gradual increase in the boundary traction (which was also seen in oil tests) as temperature reduces whilst there is a reduction in the gradient of the curve.

There is deviation in the data taken at -20 and -30 °C, a drop and recovery in traction, which appears to be starvation of the contact in these tests. This may be due to a simple reduced amount of lubricant in these tests but may also suggest a change in the behaviour of Braycote 601 EF at these temperatures.

COT for Uniflor 8971 at 40% and 0.5% SRR are shown in Fig 7 A and B respectively. As with other lubricants, traction increases as temperature decreases. Fig 7 shows there is a clear hydrodynamic trend, albeit with data at -80°C, 0.5% SRR appearing to form a separate curve.

Although, as was apparent for Braycote 601 EF, the temperature dependence is less systematic than seen with base oils:

- At high speed Fig 7 A shows -20°C and -30°C has the lowest traction.
- Fig 7 B shows particularly high, varying traction at -80°C. This temperature is below the recommended minimum application temperature of the grease and suggest the fluid is solidifying and not able to flow smoothly thorough the contact.

The data at 1 mm/s shows there is a gradual increase in the boundary traction as temperature reduces whilst there is a reduction in the gradient of the curve, a trend also seen with Braycote 601 EF. However, there is a significant shift in the data taken at -10°C to -20°C. The change in the behaviour observed at -20°C, is likely due to a change in the oil behaviour. Uniflor 8971 is believed to have a thinner, lighter (Fomblin Z15 or similar) oil than compared to Braycote 601 EF (815Z, similar to Fomblin Z25). In addition, the full grease will likely have a different composition (in terms of thickener, additives etc), changing the magnitude and temperature of the trend transition seen previously for Braycote 601 EF at -30°C to -40°C.

6.3 Further discussion

There are a number of clear differences already apparent in the data gathered to suggest differences in the performances of the fluids tested.

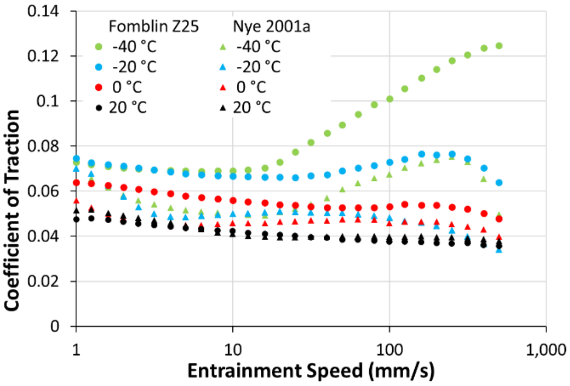

Figure 8: Comparison of oil data at 40% SRR

Fig. 8 compares some of the data gathered for the Fomblin Z25 and Nye 2001a oils, which perform similarly, between +20°C to 0°C: as comparably low CoTs are measured in this range.

There is a strong rise in both the hydrodynamic and mixed regime traction from -20°C to -40°C, for Nye 2001a. At low speeds it is therefore suggested that as temperature decreases, the traction observed for Nye 2001a become higher and there is a potential for increased wear due to boundary-mixed lubrication. By comparison the trends in the Fomblin Z25 suggest that there is a thicker, nearer mixed-hydrodynamic fluid film.

At low temperatures, between -40°C to 0°C, the data shows significant differences. These results suggest that Nye 2001a should perform significantly better in some applications (in particular those at relatively high speeds) due to the consistently lower CoTs compared to Fomblin Z25. Note, parallel observations can be made with the 0.5% SRR data. However, at temperatures below zero the dynamic viscosity of Nye 2001a is reported in the literature to be considerably higher than Fomblin Z25 [7], making this observation inconsistent with a simplistic understanding of fluid behaviour in the contact: as viscosity increases the fluid forces increase and therefore the traction. In addition, it is worth noting that the related bearing torque data at below zero temperatures, are often similar or show a potential benefit to the use of Fomblin Z25 [8] compared to Nye 2001a. However, the reported torque differences also cannot readily be correlated to the differences in dynamic viscosity.

It is discrepancies like these, where there are differences between the scientific models available in the literature, based upon fundamental lubricant properties, and empirically observed component properties (in particular torque) that the VMTM, at least in part, is designed to study. Such differences may exist due to a lack of understanding of the required fluid and contact properties, or appropriately defined models; the study of which is a key subject of interest in the literature [9 &10].

At this time, it has not been possible to use the VMTM gathered data to further the existing literature in this area. However, this is the first data gathered on a new instrument and connecting the traction data to more fundamental properties, as well as "higher" level properties such as bearing traction, remains a topic for subsequent study and analysis.

The greases exhibit more complex behaviour, however in Fig. 9 it should be clear that across most of the speed and temperature range Braycote 601 EF provides higher CoTs than seen in Nye Uniflor 8971. At near room temperature (0°C to +20°C), the CoTs for the two greases are more comparable, and lubricant selection would depend on the exact application conditions, and the relevance of other relevant lubricant properties. At lower temperatures traction differences are more apparent, demonstrating a potential benefit to using the Uniflor 8971 formulation (particularly at high speed).

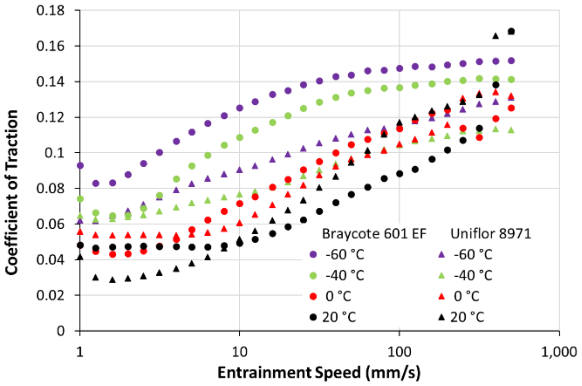

Figure 9: Comparison of grease data at 40% SRR

This data shows for the first time at a tribological level clear temperature-dependant differences in the traction properties of lubricants that may impact selection. Overall, the selection of a suitable lubricant should consider the application specific conditions to ensure the most appropriate choice. Particularly, as the other lubricant properties (such as outgassing properties and the vapour pressure) must be acceptable [11 & 12] and balanced against the traction performance.

6.4 Optical Testing

To further understand the properties of fluid lubricant contacts, interferometric images, such as the ones in Fig. 10, were captured. The interferometric images gathered during the testing for Fomblin Z25, clearly shift in colour as the speed increases. The colour (and the surrounding fringe pattern) is produced due to the characteristics of the fluid and the contact geometry, the shift in colour correlates to the height of the fluid film.

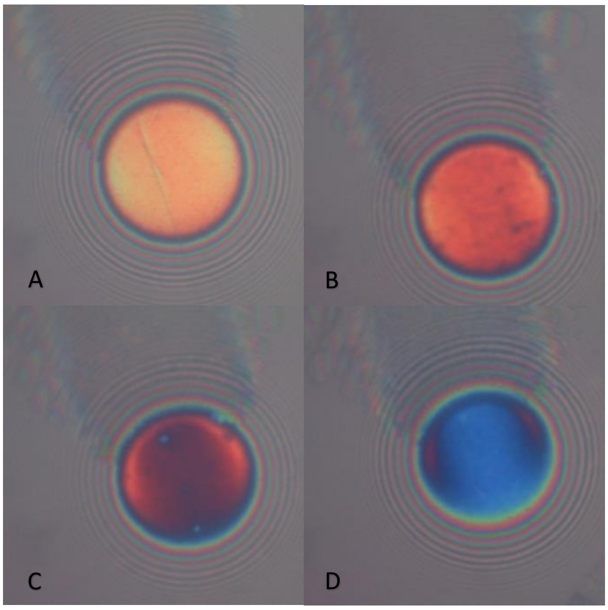

Figure 10: Interferometric images of the contact containing Fomblin z25 at -40°C, 10 N, 0.5% SRR, and 2.5 mm/s(A), 5 mm/s (B), 10 mm/s (C) and 20 mm/s (D)

These are the first images under vacuum and at low temperature. Current analysis uses the hue [13] of the image to deduce the height of the fluid film in the contact. Alternative methods are currently under review to improve the speed, accuracy, and detail of the analysis.

As speed increases the central film height also increases, as shown in Fig. 11. The relationship between the central film height; the fluid properties; and contact parameters, is a particularly well studied area in the literature [14 & 15]. In the literature a power law has been presented with an exponent of 0.67 at room temperature, in air.

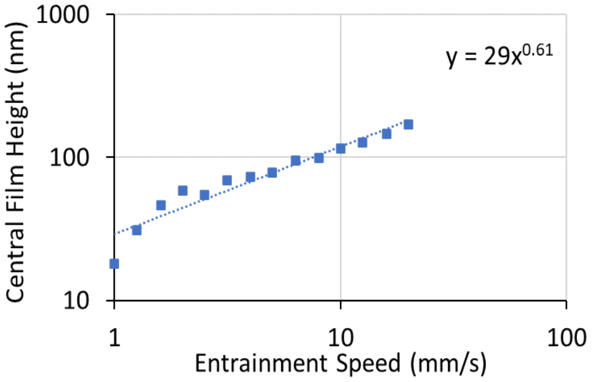

Figure 11: Measured central film height as a function of entrainment speed in the contact containing Fomblin z25 at -40°C, 10 N, and 0.5% SRR

The clear relationship between height and speed found in this analysis is comparable to the results in literature. These results demonstrate the VMTM optical setup, and subsequent analysis, can be used to directly study the fluid film properties of lubricants under thermal-vacuum conditions. For future work, the trends observed are expected to provide vital understanding of the contact and environment specific fluid properties. When combined with the traction measurements, these interferometric measurements can fully define the fluid contacts, and be used to accurately model mechanism contacts to predict the expected torque properties.

7 CONCLUSIONS

The first tests have been conducted on the new VMTM instrument to characterise the performance of vacuum lubricants. Tests were conducted from room temperature down to -80°C. The results were found to be unique for the fluid under test. To this authors knowledge this shows for the first time, at a tribological level, traction characteristics for each fluid that varied with test temperature, that could impact lubricant selection. It is concluded that:

- Temperature has a significant impact on the performance of all the fluids tested. In particularly the traction shifts towards the hydrodynamic regime as temperature decreases: showing the viscosity is increasing, and the fluid thickening and solidifying.

- There appears to be a transition in behaviour of the fluids at moderately low temperatures, approximately -30°C, which suggests a transition to a less fluid state. This transitional behaviour appears to confirm that Braycote 601 EF and Uniflor 8981 have different base oils.

- Testing below manufacturer reported minimum application temperature was shown to be problematic, in line with intuitive expectations.

The first interferometric studies and thickness measurements of a Fomblin Z25 fluid film, under thermal-vacuum conditions, are presented. The work has commenced with the first analysed results being comparable to literature trends.

Further analysis of this data is ongoing and in the future VMTM data is expected to provide more comprehensive data that can be used to model mechanism contacts. It is anticipated that the data will be used to develop a more comprehensive understanding of mechanism contacts. In particular, connecting fundamental lubricant properties to component traction, in turn supporting design decisions such as lubricant selection and optimising operating conditions.

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