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Frictional study of tungsten carbide mechanical seal under synthetic oil mixed with acrylamide powder lubrication

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KEYWORDS

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Friction
Synthetic oil
Acrylamide powder
Tungsten carbide.

ABSTRACT

The deterioration and life of mechanical seals are majorly determined by the heat generation due to the friction and depends on the frictional characteristics of rotary and stationary seal rings. The degree of lubrication plays a significant role in determining a mechanical seal's lifetime. Experimental work was carried to analyze the tribological properties of fine existing materials such as tungsten carbide versus resin impregnated carbon using a specially designed and fabricated mechanical seal test rig. The speed was kept constant at 1500rpm with an increase in load. The frictional characteristics were studied under unlubricated conditions, independent poly-alpha-olefin oil (PAO), paraffin oil, and finally 0.5wt.%, 1wt.%, 2wt.% of acrylamide powder mixed individually with poly-alpha-olefin oil and paraffin oil. After the completion of the running-in test, improvements such as lower coefficient of friction, higher load-carrying capacity, and higher wear resistance, were found in tungsten carbide under the lubrication of PAO oil with 1wt.% of acrylamide. Between two rubbing surfaces, the microcosmic rolling effect results in friction coefficient values between 0.03 and 0.05.

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1.0 INTRODUCTION

Mechanical seals were developed to eliminate and reduce the fluid leakages between the system and the mechanism. It consists of a rotating ring (softer material) that rotates with the shaft and a stationary ring (harder material) fixed to the housing. During the working, the rotating ring rubs against the stationary ring, and the contact between the two rings is maintained by the compression spring and drive mechanism which is attached to the rotating ring. This component is used on equipment such as pumps or turbines with different operating fluids and helps to prevent the contamination of the surrounding environment. The major cause of failure in the mechanical seal is the excess generation of heat at the rubbing surface between the rotating ring and stationary seal (Shankar & Praveenkumar, 2016; Shankar et al., 2015). To prevent the failure of the mechanical seals, a thin film of lubrication is to be maintained hydrodynamically between the rubbing surfaces. This will separate the two rubbing surfaces and avoid the direct rubbing action that causes wear. The reliability and efficiency of the mechanical seal majorly depend on the following parameters such as pump speed, pressure, pumping fluid, equipment design, support system, a pairing of seal face, thin-film lubricants, and bulk characteristics of seal face materials (Shankar et al., 2016). However, it is concluded that the usage of efficient thin-film lubricants will enhance the mechanical seal's service life (Adjemout et al., 2018; Kasem et al., 2018). There are several studies on mechanisms and techniques of maintaining a thin film of lubrication between the sliding surfaces. Among which, the effective methods in recent years are laser surface texturing (Kumar et al., 2020; Wang et al., 2019), thin-film coatings such as deposition of nanocrystalline diamond films, diamond-like carbon films(Ding et al., 2020; Shankar & Krishnakumar, 2016; Shankar et al., 2017), and reliable liquid lubrication between the mating surface(Samuel et al., 2020). In general, many researchers have explored lots of surface engineering techniques to reduce the breakage of mating surfaces of mechanical seals (Ding et al., 2020; Shankar & Krishnakumar, 2016; Wong et al., 2016). On the other hand, most of the studies reveal that the surface engineering techniques were not an efficient option for high load applications(Mahayuddin et al., 2020). Also, there is not enough study reported in the lubrication regime of mechanical seals with the addition of powdered friction reducers to the lubricating oil(Talib et al., 2019; Yunus et al., 2020). Among all the modes of lubrication regime in mechanical seals, identifying the most efficient lubrication mode, which controls the sealing function, wear, friction and seal life(Kumar et al., 2021; Vezjak et al., 2001) has become an essential feature of mechanical seal.

For a quite long time, it has been speculated that the frictional performance of low friction solid lubricants is controlled by "third bodies". The word "third bodies" refers to the mixture of solid lubricants, wear particles, and oil. In the context of a third body lubrication model, wear particles and solid lubricant powders are considered tribological factors.(Chong et al., 2015; Rapoport et al., 2002). The interaction between oil, solid lubricant, and wear particles at the rubbing surface interface is required to define the friction and wear behaviour of the rubbed surfaces. As an additive to lubricating oils and greases, solid lubricants such as molybdenum disulfide (MoS_2) and acrylamide powder have been used in recent years(Tang et al., 2014). MoS_2 as a lubricant is significant because of its relatively low coefficient of friction and its effective chemical stability under high temperatures and vacuums(Nallasamy et al., 2015; Rapoport et al., 2007). The good lubricity, ease of sliding, and small Van-der Waals gap between MoS_2 layers are commonly regarded as key characteristics. Huang et al. found that the frictional behaviour of magnesium alloy lubricated by oil with amide compound improves with an increase in the number of amido groups in molecules.(Huang et al., 2005). Acrylamide powder has better friction-reduction and antiwear properties than molybdenum disulfide that has longer alkyl chains, one reason is because of the molybdenum disulfide's ring-like structure is not conducive to lateral interactions between molecules of surface adsorption. In comparison with the molybdenum structure, it is noteworthy that acrylamide exhibits better frictional characteristics at high loads. On the other hand, it is simple to oxidize the double bond in acrylamide under air and high load, carboxylic acid derivative would be included in possible products. These compounds form certain kinds of friction polymer with the fresh sliding surface, allowing acrylamide powder to show better frictional characteristics than molybdenum disulfide.

Based on the above background, the solid lubricants kept in the depression between the sliding surfaces form a lubricant layer. These lubricant layers will influence the frictional characteristics of mechanical seals. This research aims to investigate the frictional characteristics of mechanical seals under dry and lubricated conditions, employing hard, fixed tungsten carbide seals and soft, tungsten carbide-impregnated carbon rotary seals. The sealing pair is investigated under conventional synthetic oil such as poly alpha olefin oil and paraffin oil. In addition to this, the synthetic oil is premixed with 0.5%, 1%, and 2% of acrylamide powder individually, and the study of frictional characteristics is carried out with the same operating condition using a mechanical seal test rig, which is specially designed to serve this application. The below are the various lubricating conditions considered for this study.

Type 1: Under dry condition (no lubricants)
Type 2: Under poly-alpha-olefin oil (PAO), no solid lubricants are added.
Type 3: Under paraffin oil, no solid lubricants added.
Type 4: Under poly – alpha – olefin oil premixed with 0.5 % of acrylamide powder.
Type 5: Under poly – alpha – olefin oil premixed with 1 % of acrylamide powder.
Type 6: Under poly – alpha – olefin oil premixed with 2 % of acrylamide powder.
Type 7: Under paraffin oil premixed with 0.5% of acrylamide powder.
Type 8: Under paraffin oil premixed with 1 % of acrylamide powder.
Type 9: Under paraffin oil premixed with 2 % of acrylamide powder.

2.0 MATERIALS AND METHODS

2.1 Sealant Lubricant Preparation

Tungsten carbide (WC)(Engqvist et al., 2000) has a wide range of applications and is also the most commonly employed face seal material because of its high hardness, high melting point, low co-efficient of friction, and high thermal stability. This material was used for the stationary seal (harder surface) and was sintering-produced into a hollow circular ring with dimensions of Ø43 × Ø33 × 8mm (od × id × thickness). The initial roughness of the tungsten carbide seal surface was found to be in the range of 0.04 µm to 0.05 µm measured by Mitutoyo SJ-410 roughness tester and it is accomplished by diamond polishing. The stationary seal arrangement consists of a tungsten carbide ring of dimensions Ø43 × Ø33 × 8mm (od × id × thickness), which is enclosed inside the step bore on a cylindrical rubber outer cover having size Ø52 × Ø33 ×10mm (od × id × thickness). The stationary and rotary seal is shown in Figure 1. On the other side, resin-impregnated carbon has attracted considerable attention and is widely used as a rotating seal (softer surface) due to its anti-friction properties, superior wear resistance.

The rotating seal rings were commercially purchased with the dimension Ø45 × Ø38mm (od × id). The comparison of the mechanical and physical characteristics of the tungsten carbide seal and the resin-impregnated carbon seal is shown in Table 1. Both poly-alpha-olefin oil (PAO), synthetic oil, and paraffin oil were purchased commercially from Scientific Lubricants Private Limited, India, and Table 2 shows their properties. Table 3 lists the parameters of finely ground technical grade acrylamide powder that was purchased commercially. Further, 0.5%, 1%, and 2% of acrylamide powder were added to PAO oil and paraffin oil, respectively. A magnetic stirrer is used to continuously stir the solution for 3 hours at 40°C until the acrylamide powder becomes completely soluble and evenly distributed. The prepared seal lubricant mixed with acrylamide powder is shown in Figure 2.

Table 1: Physical and mechanical properties of the seals.

Material description	Physical and mechanical properties			
	Hardness	Specific heat (J/kg K)	Thermal conductivity (W/m K)	Density (kg/m^3)
Resin impregnated carbon	93 Shore A	858	10.45	1840
Tungsten carbide	2850 HV	12.33x10^4	11.88	15.35x10^4

Table 2: Properties of PAO oil & paraffin oil.

Properties	PAO oil	Paraffin oil
Density (g/cc)	0.8158	0.811
Flash point (°C)	239	176
Dynamic viscosity at 100°C (mm^2/s)	5.5	4.48
Dynamic viscosity at 40°C (mm^2/s)	31.8	33
Viscosity index (VI)	139	109
Pour point (°C)	-26	-8

Table 3: Properties of acrylamide powder.

Properties	Value
Molecular Weight	71.08
Melting Point	84.5°C
Boiling Point	125°C
Water Solubility	2155 g/L at 30°C
Density	1.122
Vapor Density (air = 1)	2.46
Vapor Pressure	7 × 10^{-3} torr at 20°C
Flash Point	138°C

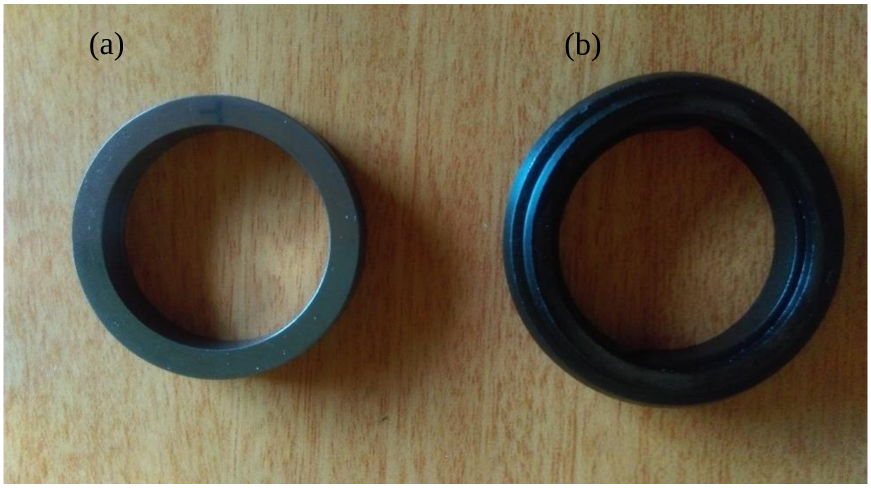

Figure 1: Image of stationary seal & rotary seal (a) tungsten carbide seal and (b) resin impregnated carbon seal.

(a) (b)

Figure 2: Photography of PAO oil & Paraffin oil (a) PAO oil mixed with acrylamide powder and (b) Paraffin oil mixed with acrylamide powder.

2.2 Mechanical Seal Test Rig

The mechanical seal test rig was designed specifically to conduct tests on different kinds of seal materials and multiple sizes of seals as shown in the Figure. 3. The machine is provided with a top holder fitted containing the rotary seal, which is pressed over the hard surface on the stationary seal. Appropriate spring pressure was maintained between the rotating and stationary seals to ensure full engagement. The fluid chamber contains a stationary seal that was made to press against the rotary seal, which was rotated by the spindle. A variable frequency drive was used to control the speed of the motor and to maintain uniform torque at all speeds. An electric motor with a belt drive rotates the spindle. Dead weights are placed on the constructed pan at the end of the lever arrangement to apply the load. A thermocouple was used to measure the temperature of the stationary seal's outer diameter, which was placed on the side of the lower chamber with the tip touching the outer diameter of the stationary seal. The spindle speed was measured using the proximity sensor. The fluid chamber consists of two ports, through one port, the inlet fluid was made to flow on the contact zone, which is connected to the pump. In the other port, the working fluid is drained to the tank. A pressure gauge and pressure relief valve are integrated into the lubrication unit to provide the required pressure to the fluid flowing in the chamber. Through the inlet port, the pumped fluid enters the chamber and rises into the sealing zone. It then flows out through the other hole in the bottom specimen holder back into the tank through a throttle valve. The discharge of the lubricant was carried out at the rate of 35 drops/sec with the help of the throttle valve. With the help of a data acquisition card (I-DAS), which is integrated into the mechanical seal test rig, the signals obtained from the above-mentioned sensors were sampled. The data acquisition card was controlled by the WINDUCOM software (Ducom Instruments).

2.3 Testing Procedure

According to Figure 3, all tests were conducted on the mechanical seal test rig. The fluid chamber contains a stationary ring that allows the ring to be self-aligned, as well as being loaded axially against the upper rotating ring. In the beginning, an initial load of 75N was applied at the end of the lever for the stationary and rotary ring to be fully engaged. Each test includes a constant speed of 1500rpm and a 3600s running-in period for nine loading conditions. After running-in, the load between the rings was varied from 75N to 325N in a step of 50N (75N, 125N, 175N, 225N, 275N, and 325N). The run-in time for each load was 600s. Tests were stopped after 5min for each loading condition. WINDUCOM was used to record the seal face temperature, friction torque, and coefficient of friction, the same method was repeated for all stationary tungsten carbide rings and rotating seals of resin-impregnated carbon.

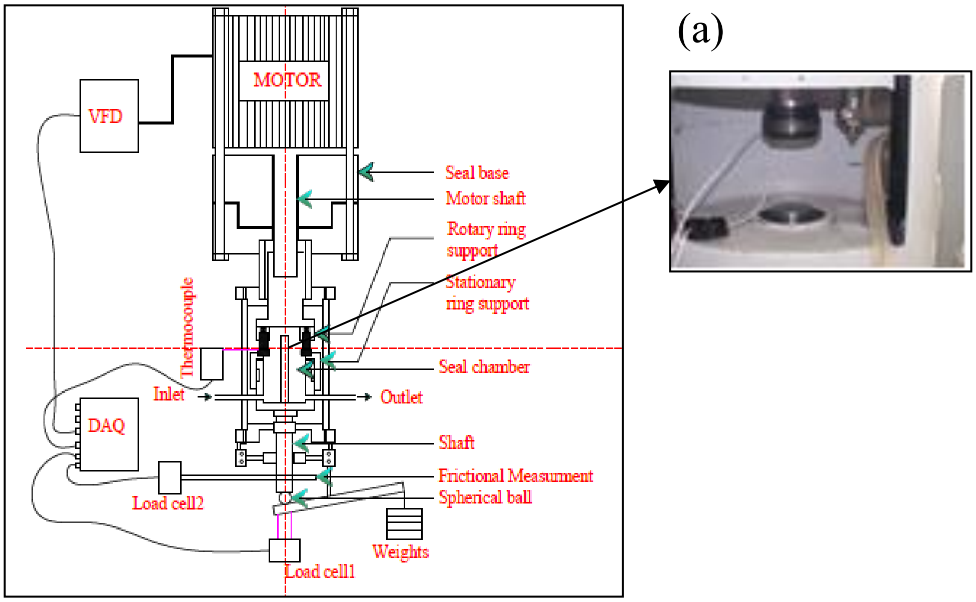

Figure 3: Layout diagram of the mechanical seal test rig and (a) View of placement of rotating and mating ring.

3.0 RESULTS AND DISCUSSION

3.1 Friction Coefficient

3.1.1 Dry Lubrication

All of the experiments were done with three samples, and Figure 4 displays the average friction coefficients that were obtained. The coefficient of friction reaches its stable value for each loading condition after approximately 200s, which was found to be consistent with earlier research. (Chowdhury et al., 2011). In a dry running-in test for tungsten carbide seals, friction at the initial stage (at 75N load) remained constant (=0.172). After initial running in, the surface layer breaks up, and the clean surface comes into contact, increasing friction coefficient values due to wear trapped particles that contributed to increased roughness, face temperature, and friction force. Therefore, the friction coefficient is found to fluctuate and the value of the friction coefficient enters a steady state after a certain running-in time, roughly after 200s. At a load of 75N, the friction coefficients were calculated and shown in Figure 4 as an average (=0.169). As a result of asperity interaction between the stationary and rotating seal, wear debris particle is formed from the resin impregnated carbon asperities being sheared off by the tungsten carbide. At the initial running – in test, more wear debris particles are formed and which increased the roughness of the surface resulting in higher friction coefficient. After 175N load, there is decrease in asperity interaction between the stationary and rotating seal. This resulted in lesser wear debris and roughness, which contributed for the decrease in friction coefficient. This friction characteristics and factors influencing was found to be in agreement with the previous studies (Shankar et al., 2016). For the other loading conditions, the same phenomenon was noticed. Figure 4 shows the average friction coefficient for each load of 125N, 175N, 225N, 275N, and 325N. Figure 9(a) shows the microstructure of the tungsten carbide and resin impregnated carbon sliding surfaces after a dry running-in test, where wear scars were found.

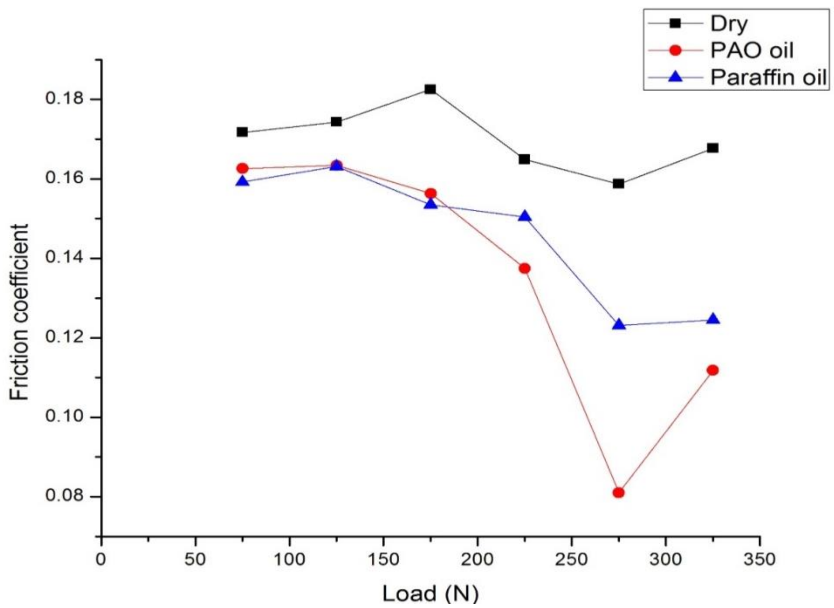

Figure 4: Variations of friction coefficient for dry and oil lubrication.

3.1.2 PAO Oil Lubrication

In the case of poly-alpha-olefin oil-lubricated condition, for tungsten carbide seal, at the load of 75N, 125N, 175N, 225N, 275N, and 325N, the initial friction coefficient values were μ=0.127,0.125,0.133,0.131,0.117,0.122 and fluctuating values of friction coefficient were found and attain a steady-state friction value of μ=0.163,0.164,0.156,0.137,0.081,0.118 respectively. The average friction coefficient at each load of 125N, 175N, 225N, 275N, and 325N was computed and shown in Figure 4. Since PAO oil contains a large number of flexible alkyl groups that can arrange themselves in a variety of arrangements, polymer molecules have a difficult time aligning in an ordered manner (Tasdemir et al., 2013). This allowed for a lower surface contact between the stationary ring (tungsten carbide seal) and rotating ring (resin impregnated carbon seal), reducing the friction coefficient values(A Chowdhury et al., 2014). This resulted in lower intermolecular interaction between the molecules present in the sliding surface. During the running-in test, there is a continuous flow of PAO oil on the sliding surface, which results in uneven agglomeration of wear debris particles formed from resin impregnated carbon along with flexible alkyl groups. This results in unusual behavior of friction coefficient. Under the PAO oil running-in test and wear scar, figure 9(b) shows the microstructure of the sliding surfaces of tungsten carbide and resin-impregnated carbon.

3.1.3 Paraffin Oil Lubrication

In the case of paraffin oil-lubricated condition, for tungsten carbide seal, at the load of 75N, 125N, 175N, 225N, 275N, and 325N, the initial coefficient of friction coefficient values were μ=0.137, 0.133, 0.121, 0.141, 0.127, 0.132 and friction coefficient values were found to be fluctuating dynamically and attain a steady-state friction value of μ=0.159, 0.163, 0.153, 0.150, 0.123, 0.124 respectively. The average friction coefficient at each load of 125N, 175N, 225N, 275N, and 325N was computed and shown in Figure 4. Paraffin oil was acted as a heat transfer oil containing light mixtures of higher alkanes (Liu et al., 2016) and is non-compressible, separating the sliding surface of the stationary ring (tungsten carbide seal) and the rotating ring (resin impregnated carbon seal) by a thin film, thus reducing the coefficient of friction(Peng et al., 2010; Yazawa et al., 2014). During the running-in test, there is a continuous flow of paraffin oil on the sliding surface, which results in uneven agglomeration of wear debris particles formed from resin impregnated carbon along with higher alkanes groups. This results in unusual behavior of friction coefficient. The average coefficient of friction at each load of 125N, 175N, 225N, 275N, and 325N was computed and shown in Figure 5. Figure 9(c) illustrates the microstructure of the sliding surface of the tungsten carbide seal when lubricated with paraffin oil.

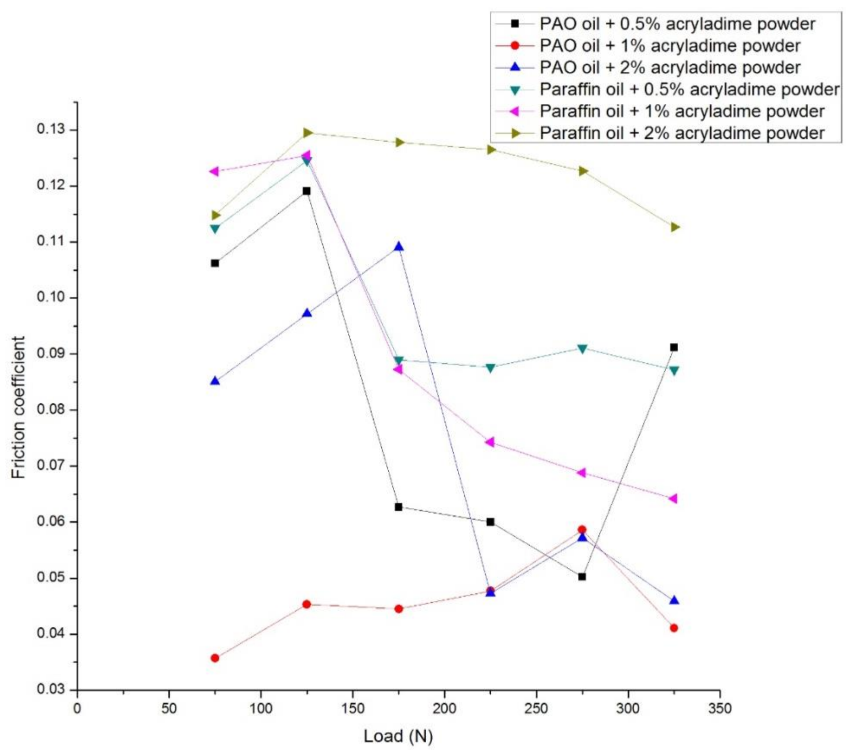

Figure 5: Variations of friction coefficient for acrylamide powder mixed oil lubrication.

3.1.4 Acrylamide Powder Mixed with PAO Oil and Paraffin Oil Lubrication

Initial friction coefficient values of 0.5wt %, 1wt %, and 2wt % of acrylamide powder mixed with PAO oil were 0.095, 0.071, 0.052, and the coefficient values fluctuated between these values and achieved a steady-state friction value of 0.106, 0.035, 0.085 respectively. Whereas under 0.5wt%, 1wt%, and 2wt% of acrylamide powder mixed with paraffin oil at the initial load of 75N, for tungsten carbide seal exhibited an initial friction coefficient value of μ are 0.093, 0.113, 0.099 and fluctuating values of friction coefficient were found and attain a steady-state friction coefficient value of μ are 0.112, 0.123, 0.114 respectively. It reduces the coefficient of friction and increases the load-carrying capacity of the seal by creating a microcosmic rolling effect between two rubbing surfaces (Huang et al., 2005; Jiang et al., 2005). From the Figure 5, it is evident that the addition of acrylamide powder above 1wt% in PAO and paraffin oil results in the agglomeration of monomer unit of acrylamide powder, which results in the increase of friction coefficient. An efficient tribofilm is formed on the sliding surface by the lubricant mixed with 1 wt.% of acrylamide powder. When increasing the wt% of acrylamide powder mixed in PAO and paraffin oil above 1%, due to more agglomeration of acrylamide monomer unit, the efficiency of tribofilm is reduced, hence the lower frictional performance is exhibited as shown in the Figure 5. The same frictional behaviour was found for tungsten carbide seal under both PAO oil and paraffin oil individually mixed with 0.5wt%, 1wt%, and 2wt% of acrylamide powder at all remaining normal loads of 125N, 175N, 225N, 275N, and 325N. The average friction coefficient at each load of 75N, 125N, 175N, 225N, 275N, and 325N was computed and shown in Figure 5. Among all the combinations of lubricating conditions, PAO oil mixed with 1wt% of acrylamide has shown a low friction coefficient in the range of μ= 0.04 – 0.05, and the tribo film is formed as shown in Figure 9(d) and thereby no traces of wear scar were found.

3.2 FRICTION TORQUE

Frictional torque is largely influenced by the increase in normal load (N), which was confirmed from Figures 6 & 7. With an increase in normal load, wear debris detaches from the surface and increases its roughness (Yu et al., 2002). Besides, the increase in frictional torque is inevitably attributed to the increase in the mating surface's sliding resistance(Shankar & Praveenkumar, 2016; Shankar et al., 2015). Figure 6 illustrates the variation of frictional torque of tungsten carbide seal under dry and oil lubrication for various normal loads. Also from Figure 7, it is evident that the 0.5wt%, 1wt%, 2wt% of acrylamide powder individually mixed with PAO oil and paraffin oil lubrication resulted in low frictional force than dry, PAO oil, and paraffin oil lubrication, due to low friction and shear strength values. When compared to all the combinations of lubrication, PAO oil mixed with 1wt% of acrylamide powder mixed resulted in the lowest frictional torque.

3.3 FACE TEMPERATURE RISE

The increase in face temperature was one of the important parameters that had a substantial impact on the frictional properties and life span of the mechanical seals. Under dry, poly-alpha-olefin oil, paraffin oil, and different weight proportions of 0.5wt %, 1wt %, and 2wt % of acrylamide powder combined individually with PAO oil and paraffin oil lubrication, the face temperature rise was regularly seen in tungsten carbide seals. During the running-in test, there is a rise in face temperature due to sliding friction. This result in performance degradation and unstable friction properties. Hence, monitoring the face temperature rise periodically and maintaining a lower rise in face temperature is very important and necessary action. The increase in the face temperature of samples examined in the present case is shown in Figure 8 . Despite this, tungsten carbide seals with 1 wt% of acrylamide powder mixed with PAO oil showed the lowest temperature rise of 55.23^{o}C under all combinations of lubricants, tungsten carbide seals, and lubricants.

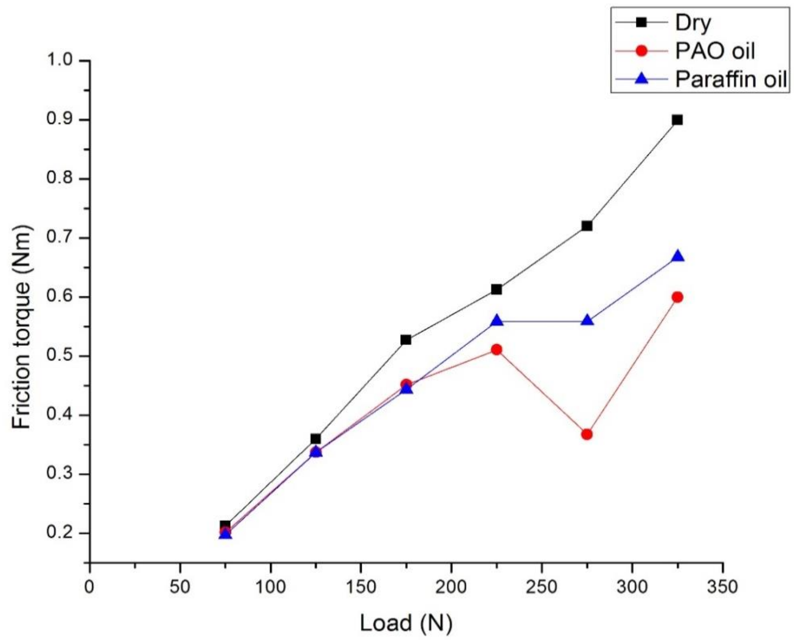

Figure 6: Variations of friction torque for dry and oil lubrication.

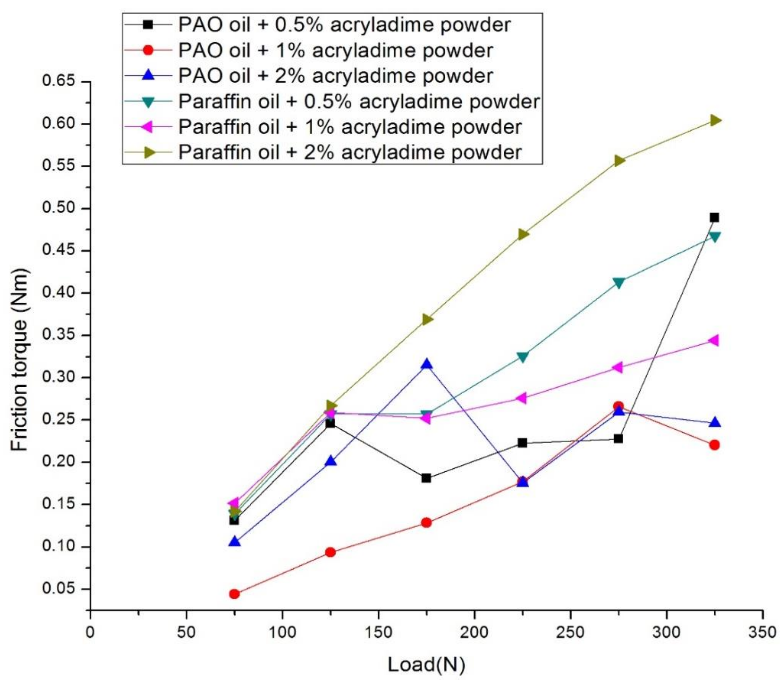

Figure 7: Variations of friction torque for acrylamide powder mixed oil lubrication.

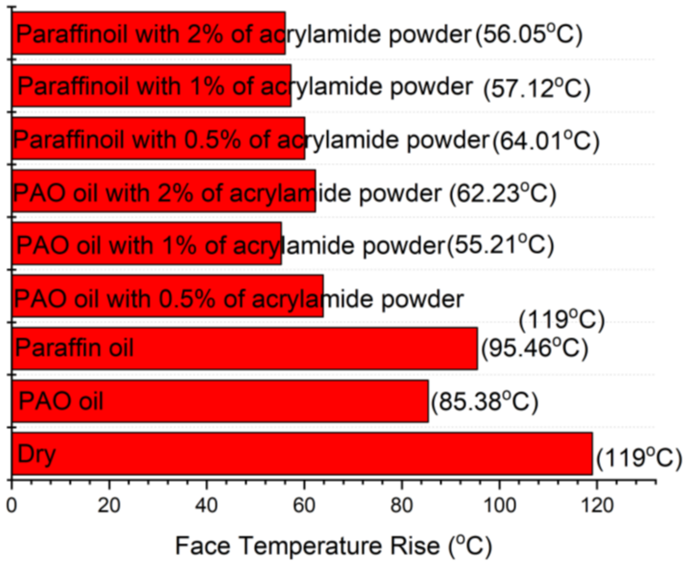

Figure 8: Variations of face temperature for dry, PAO oil, paraffin oil, acrylamide powder mixed oil lubrication.

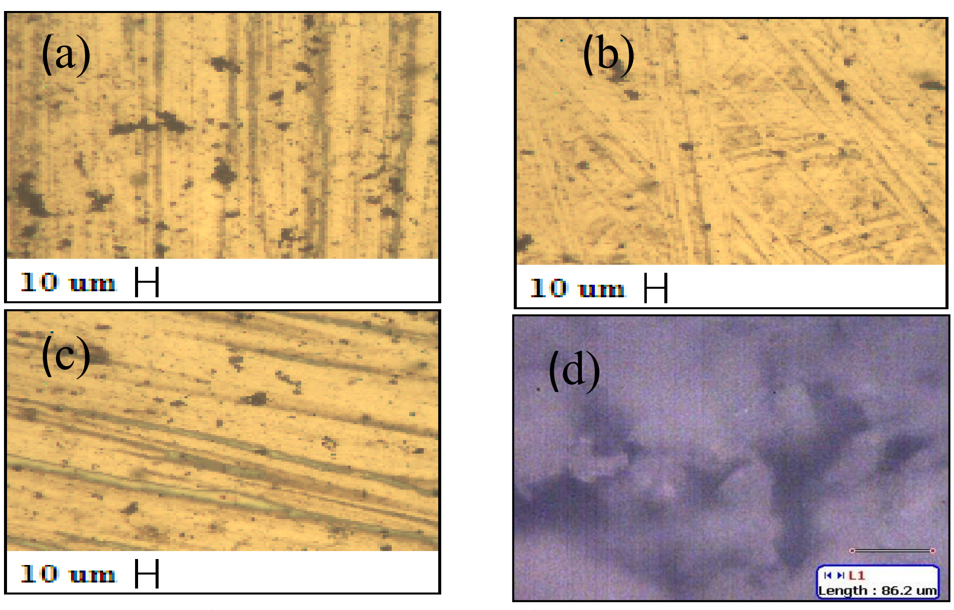

Figure. 9: Microstructure of tungsten carbide seal surface against resin impregnated carbon (a) dry (b) PAO oil (c) paraffin oil (d) tribo film by acrylamide powder.

CONCLUSIONS

The present work uses a specially designed mechanical seal test rig to evaluate the fundamental friction of carbon moving against tungsten carbide. Overall, it was concluded that the monomer unit of acrylamide causes a microcosmic rolling effect between two rubbing surfaces thus reducing the friction coefficient. The friction properties of tungsten carbide versus resin impregnated carbon, 0.5wt%, 1wt%, and 2wt% of acrylamide powder mixed individually with PAO oil and paraffin oil lubrication were investigated, the following results are stated as follows. As a result of high friction coefficients, high friction torques, and high face temperatures, the lifetime of the mechanical seal is shortened when running in dry conditions. Running-in tests with PAO oil and paraffin oil resulted in lower friction coefficients, friction torques, and face temperatures than non-lubricated conditions. The PAO oil mixed with 1wt% of acrylamide had a better coefficient of friction than paraffin oil mixed with 0.5wt%, 1wt%, and 2wt% of acrylamide powder individually. This study involves the evaluation of the optimum acrylamide powder wt% to be mixed with the PAO and paraffin oil. The running-in test involving 2wt% of acrylamide powder lubrication results in more agglomeration of acrylamide monomer units on the sliding surface. This in turn increases the drag friction, which eventually increases the friction coefficient. At the 1wt% of acrylamide powder lubrication, less agglomeration of acrylamide forms an effective tribofilm on the sliding surface, which shows better frictional characteristics. Acrylamide containing monomer unit of $CH_2CHCONH_2$ caused a microcosmic rolling effect between two rubbing surfaces, thus exhibiting better friction characteristics. Above 1wt%, addition resulted in an agglomerate of acrylamide powder at the sliding surface, thereby lowering the frictional characteristics of the mechanical seal. Based on the success of the acrylamide powder mixed with PAO oil and paraffin oil lubrication, an economically friendly lubricant is developed and also exhibits excellent friction behaviour and can be used as an alternate lubricant for various mechanical seal applications.

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