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TRIBOLOGICAL PROPERTIES OF A RUBBER SEAL UNDER OPERATION WITH OIL CONTAINING MoS_2 NANOPARTICLES

TRIBOLOGICZNA OCENA PRACY WĘZŁA USZCZELNIAJĄCEGO PRZY OBECNOŚCI NANOCZĄSTEK MoS_2 W CZYNNIKU USZCZELNIANYM

Key words: mechanical seals, oils, friction.

Abstract: The issues associated with sealing operation are of vital significance due to their function in mechanics. The most universal, simple, and cheap solution of seals are O-rings. They are most commonly used for all seals. The article evaluates the operation characteristics of an O-ring seals under operation with oils containing MoS_2 nanoparticles. The measurements were made on the sealing node model in a hydraulic cylinder where the round cross section seal cooperated with the piston rod. The changes of the friction force during rod movement resulting from the friction between the seal and the rod were analysed. The investigations presented in this paper allow one to conclude that, for the assumed research conditions, the average values of the friction force during instroke are higher for PAO oil with MoS_2 additive in comparison to pure PAO base oil. In addition, the boundary velocity of the rod above in which the decrease of friction force was observed is higher for pure PAO oil.

Słowa kluczowe: uszczelnienia, oleje, tarcie.

Streszczenie: Zagadnienia związane z wszelkimi aspektami działania uszczelnień są bardzo istotne z uwagi na konsekwencje wynikające z ich nieprawidłowego działania. Szeroko stosowanym i najbardziej uniwersalnym rozwiązaniem są uszczelnienia typu O-ring. W artykule omówiono wyniki przeprowadzonych badań, których celem była ocena charakterystyki pracy uszczelnienia w ruchu posuwisto zwrotnym działającego w kontakcie z olejami zawierającymi nanocząsteczki MoS2. Pomiary wykonano na modelu węzła uszczelniającego w cylindrze hydraulicznym. Badaną parą uszczelniającą było tłoczysko i pierścień uszczelniający typu O-ring. Analizie poddano zmiany siły tarcia podczas roboczego suwu tłoczyska, oraz wpływ na ich wartość prędkości przesuwu tłoczyska. Uzyskane podczas badan wyniki pozwalają stwierdzić, że w zakresie ocenianych warunków pracy uszczelnienia średnie wartości siły tarcia podczas dośrodkowego ruchu tłoczyska są większe przy smarowaniu czystym olejem PAO w porównaniu z olejem PAO z dodatkiem cząsteczek MoS2. Graniczna prędkość posuwu tłoczyska, powyżej której obserwowane jest zmniejszenie wartości oporów tarcia jest wyższa dla czystego oleju PAO.

INTRODUCTION

The scientists have paid a lot of attention to the issues associated with sealing. Both practical as well as theoretical aspects of sealing have been analysed. Important problems lead to the sealing malfunction. Therefore, this subject matter is still raised and undertaken on various research levels. The issues associated with sealing operation are of vital significance due to their function in mechanics.

In order to seal two elements and enable them a relative motion, many types of seals can be used.

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Depending on the construction, they enable leak-free operation in the wide range of sealing liquid pressure and velocity. The most universal, simple, and cheap solution of seals are O-rings with a round cross-section. They are most commonly used for all seals. The ease of application is the reason why they can be found in various constructions. They can be made of different materials. They can operate as static and dynamic seals, as well as radial or face seals. In dynamic applications, they can operate as reciprocating, oscillating, or rotating seals **[L. 1, 2]**.

For many applications, the seals are made of polymeric materials. The friction of this type of elastic material on the hard surface of the sealed metal element is characterized by specific features **[L. 3–6]**.

The oil used in this research was synthetic base oil Polyalphaolefin (PAO) in an additive-free version as well as a version with an additive nanopowder of molybdenum disulphides (MoS_2). The use of nanoparticles as lubricant additives has proved to enhance the tribological properties of surfaces in relative motion **[L. 7]**. The friction and wear reducing potential of MoS_2 nanoparticles for automotive applications has been a subject of interest in recent years **[L. 8–10]**. The tribological properties of MoS2 are due to both a mechanical effect (i.e. acting as an efficient friction modifier and separating the surfaces) and a chemical effect (i.e. acting as an AW and EP additive by the formation of additive derived tribolayers) **[L. 11]**.

In order to obtain significant benefits in terms of friction, it is important for particles to remain at the contact interface, and the friction benefit may be compromised when the particles get entrapped or exfoliated within the tribofilm.

The aim of the paper was to evaluate the operation characteristic of O-ring seals under operation with oils containing MoS_2 nanoparticles. The measurements were made on the model sealing node in a hydraulic cylinder where the round cross section seal cooperated with the piston rod.

O-RING SEAL CHARACTERISTIC

The early 1930s saw a systematic and detailed study on the issues associated with the use of O-ring seals. The research by D. Denny and C. Whitea in the 1940s originated the concept of the operation of elastomeric seals in reciprocating movement. A large number of other researchers were concerned with the problems associated with the phenomena occurring at the seal–counterface contact. For this purpose, they used numerous technics in order to analyse the conditions on the contact surface between the seal and the shaft **[L. 12–16]**.

Thanks to symmetrical cross sections, O-ring seals are the elements of bi-directional operation and can be applied both as a single element and as part of a complex sealing set. Their advantages are as follows: simple and compact construction, easy assembly in a groove, and the small size of the groove itself. The application of this type of seals is a very inexpensive solution. The O-ring can be used in a wide range of successful applications, both static and dynamic. An example of the O-ring type seal application is presented in **Figure 1**. Ring compression takes place during the assembly when it becomes squeezed radially or axially in the groove. Thanks to the squeeze, sealing is also obtained in the case of zero pressure of sealing liquid. The ring elasticity forces generate contact pressure indispensable to prevent leakage. The compensation of dimensional differences resulting from the dimensional tolerance of the elements is also possible. The force of the squeeze can also influence the friction force during operation.

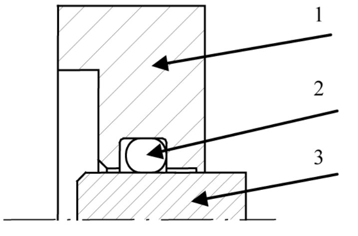

Fig. 1. The example of the O – ring application for rod sealing (internal sealing), radial installation: 1 – housing, 2 – seal, and 3 – rod

Rys. 1. Przykład zastosowania pierścienia O – ring do uszczelnienia tłoczyska, montaż promieniowy; 1 – gniazdo uszczelki; 2 – uszczelka; 3 – tłoczysko

D. Denny and later D. Dowson and P. Swales analysed the samples interacting with the rotating disk. M. Schouten investigated the properties of seals characterised by different materials and construction. G. Field, B. Nau, and P. Wernecke measured the pressure distribution and film thickness using electrical transducers. The measurements conducted in a similar procedure, but done using optical interferometry techniques, were described by Y. Kanzaki **[L. 17–22]**. For the calculation of elastomeric seals, the inverse method of elastohydrodynamics developed in the bearing theory was also adapted **[L. 23–25]**.

F. Hirano and M. Kaneta researched the computational solution for various gradients of liquid pressure under the seal **[L. 26]**. The most important conclusion drawn from their measurement says that there is a certain lower border of the proportion between the length of the stroke and contact width for which periodic change of the gap height under the seal and also that the hydrodynamic friction remain stable.

The liquid flow in the zone under the seal is triggered by liquid dragged by the moving surface of the rod until the balance is achieved. However, with each stroke of the rod in the process of lubricating film formulation, the element of randomness will play a certain part, which does not allow complete control the process **[L. 27, 28]**.

By numerical calculation, G. Field and B. Nau assessed the profile of the lubricating film for the presumed contact stress distribution and distinct hardness of the seal material. L. Ruskell also conducted similar studies applying the general method of the analysis of elastohydrodynamic lubrication problems, which was developed by K. Oh and S. Rohde **[L. 29, 30]**. However, the aforementioned models do provide a quantitative evaluation of the phenomena occurring during the sealing process.

EXPERIMENTAL DETAILS

In order to evaluate the operation parameters of the sealing node with the use of the chosen oil, O-ring seals were applied in tests. The scheme of the test node is schematically shown in **Fig. 2a**. In addition, **Fig. 2b** shows particular elements of the test node. One side of the oil chamber was fitted to the casing via a force transducer. This means of mounting allows one to measure friction force between the seal and the rod.

The rod with a diameter of 18 mm was sealed with the ring squeezed in the groove of the housing. The surface of the rod was coated with Chromium. The layer thickness was equal to 15 µm, and the surface hardness was 57 HRC. The O-ring was housed in a groove with the diameter of 27.60 mm. The cord diameter of the O-ring was 10 mm, and inner ring diameter corresponds to outside diameter of the rod, i.e. 18 mm.

The measurements of roughness parameters were performed using a Hommel Tester T1000. The values of the typical and basic roughness parameters of rod surface, i.e. Ra – arithmetic mean roughness value, Rt – valley -to-peak roughness, and Rz – mean roughness, corresponded to the recommended range for this type of seal. The rod surface was prepared in such a way that it would not have an impact on the results of the conducted measurements. The shaft surface contacting with the seal was characterised by the following roughness parameters: Ra = 0.05 µm, Rz = 0.54 µm, and Rt = 0.72 µm. The specified values can be regarded as recommended. The roughness profile of the surface is presented in **Fig. 3**. The rod interacts with the elastic surface of the seal of a considerably lower hardness. Due to such operation conditions, the changes of the roughness parameters of the rod surface were not observed.

The mechanical properties of the seal material are as follows: hardness – IRHD 69, Young's modulus – 8,4 MPa, tensile strength – 25,7 MPa, and elongation – 230%.

All the measurements were recorded after five minutes of the node operation. This procedure allowed obtaining the stabilization of the operating conditions. During rod stroke, the friction force between the rod and the seal was measured. The measurements were conducted for both directions of the rod movement, namely during instroke and outstroke. During the tests inside the oil chamber, atmospheric pressure was maintained. The friction force was measured during the continuous operation of the test stand.

a) b)

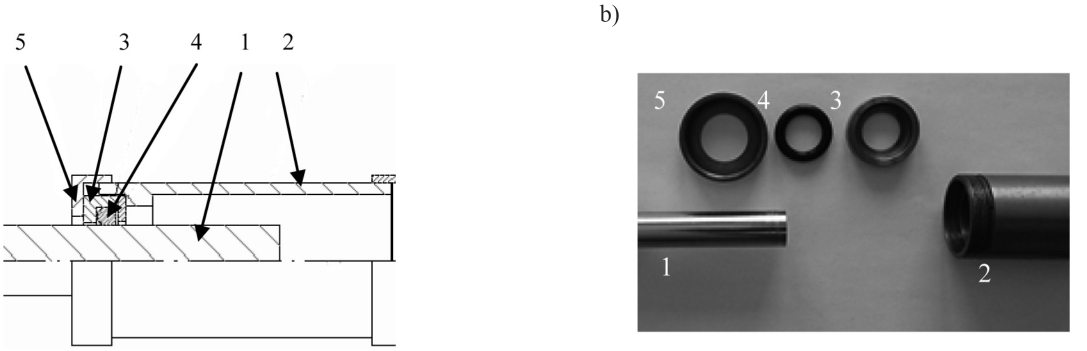

Fig. 2. The test cell: (a) the schematic diagram of the test cell: 1 – rod, 2 – chamber, 3 – housing, 4 – seal, and 5 – cover; (b) the elements of the sealing nod

Rys. 2. Budowa testowego węzła tarcia: a) schemat: 1 – tłoczysko, 2 – gniazdo uszczelki, 3 – uszczelka, 4 – komora olejowa, 5 – pokrywa; b) elementy zestawu

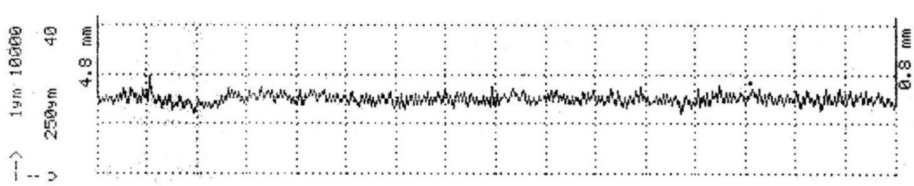

Fig. 3. The roughness profile of the shaft (Ra = 0.05 µm, Rz = 0.54 µm, Rt = 0.72 µm)

Rys. 3. Profil chropowatości powierzchni tłoczyska

The tests were carried out with two oils: pure PAO oil and the PAO oil with an additive of MoS_2 nanoparticles (NPs). The base oil used in this study was NEXBASE® 2008 polyalphaolefine 8 (PAO) with a viscosity of 8 mm²/s at 100°C. The diameter of the NPs was in the range of 100–150 nm. The MoS_2 nanoparticles were blended with PAO oil in a 2% weight concentration.

These oils can be used, among others, as the base oil for lubricant formulation. The basic properties of these oils are presented in **Table 1**.

The dynamic viscosity was measured at 40°C using a Physica Modular Rheometer Series (MCR) 101 parallel-plate system (Anton Paar, Austria) with a shear rate of 100 (1/s). Wettability was measured using a goniometer with a Hamilton Microliter syringe 500 µL, and a 5 µL drop was placed on the surface of a workpiece sample and its contact angle was obtained by image processing.

Table 1. Basic properties of oils – Characteristics of examined oils

Tabela 1. Podstawowe właściwości zastosowanych olejów – Charakterystyka zastosowanych olejów

Feature	PAO oil	PAO oil + 2% MoS_2
Colour	colourless	Black
Smell	scentless	scentless
Density [kg/m³]	0.83	0.68
kinematic viscosity at 100°C [mm²/s = cSt]	8.0	8.75
Dynamic Viscosity [mPa·s]	33.26 ±0.26	45.60 ±2.50
Contact angle in ° (Room temperature)	20.8 ±1.3	24.0 ±1.1

RESULTS AND DISCUSSION

Friction force during seal operation was evaluated on the basis of the series of conducted measurements. **Figures 4** and **5** show the registered values of friction force in the subsequent cycles for instroke and outstroke in the case of the operation of the friction node with pure PAO oil. As it indicated earlier, the friction forces were registered in stabilized operating conditions. Therefore, as it can be observed in the **Fig. 4** presenting the course of friction force, the subsequent strokes are repetitive. The courses of the friction forces with the same pressure and velocity have an analogous scheme with a clearly observed increase of force values in the first phase of the stroke. This refers to both the instroke and outstroke. However, one could observe the differences between maximum and average values of the friction force for the case of instroke and outstroke. In each cycle, higher values of friction force for outstroke in comparison to instroke were registered.

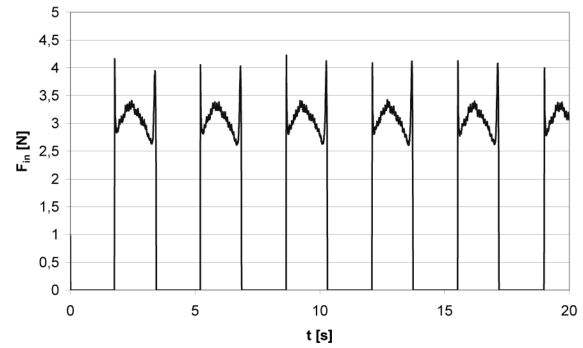

Fig. 4. Friction force on seal versus time, instroke, PAO oil

Rys. 4. Siła tarcia uszczelki w funkcji czasu, skok dośrodkowy, olej PAO

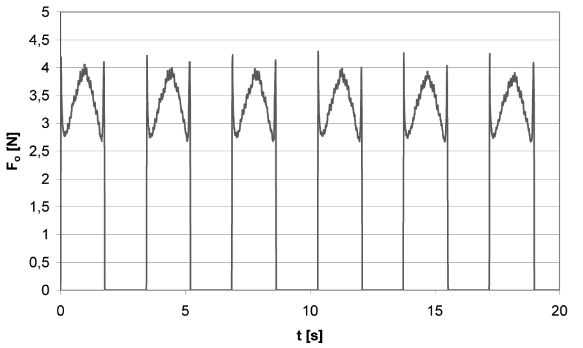

Fig. 5. Friction force on seal versus time, outstroke, PAO oil

Rys. 5. Siła tarcia uszczelki w funkcji czasu, skok odśrodkowy, olej PAO

For the sealing in reciprocating movement, friction conditions depend on the relative speed of sliding elements. The differences in recorded friction force during rod stroke arise from the operating conditions. Friction conditions usually can be characterized as a mixed friction regime, as was indicated by Salant **[L. 31]**. At the final points of the rod movement, considerably higher values of friction forces are recorded. This is because the relative speed of the surface of the rod and the shaft is zero. At the initial phase of the rod movement, at the beginning point of the outstroke, friction forces reach almost 25% higher values than in the remaining part of the stroke.

The differences of the recorded value of friction force during one whole stroke are higher for outstroke, and, in this case, they exceed 20%. However, for the instroke, they are 50% lower and reach 10%.

The course of one cycle can be analysed based on **Fig. 6**. This figure depicts the course of change of friction force during the instroke and outstroke following each other. Therefore, negative values presented in the figure show the friction force during instroke. The cycle shown in the figure is one chosen out of many subsequent ones. In order to obtain stable operating conditions, the course was registered after the running-in period which lasted 5 minutes. . Therefore, it can be assumed that the courses are representative for given operating conditions. As the figure shows, the changes of the friction forces are lower during instroke.

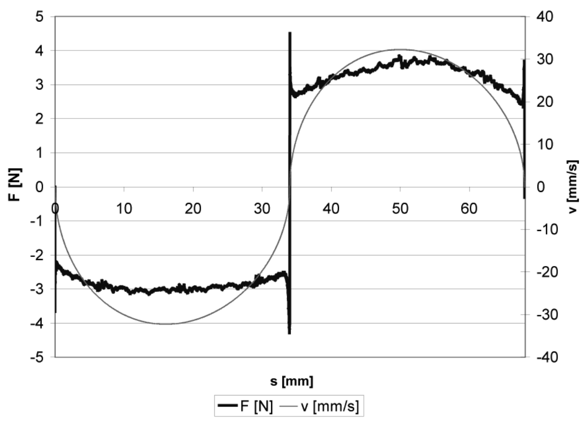

Fig. 6. A comparison of friction forces on the seal during one instroke and outstroke for PAO oil

Rys. 6. Porównanie zmian siły tarcia uszczelki podczas jednego suwu dośrodkowego i odśrodkowego dla oleju PAO

Predominantly, the thickness of the lubricating film is the main factor responsible for the friction force during rod movement. The thickness of the lubricating film on the contacting surfaces changes according to the topography of the elements. In this research, the topography of the rod surface is significant. However, material properties of the elastomeric element also play a dominant role on the lubricating film thickness. It can be assumed that the essential part of the friction force value culminate the interaction of the metal element hard surface roughness profile.

If we assume that, during a single stroke of the rod, all the parameters deciding the thickness of the lubricating film do not change considerably, we can also estimate the thickness of the lubricating film on the basis of the friction force. The above observations confirm the results of theoretical analyses described by Salant **[L. 31]**. He indicated that the conditions of mixed lubrication are the dominating friction conditions. He also paid attention to the fact that film thickness during instroke is larger than during the outstroke. Such conditions of fluid transport under the seal have an effect on the sealing effectiveness and prevent leakage conditions. He also indicated that the resistance to flow during particular strokes is the determining factor. Therefore, in order to keep zero net leakage, the condition that the instroke fluid transport exceeds the outstroke transport must be fulfilled.

The capability for forming lubricating film depends on sliding speed. In order to present the influence of rod speed on friction force, the average values of friction force for instroke at various rod speeds are presented in the **Fig. 7**. The spread of test results is marked in the figure with the error bars.

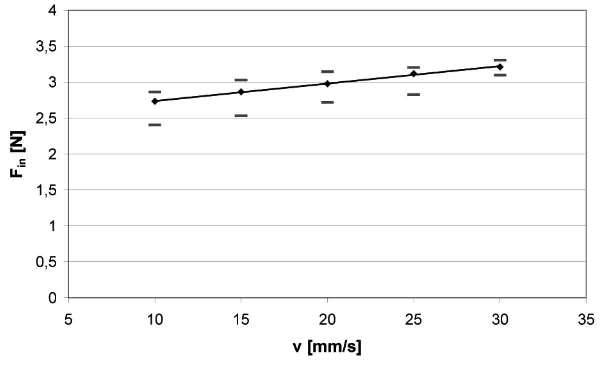

Fig. 7. Friction force on seal versus rod velocity [mm/s]; instroke; PAO oil

Rys. 7. Siła tarcia uszczelki w funkcji prędkości tłoczyska, skok dośrodkowy, olej PAO

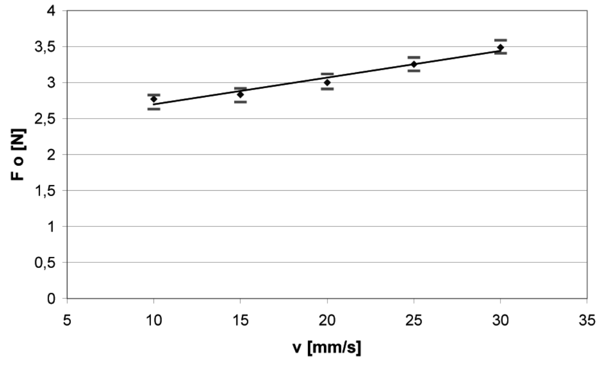

Fig. 8. Friction force on seal versus rod velocity [mm/s]; outstroke; PAO oil

Rys. 8. Siła tarcia uszczelki w funkcji prędkości tłoczyska, skok odśrodkowy, olej PAO

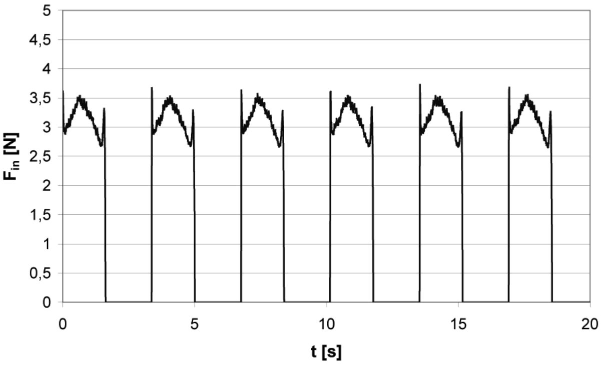

Fig. 9. Friction force on seal versus time, instroke, PAO oil + MoS_2 NPs

Rys. 9. Siła tarcia uszczelki w funkcji czasu, skok dośrodkowy, olej PAO +MoS_2

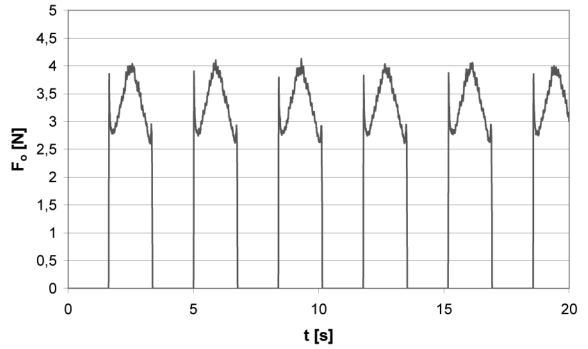

Fig. 10. Friction force on seal versus time, outstroke, PAO oil + MoS_2 NPs

Rys. 10. Siła tarcia uszczelki w funkcji czasu, skok odśrodkowy, olej PAO +MoS_2

Analogously, this relationship for the outstroke is shown in **Fig. 8**. Comparing the aforementioned figures, we can observe higher mean values of friction force for the outstroke than the instroke at the same velocity. This can result from the easier liquid access to the sealing area during instroke. During the stroke, the pressure on the entry into the sealing zone is always higher than on the opposite side of the seal. The highest values of the friction force occur at high velocity during outstroke.

As it can be observed in the presented figures, the registered friction force was lower for instroke, and it is clearly visible for the speed higher than 20 mm/s. At the speed of 30 mm/s, the observed friction force was above 7% larger for the outstroke in comparison to the instroke. The differences are not so clear for lower speeds. At the inner side of the seal, where oil is found, it is possible to deliver it to the friction zone. Small friction speed is not conducive to create a pressure distribution most suitable to insure zero leakage operation in the friction zone. As indicated earlier, zero leakage is only possible when keeping proper fluid transport in sealing zone. This can be the reason for the occurrence of larger friction force values scatter at lower sliding speeds.

Figures 9 and **10** indicate the results obtained using PAO oil with MoS_2 NPs additive, so that they can be compared to the courses of friction force for pure PAO oil above. **Figure 9** presents the course of the changes of the friction force for the following cycles of the rod movement during instroke, and **Fig. 10** shows the course of friction force changes during outstroke.

Figure 11 depicts the tests with the use of PAO oil with the addition of MoS2 nanoparticles (NPs) analogous to the earlier ones. The comparison of single strokes for both kinds of oil shows parallels in their course. However, one can notice a difference in the values of maximum friction forces. The differences for both maximum and average values obtained during measurements for both kinds of oils are even easier to be observed on the basis of their statistical analysis. The following figures show average values of friction forces obtained for various slide speeds for instroke and outstroke.

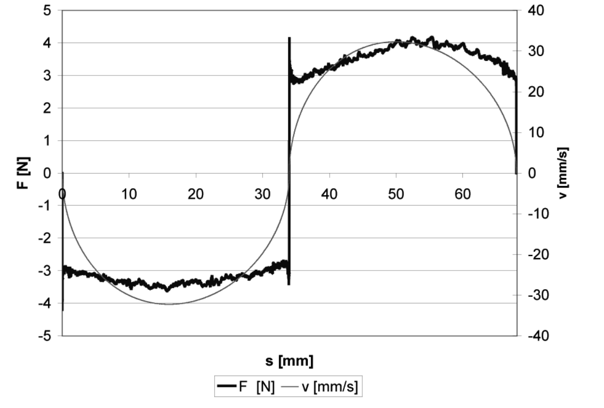

Fig. 11. The comparison of friction force on seal during one instroke and one outstroke for PAO oil + MoS_2 NPs

Rys. 11. Porównanie zmian siły tarcia uszczelki podczas jednego suwu dośrodkowego i odśrodkowego dla oleju PAO + MoS_2 NPs

We can assume that sedimentous and embedded MoS_2 NPs on frictional surfaces have an influence on the observed differences of friction force. Their agglomeration on the surfaces of the rod and seal is the reason for seal sliding on the formed MoS_2 derived layer in conditions of diminished fluid film thickness.

This process is schematically illustrated in **Fig. 14**. This situation changes the correlation between the sliding speed and friction force. In the case of a film thickness significantly larger than the size of nanoparticles, the sliding conditions will practically correspond to the conditions of pure PAO oil. However, diminishing the film thickness changes sliding conditions. It is of vital significance in the case of the decline of the lubricating film, reducing sliding speed to zero.

The comparison of the average values of friction force during the outstroke, presented respectively in the **Figs. 12** and **13**, indicates that they are alike. However, during the instroke for the tested range of speed, i.e. from 10 to 30 mm/s, a slight uniform increase in the friction force took place after the application MoS_2 NPs additive. The friction force increases by about 8% at the lowest speeds, and this increase is reduced at the higher sliding speed.

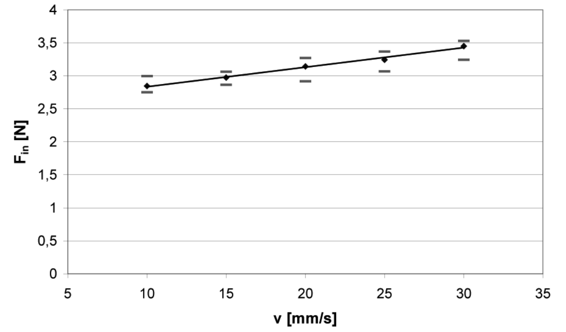

Fig. 12. Friction force on seal versus rod velocity [mm/s]; instroke; PAO oil + MoS2 NPs

Rys. 12. Siła tarcia uszczelki w funkcji prędkości tłoczyska, skok dośrodkowy, olej PAO +MoS_2 NPs

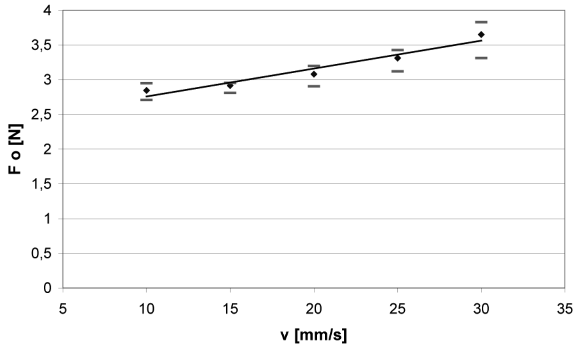

Fig. 13. Friction force on seal versus rod velocity [mm/s]; outstroke; PAO oil + MoS_2 NPs

Rys. 13. Siła tarcia uszczelki w funkcji prędkości tłoczyska, skok odśrodkowy, olej PAO +MoS_2 NPs

A very similar correlation of friction force versus sliding speed for outstroke (both for pure PAO oil and the oil with the MoS_2 NPs additive) indicates that friction conditions do not change on the outer side of the seal. The observed differences of the average values of friction force within the whole range of the evaluated sliding speeds do not exceed 2%. However, the differences reaching 10% during instroke can be observed. Therefore, MoS_2 nanoparticles can be deposited on the inner side of the seal, which will have an influence on sliding conditions.

Based on the obtained results of the measurements, one can infer that, during the movement of the piston rod, the nanoparticles present in oil can successively agglomerated on the surface of a rod. Therefore, after over a dozen of working strokes, they will be also found on the outer side of the seal. When they are spread on the surface, the effect of diminishing friction forces during the outstroke can be observed. One can also notice that the values of friction forces are stabilized. This situation was vividly illustrated on schematic diagrams. The state during the initial working phase is presented in **Fig. 14a**. The nanoparticles as a dispersion in oil are found only on the inner side of the seal. During the movement of the piston rod, they have the possibility of contact with the surface of the rod on the whole length of its stroke. In this situation, MoS_2 NPs may remain on the surface of the rod. Gradually, they may be deposited in the roughness valleys of the profile of surface. Therefore, the situation that takes shape after the initial working phase can be illustrated schematically as shown in **Fig. 14b**. MoS_2 NPs do not remain permanently associated with the surface of the rod. In the case of the change of oil to pure PAO without the addition of MoS_2 NPs, the nanoparticles are partially removed from the surface of the rod. One proof of this is the observed change in the friction force during the outstroke, which would mean the return to the working conditions equivalent to the application of pure PAO oil. These changes taking place can be explained with the conditions of seal operation. Due to elasticity of the material of the seal, the movement of the rod may in effect remove the nanoparticles which are found on the surface of the rod. Substantial unit pressures do not occur in the sealing zone. It is worth underlining that the most significant requirement in relation to the analysed elements is to preserve the leak free condition during the movement of the rod. That is why all the results of the measurements were obtained maintaining leak free condition.

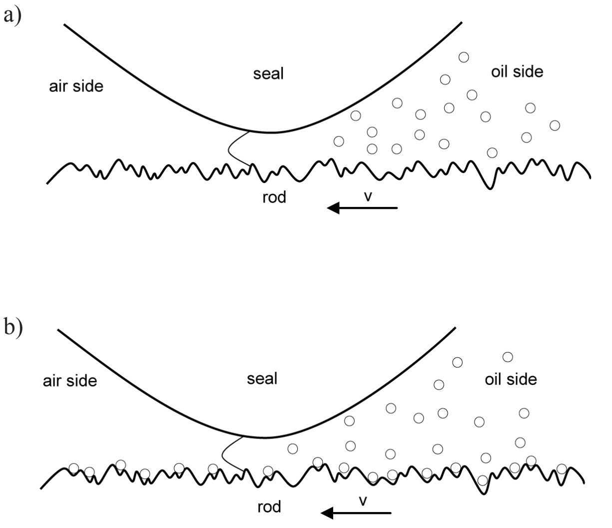

Fig. 14. Schematic drawing showing the agglomeration of the MoS_2 NPs on the surfaces of rod and seal: a) initial working phase, b) NPs may remain on the surface of the rod

Rys. 14. Schemat ilustrujący odkładanie nanocząstek MoS_2 na powierzchni tłoczyska: a) początkowa faza współpracy; b) nanocząstki MoS_2 naniesione na powierzchni tłoczyska

SUMMARY AND CONCLUSIONS

In this study, the experimental procedure was carried out with two oils, i.e. first, the reference pure PAO base oil and then with PAO oil with an additive of MoS_2 nanoparticles (NPs).

Investigations presented in this paper allow us to draw the following conclusions:

For the assumed research conditions, at the velocity above 20 mm/s, the average values of the friction force during instroke are 6% higher for PAO oil with MoS_2 additive in comparison to pure PAO base oil.

Boundary velocities above which the decrease of friction force was observed, which testified to the forming of the lubricating layer during the rod stroke, were as follows: pure PAO – 7 mm/s, and PAO oil with MoS_2 additive – 4.5 mm/s.

The presence of the particles in the oil influences the fluid transport to the sealing zone. Further steps include more detailed evaluation of the presented NPs in oil on the phenomena that occurred in the sealing zone. Conducting an analysis of fluid transport in this zone seems to be the next logical step in this research.

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