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LUBRICITY OF OIL-REFRIGERANT MIXTURES WITH R600a UNDER STARVED LUBRICATION CONDITIONS

WŁAŚCIWOŚCI SMARNE MIESZANIN OLEJÓW MINERALNYCH Z CZYNNIKIEM CHŁODNICZYM R600a W WARUNKACH SKĄPEGO SMAROWANIA

Key words: oil/refrigerant mixture, lubricity, starved lubrication conditions.

Abstract

In refrigeration nowadays, there is a dynamic return to the use of natural refrigerants such as hydrocarbons. These substances do not contain fluorine and chlorine, which contribute to the enlargement of the ozone hole and the greenhouse effect. Hydrocarbons, however, are substances from the A3 safety group (flammable) and are currently mainly used in low-capacity devices. The most commonly used refrigerant in this group is R600a (isobutene).

In refrigeration compressors, a situation may occur where the amount of oil in friction nodes is insufficient. In this case, there may be poor lubrication conditions. A situation may also arise in which the lubricant in the friction areas runs out, and the lubrication of the friction nodes will be performed exclusively by the refrigerant.

The article presents a concept of a test method allowing an assessment of lubricity properties of oils for refrigeration compressors in the mixture with a refrigerant in the conditions of poor lubrication and in the absence of lubrication with a lubricant. It also contains the results of wear tests that enable an evaluation of the lubricity properties of oil-refrigerant mixtures in the conditions of poor lubrication. The results were obtained for ecological, and recommended for a wider future use, R600a refrigerant with mineral oils.

It is also indicated that it is possible to compare various refrigerants in the absence of lubricant and to replicate lubricity properties of oil-refrigerant mixtures in the conditions of poor lubrication and to apply the proposed method for the evaluation of different lubricants in use with a selected refrigerant.

Słowa kluczowe: mieszanina olej/czynnik chłodniczy, właściwości smarne, skąpe smarowanie.

Streszczenie

Obecnie w chłodnictwie następuje dynamiczny powrót do stosowania naturalnych czynników chłodniczych takich jak węglowodory. Są to substancje niezawierające fluoru i chloru, które przyczyniają się do powiększania dziury ozonowej oraz efektu cieplarnianego. Węglowodory to jednak substancje z grupy bezpieczeństwa A3 (palne) i są obecnie głównie wykorzystywane w urządzeniach o małej wydajności. Najpowszechniej stosowanym czynnikiem chłodniczym w tej grupie urządzeń jest R600a (izobutan).

W sprężarkach chłodniczych może wystąpić sytuacja, w której ilość oleju w węzłach tarcia jest niewystarczająca. Wówczas mogą wystąpić skąpe warunki smarowania. Może również zaistnieć sytuacja, w której środka smarnego zabraknie w obszarach tarcia, a smarowanie węzłów będzie realizowane tylko przez czynnik chłodniczy.

W artykule przedstawiono koncepcję metody badań pozwalających na ocenę właściwości smarnych olejów do sprężarek chłodniczych w mieszaninie z czynnikiem chłodniczym w warunkach skąpego smarowania oraz braku smarowania środkiem smarnym. Umieszczono również wyniki badań zużyciowych pozwalających na ocenę właściwości smarnych mieszanin olej – czynnik chłodniczy w warunkach skąpego smarowania uzyskanych dla ekologicznego i wskazanego do szerszego stosowania w przyszłości czynnika chłodniczego R600a z olejami mineralnymi.

Wskazano również na możliwości porównania między sobą różnych czynników chłodniczych podczas braku środka smarnego oraz odwzorowania właściwości smarnych mieszanin olej/czynnik chłodniczy w warunkach skąpego smarowania i wykorzystania proponowanej metody do oceny rożnych środków smarnych do zastosowania z wybranym czynnikiem chłodniczym.

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INTRODUCTION

Due to the fact that hydrocarbons (HC), such as isobutene R600a do not cause the expansion of the ozone hole and have a minute effect on the formation of the greenhouse effect, they belong to the prospective refrigerants **[L. 1]**. Pure isobutene primarily constitutes a replacement for R12 in low-capacity devices, mainly in home refrigerators. One estimates that, of all domestic refrigeration devices in the EU, 98% use isobutene as the working medium **[L. 2]**. Mineral oils are dedicated for cooperation with R600a **[L. 3]**.

While circulating in the system, the refrigerant is always in contact with the lubricating oil. Depending on the value of the prevailing pressure and temperature in a particular part of the system, a mixture of oil–refrigerant of a specific composition is formed. Such a situation may negatively affect the cooperation of friction nodes in a refrigeration compressor, which may manifest by an excessive wear of moving parts.

Generally, refrigeration compressors break down due to two types of damage: electrical and mechanical. The causes of electrical damage (e.g., incorrect voltage or connection, local or complete burn-out) are not related to the oil–refrigerant mixture. In turn, most mechanical damages (e.g., ineffective lubrication, i.e. lack of oil or its dilution with a refrigerant, insufficient amount of oil, liquid impact) are caused by the interaction between the lubricating oil and refrigerant. The research methodology and the results of the model tests allow one to assess the lubricity properties of oil–refrigerant mixtures have already been presented by the authors in **[L. 3–7]**.

A situation in which friction nodes lack oil is the cause of insufficient cooling, and thus too high temperature in the refrigerated space. The lack of oil can be caused by too short work cycles, excessive foaming of oil, and long periods of minimal repletion of the compressor with oil (this amount is not transported to the friction nodes) with a simultaneous incorrect selection of refrigerant tubing. During short work cycles, the compressor may transport oil to the system in the quantities larger than the ones returned to the compressor, which leads to the reduction in the level of oil. When the foaming of oil occurs inside the crankcase, the oil is collected by the refrigerant in the gaseous state and compressed inside the system. If this state prevails, the level of oil may decrease. An insufficient quantity of oil in friction nodes can lead to the occurrence of poor lubrication conditions. The poor lubrication conditions in refrigeration compressors can also occur when the device is switched on or off **[L. 8, 9]**.

The results of testing mixtures of lubricating oil–refrigerant during poor lubrication have been presented in several articles **[L. 10–12]**. The authors of this work **[L. 10]** used a pin-on-disc test station. Most tests were performed with the use of polyalkylene glycol oil (PAG) and R134a. In several tests, polyester oils (POE) have been used, which are compatible with this refrigerant. The conditions of poor lubrication were obtained by applying different quantities of the lubricating medium on the surface of the upper sample (the disc) through a lubricant supply system embedded in the test chamber. Following pre-mixing with the liquid refrigerant, the lubricant was supplied in the friction area by a special nozzle in the form of oil mist. The atomization was done continuously. The tests were carried out under constant conditions. All tests were performed under refrigerant pressure of 0.17 MPa, and the temperature of 12±1°C, which are the operating conditions of friction nodes of refrigeration compressors with a swash plate using R134a. The courses of the friction coefficient and roughness profiles were also analysed.

In **[L. 11]**, the mixture of mineral oil (MO) with R600a was analysed. A constant amount of lubricant (100 mg) was fed into the area of the operation of the model pin-on-disc friction node. Next, R600a was continually supplied into the test chamber. The authors specified neither the pressure of the refrigerant nor the time of formation of oil–refrigerant mixture. The tests were performed in the ambient temperature of 23±1°C. The course of the friction coefficient and the loss of the mass of the disc-shaped sample were analysed. For comparison, tests were also carried out in which air was used instead of the cooling medium. On the basis of the charts included in **[L. 11]**, one can state that the friction coefficient in the presence of air is 50–90% greater than in the presence of R600a. The test results pointed to approx. twice as large mass loss in the case of tests using R600a in comparison with the tests in the air.

In order to obtain the conditions of poor lubrication, the authors of papers **[L. 12, 13]** applied one drop of lubricating medium (weighing approximately 22 mg) onto one of the samples constituting the model friction node. This amount was to enable the formation of the boundary layer.

This article presents the following:

– The concept of a test method allowing one to assess the lubricity properties of oils for refrigeration compressors in the mixture with a cooling medium in the conditions of poor lubrication; and,
– The results of wear tests allowing the assessment of lubricity properties of oil-refrigerant mixtures in the conditions of poor lubrication obtained for the ecological, and recommended for a future wider use, R600a with mineral oils.

THE TEST METHOD

In order to assess lubricity properties of oils for refrigeration compressors in the mixture with a refrigerant in the conditions of poor lubrication, a sample wear in the shape of a block of the model block-on-ring was used (**Fig. 1a**). The above coupling was selected because its character of motion is equivalent to the geometry of elements of the crankshaft mechanism of reciprocating refrigeration compressors.

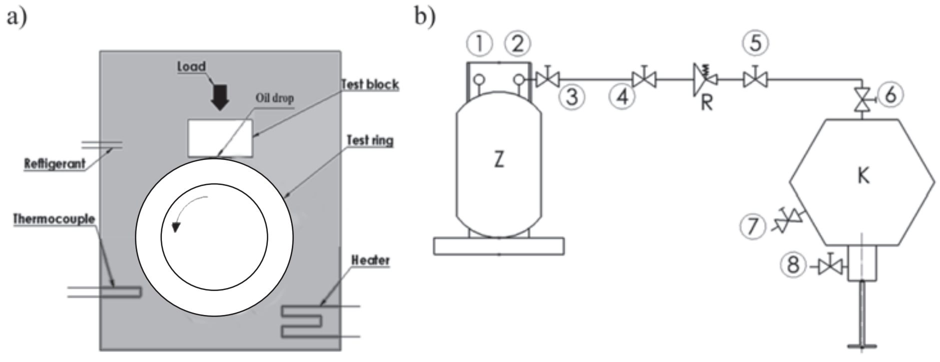

Fig. 1. (a) Scheme of the hermetic block-on-ring type wear tester, (b) the instrumentation for supplying refrigerant: Z – refrigerant cylinder, R – pressure reducer, K – chamber, 1–8 – ball valves

Rys. 1. (a) Schemat komory stanowiska badawczego z węzłem tarcia typu rolka–klocek, (b) idea zasilania komory badawczej czynnikiem chłodniczym: Z – zbiornik czynnika chłodniczego, R – reduktor ciśnienia, K – komora badawcza, 1–8 – zawory kulowe

In recent years, tests stands of the block-on-ring type have frequently been used to carry out tribological tests involving oil–refrigerant mixtures **[L. 14–18]**. Some of these tests dealt with oil mixture with R600a **[L. 14, 18]**. The description of a model friction pair was presented in **[L. 4]**.

In the proposed test method, the process of sample wear takes place under the following conditions:

– Enabling the accomplishment of a clear loss of material in a relatively short period of time, and
– Reflecting the actual states in the exploitation of refrigeration compressors.

In a test stand (**Fig. 1b**), one can replicate mechanical forces characteristic for the compressor start following a long standstill period. The concentration of the medium in the mixture with oil inside the compressor is then the highest.

During the main tests and prior to each one, the samples were ultrasonically cleaned in acetone for 15 minutes, and then embedded in the test chamber. In order to form the oil-refrigerant mixture, one must first remove the air from the test chamber and supply it with a drop of oil (approximately 30 mg). The refrigerant of a selected pressure (p_s) must then be supplied to the test chamber, and the conditions must be maintained for a specified time (τ_m). Once the mixture has been formed, a wear test of the duration (τ_t) must be carried out. After each test, one must disassemble the samples and measure the width trace of wear on the block-shaped sample and calculate the wear volume.

The main tests of lubricity properties were preceded by preliminary tests. The aim of these tests was to determine the wear test duration time (τ_t) for the conditions of poor lubrication.

While performing the tests necessary for the assessment of the lubricity properties of mineral oils (MO) and their mixtures with isobutene (R600a), the pressure of 0.21 MPa (p_s) in the test chamber was maintained. This value corresponds to the saturation pressure of R600a at the temperature of 23°C. The refrigerant pressure was pre-determined in the previous studies **[L. 3]**.

Figure 2 depicts the results of the wear tests realized in mineral oil at the air pressure of 0.21 MPa in the chamber for different wear test duration time τ_t. According to the concept presented in **[L. 6]**, a minimum sample wear of 0.5 mm^3 can be achieved after 10 minutes, and this value was selected for application of the main tests.

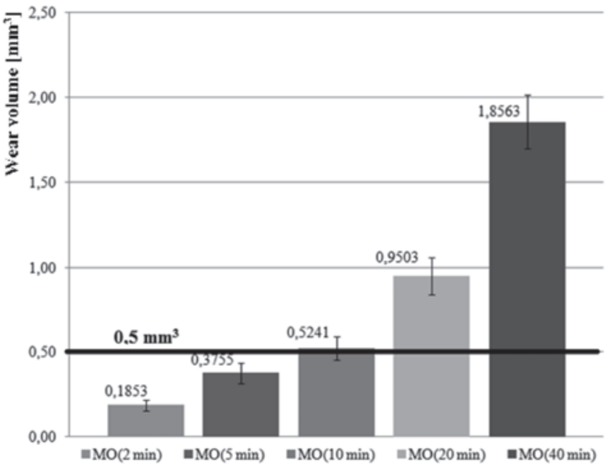

Fig. 2. Wear tests duration time selection for mineral oils in starved lubrication conditions (p_s = 0.21 MPa)

Rys. 2. Selekcja czasu trwania testu zużyciowego dla olejów mineralnych w warunkach skąpego smarowania (p_s = 0,21 MPa)

All tests were carried out at the sliding speed of 0.5 m/s. During each test run, the load was first changed in steps of 20 N every 30 seconds until the value of 120 N (total duration of 3 minutes), and then, at the maximum load of the friction node, an additional 10-minute wear test was carried out. Such parameters enable one to achieve a clear loss of material in a relatively short period of time. The wear tests were carried out with the test parameters determined above (τ_t) or earlier (τ_m i p_s) in **[L. 3, 5]**, such as the following:

– The refrigerant pressure in the test chamber (ps) for R600a was 0.21 MPa, and this value is equivalent to the saturation pressure of R600a at the temperature of 23°C.
– The wear test duration time (τ_t) was 10 minutes,
– The oil-refrigerant mixture formation time (τ_m) was 1200 minutes (this parameter was individually determined for the mixtures of mineral oils MO with R600a) **[L. 5]**.

The procedure of obtaining the oil-refrigerant mixture is essential for the used test method. In order to accomplish this task, it became necessary to construct a suitable chamber equipped with instruments for supplying a refrigerant and setting test parameters according to the procedure presented in **[L. 3]**.

The test parameters for lubricity properties of oils for refrigeration compressors in the mixture with R600a in the conditions of poor lubrication are shown in **Table 1**.

Table 1. Individually selected parameters for mineral oil/refrigerant R600a mixture in starved lubrication conditions
Tabela 1. Zestawienie parametrów badań olejów do sprężarek chłodniczych w mieszaninie z czynnikiem chłodniczym R600a w warunkach skąpego smarowania

Parameter	Unit	Value
Sliding velocity	[m/s]	0,5
Friction node load	[N]	0-120 (with 20 N step)
Amount of lubricant	mg	30 (1 drop)
Method of forming oil – refrigerant mixture	-	Without limiting supply of refrigerant
Refrigerant pressure	MPa	0,21
Wear tests duration time	[min]	10 (+3)
Oil – refrigerant mixture formation time	[min]	1200

For each series of tests (**Table 2**), three wear tests were carried out. During the tests from Series 1 (the air) and 2 (R600a), the pressure (p_s) was maintained in the chamber, yet, no lubricant was provided. In turn, for Series 3 (MO) and 4 (MO/R600a), the pressure (p_s) was maintained in the chamber while supplying it with air in Series 3 and isobutene R600a in Series 4, respectively. During Series 3 and 4, a small amount of mineral oil (1 drop) was fed into the friction node.

Table 2. Summary of research series
Tabela 2. Zestawienie serii badań

Series number	Lubricant
1	Air
2	R600a
3	MO
4	MO/R600a

TEST RESULTS

The moment of force in the friction node was measured during tests, and the friction coefficient was determined from the following formula:

$$\mu = \frac{M}{Pr}$$

where
μ – friction coefficient, [-],
M – moment of force [Nm],
P – load, (pressure force), [N],
r – the inner radius of the sleeve, [m].

The value of the friction coefficient for the four series of tests is presented in **Figs. 3, 4** and **5**. **Fig. 3** shows the course of value of the friction coefficient for all of the test series at an increasing load (the first 3 minutes of the test).

From **Fig. 3**, one can draw a conclusion that the value of the friction coefficient in the performed tests does not depend on the load of the friction node. The mean value of the friction coefficient for Series 1 (air) during the period in which the load was being increased (the first 180 s) amounts to 0.47, and, for Series 2 (R600a), it is 0.19. One can then conclude that the coefficient of friction in the presence of the air is more than 100% greater than in the presence of R600a. The result confirms the tendencies previously demonstrated in **[L. 11]**.

On the other hand, the mean value of the friction coefficient for Series 3 (MO) in the period in which the load was being increased is 0.19. Similarly, for Series 4 (MO/R600a), it also amounts to about 0.19. One cannot then confirm a significant impact of the presence of refrigerant on the value of the coefficient of friction.

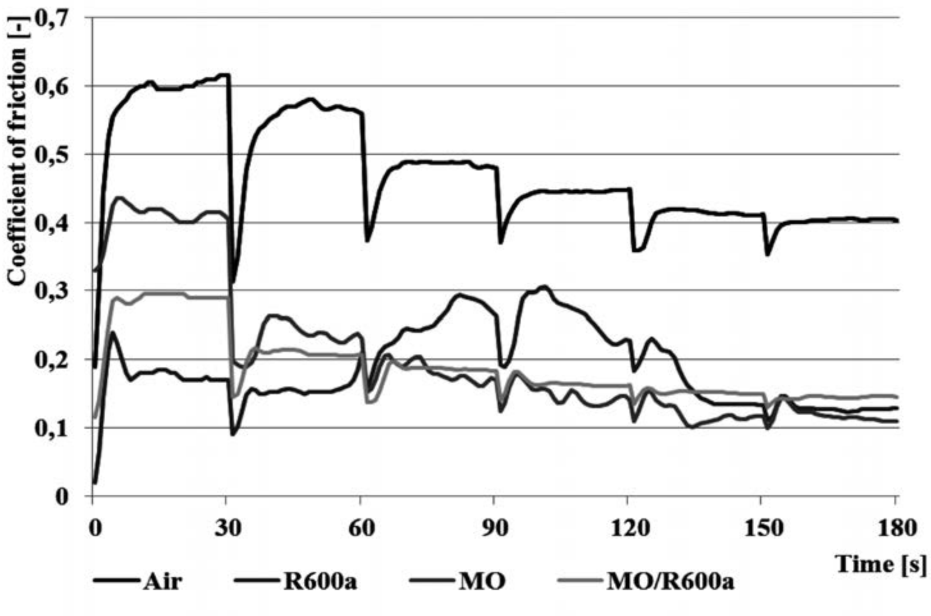

Fig. 3. Coefficient of friction for four research series with increasing load
Rys. 3. Wartości współczynnika tarcia dla czterech serii badawczych przy wzrastającym obciążeniu

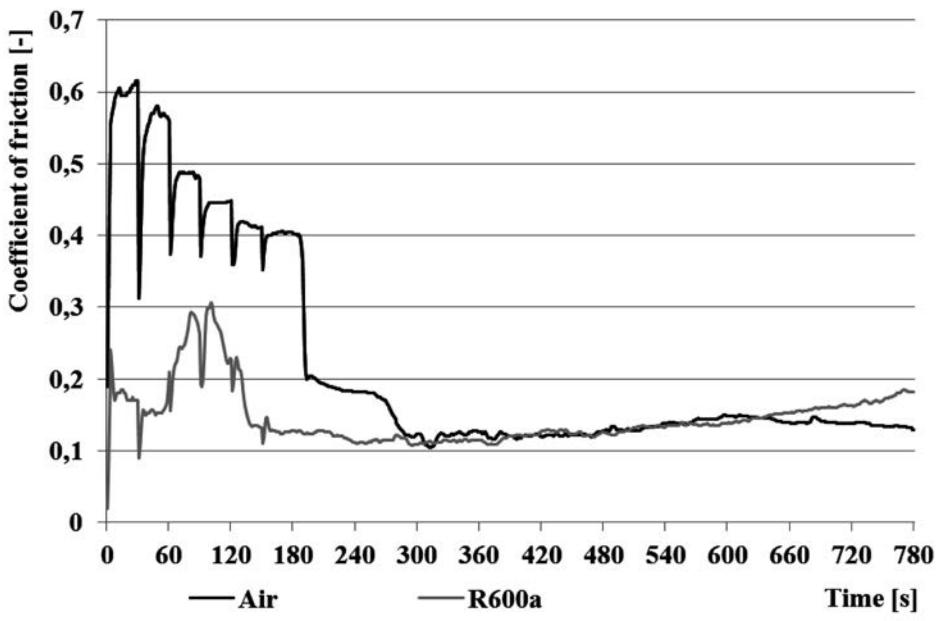

Fig. 4. Coefficient of friction for series 1 and 2 at constant maximum load of 120 N
Rys. 4. Wartości współczynnika tarcia dla serii 1 i 2 stałym obciążeniu maksymalnym 120 N

Figure 4 depicts the progression of the friction coefficient value for Series 1 and 2 at a constant maximum load of 120 N.

From the courses of the value of the friction coefficient at a constant maximum load presented in **Fig. 4**, one can conclude that, for Series 1 (air), the friction coefficient first stabilized at the level of approximately 0.11, and then increased in the time of the performed test run to the value of approx. 0.16. The mean value of the friction coefficient for the entire test run for Series 1 was 0.22. In turn, for Series 2 (R600a), the coefficient of friction first stabilized at the level of approx. 0.11, and then grew in the time of the performed test run to the value of approx. 0.19. The mean value of the friction coefficient for Series 2 stood at 0.17.

Figure 5 presents the courses of friction coefficient values for Series 3 and 4 at a constant maximum load of 120 N.

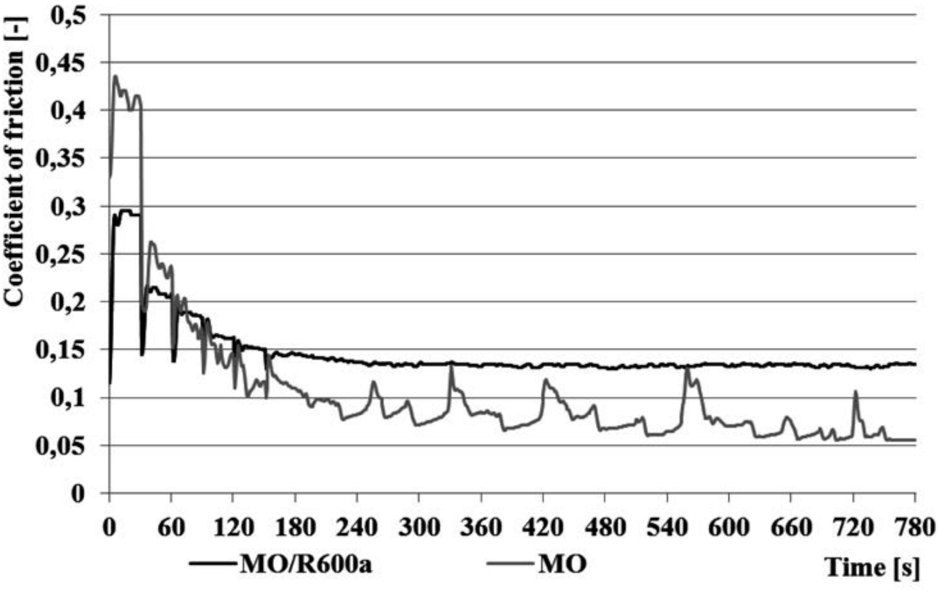

Fig. 5. Coefficient of Friction for Series 3 and 4 at constant maximum load of 120 N
Rys. 5 Wartości współczynnika tarcia dla serii 3 i 4 przy stałym obciążeniu maksymalnym 120 N

On the basis of the courses of friction coefficient values at a constant load presented in **Fig. 5**, one can conclude that, for Series 3 (MO), the friction coefficient fluctuated around the value of 0.07. The observed peaks after about 180 s may indicate adhesive wear or anti-seizure performance of additives. The mean value of the friction coefficient for the entire test run for Series 3 was 0.11. In turn, for Series 4 (MO/R600a), the friction coefficient stabilized at the level of approx. 0.14. The mean value of the friction coefficient for Series 4 was 0.15.

Figure 6 illustrates the values of the mean sample wear volume after the tests from four test series. The bars in the graph represent the spread in the form of a standard deviation.

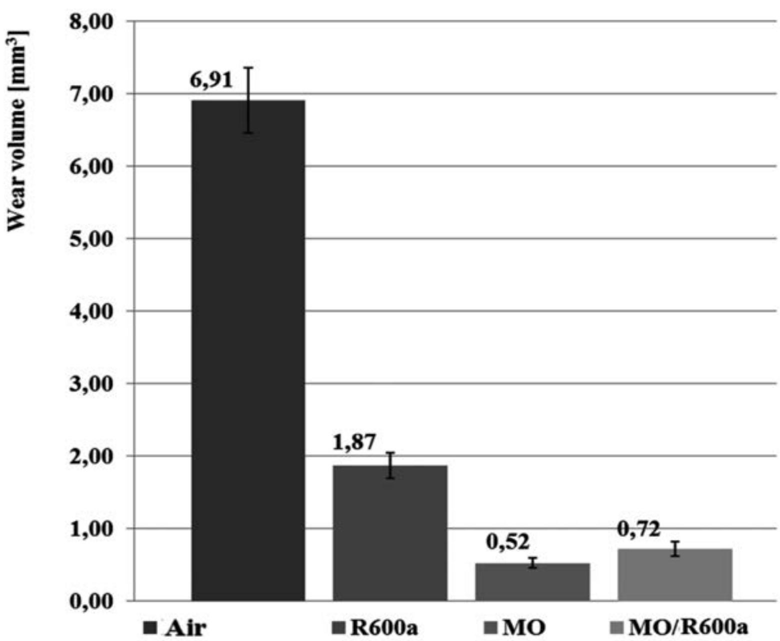

Fig. 6. Wear volume results after four research series
Rys. 6. Średnie zużycie objętościowe próbek po testach z czterech serii badawczych

In the case of the first series (air), the wear volume is 6.91 mm^3, and, for the second series (R600a), it is 1.87 mm^3. This result indicates more than three times worse lubricity properties of the air in relation to R600a refrigerant in situations when the friction node lacks lubricant. This relation contradicts the research carried out in **[L. 11]**.

One can notice a significant improvement of lubricity properties in the series where a small amount of lubricant was supplied. In the case of the third series (MO), the wear volume amounts to 0.52 mm^3, and, for the fourth one (MO/R600a), it is 0.72 mm^3. By comparing Series 3 and 4, one can conclude that the presence of a refrigerant in mineral oil at poor lubrication worsens its lubricity properties by approx. 40%.

On the other hand, a comparison of the results of Series 3 and 4 shows that even a small amount of lubricant reduces the wear of the elements of friction node even thirteen times. By comparing Series 2 and 4, one can conclude that even a small amount of lubricant in the presence of a refrigerant at poor lubrication can improve lubricity properties almost three times.

The obtained results (**Fig. 6**) indicate that the applied method of evaluating lubricity properties is effective, because it allows both to replicate the effect of the presence of refrigerant in a small amount of lubricant on lubricity properties, to compare different cooling media when there is lack of lubricant, and to map lubricity properties of oil-refrigerant mixtures in the conditions of poor lubrication.

SUMMARY

In the friction nodes of refrigeration compressors, a situation can occur in which the amount of oil is insufficient. Then, poor lubrication conditions may occur. In refrigeration compressors, poor lubrication can also take place when the device is switched on and off. In addition, a situation may arise where the lubricant runs out in the areas of friction by refrigerant, and lubrication of the friction nodes shall be performed exclusively by the refrigerant.

The article presents the concept of research allowing one to assess the lubricity properties of oils for refrigeration compressors in the mixture with a refrigerant in the conditions of poor lubrication and the lack of lubrication by a lubricant. The article also includes the results of wear tests enabling the evaluation of lubricity properties of oil-refrigerant mixtures in the conditions of poor lubrication obtained for the ecological, and recommended for future use, R600a refrigerant with mineral oils.

The test results confirmed that the mean coefficient of friction can become signal information in the comparison between the tested lubricants. However, lubricity properties should be demonstrated by the wear of friction nodes. It turned out that, when there is no lubricant, R600a refrigerant has several times better lubricity properties than the air. On the other hand, in the conditions of poor lubrication, R600a forms a mixture with mineral oil, which results in the deterioration of its lubricity properties. The oil-refrigerant mixture has approx. 40% worse lubricity properties than mineral oil which does not form a mixture with the air.

The obtained results allow one to conclude that the proposed test method and the applied stand properly imitate the impact of the presence of refrigerant in a small amount of lubricant on lubricity properties. By using the presented test method, one can compare different refrigerants in the absence of lubricant. It is also possible to replicate lubricity properties of oil-refrigerant mixtures in conditions of poor lubrication and to use the proposed method for assessing various lubricants for use with a selected refrigerant.

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