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THE EVALUATION OF TRIBOLOGICAL PROPERTIES OF MINERAL OILS-R600a REFRIGERANT MIXTURES UNDER STARVED LUBRICATION CONDITIONS

OCENA WŁAŚCIWOŚCI TRIBOLOGICZNYCH OLEJÓW MINERALNYCH PRZEZNACZONYCH DO STOSOWANIA Z WĘGLOWODOROWYMI CZYNNIKAMI CHŁODNICZYMI W WARUNKACH SKĄPEGO SMAROWANIA

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

Abstract In refrigeration compressors, the amount of oil in tribocontacts in certain situations may be insufficient. In this case, poor lubrication conditions may occur. There may also be a situation in which the areas of lubrication lack lubricant and the lubrication of the friction pairs will be carried out by only the refrigerant.

The requirements related to legal regulations and concerning refrigerants result in the return to the use of natural substances such as hydrocarbons. These substances do not contribute to the enlargement of the ozone hole and the greenhouse effect. The most commonly used refrigerant in the group of low-capacity devices is R600a (isobutene).

The article verifies the test method allowing one to assess lubricity properties of oils for refrigeration compressors in the mixture with a refrigerant under the conditions of poor lubrication. The article also contains the results of wear tests which allow one to assess and contrast lubricity properties of oil–refrigerant mixtures for three mineral oils of the same viscosity grade under the conditions of poor lubrication in cooperation with R600a. The tests were performed for the air, R600a, mineral oils, and oil–refrigerant mixtures.

Słowa kluczowe: olej/czynnik chłodniczy, smarność, warunki skąpego smarowania.

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

Wymuszenia związane z przepisami prawnymi dotyczącymi czynników chłodniczych skutkują powrotem do stosowania naturalnych substancji, np. węglowodorów. Są to substancje, które nie przyczyniają się do powiększania dziury ozonowej oraz efektu cieplarnianego. Najpowszechniej stosowanym czynnikiem chłodniczym w grupie urządzeń o małej wydajności jest R600a (izobutan).

W artykule przedstawiono weryfikację metody badań pozwalających na ocenę właściwości smarnych olejów do sprężarek chłodniczych w mieszaninie z czynnikiem chłodniczym w warunkach skąpego smarowania. Umieszczono również wyniki badań zużyciowych pozwalających na ocenę i porównanie właściwości smarnych mieszanin olej–czynnik chłodniczy dla trzech olejów mineralnych o tej samej klasie lepkości w warunkach skąpego smarowania przy współpracy z czynnikiem chłodniczym R600a. Badania wykonywano dla powietrza, czynnika chłodniczego R600a, olejów mineralnych oraz mieszanin olej–czynnik chłodniczy.

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INTRODUCTION

Tightening legislation concerning refrigerants from the group of fluorinated gases (the "F-gases") and introducing such legal provisions on substances that deplete the ozone layer and some fluorinated greenhouse gases (Journal of Laws 2015.881) **[L. 1]** and the Regulation of the European Parliament and Council (EU) No 517/2014 on fluorinated greenhouse gases and the invalidation of the regulation **[L. 2]** have brought significant changes in the refrigeration sector in recent years. It is estimated that, by the end of the year 2018, as compared to 2015, the total volume of the fluorinated refrigerants admitted to trading decreased by more than half **[L. 3]**. In addition, the previously collected supply of refrigerants had already been used up.

The "F-gases" do not include hydrocarbons (HC), due to their lack of impact on the enlargement of the ozone hole and a very negligible influence on the formation of the greenhouse effect, i.e. R600a isobutene **[L. 4]**. This substance is being increasingly used in refrigeration installations. For cooperation with R600a, there are mineral oils selected for it **[L. 5]**.

The lubrication of friction pairs of refrigeration compressors is usually ensured by a mixture of compressor oil and refrigerant under the conditions of full availability of the refrigerant **[L. 5–10]**. However, undesirable situations may occur during the work of a refrigeration appliance. One of the possible causes of exploitation damage to refrigeration compressors is the lack of refrigerant or its insufficient quantity in friction pairs **[L. 10]**. Attempts to describe this and other causes of damage to refrigeration compressors were made in, inter alia **[L. 11–14]**.

Tests of lubricant oil-refrigerant mixtures under the conditions of poor lubrication had previously been carried out at the test bench of the pin-on-disc type **[L. 15–17]**. In order to obtain the conditions of poor lubrication, one drop of lubricant per one sample forming the model friction pair was applied. This amount was to enable the formation of the boundary layer.

This article presents the results of wear tests allowing one to assess and compare lubricity properties of oil-refrigerant mixtures under the conditions of poor lubrication obtained for the ecological and indicated for wider future use R600a refrigerant with mineral oils of the same viscosity grade.

TEST METHOD

In recent years, test benches of the block-on-ring type have been used for implementing tribological test involving oil-refrigerant mixtures **[L. 18–22]**. Some of these studies also concerned mixtures of oils with R600a **[L. 18, 22]**.

In order to evaluate lubricity properties of oil for refrigeration compressors in the mixture with refrigerant under the conditions of poor lubrication, sample wear was used in the shape of a block of the model block-on-ring node. The guidance concerning the experiment is given in **[L. 10]**.

While producing the oil-refrigerant mixture, the air was removed from the test chamber and a drop of oil (approx. 30 mg) was supplied into it. Then the chamber was supplied with a refrigerant of a selected pressure (p_s), and these conditions were maintained for a specified time (τ_m) **[L. 10]**. After the mixture had been formed, a wear test of the duration time (τ_t) was carried out.

Following each test, the samples were disassembled and the width trace of wear was measured on the sample of the block shape, and then the volume wear was calculated. The test parameters, such as the mixture formation time (τ_m) and the wear test duration time (τ_t) for the conditions of poor lubrication, were set in the previous works **[L. 5, 10]**. The set of test parameters is summarized 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 20N 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

Three mineral oils (MO1, MO2, and MO3) of viscosity grade VG 32 and dedicated for cooperation with R600a were selected in this article so as to compare lubricity properties under the conditions of poor lubrication. **Table 2** presents a summary of the performed series of tests. For each experimental series **(Table 2)**, three wear tests were carried out. During the tests in Series 1 (the air) and Series 5 (R600a) pressure (p_s) was maintained in the chamber, but the lubricant was not supplied. In turn, for series 2–4 (MO) and 6–8 (MO/R600a) pressure (p_s) was maintained in the chamber while supplying it with the air in Series 2–4 and isobutene R600a in Series 6–8, respectively. In Series 2–4 and 6–8, a small amount of mineral oil (one drop) was supplied into the friction pair.

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

Series number	Lubricant
1	Air
2	MO1
3	MO2
4	MO3
5	R600a
6	MO1/R600a
7	MO2/R600a
8	MO3/R600a

RESEARCH RESULTS

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

$$\mu = \frac{M}{P r}$$

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

The value of the coefficient of force for the first four series of the performed tests is shown in **Figs. 1 and 2**. The waveforms show the changes in the coefficient of friction for refrigeration compressor oils in the absence of contact with the refrigerant and may illustrate an operational situation in which there was a leak of refrigerant from the refrigeration installation. **Fig. 1** presents the changes in the values of the coefficient of friction for the first four experimental series with an increasing load (the first 3 minutes of the tests).

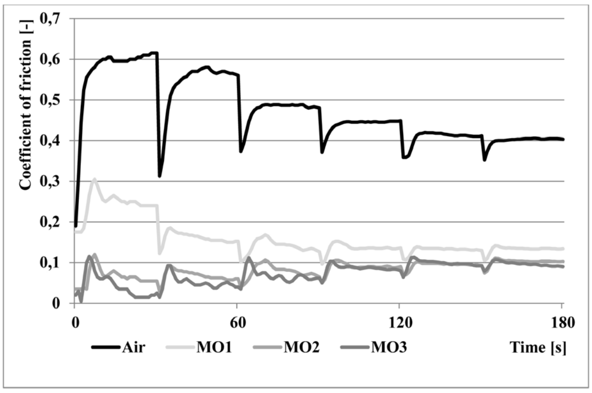

Fig. 1. Coefficient of Friction for first four research series with increasing load
Rys. 1. Wartości współczynnika tarcia dla pierwszych czterech serii badawczych przy wzrastającym obciążeniu

It can be concluded from **Fig. 1** that the value of the coefficient of friction in the performed tests does not depend on the load of the friction pair. The mean value of the coefficient of friction for Series 1 (the air) in the period in which the load was increased (the first 180s) amounts to 0.47, Series 2 (MO1) is 0.15, Series 3 (MO2) is 0.08, and Series 4 (MO3) is 0.07. In general, it can be concluded that the coefficient of friction in the presence of air is at least three times higher than in the presence of mineral oils. This result confirms the assumption that lubrication improves when the lubricating medium is applied in the friction pair. In turn, one can notice slightly worse lubricating conditions when using MO1.

Figure 2 shows the values of the coefficient of friction for Series 1–4 at a constant maximum load of 120 N.

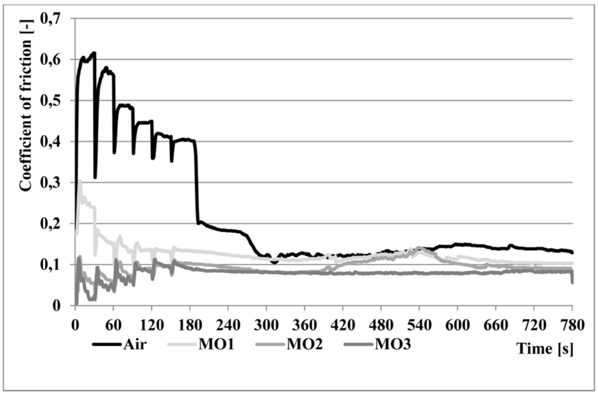

Fig. 2. Coefficient of Friction for first four research series at constant maximum load of 120 N
Rys. 2. Wartości współczynnika tarcia dla pierwszych czterech serii badawczych przy stałym obciążeniu maksymalnym 120 N

Figure 2 demonstrates that the mean value of the coefficient of friction at a constant maximum load of 120N for Series 1 (the air) is 0.14, Series 2 (MO1) is 0.12, Series 3 (MO2) is 0.10, and Series 4 (MO3) is 0.08, respectively. Therefore, one can generally state that the coefficient of friction in the presence of a small amount of mineral oils is higher by 14–43% than in the absence of lubrication.

The values of the coefficient of friction for the last four experimental series are shown in **Figs. 3 and 4**. The waveforms of the coefficient of friction for the last four experimental series at an increasing load are presented in **Fig. 3**.

On the basis of **Fig. 3**, it can be concluded that the coefficient of friction in the implemented test runs 5–8 (the mixture of oil with a refrigerant) does not depend on the load of the friction pair. On the other hand, in Series 5 (R600a), the coefficient of friction changes significantly along with subsequent load changes – from about 0.12 to

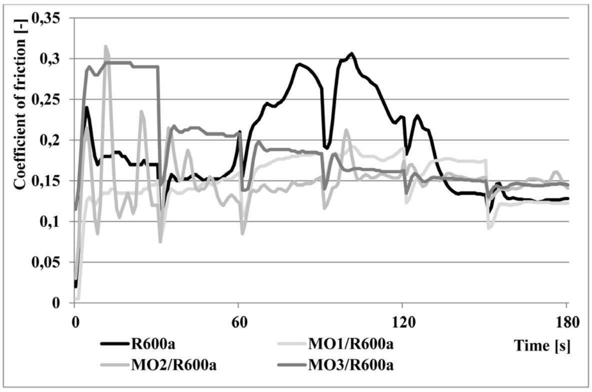

Fig. 3. Coefficient of Friction for four last research series with increasing load

Rys. 3. Wartości współczynnika tarcia dla czterech ostatnich serii badawczych przy wzrastającym obciążeniu

even 0.30. The mean value of the coefficient of friction for Series 5 (R600a) in the period in which the load was increased amounts to 0.19, for Series 6 (MO1/R600a), it is 0.15, for Series 7 (MO2/R600a), it is 0.15, and, for series 8 (MO3/R600a), it is 0.19. It can therefore be stated that the coefficient of friction in the presence of a small amount of mineral oils MO1 and MO2 in the mixture with R600a is more than 20% lower than in the case of the absence of lubrication in the absence of R600a and in the case of lubricating by mixture of MO3 and R600a.

Figure 4 shows the waveforms of the value of the coefficient of friction for Series 5–8 at a constant maximum load of 120 N.

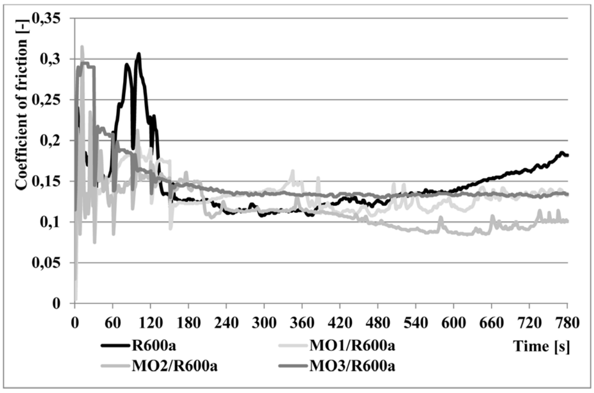

Fig. 4. Coefficient of Friction for the last four research series at constant maximum load of 120 N

Rys. 4. Wartości współczynnika tarcia dla czterech ostatnich serii badawczych przy stałym obciążeniu maksymalnym 120 N

Figure 4 demonstrates that the mean value of the coefficient of friction at a constant maximum load of 120N is the following: Series 5 (R600a) = 0.15, Series 6 (MO1/R600a) = 0.13, Series 7 (MO2/R600a) = 0.11, and series 8 (MO3/R600a) = 0.15. Overall, it can be stated that the coefficient of friction in the presence of a small amount of mineral oils in the mixture with R600a does not change in the case of MO3, since it is lower by approx. 13% in the case of MO1 and by approx. 27% in the case of MO2. It is worth noting that, in the case of oil-refrigerant mixtures, the value of the coefficient of friction with time was stable or decreased slightly, while this value increased in the absence of oil (Series 5).

Figures 5 and 6 illustrate the values of the mean sample wear volume after the tests of all eight experimental series. The wear quantity is the measure of lubricity properties of the tested substances. The columns in the charts present the dispersion in the form of a standard deviation.

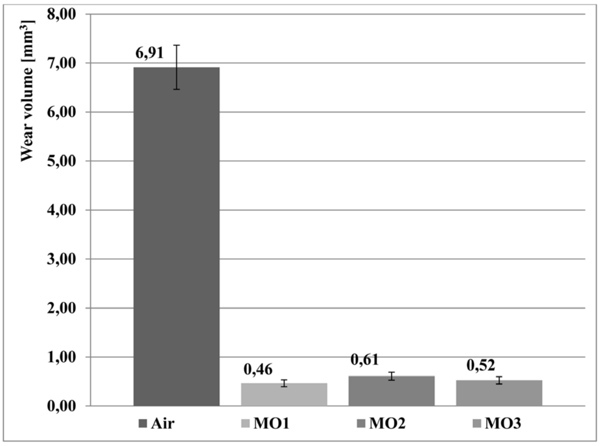

Fig. 5. Wear volume results after first four research series

Rys. 5. Średnie objętościowe zużycie próbek po testach z pierwszych czterech serii badawczych

The results presented in **Fig. 5** concern the mean wear volume of samples after the tests from the first four experimental series. The wear volumes amount to the following: Series 1 (the air) = 6.91 mm^3, Series 2 (MO1) = 0.46 mm^3, Series 3 (MO2) = 0.51 mm^3, and Series 4 (MO3) = 0.62 mm^3. This result is the evidence for more than tenfold worse lubricating properties of the air in relation to the tested mineral oils under the conditions of poor lubrication. While comparing Series 2 and 4, it can be stated that the tested mineral oils in poor lubrication differ in their lubricating properties by up to 35%. In the conditions of poor lubrication, it is MO1 that has the best lubricity properties, MO3 has slightly worse ones, and the worst lubricity properties are shown by MO2.

The results presented in **Fig. 6** concern the mean wear volume of samples after the tests from the last four experimental series. The wear volumes are as follows: Series 5 (R600a) = 1.87 mm^3, Series 6 (MO1/R600a) = 1.10 mm^3, Series 3 (MO2/R600a) = 1.50 mm^3, and Series 4 (MO3/R600a) = 0.72 mm^3. This result confirms nearly 300% better lubricating properties in the presence of a small amount of lubricant in the friction pair (the comparison of Series 5 and 8). By comparing Series 6, 7, and 8, it can be stated that, at poor lubrication, the tested mineral oils mixed with R600a differ in their

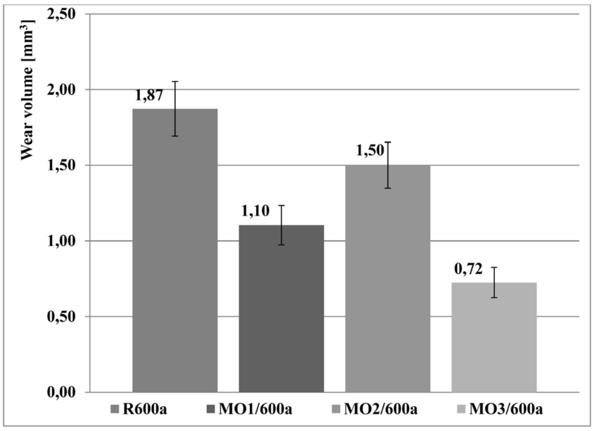

Fig. 6. Wear volume results after last four research series
Rys. 6. Średnie objętościowe zużycie próbek po testach z ostatnich czterech serii badawczych

lubricity properties even by 108%. In the conditions of poor lubrication with a mixture of oil and refrigerant, it is the mixture of MO3/R600a that has the best lubricity properties, the mixture of MO1/R600a has slightly worse ones, and the worst lubricity properties are shown by the mixture of MO2/R600a.

While comparing Series 1 and 5, it can be concluded that the lubricity properties of the air are more than three times worse in relation to R600a in situations when there is no lubricant in the friction node. This relation contradicts similar research carried out in **[L. 16]**. On the other hand, when determining the influence of the refrigerant on mineral oils and their lubricity properties, one can point to their deterioration by approximately the following values:

– 140% for MO1 (the comparison of Series 2 and 6),
– 146% for MO2 (the comparison of Series 3 and 7), and
– 38% for MO3 (the comparison of Series 4 and 8).

The obtained results (**Figs. 5 and 6**) indicate that the applied method of assessing lubricity properties is effective, because it allows one to map the influence of a refrigerant in a small amount of a lubricant on lubricity properties, to compare various refrigerants in the absence of a lubricant, and to map lubricity properties of oil/refrigerant mixtures under the conditions of poor lubrication.

SUMMARY

In refrigeration compressors, a situation may take place in which the amount of lubricant in friction pairs is insufficient. As a result of operating problems or when switching on/off the refrigeration appliance, poor lubrication may occur. In addition, a certain situation may occur in which lubrication of friction pairs will be carried out by the refrigerant exclusively. In extreme situations, due to the loss of tightness of the refrigeration system, the friction pairs may cooperate without lubrication, in the air.

The article presents the results of the wear tests allowing one to assess lubricity properties of mineral oils intended for use in refrigeration compressors with R600a. The tests were carried out for the conditions of poor lubrication with the use of three mineral oils of the same viscosity grade VG 32, both for the oils alone and in the mixture with R600a. For comparative purposes, there were tests carried out with no lubricant – in the atmospheric air, and R600a.

The test results confirmed that the mean coefficient of friction may be the signal information in the comparisons between the tested lubricants. On the other hand, lubricating properties should be demonstrated by the wear of friction pairs.

It was found that, in the tests of pure lubricants under the conditions of poor lubrication, while reducing the value of the coefficient of friction even by 43%, their presence allows for more than tenfold improvement of lubricity properties. In addition, the coefficient of friction in the presence of the air is at least three times higher than in the presence of mineral oils.

As for the lubrication with oil-refrigerant mixtures under the conditions of poor lubrication, it was observed that the value of the coefficient of friction is up to 300% lower than in the case of no lubrication in the presence of refrigerant. The test results also indicate lubricity properties that are almost three times better in the presence of a small amount of lubricant in the friction pair as compared to the lubrication with R600a alone.

On the other hand, at poor lubrication, the tested mineral oils in the mixture with R600a differ in their lubricity properties even by 100%.

The obtained results make it possible to state that the proposed research method and the applied test stand properly imitate the conditions of poor lubrication in refrigeration compressors. By using the presented method, one can compare various refrigerants in the absence of lubricant and in the lubrication by oil-refrigerant mixtures under the conditions of poor lubrication.

The results presented in the article confirm that it is not possible to effectively assess lubricity properties of refrigeration compressor oil under the conditions of poor lubrication on the basis of the results of tests characterizing the oil. In the case of MO/R600a mixtures, while classifying the tested lubricants according to the increasing sample wear, a different order was obtained than for the oils themselves.

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