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LUBRICATING PROPERTIES OF POLYESTER OILS AND R404A REFRIGERANT MIXTURES UNDER STARVED LUBRICATION CONDITIONS

WŁAŚCIWOŚCI SMARNE MIESZANIN OLEJÓW POLIESTROWYCH Z CZYNNIKIEM CHŁODNICZYM R404A W WARUNKACH SKĄPEGO SMAROWANIA

Key words: oil/refrigerant mixture, lubricating properties, starved lubrication.

Abstract: There has been a dynamic shift towards the use of ecological refrigerants in the refrigeration industry. Currently, they must not contain fluorine and chlorine. The substances that deplete the ozone layer have already been withdrawn, and the refrigerants that increase the greenhouse effect are getting restricted. Until recently, R404A was a quite commonly used HFC refrigerant for commercial refrigeration equipment in both small and large systems. Although R404A refrigerant has considerable greenhouse effect potential, it has not been banned from use in existing refrigeration systems. The widespread use of R404A refrigerant requires appropriate compressor lubricants.

In refrigeration compressors, the amount of oil in friction pairs in certain situations may be insufficient. In that event, poor lubrication conditions may occur. There may also be a situation in which the areas of friction lack lubricant and friction pairs are lubricated only by the refrigerant.

The article contains a methodical selection of test parameters for polyester oils, allowing one to assess the lubricating properties of the mixtures of oils for refrigeration compressors and refrigerants under poor lubrication conditions. The article also includes the results of wear tests which allow one to evaluate the lubricating properties of oil-refrigerant mixtures under starved lubrication conditions for R404A refrigerant and polyester oils.

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

Streszczenie: Obecnie w chłodnictwie następuje dynamiczny zwrot w kierunku stosowania ekologicznych czynników chłodniczych. Dość powszechnie stosowanym czynnikiem chłodniczym z grupy HFC dla komercyjnych urządzeń chłodniczych zarówno w małych jak i dużych instalacjach był do niedawna R404A, co wiąże się z potrzebą doboru odpowiednich sprężarkowych środków smarnych.

W sprężarkach chłodniczych może wystąpić sytuacja, w której ilość oleju w węzłach tarcia jest niewystarczająca. Wówczas mogą wystąpić skąpe warunki smarowania lub smarowanie tylko przez czynnik chłodniczy.

W artykule przedstawiono metodyczny dobór parametrów badań pozwalających na ocenę właściwości smarnych olejów do sprężarek chłodniczych w mieszaninie z czynnikiem chłodniczym w warunkach skąpego smarowania dla olejów poliestrowych. Umieszczono również wyniki badań zużyciowych pozwalających na ocenę właściwości smarnych mieszanin olej – czynnik chłodniczy w warunkach skąpego smarowania uzyskanych dla czynnika chłodniczego R404A z olejami poliestrowymi.

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INTRODUCTION

The refrigerant is constantly in contact with lubricating oil while circulating in the system. An oil-refrigerant mixture with specific composition is formed depending on the pressure and temperature in a given system area. The presence of refrigerant in the lubricant may negatively affect the moving parts in the refrigeration compressor and result in excessive wear of the parts. Previous articles **[L. 1, 2]** indicate that damage to refrigeration compressors is largely caused mechanically, mainly because of ineffective lubrication, i.e., lack of oil or its dilution with refrigerant and insufficient quantity of oil.

Tribological tests aimed at evaluating lubricants for refrigeration compressors partially reflected operational problems of real equipment. In broad terms, the papers **[L. 3–6]** attempted to evaluate various lubricants under the circumstances where oil was diluted with refrigerant, and the quantity of lubricant was sufficient. The authors present the research methodology and the results of model tests that allow one to assess the lubricating properties of oil/refrigerant mixtures **[L. 7–11]**.

Lack of oil or its insufficient quantity in friction pairs have also been analysed in previous works **[L. 12–14]**. Lack of oil or its insufficient quantity in friction pairs may be caused by: too short work cycles of a refrigeration compressor, excessive oil foaming and long periods of the minimum filling of the compressor with oil when the diameters of refrigeration system tubes are incorrect **[L. 12, 13]**. Insufficient oil in friction pairs may result in starved lubrication conditions, and poor lubrication may also occur in refrigeration compressors when the equipment turns on or off.

Test results for lubricating oil-refrigerant mixtures under poor lubrication conditions have been presented in several articles **[L. 13, 14]**. In the work **[L. 13]**, the mixture of mineral oil (MO) and R600a refrigerant was analysed. A fixed quantity of lubricant (100 mg) was applied to the area of cooperation of a model pin-on-disc type friction pair. R600a refrigerant was then continuously supplied to the test chamber. The authors did not provide the refrigerant pressure and the formation time of oil/refrigerant mixture. The tests were performed at an ambient temperature of 23 ±1°C. The friction coefficient course and the disc-shaped sample's wear were analysed. For comparison, tests in which air was used instead of refrigerant were also carried out. Based on the diagrams presented in **[L. 13]**, it can be concluded that the friction coefficient in the presence of air is 50–90% higher than in the presence of R600a. The results of the tests showed about twice as much weight loss in the tests using R600a refrigerant compared to the tests in the air.

In order to obtain poor lubricating conditions, the authors of **[L. 12, 14, 15]** applied one drop of lubricant (weighing about 22 mg) to a model friction pair sample. The amount was to enable the formation of a boundary layer. While in **[L. 16]**, lubricant was uniformly sprayed onto the element's surface in the amount of 0.4 $\mu l/cm^2$ using precision spraying equipment. Another trial also involved the continuous application of lubricant, in this case in the amount of 25–35 mg/min **[L. 17]**.

It should be noted that the European legal requirements have eliminated the use of ozone-depleting refrigerants – with ODP other than 0 (ODP – Ozone Depletion Potential) **[L. 18]**. In recent years, the value of the GWP ((GWP – Global Warming Potential) coefficient has been gradually reduced, which results in dynamic changes in the use of refrigerants in new systems **[L. 19]**.

Until recently, R404A was a quite commonly used HFC refrigerant for commercial refrigeration equipment in both small and large systems. It was widely used, inter alia, in the food industry and transport refrigeration. R404A refrigerant has considerable greenhouse effect potential (GWP = 3922), so replacements with a low GWP coefficient and comparable efficiency parameters are currently being sought **[L. 20, 21]**.

Although R404A refrigerant has been replaced in new systems, it has not been banned from use in existing ones. Consequently, there is a need to select lubricants compatible with the refrigerant.

The article presents:

- methodical selection of test parameters for evaluating the lubricating properties of the mixtures of oils for refrigeration compressors and refrigerants under the conditions of poor lubrication for polyester oils,
- wear test results for evaluating the lubricating properties of oil-refrigerant mixtures under starved lubrication conditions for R404A refrigerant and polyester oils.

TEST METHOD

The wear of a model block-on-ring type friction pair sample (**Fig. 1a**) is a measure of the lubricating properties of refrigeration compressor oil-refrigerant mixture under starved lubrication conditions. The type was selected because the nature of the movement corresponds to the geometry of the crankset elements of reciprocating refrigeration compressors.

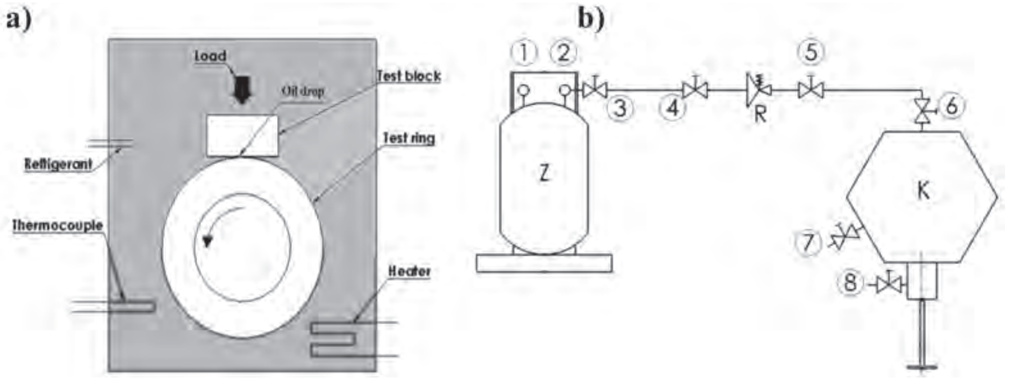

Fig. 1. (a) Scheme of the hermetic block – on – ring type wear tester, (b) the instrumentation for supplying refrigerant: Z – refrigerant cylinder, R – pressure reducer, K – chamber, 1 – 8 – ball valves

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

Block-on-ring type test stands were used **[L. 22–24]** in order to assess the lubricating properties of oil-refrigerant mixtures. The description of the model friction pair can be found in **[L. 2]**.

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

- enabling a clear sample wear in a relatively short time,
- reflecting the actual operating conditions of refrigeration compressors, in this case, poor lubrication with an oil-refrigerant mixture.

On the test stand (**Fig. 1b**), one may reproduce forces characteristic of starting the compressor after an extensive stand-still period. This is when the concentration of the refrigerant in the mixture inside the compressor is the highest.

During the main test, samples must be ultrasonically cleaned in acetone for 15 minutes before each trial and then installed in the test chamber. In order to produce the oil-refrigerant mixture, the air must be removed from the test chamber, and a drop of oil (approximately 30 mg) must be supplied there. In the next stage, the refrigerant with the selected pressure (p_s) should be supplied to the chamber, and the conditions should be maintained for a specified time (τ_m). A wear test of the duration time (τ_t) should be carried out when the mixture has been formed. After each trial, the samples should be disassembled, and the width trace of wear should be measured on the sample of the block shape, and then the volume wear should be calculated.

The main tests of lubricating properties were preceded by preliminary tests, whose purpose was to determine the duration time of the wear test (τ_t) for poor lubrication conditions.

While performing the tests necessary to assess the lubricating properties of polyester oils (POE) and their mixtures with the refrigerant (R404A), a pressure of about 1.10 MPa (p_s) was maintained in the test chamber. The value corresponds to the saturation pressure of R404A refrigerant at 23°C. The refrigerant pressure was determined in earlier tests in **[L. 25]**.

Figure 2 presents the results of the wear tests for polyester oil carried out at an air pressure of 1.10 MPa in the chamber, with various test duration times τt. According to the concept introduced in **[L. 10]**, the minimum sample wear of 0.5 mm^3 may be obtained after 10 minutes, which is the value selected for the main tests.

All the tests were performed at a sliding speed of 0.5 m/s. During each test run, the load was first changed in steps by 20 N every 30 seconds until reaching 120 N (total time 3 minutes), after

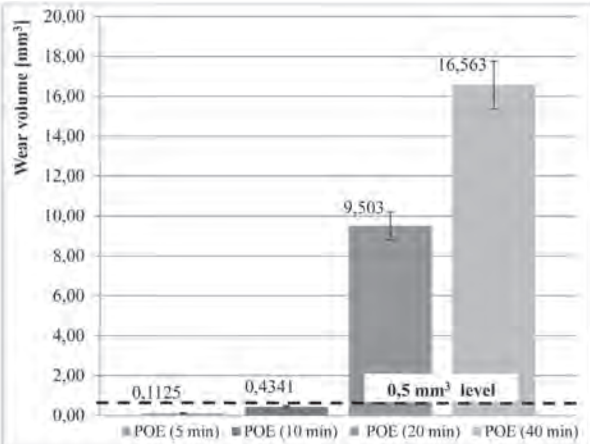

Fig. 2. Wear tests duration time selection for mineral oils in starved lubrication conditions (p_s = 1.10 MPa)

Rys. 2. Selekcja czasu trwania testu zużyciowego dla olejów poliestrowych w warunkach skąpego smarowania (p_s = 1,10 MPa)

which, at the maximum load of the friction pair, an additional 10-minute wear test was carried out. The parameters allow one to obtain a clear sample wear in a relatively short time. The wear tests were performed using the parameters specified above (τ_t) or earlier (τ_m and p_s) in **[L. 7, 9]**, such as:

– refrigerant pressure in the test chamber (p_s) for R404A refrigerant of 1.10 MPa – the value corresponds to the saturation pressure of R404A refrigerant at 23°C,
– duration time of the wear tests (τ_t) of 20 minutes,
– formation time of oil-refrigerant mixture (τ_m) of 40 minutes (the parameter has been determined individually for the mixtures of polyester oils (POE) and R404A refrigerant) **[L. 9]**.

The procedure for obtaining the oil-refrigerant mixture is important for the test method used. In order to obtain it, an appropriate chamber outfitted with equipment for supplying the refrigerant had to be constructed, and the test parameters according to the procedure presented in **[L. 7]** had to be determined.

Table 1 shows the parameters for testing the lubricating properties of oils for refrigeration compressors mixed with R404A refrigerant in poor lubrication conditions.

Three wear tests were performed for each test series (**Table 2**). During series 1 (the air) and 2 (R404A) tests, the chamber was pressurised (p_s), but no lubricant was supplied. While for series 3 (POE) and 4 (POE/R404A), the chamber was pressurised (p_s), and the air was supplied in series 3, whereas R404A refrigerant was supplied in series 4. In series 3 and 4, a small quantity (1 drop) of polyester oil was introduced into the friction pair.

Table 1. Individually selected parameters for mineral oil/refrigerant R404A mixture in starved lubrication conditions

Tabela 1. Zestawienie parametrów badań olejów do sprężarek chłodniczych w mieszaninie z czynnikiem chłodniczym R404A 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	1,10
Wear tests duration time	[min]	20 (+3)
Oil – refrigerant mixture formation time	[min]	40

Table 2. Summary of research series

Tabela 2. Zestawienie serii badań

Series number	Lubricant
1	Air
2	R404A
3	POE
4	POE/R404A

TEST RESULTS

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

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

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

The value of the coefficient of force for the four series of tests performed is shown in **Figures 3, 4** and **5**. **Figure 3** presents the changes in the coefficient of friction values for all the test series with an increasing load (the first 3 minutes of the test).

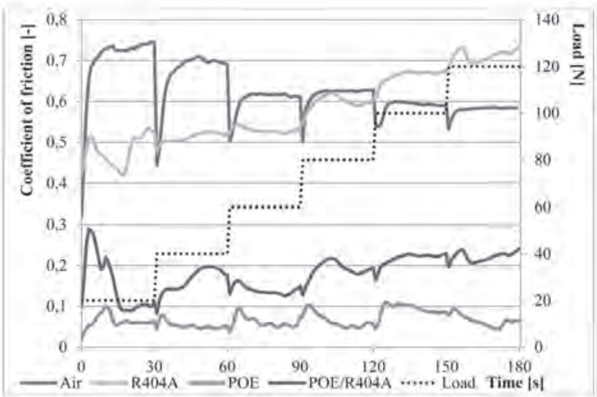

Fig. 3. Coefficient of Friction for four research series with increasing load

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

It can be concluded from **Figure 3** that the value of the coefficient of friction in the performed tests may 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 180 seconds) amounts to 0.63, and for series 2 (R404A), it amounts to 0.58. Thus, the coefficient of friction in the presence of air is slightly higher than in the presence of R404A.

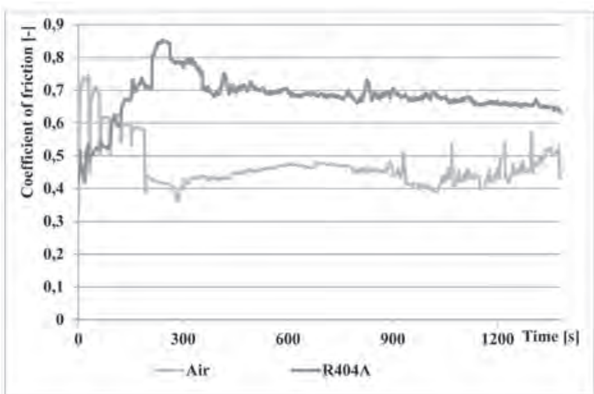

Fig. 4. Coefficient of Friction for 1 and 2 series at constant maximum load of 120 N

Rys. 4. Wartości współczynnika tarcia dla serii 1 i 2 przy stałym obciążeniu maksymalnym 120 N

The mean coefficient of friction for series 3 (POE) in the period in which the load was increased amounted to 0.09, whereas for series 4 (POE/R404A), it amounted to approx. 0.18. Therefore, it may be concluded that the presence of refrigerant in oil increases twice the value of the coefficient of friction.

Figure 4 presents the changes in the friction coefficient values for series 1 and 2 at a constant maximum load of 120 N.

The changes in the values of the coefficient of friction at constant maximum load in **Figure 4** show that for series 1 (the air), the coefficient of friction fluctuated between 0.4 and 0.5. The mean value of the coefficient of friction for the entire test run for series 1 was 0.48, while for series 2 (R404A), the coefficient of friction first increased up to approximately 0.85 and then decreased with the time of the test run to approx. 0.65. The mean value of the coefficient of friction for series 2 was 0.69.

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

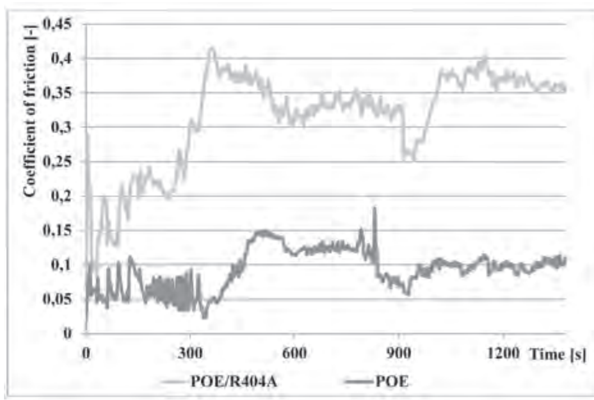

Fig. 5. Coefficient of Friction for 3 and 4 series at constant maximum load of 120 N

Rys. 5. Wartości współczynnika tarcia dla serii 3 i 4 przy stałym obciążeniu maksymalnym 120 N

The changes in the values of the coefficient of friction at constant maximum load in figure 5 show that for series 3 (POE), the coefficient of friction fluctuated between approx. 0.05 and 0.15. The observed peaks after about 800 seconds may indicate adhesive wear or the effect of anti-seize additives. The mean value of the coefficient of friction for the entire test run for series 3 was 0.09. The coefficient of friction for series 4 (POE/R404A) presented high variability in the range from 0.20 to 0.40. The mean value of the coefficient of friction for series 4 was 0.29.

Figure 6 illustrates the values of the mean sample wear volume after the four series of tests. The bars in the graph represent the dispersion as standard deviation.

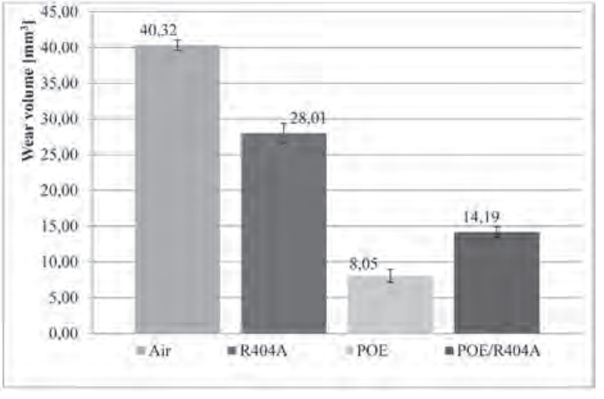

Fig. 6. Wear volume results after four research series
Rys. 6. Średnie zużycie objętościowe próbek po testach z czterech serii badawczych

The wear volume is 40.32 mm^3 for the first series (the air) and 28.01 mm^3 for the second series (R404A). The result indicates approx. 30% worse air lubricating properties than R404A refrigerant in situations where the friction pair runs out of lubricant.

A significant improvement in lubricating properties was noticed for the series with a small amount of lubricant. The wear volume for series 3 (POE) is 8.05 mm^3 and for series 4 (POE/R404A) is 14.19 mm^3. When comparing series 3 and 4, it can be concluded that the presence of R404A refrigerant in polyester oil under the conditions of starved lubrication deteriorates its lubricating properties by approx. 75%.

A comparison of the results for series 1 and 3 indicates that even a small amount of lubricant reduces the wear of the friction pair elements by up to five times. When comparing series 2 and 4, it can be concluded that even a small amount of lubricant in the presence of refrigerant under starved lubrication conditions may improve lubricating properties almost twice.

The obtained results (**Fig. 6**) indicate that the applied method of evaluating lubricating properties is effective because it both imitates the effect of the presence of refrigerant in a small amount of lubricant on the lubricating properties, compares various refrigerants with each other in the absence of lubricant and represents the lubricating properties of oil/refrigerant mixtures under the conditions of starved lubrication.

SUMMARY

In refrigeration compressors, an extreme operational situation may occur in which the amount of oil in friction pairs is insufficient. Poor lubrication in refrigeration compressors may also occur when switching on/off the equipment. In addition, there may be a situation where the friction areas of the refrigerant lack lubricant and the lubrication of friction pairs will be carried out by the refrigerant exclusively.

The article presents a methodical selection of test parameters for polyester oils that allow one to evaluate the lubricating properties of refrigeration compressor oils and refrigerant mixtures under starved lubrication conditions. It also contains the results of wear tests which allow one to assess the lubricating properties of oil-refrigerant mixtures under starved lubrication conditions obtained for R404A refrigerant with polyester oils.

The test results confirm that the mean coefficient of friction can be signal information when comparing the tested lubricants. However, the wear of friction pair elements should assess the lubricating properties. It turned out that in the absence of lubricant, R404A refrigerant has approx. 30% better lubricating properties than the air. On the other hand, in conditions of poor lubrication, the presence of R404A refrigerant triggers the formation of a mixture with polyester oil, which results in the deterioration of its lubricating properties. The oil/refrigerant mixture has approx. 75% worse lubricating properties than polyester oil that does not form a mixture with air.

The obtained results demonstrate that the proposed test method and the used test stand properly imitate the effect of the presence of refrigerant in a small amount of lubricant on the lubricating properties. With the presented test method, one may recreate the lubricating properties of oil/refrigerant mixtures in starved lubrication conditions and use it to evaluate various lubricants compatible with the selected refrigerant. The presented procedure of assessing lubricating properties in starved lubrication conditions may be used to search more effective formulations of polyester oils suitable for R404A refrigerant.

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