ISSN 0208-7774 TRIBOLOGIA 1/2024 p. 43–56
DOI: 10.5604/01.3001.0054.4654

Kasper GÓRNY[*], **Przemysław TYCZEWSKI**[**]

LUBRICATION BEHAVIOR OF THE POE/R452A MIXTURE AT DIFFERENT SLIDING VELOCITIES UNDER STARVED LUBRICATION CONDITIONS

WŁAŚCIWOŚCI SMARNE MIESZANINY POE/R452A PRZY RÓŻNYCH PRĘDKOŚCIACH ŚLIZGANIA W WARUNKACH SKĄPEGO SMAROWANIA

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

Abstract: There are no international standards guiding tribological testing in oil-refrigerant mixtures. The conditions for tribological tests, including sliding velocity, are chosen arbitrarily. The article presents an attempt to examine the influence of the sliding velocity of friction pair elements on the coefficient of friction and lubricating properties of compressor polyester oil (POE) and its mixture with the R452A refrigerant (POE/R452A) under starved lubrication conditions. The R452A refrigerant is currently widely used in transportation refrigeration. The authors' original test procedure with the use of a model block-on-ring type friction pair was applied to evaluate the lubricating properties of the oil-refrigerant mixture. Tests were conducted in three operational situations: no lubrication, starved lubrication with POE oil, and starved lubrication with the POE/R452A mixture. In each case, the tests were performed at different sliding velocities and the same sliding distance. A series of tests was also conducted where the load was increased in steps by 20 N to determine the relationship between the coefficient of friction, sliding velocity, and load on the friction pair.

The results support the potential use of higher sliding velocities and the reduction in test duration. For starved lubrication with the POE oil and the POE/R452A mixture, the differences in wear at specific velocities for the same sliding distance reached up to 30%, and the rankings of lubricating properties at different velocities remained unchanged.

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

Streszczenie: Badania tribologiczne w mieszaninie olejczynnik chłodniczy nie są objęte żadnymi międzynarodowymi normami. Stosowane warunki testów tribologicznych, w tym prędkość ślizgania, są dobierane w sposób uznaniowy. W artykule przedstawiono próbę sprawdzenia wpływu prędkości ślizgania elementów węzła tarcia na wartość współczynnika tarcia i właściwości smarne sprężarkowego oleju poliestrowego (POE) i jego mieszaniny z czynnikiem chłodniczym R452A (POE/R452A) w warunkach skąpego smarowania. Czynnik chłodniczy R452A jest aktualnie szeroko wprowadzany do stosowania w chłodnictwie transportowym.

Wykorzystano własną metodę oceny właściwości smarnych mieszaniny olej–czynnik chłodniczy z wykorzystaniem modelowego węzła tarcia typu rolka–klocek. Wykonano badania przy trzech sytuacjach eksploatacyjnych: bez smarowania, przy skąpym smarowaniu olejem POE i przy skąpym smarowaniu mieszaniną POE/R452A. W każdym przypadku wykonano testy przy różnych prędkościach ślizgania i takiej samej drodze tarcia. Wykonano również serię testów, w której skokowo zwiększano obciążenie ze skokiem 20 N celem określenia zależności współczynnika tarcia od prędkości ślizgania i obciążenia węzła tarcia.

Wyniki badań potwierdzają możliwość wykorzystania większych prędkości ślizgania i skrócenia czasu przeprowadzania testów. Przy skąpym smarowaniu olejem POE i mieszaniną POE-R452A różnice dla poszczególnych stopni prędkości przy tej samej drodze tarcia wznosiły maksymalnie 30%, a rankingi właściwości smarnych dla różnych prędkości pozostają takie same.

---

[*] ORCID: 0000-0002-5551-2690. Poznan University of Technology, Faculty of Civil and Transport Engineering, Institute of Machines and Motor Vehicles, Piotrowo 3 Street, 60-965 Poznań, Poland, e-mail: kasper.gorny@put.poznan.pl.

[**] ORCID: 0000-0001-7771-7091. Poznan University of Technology, Faculty of Civil and Transport Engineering, Institute of Machines and Motor Vehicles, Piotrowo 3 Street, 60-965 Poznań, Poland, e-mail: przemyslaw.tyczewski@put.poznan.pl.

INTRODUCTION

Friction pairs in refrigeration compressors are lubricated with oil-refrigerant mixtures, which poses a challenge in determining the exact contribution of individual components that act as lubricant in actual operation. However, it is assumed that the composition is determined by thermodynamic parameters in a refrigeration system and depends on temperature and pressure **[L. 1–3]**.

Damage to refrigeration compressors during regular and proper refrigeration system operation occurs relatively rarely when the operational parameters of the refrigeration system are properly selected and an appropriate refrigerant is chosen. Such damage is more likely to occur under extreme operational conditions with an increased likelihood of mixed friction and wear of friction pair elements. In an airtight installation, where moisture and external contaminants or products of undesirable chemical reactions are not present, friction pair wear may occur as a result of the influence of an oil-refrigerant mixture. When the amount of oil in a compressor is insufficient, starved lubrication with the oil-refrigerant mixture may occur. Insufficient oil quantity may result from its accumulation in heat exchangers (condenser and evaporator) or in other parts of the refrigeration system. This is often caused by external forcing that may alter the lubricant viscosity (low temperatures), and by a problem with its transportation through refrigerant or by a decrease or sudden change in refrigerant velocity, thereby preventing the required quantity of oil from being carried from the refrigeration system to the compressor in the required quantity.

A number of studies **[L. 4–28]** have been carried out to select lubricants for proper cooperation in oil-refrigerant mixtures. The studies focused on different operating conditions of refrigeration systems and various operational situations that may occur in the friction pairs of refrigeration compressors. For instance, studies **[L. 4–8]** involved testing friction pairs under extreme evaporation or condensation conditions. Other studies **[L. 4, 9–11]** tested friction pairs under nominal evaporation pressure or startup at low ambient temperature with a foaming effect **[L. 12–13]**. Some studies identified the conditions existing in friction pairs after a prolonged compressor downtime as the most critical for the longevity of refrigeration compressors **[L. 10, 14–15]**.

With the growing demand for more environmentally friendly refrigerators, the need to select suitable lubricants that meet various operational criteria in combination with refrigerants has arisen. Comprehensive studies conducted in recent years aim to identify suitable substances that can provide the proper functioning of refrigeration systems and ensure the required performance parameters **[L. 16–22]**.

Attempts to assess the effectiveness of lubricating friction pairs with oil-refrigerant mixtures have also been presented in other recent studies **[L. 7–8, 23–28]**.

To compare oil-refrigerant mixtures, it is necessary to conduct tests under identical conditions for different mixture components. In tribological tests of oil-refrigerant mixtures, the most frequently mentioned parameters for mixture preparation include: lubricant quantity, refrigerant pressure and temperature, and the time required for oil-refrigerant mixture formation. The relevant tribological testing parameters include: test duration, friction pair load, sliding velocity, and sliding distance. The parameters are not always clearly stated and provided by the authors. Usually, studies compare the wear in tests conducted at different sliding velocities and the same test duration, which results in different sliding distances **[L. 14, 29–30]**.

Studies **[L. 14, 29–30]** attempt to determine the influence of sliding velocity on the lubricating properties of oil-refrigerant mixtures. In the study **[L. 14]**, a pin-on-disc type test stand was used with samples made of alloy steel and grey cast iron, along with an immersion lubrication system employing a mixture of oil refrigerant for POE and PAG oils and carbon dioxide (R744 refrigerant). In the tests, a constant load of approximately 500 N and three different sliding velocities (0.725; 1.425; and 2.85 m/s) were applied at the same test duration (120 minutes). Based on the results of wear measurements, the authors concluded that increasing the sliding velocity led to a reduction in wear despite the increase in sliding distance. The coefficient of friction decreased with an increase in the sliding velocity.

In another study **[L. 29]**, parameter K was introduced, which represented the product of the applied load and the sliding distance, to compare different sliding velocities for the same test duration and varying levels of friction load. This allowed determining the scale of wear growth with an increase in sliding distance for various sliding velocities, but it did not directly provide insight into the influence of sliding velocities at a fixed sliding distance. For this study, a mixture of R410A and POE served as lubricant.

In study **[L. 30]**, which involved the PAG/R744 mixture, the coefficient of friction was analysed for various sliding velocities, and a coefficient considering the volume of wear in relation to the sliding distance and load (unit: mm3N-1m-1) was introduced for wear evaluation. This allowed for the consideration of the influence of the sliding distance on wear while comparing tests with different sliding distance and sliding velocities, and the same test duration.

The assessment of the impact of various sliding velocities on the wear of friction pairs and the coefficient of friction has been the subject of studies **[L. 31–32]** in recent years. The studies did not concern lubrication with oil-refrigerant mixtures. Other lubricants were subject to evaluation, for which attempts were also made to assess the impact of the sliding velocity on the tribological properties of friction pairs. The studies compared wear and the coefficient of friction for the same sliding velocity and sliding distance, but at different test duration times.

Until recently, R404A was a quite commonly used HFC refrigerant for commercial refrigeration equipment, in both small and large systems – according to **[L. 33]**, it was even 32% in 2019, although the value is likely to be decreasing now. Given its significant global warming potential (GWP = 3,922), there is a current demand for substitutes with lower GWP and comparable efficiency attributes. R452A **[L. 34]** is one of the substitutes for the refrigerant R404A in transport refrigeration. The components of this refrigerant are as follows: 11% – R32, 59% – R125, and 30% – R1234yf. Based on hydrofluoroolefins, the R452A refrigerant has a lower global warming potential (GWP=1,945) compared to R404A. As the outlet temperature of the compressor is similar for both R452A and R404A, the former can be employed without the need for any design modifications to the refrigeration system **[L. 35]**.

The tribological characteristics of the R452A refrigerant have not been thoroughly investigated so far. A study on the lubrication properties of polyether vinyl (PVE) oil mixtures, including those with refrigerants R404A and R452A, is detailed in reference **[L. 36]**. There is, however, substantial evidence suggesting that the R452A refrigerant should work effectively in combination with POE oils **[L. 34–35, 37–41]**.

The earlier studies aimed at assessing the lubricating properties of oil-refrigerant mixtures were carried out at relatively low and constant sliding velocities of friction pair elements **[L. 40––44]**. The aim of this article was to assess higher sliding velocities for the evaluation of lubricating properties. Using higher sliding velocities could potentially decrease the test duration if no substantial differences are identified for specific velocity levels at the same sliding distance.

The primary aim of this article is to examine the influence of the sliding velocity of friction pair elements on the coefficient of friction and lubricating properties of compressor polyester oil (POE) and its mixture with the R452A refrigerant (POE/R452A) under starved lubrication conditions. To achieve the objective, tests were conducted under three operational conditions: no lubrication, starved lubrication with POE oil, and starved lubrication with the POE/R452A mixture. For each case, the tests were conducted at different sliding velocities and the same sliding distance. Comparative assessment of lubricating properties for the conducted tests involved comparing the results in terms of wear resulting from the same conditions – load and sliding distance. Among the analysed lubricants, the one with lower wear will present better lubricating properties.

TEST METHOD

The authors' original test procedure was employed for the assessment of lubricating properties in the oil-refrigerant mixture. The method has been thoroughly discussed in a previous article **[L. 42]**. According to the proposed concept, lubricating properties are evaluated based on the wear of a sample in a block-on-ring tribological test using an oil-refrigerant mixture (**Fig. 11**).

The test procedure for oil-refrigerant mixtures commences with the formation of an oil-refrigerant mixture in a test chamber containing a friction pair. The required appropriate duration of the interaction of the refrigerant with the oil should be determined through preliminary tests. For the POE/R452A oil-refrigerant mixture, the formation time was established in a previous study **[L. 41]** to be 40 minutes (2,400 s). Earlier findings made it possible to specify an appropriate wear test duration for

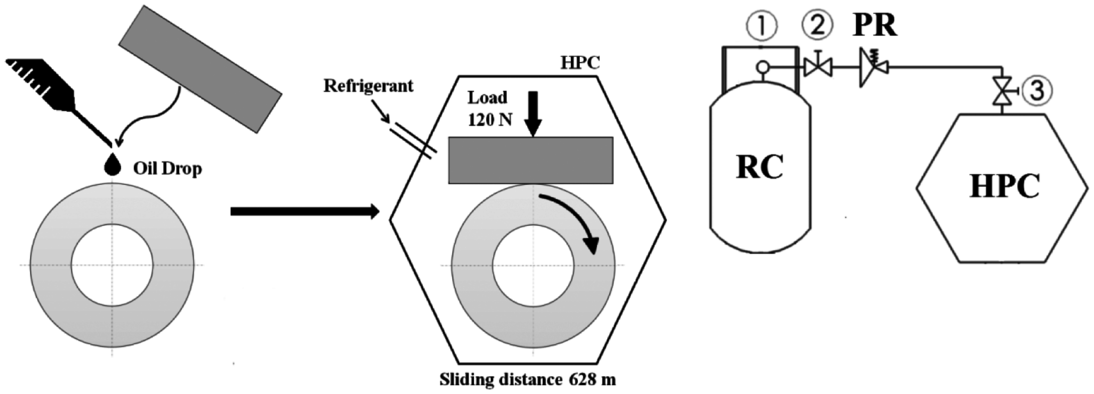

Fig. 1. (a) Oil-refrigerant mixture formation, (b) the instrumentation for supplying refrigerant: RC– refrigerant cylinder, PR – pressure reducer, HPC – high pressure chamber, 1–3 – ball valves

Rys. 1. (a) Przygotowanie mieszaniny olej–czynnik chłodniczy, (b) idea zasilania komory badawczej czynnikiem chłodniczym: RC – zbiornik czynnika chłodniczego, PR – reduktor ciśnienia, HPC – komora wysokociśnieniowa, 1–3 – zawory kulowe

a relative velocity of approximately 0.5 m/s, which amounted to 20 minutes (1,200 s). The duration of the wear test was established in a separate study based on a series of tests gradually increasing this parameter (and consequently the sliding distance).

With the known ring rotational speed (ω and its radius (r = 0.01 m), it becomes possible to calculate the sliding velocity using the formula:

$$v = \frac{2\pi r\omega}{60} \tag{1}$$

where: v – relative velocity [m/s], r – ring radius [mm], ω – rotational speed [rpm].

The specified rotational speed of 500 [rpm] corresponds, as per equation 1, to a sliding velocity of 0.5236 m/s. The value will be presented in the text as 0.5 m/s. The determined test duration of 1,200 s at a relative velocity of 0.5236 m/s results in a sliding distance of approximately 628 meters. **Table 1** presents different sliding velocities corresponding to the sliding distance.

The equation below is used to estimate the volume of the material removed from the frictional contact area:

$$V = 0.5sr^2 \cdot \left\{ 2\arcsin\left(\frac{x}{2r}\right) - sin\left[2\arcsin\left(\frac{x}{2r}\right)\right]\right\} \tag{2}$$

where: V – volume wear of the sample [mm^3], s – sample (block) width [mm], r – radius of the counter-sample (ring) [mm], x – width trace of sample wear [mm].

Table 1. Research parameters for different sliding velocities and the same sliding distance

Tabela 1. Zestawienie parametrów badań przy różnych prędkościach ślizgania dla tej samej drogi tarcia

Speer grade	Rotation speed [rpm]	Accurate sliding velocity [m/s]	Sliding velocity – designation in the text [m/s]	Wear tests duration time [s]	Sliding distance [m]
1	500	0.5236	0.5	1,200	628
2	1,000	1.0472	1.0	600	
3	1,500	1.5708	1.5	400	

Three wear tests were carried out for each test series (**Table 2**). During the tests from series 1–3 (air) and 4–6 (POE), the chamber pressure was adjusted to the saturation pressure to produce the POE/R452A mixture (1.20 MPa). For series 7–9 (POE/R452A), a chamber pressure of 1.20 MPa was maintained when introducing the R452A refrigerant into the chamber. For series 4–9, a small amount of polyester oil (1 drop) was introduced into the friction pair.

The formation time of the oil-refrigerant mixture for POE/R452A, allowing for achieving

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

Series number	Lubricant	Sliding velocity [m/s]
1	Air	0.5
2	Air	1.0
3	Air	1.5
4	POE	0.5
5	POE	1.0
6	POE	1.5
7	POE/R452A	0.5
8	POE/R452A	1.0
9	POE/R452A	1.5

a state close to saturation and the maximum refrigerant concentration in the oil mixture under specific conditions, was defined earlier in a previous work **[L. 40]**. The oil-refrigerant mixture is formed through the direct interaction of both substances confined in a sealed chamber with a model test friction pair (**Fig. 11**). The refrigerant pressure in the test chamber for the R452A refrigerant was 1.20 MPa, which corresponds to the saturation pressure of the R452A refrigerant at a temperature of 23°C.

Table 3 presents the test parameters for evaluating lubricating properties of oils for refrigeration compressors in a mixture with the R452A refrigerant under starved lubrication conditions. A series of tests was also conducted for the purposes of this article where the load was increased in steps by 20 N. The tests aimed to evaluate the relationships between the coefficient of friction, sliding velocity, and load on the friction pair under the conditions of starved lubrication with POE oil, the POE/R452A mixture or without lubrication (series 1–9).

The model friction pair used for wear testing is illustrated in **Figure 1**. The samples were cuboid-shaped with a width of 6 mm. Cylinders of 20 mm diameter were used as counter-samples. Friction pair elements were constructed using materials commonly used in refrigeration compressors. Samples were made from an aluminium alloy, while counter-samples were made from grey cast iron. Prior to each test, the samples were cleaned for about 15 minutes in an ultrasonic cleaner.

Table 3. Selected parameters for the same sliding distance
Tabela 3. Zestawienie parametrów badań przy jednakowej drodze tarcia

Parameter	Unit	Series number								
		1	2	3	4	5	6	7	8	9
Accurate sliding velocity	[m/s]	0.524	1.048	1.572	0.524	1.048	1.572	0.524	1.048	1.572
Wear tests duration time	[s]	1,200	600	400	1,200	600	400	1,200	600	400
Amount of lubricant	g	0			0.03 (1 drop)					
Oil – refrigerant mixture formation time	[s]	0						2,400		
Sliding distance	[m]	628								
Friction pair load	[N]	120								
Refrigerant pressure	MPa	1.20								

TEST RESULTS AND DISCUSSION

During the tests, the torque magnitude was measured in the friction pair, and the coefficient of friction was calculated using the following formula:

$$\mu = \frac{M}{Pr} \tag{3}$$

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

Figure 2 presents the mean values of the coefficient of friction with respect to the load for the first three test series, which involved tests without lubricant at various relative velocities.

The results shown in **Figure 2** indicate that the value of the coefficient of friction, without lubricant and at various relative velocities, depends on the load applied to the friction pair in different ways. As the load increases, the coefficient of friction value for series 1 (0.5 m/s) decreases from approximately 0.53 for lower loads (20 N) to approximately 0.38 for higher loads (120 N). The

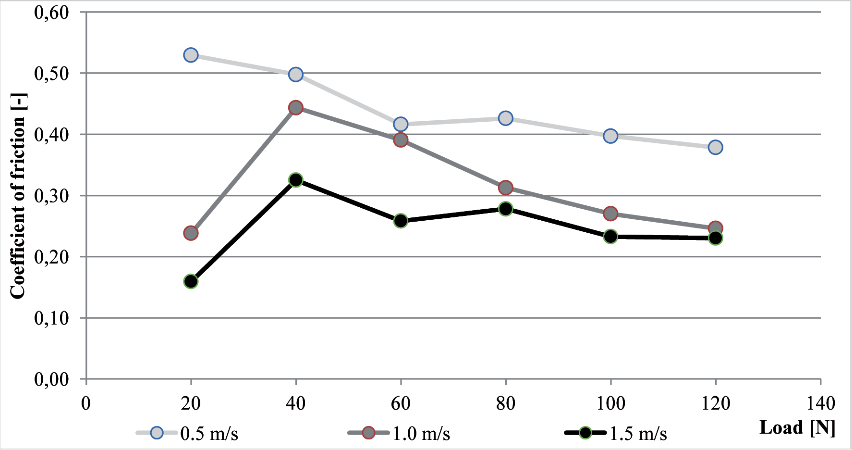

Fig. 2. Coefficient of friction for tests without lubricant (series 1–3) with increasing load
Rys. 2. Wartości współczynnika tarcia dla serii bez środka smarnego (serie 1–3) przy wzrastającym obciążeniu

coefficient of friction for series 2 and 3 (1.0 and 1.5 m/s) is lower and has a peak value at a load of 40 N. The maximum value is approximately 0.44 for series 2 and approximately 0.32 for series 3. Once these values are reached, the coefficient of friction declines as the load increases, reaching approximately 0.23, both for series 2 and 3.

Figure 3 illustrates the mean values of the coefficient of friction with respect to the load for the tests involving starved lubrication with POE oil at various relative velocities.

The results shown in **Figure 3** indicate that the value of the coefficient of friction for the tests conducted under the conditions of starved lubrication with POE oil at various velocities show lower variability compared to the tests conducted without lubrication. For series 4 (0.5 m/s), the coefficient of friction value varies between approximately 0.19 and 0.21 as the load increases. For series 5 and 6 (1.0 and 1.5 m/s), the coefficient of friction is lower and slightly decreases with the applied load: for series 5 from around 0.14 to around 0.11, and for series 6 from around 0.13 to around 0.10.

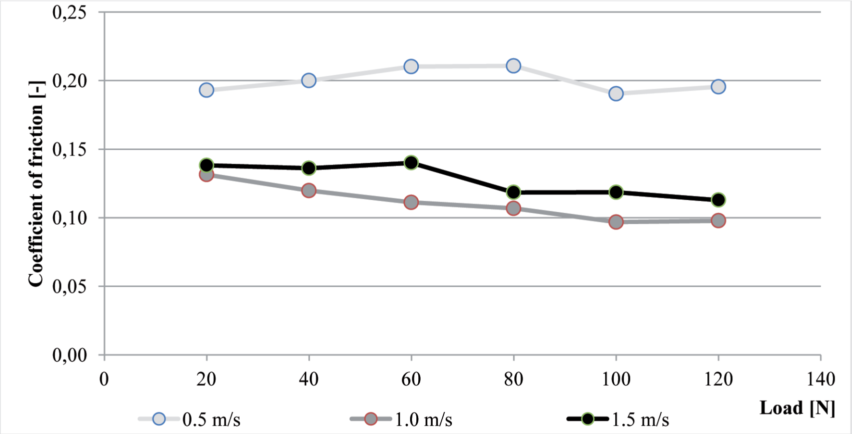

Fig. 3. Coefficient of friction for tests with POE lubricant (series 4–6) with increasing load
Rys. 3. Wartości współczynnika tarcia dla serii z olejem poliestrowym (serie 4–6) przy wzrastającym obciążeniu

Figure 4 presents the mean values of the coefficient of friction with respect to the load for the tests involving starved lubrication with the POE/R452A mixture at various relative velocities.

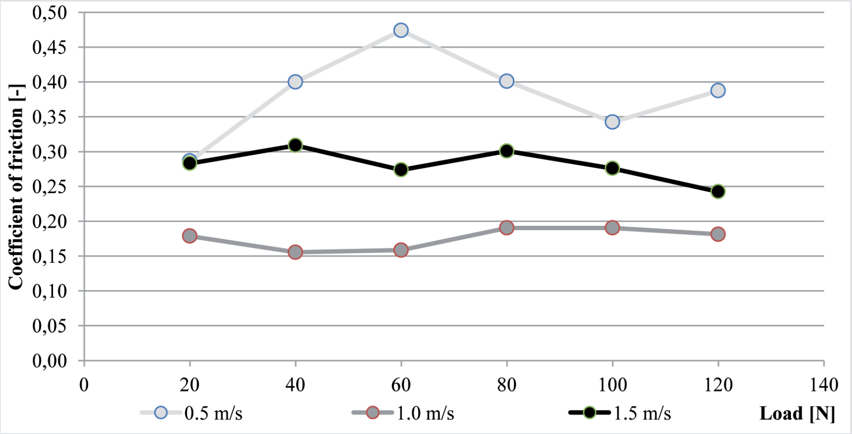

Fig. 4. Coefficient of friction for tests with the POE/R452A mixture (series 7–9) with increasing load
Rys. 4. Wartości współczynnika tarcia dla serii z mieszaniną POE/R452A (serie 7–9) przy wzrastającym obciążeniu

The results shown in **Figure 4** indicate that the value of the coefficient of friction for the tests conducted under the conditions of starved lubrication with the POE/R452A mixture at various velocities demonstrates a distinct dependence on the relative velocity of friction pair elements. The coefficient of friction value for series 7 (0.5 m/s) increases as the load is raised, from 0.28 at a load of 20 N to 0.49 at a load of 60 N, and then decreases to approximately 0.34 to 0.40 for higher loads. Lower friction coefficient values are achieved for the highest of the tested relative velocities in series 9 (1.5 m/s), with the value of the parameter fluctuating between approximately 0.24 and 0.31. For series 8, at a medium relative velocity (1.0 m/s), the coefficient of friction is lower and ranges between approximately 0.15 and 0.19.

As a general observation, it can be concluded that as the load increases, the presence of even a small amount of lubricant results in an improvement of operational conditions in a friction pair and lower values of the coefficient of friction for each of the tested relative velocities. For all tested lubrication conditions (without lubrication, starved lubrication with POE oil, and starved lubrication with the POE/R452A mixture), the highest values of the coefficient of friction for specific load levels were observed at the lowest relative velocity of the friction pair elements (0.5 m/s). For starved lubrication with the POE/R452A mixture, a noticeable dependence of the values of the coefficient of friction on relative velocity is evident at all load levels. The highest friction coefficient values were observed at a velocity of 0.5 m/s, slightly lower at 1.5 m/s, and markedly lowest at 1.0 m/s.

Figure 5 presents changes in the values of the coefficient of friction at a constant load of 120 N for the first three test series, which involved tests without lubrication at various relative velocities.

The results shown in **Figure 5** indicate that the value of the coefficient of friction at a constant maximum load of 120 N for the series without lubrication shows no significant difference for relative velocities of 1.0 and 1.5 m/s, ranging from 0.15 to 0.22. In contrast, for the lowest velocity of 0.5 m/s, the value of the coefficient of friction is noticeably higher, ranging from 0.36 to 0.42 and showing small amplitudes in the first part of the test. In the second part of the test, the amplitudes of individual peaks increase and the range of the values of the coefficient of friction varies from 0.33 to even 0.50.

Figure 6 illustrates changes in the values of the coefficient of friction at a constant load of 120 N for the tests conducted under the conditions of starved lubrication with POE oil at various relative velocities.

The results shown in **Figure 6** indicate that (similarly to the tests without lubrication) the value of the coefficient of friction at a constant maximum load of 120 N for the series with starved lubrication with POE oil shows no significant difference for relative velocities of 1.0 and 1.5 m/s, ranging from 0.07 to 0.14. The values are lower than those observed in tests without lubrication. For the lowest velocity of 0.5 m/s, the values of the coefficient of friction are noticeably higher and show large

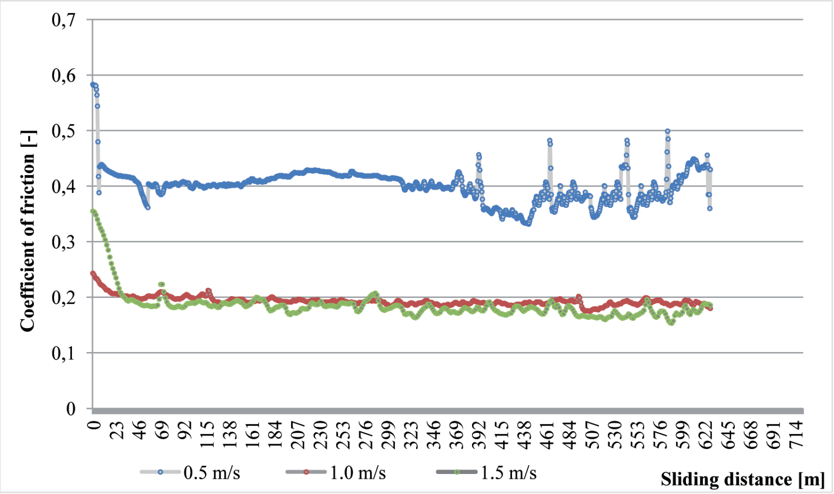

Fig. 5. Coefficient of friction for tests without lubricant (series 1–3) with load 120 N
Rys. 5. Wartości współczynnika tarcia dla serii bez środka smarnego (serie 1–3) przy obciążeniu 120 N

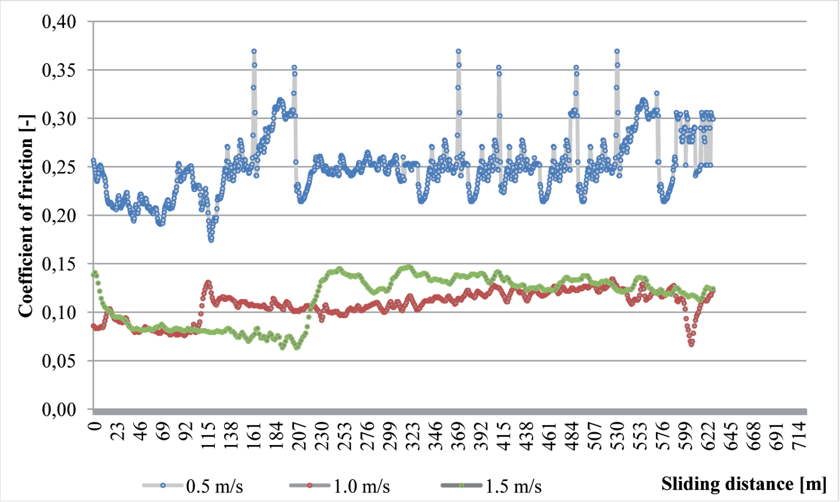

Fig. 6. Coefficient of friction for tests with POE lubricant (series 4–6) with load 120 N
Rys. 6. Wartości współczynnika tarcia dla serii z olejem poliestrowym (serie 4–6) przy obciążeniu 120 N

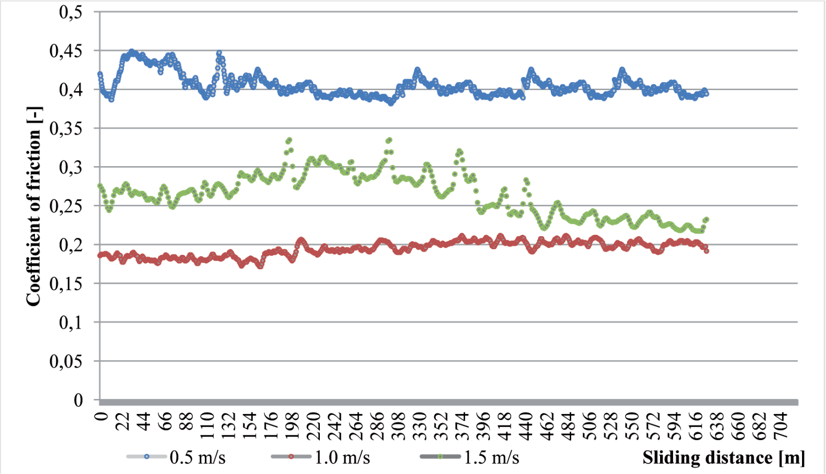

Fig. 7. Coefficient of friction for tests with the POE/R452A mixture (series 7–9) with load 120 N
Rys. 7. Wartości współczynnika tarcia dla serii z mieszaniną POE/R452A (serie 7–9) przy obciążeniu 120 N

amplitudes of individual peaks. The values of the coefficient of friction vary between 0.17 and as high as 0.37. For a velocity of 0.5 m/s, starved lubrication with POE oil also resulted in decreased values of the coefficient of friction compared to the tests without lubrication.

Figure 7 presents changes in the values of the coefficient of friction at a constant load of 120 N for the tests conducted under the conditions of starved lubrication with the POE/R452A mixture at various relative velocities.

The results shown in **Figure 7** indicate that the value of the coefficient of friction for the tests conducted under the conditions of starved lubrication with the POE/R452A mixture at a load of 120 N for various relative velocities demonstrates a distinct dependence on the relative velocity of friction pair elements. The value of the coefficient of friction for series 7 (0.5 m/s) fluctuates between approximately 0.38 and 0.45. Lower values of the coefficient of friction are observed for the highest tested relative velocity in series 9 (1.5 m/s), with the parameter ranging from around 0.22 to around 0.34. For the series with a medium relative velocity in series 8 (1.0 m/s), the coefficient of friction is lower and ranges from approximately 0.17 to 0.21.

As a general observation, it can be concluded that at a constant load of 120 N, the presence of even a small amount of lubricant results in an improvement of operational conditions in a friction pair and in lower values of the coefficient of friction for each of the tested relative velocities. For all tested lubrication conditions (no lubrication, starved lubrication with POE oil, and starved lubrication with the POE/R452A mixture), the highest values of the coefficient of friction for specific load levels were observed at the lowest relative velocity of the friction pair elements (0.5 m/s). For starved lubrication with the POE/R452A mixture, a noticeable dependence of the values of the coefficient of friction on relative velocity is evident at all load levels. The highest values of the coefficient of friction were observed at a velocity of 0.5 m/s, slightly lower at 1.5 m/s, and markedly lowest at 1.0 m/s. With respect to the conditions with starved lubrication with POE oil and no lubrication, the differences in the values of the coefficient of friction at velocities of 1.0 and 1.5 m/s are insignificant.

The results shown in **Figure 8** refer to the mean wear volume of the samples tested in series 1–3 under no lubrication at various relative velocities of friction pair elements, for a constant sliding distance of approximately 628 metres.

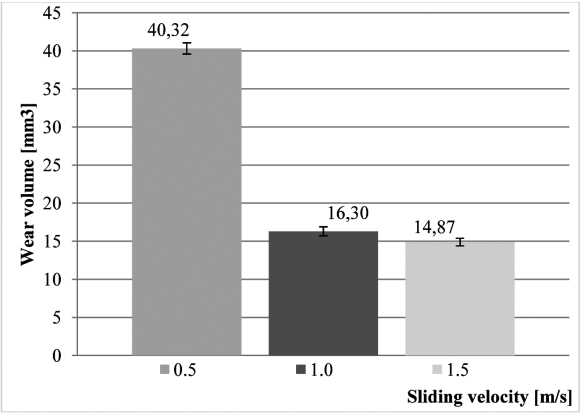

Fig. 8. Wear volume results after tests without lubricant (series 1–3)

Rys. 8. Średnie zużycie objętościowe dla serii bez środka smarnego (serie 1–3)

The wear volume for series 1 (0.5 m/s) is 40.32 mm^3, for series 2 (1.0 m/s) – 16.30 mm^3, and for series 3 (1.5 m/s) – 14.87 mm^3. Lack of lubrication at the lowest velocity results in significantly lower wear resistance, even nearly three times worse than at higher velocities. The differences in wear between the velocities of 1.0 and 1.5 m/s are nearly 10%.

The results shown in **Figure 9** refer to the mean wear volume of the samples tested in series 4–6 under the conditions of starved lubrication with POE oil at various relative velocities of friction pair elements, but for a constant sliding distance of approximately 628 metres.

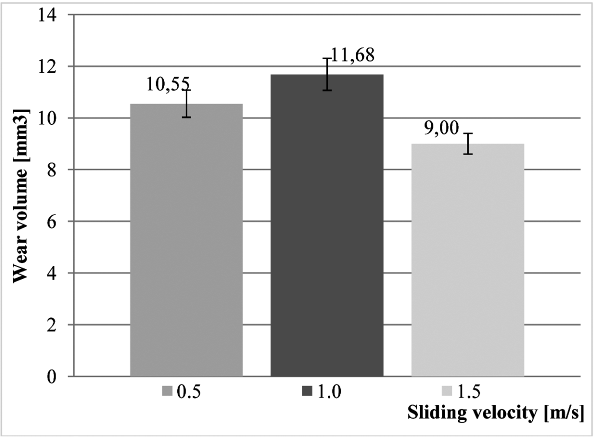

Fig. 9. Wear volume results after tests with POE lubricant (series 4–6)

Rys. 9. Średnie zużycie objętościowe dla serii z olejem poliestrowym (serie 4–6)

Under the conditions of starved lubrication with POE oil, the differences between individual velocities are not considerable. The wear volume for series 4 (0.5 m/s) is 10.55 mm^3, for series 5 (1.0 m/s) – 11.68 mm^3, and for series 3 (1.5 m/s) – 9.00 mm^3. The highest wear resistance was observed for the highest velocity (1.5 m/s). The differences in wear with respect to the maximum wear achieved (in series 5) are just below 30%.

The results shown in **Figure 10** refer to the mean wear volume of the samples tested in series 7–9 under the conditions of starved lubrication with the POE/R452A mixture at various relative velocities and for a constant sliding distance.

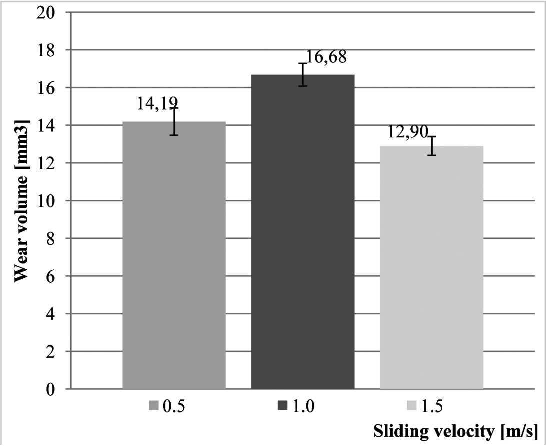

Fig. 10. Wear volume results after tests with the POE/R452A mixture (series 7–9)

Fig. 10. Wear volume results after tests with POE/R452A mixtures (series 7–9)

Under the conditions of starved lubrication with the POE/R452A mixture, the observed wear volume for series 7 (0.5 m/s) was 14.19 mm^3, for series 8 (1.0 m/s) – 16.68 mm^3, and for series 9 (1.5 m/s) – 12.90 mm^3. The best wear resistance was observed for the highest velocity (1.5 m/s). The difference in wear with respect to the maximum wear achieved (in series 5) was nearly 30%. The differences between the obtained results are similar to the ones for starved lubrication with POE oil. It is worth adding that in **Figures 8–10** the slopes indicate the standard deviation of the average of at least 3 tests performed.

In conclusion, the results indicate that the highest values of the coefficient of friction were recorded for the lowest relative velocity 0.5 m/s for each lubrication type (air, starved lubrication with POE oil, and starved lubrication with the POE/R452A mixture). The trend was not confirmed in every case by the wear of friction pair elements. For the tests without lubrication, there was a clear increase in wear at the lowest velocity of 0.5 m/s, and for velocities of 1.0 and 1.5 m/s, wear levels were comparable for the same sliding distance.

For starved lubrication with POE oil and the POE/R452A mixture, the highest wear did not occur at the lowest velocity. In both cases, the highest wear occurred at a velocity of 1.0 m/s and the lowest one at a velocity of 1.5 m/s. It is worth noting that both for starved lubrication with POE oil and the POE/R452A mixture, the differences in observed wear reached up to 30% when comparing different velocities for the same sliding distance.

Table 4 presents the wear test results at various relative velocities of friction pair elements, but for the same sliding distance of approximately 628 meters. The compilation includes all lubrication types tested: no lubrication, starved lubrication with POE oil, and the POE/R452A mixture. In each case, the lowest wear was observed for the highest relative velocity of 1.5 m/s. For the tests without

Table 4. Effect of sliding velocity of friction pair elements on lubricating properties

Tabela 4. Ocena wpływu prędkości względnej elementów węzła tarcia na właściwości smarne

Lubricant	Sliding velocity [m/s]	Series number	Wear volume [mm^3]	Percentage [%]	Ranking	Temperature at contact area after test [^{o}C]
Air	0.5	1	40.32	271	3	72
	1.0	2	16.30	110	2	95
	1.5	3	14.87	100	1	129
POE	0.5	4	10.55	117	2	66
	1.0	5	11.68	130	3	81
	1.5	6	9.00	100	1	87
POE/R452A	0.5	7	14.19	110	2	48
	1.0	8	16.68	129	3	58
	1.5	9	12.90	100	1	83

lubrication, the highest wear occurred at the lowest velocity of 0.5 m/s, while for the tests conducted under the conditions of starved lubrication with both POE oil and the POE/R452A mixture, the highest wear was observed at a velocity of 1.0 m/s.

It is also worth noting that with the rise in relative velocity, there was an increase in temperature at the contact area after the test (Tab.4). For the tests without lubrication, the corresponding temperatures were 72°C for a velocity of 0.5 m/s, 95°C for a velocity of 1.0 m/s, and 129°C for a velocity of 1.5 m/s. An increase in temperature at the contact area after the test was also observed for starved lubrication with POE oil (from 66 to 87°C) and the POE/R452A mixture (from 48 to 83°C). It can be assumed that the application of even a small amount of lubricant facilitates the heat transfer from the contact area, which results in a lower temperature after the test. The phenomenon becomes particularly pronounced in the presence of refrigerant within the contact area.

SUMMARY

In refrigeration compressors, an extreme operational situation may take place in which the amount of oil in friction pairs is insufficient. Starved lubrication may also occur when switching on/off the equipment. Starved lubrication with an oil-refrigerant mixture is often compared to lubrication using only oil or the absence of lubricant.

Previous tribological studies involving oil-refrigerant mixtures fail to provide an assessment of the influence of various sliding velocities at the same sliding distance. The impact of sliding velocity can be indirectly evaluated by introducing parameter K, representing the product of load and sliding distance for the same test duration and various levels of load on a friction pair.

The article presents the wear test results allowing for a direct evaluation of the influence of the sliding velocity of friction pair elements on the coefficient of friction and lubricating properties of polyester refrigeration compressor oil (POE) and its mixture with R452A refrigerant (POE/R452A) under the conditions of starved lubrication. In the pursuit of the objective, tests were conducted under three operational conditions: no lubrication, starved lubrication with POE oil, and starved lubrication with the POE/R452A mixture. The tests were conducted at various sliding velocities while keeping the sliding distance constant. For the purposes of the article, a series of tests was also conducted where the load was increased in steps by 20 N. The tests aimed to assess the relationship between the coefficient of friction and the sliding velocity and load of the friction pair under conditions of starved lubrication with POE oil, the POE/R452A mixture or without lubrication.

For all tested lubrication types (no lubrication, starved lubrication with POE oil, and starved lubrication with the POE/R452A mixture), the highest coefficient of friction values for individual load levels were observed at the lowest relative velocity of friction pair elements (0.5 m/s). It is worth noting that with respect to the POE/R452A mixture, the lowest values of the coefficient of friction for increasing load were registered at a medium velocity of 1.0 m/s.

At a constant load of 120 N, the application of even a small amount of lubricant results in an improvement of operational conditions in a friction pair and in lower values of the coefficient of friction for each of the tested relative velocities. For all tested lubrication types, the highest coefficient of friction values for individual load levels were observed at the lowest relative velocity (0.5 m/s). For starved lubrication with the POE/R452A mixture, the highest coefficient of friction values were observed at a velocity of 0.5 m/s, slightly lower at 1.5 m/s, and markedly lowest at 1.0 m/s. Under the conditions of starved lubrication with POE oil and without lubrication, the differences in the coefficient of friction values for velocities of 1.0 and 1.5 m/s were minor.

The observed values of the coefficient of friction do not always reflect the degree of wear of the friction pair elements. For the tests without lubrication, significantly higher wear occurred at the lowest velocity of 0.5 m/s, while at velocities of 1.0 and 1.5 m/s the wear was comparable. For starved lubrication with POE oil and the POE/R452A mixture, the highest wear did not occur at the lowest velocity. In both cases, the highest wear was observed at a velocity of 1.0 m/s and the lowest at 1.5 m/s. It is worth noting that both for starved lubrication with POE oil and the POE/R452A mixture, the differences in observed wear reached up to 30% when comparing different velocities for the same sliding distance.

For all tested lubrication types, with the rise in sliding velocity for the same sliding distance, there was an increase in temperature at the contact area. Starved lubrication with POE oil resulted in a lower temperature rise, whereas for lubrication with the POE/R452A mixture, the temperature at the contact area was lower compared to POE oil lubrication at each sliding velocity.

The results presented in the article, obtained through the wear tests designed to directly evaluate how the sliding velocity of friction pair elements influences the coefficient of friction and lubrication properties, support the potential use of higher sliding velocities and the reduction in test duration. For starved lubrication with POE oil and the POE/R452A mixture, the differences in wear at specific velocities for the same sliding distance reached up to 30%, and the rankings of lubricating properties at different velocities remained unchanged.

REFERENCES

1. Daniel G., Anderson M.J., Schmid W., Tokumitsu M.: Performance of Selected Synthetic Lubricants in Industrial Heat Pumps. Heat Recovery Systems, Vol. 2/4, 1982, pp. 359–368. DOI: 10.1016/0198-7593(82)90054-6.
2. Seeton Ch.: Estimation of refrigerant-oil mixture viscosities for alternative refrigerants using solubility data. ASHRAE Winter Meeting, Chicago 2006.
3. Leung M., Jotshi C.K., Goswami D.Y., Shah D.O., Gregory A.: Measurements of absorption rates of HFC single and blended refrigerants in POE oils. HVAC&R Research, vol. 2, 1998, pp. 141–151. DOI: 10.1080/10789669.1998.10391396.
4. Jollev S.: New and Unique Lubricants for Use in Compressors Utilizing R-134a Refrigerant. International Refrigeration and Air Conditioning Conference, Purdue University, Indiana, USA, 1990, pp. 145–152.
5. Chul Na B., Jin Chun K., Han D.C.: A tribological study of refrigeration oils under HFC-134a environment. Tribol. Int. 30 (9):707716, 1997. DOI: 10.1016/S0301-679X(97)00072-8.
6. Ciantar C., Hadfield M., Smith A., Swallow A.: The influence of lubricant viscosity on the wear of hermetic compressor components in HFC-134a environments. Wear 236 (1), 1999, pp. 1–8, DOI: 10.1016/S0043-1648(99)00267-7.
7. Garland N.P., Hadfield M.: Tribological analysis of hydrocarbon refrigerants applied to the hermetic compressor. Tribol. Int. 38, pp. 732–739, 2005. DOI: 10.1016/J.TRIBOINT.2004.10.009.
8. Cannaday M.L., Polycarpou A.A.: Tribology of unfilled and filled polymeric surfaces in refrigerant environment for compressor applications. Tribol. Lett. 19, pp. 249–262. DOI: 10.1007/S11249-005-7441-9.
9. Sheiretov T., Van Glabbeek W., Cusano C.: Simulative friction and wear study of retrofitted swash plate and rolling piston compressors, Int. J. Refrigeration, 1995, Vol. 18, No. 5, pp. 330–335, DOI: 10.1016/0140-7007(95)00017-6.
10. Yoon H., Sheiretov T., Cusano C.: Tribological evaluation of various aluminum alloys in lubricant/refrigerant mixtures, International Compressor Engineering Conference, 1996. Paper 1096.
11. Demas N.G., Polycarpou A.A.: Tribological investigation of cast iron air-conditioning compressor surfaces in CO_2 refrigerant. Tribol. Lett. 22 (3), pp. 271–278, 2006. DOI: 10.1115/IJTC2006-12064.
12. Yanagisawa T., Shimizu T., Fukuta M., 1991. Foaming characteristics of an oil–refrigerant mixture. Int. J. Refrigeration, 14 (3), pp. 132–136. DOI: 10.1016/0140-7007(91)90066-P.
13. Li H., Hrnjak P.: Effect of Flow Regime in the Horizontal Inlet Header on Refrigerant-Oil Mixture Distribution in a MAC Microchannel Evaporator. SAE Technical Paper 2014-01-0701, 2014. DOI: 10.4271/2014-01-0701.
14. Hong-Gyu J., Se-Doo O., Young-Ze Lee. Friction and wear of the lubricated vane and roller materials in a carbon dioxide refrigerant. Wear, 267/5–8, pp. 1252–1256, 2009. DOI: 10.1016/J.WEAR.2008.12.097.

15. Górny K., Stachowiak A., Tyczewski P., Zwierzycki W.: Lubricity evaluation of oil-refrigerant mixtures with R134a and R290, Int. J. Refrigeration 69, 2016 pp. 261–271. DOI: 10.1016/J.IJREFRIG.2016.06.011.
16. Hegar M., Kolda M.: System Drop-in Tests of Refrigerant DR-34 (R-452A) in a Trailer Refrigeration Unit Designed for R-404A. AHRI Low-GWP AREP Report NO. 41, 2015.
17. Wang X., Amrane K.: AHRI Low Global Warming Potential Alternative Refrigerants Evaluation Program (Low-GWP AREP) – Summary of Phase II Testing. Results. In: Proc. of International Refrigeration and Air Conditioning Conference, 2016, Paper 2064, pp. 1–10.
18. Emani M.S., Roy R., Mandal B.K., 2017. Development of refrigerants: a brief review. Indian J. Sci. Res. 14 (2), pp. 175–181.
19. Harby K.: Hydrocarbons and their mixtures as alternatives to environmental unfriendly halogenated refrigerants: An updated overview. Renewable and Sustainable Energy Reviews Volume 73, 2017, pp. 1247–1264. DOI: 10.1016/J.RSER.2017.02.039.
20. Karnaz J.: Evaluating Lubricants For Lower GWP Refrigerant Compressor Operations. In: Proc. of International Refrigeration and Air Conditioning Conference, 2017, Paper 1239, pp. 1–10.
21. Polonara F., Kuijpers L.J.M., Peixoto R.A.: Potential impacts of the Montreal Protocol Kigali Amendment to the choice of refrigerant alternatives. International Journal of Heat and Technology, Vol. 35, 2017, Special Issue 1, pp. S1–S8. DOI: 10.18280/IJHT.35SP0101.
22. Bhuttaa M.U., Khan Z.A., Garland N., Ghafoor A.: A Historical Review on the Tribological Performance of Refrigerants used in Compressors. Tribology in Industry, 2018. Vol. 40, No. 1, pp. 19–51. DOI: 10.24874/TI.2018.40.01.03.
23. Birol Y., Birol F.: Sliding wear behaviour of thixoformed AlSiCuFe alloys. Wear 265, 2008, pp. 1902–1908. DOI: 10.1016/J.WEAR.2008.05.001.
24. Akram, M.W., Polychronopoulou, K., Polycarpou, A.A.: Lubricity of environmentally friendly HFO-1234yf refrigerant. Tribol. Int. 57, 2013, pp. 92–100. DOI: 10.1016/J.TRIBOINT.2012.07.013.
25. Akram M.W., Polychronopoulou K., Polycarpou A.A.: Tribological performance comparing different refrigerant–lubricant systems: the case of environmentally friendly HFO-1234yf refrigerant. Tribol. Int. 78, 2014 pp. 176–186. DOI: 10.1016/J.TRIBOINT.2014.05.015.
26. Tanaka M., Matsuura H., Taira S., Nakai A.: Selection of a refrigeration oil for R32 refrigerant and evaluation of the compressor reliability. In: Proc. of International Compressor Engineering Conference, 2014, Paper 2299, pp. 1–10.
27. Sariibrahimoglu K., Kizil H., Aksit M., Efeoglu I., Kerpicci, H.: Effect of R600a on tribological behavior of sintered steel under starved lubrication. Tribol. Int. 43, 2010 pp. 1054–1058. DOI: 10.1016/J.TRIBOINT.2009.12.035.
28. Akram MW, Polycarpou AA. Wear Mechanisms of Gray Cast Iron in the Presence of Environmentally Friendly Hydrofluoroolefin-Based Refrigerant and the Effect of Tribofilm Formation. J. Tribol, 2015, 137(4):041602. DOI: 10.1115/1.4030711.
29. Young-Ze Lee, Se-Doo Oh: Friction and wear of the rotary compressor vane–roller surfaces for several sliding conditions. Wear 255, 2003, pp. 1168–1173. DOI: 10.1016/S0043-1648(03)00278-3.
30. Mishra S.P.; Polycarpou A.A.: Tribological studies of unpolished laser surface textures under starved lubrication conditions for use in air-conditioning and refrigeration compressors. Tribol. Int., 2011, 44, pp. 1890–1901. DOI: 10.1016/J.TRIBOINT.2011.08.005.
31. Deepak M. Shinde and Prasanta Sahoo: INFLUENCE OF SPEED AND SLIDING DISTANCE ON THE TRIBOLOGICAL PERFORMANCE OF SUBMICRON PARTICULATE REINFORCED Al-12Si /1.5 WT% B4C COMPOSITE. International Journal of Metalcasting/Volume 16, Issue 2, 2022. DOI: 10.1007/s40962-021-00636-1.
32. Ananth S., Sivaprakasam P., Udaya Prakash, Maheandera Prabu P., Varatharaju Perumal, Kalusuraman G.: Tribological Behavior and Surface Characterization of Gray Cast Iron-EN31 Steel under Lubricated Sliding Conditions. Journal of Nanomaterials Volume 2021, Article ID 7725959. DOI: 10.1155/2021/7725959.

33. Llopis R., Calleja-Anta D., Sanchez D., Nebot-Andres L., Catalan-Gil J., Cabello R.: R-454C, R-459B, R-457A and R-455A as low-GWP replacements of R-404A: Experimental evaluation and optimization. International Journal of Refrigeration 106, 2019, pp. 133–43. DOI: 10.1016/J.IJREFRIG.2019.06.013.
34. Li G.: Comprehensive investigation of transport refrigeration life cycle climateperformance, Sustain. Energy Technol. Assess., 2017, 21, pp. 33–49. DOI: 10.1016/J.SETA.2017.04.002.
35. Atİlla G. Devecİoğlu & Vedat Oruç: Experimental comparison of R404A and R452A in refrigeration systems, Science and Technology for the Built Environment, 27, 1, 2021, pp. 61–69. DOI: 10.1080/23744731.2020.1796419.
36. Matsumoto T., Kaneko M., Kawaguchi Y.: Evaluations of PVE Lubricants for Refrigeration and Air Conditioning system with the Low GWP Refrigerants. IOP Conf. Series: Materials Science and Engineering 232, 2017. DOI: 10.1088/1757-899X/232/1/012091.
37. Karnaz J.: Evaluating Lubricants For Lower GWP Refrigerant Compressor Operations, International Compressor Engineering Conference, 2016, Paper 2434.
38. Saleem A., Kim M-H.: Miscibility analysis of polyol-ester based oil SW32 with R404A and low-GWP refrigerant R452A. Int J Refrigeration, 2021, 129, pp. 22–31. DOI: 10.1016/J.IJREFRIG.2021.05.002.
39. Devecioglu A.G., Oruç V.: Experimental comparison of R404A and R452A in refrigeration systems. Science and Technology for the Built Environment, 2021, 27, pp. 61–69. DOI: 10.1080/23744731.2020.1796419.
40. Górny K., Stachowiak A., Tyczewski P., Zwierzycki W.: Lubricity of selected oils in mixtures with the refrigerants R452A, R404A, and R600a, Tribology International 134, 2019, pp. 50–59. DOI: 10.1016/J.TRIBOINT.2018.12.033.
41. Górny K., Stachowiak A., Tyczewski P., Zwierzycki W.: Mixtures of Lubricants and Ecological Refrigerants under Starved Lubrication Conditions, Materials, 2022, Volume 15, Issue 21, 7747. DOI: 10.3390/ma15217747.
42. Górny K., Stachowiak A., Tyczewski P., Zwierzycki W.: Lubricity evaluation of oil-refrigerant mixtures with R134a and R290, International Journal of Refrigeration 69, 2016, pp. 261–271. DOI: 10.1016/J.IJREFRIG.2016.06.011.
43. Górny K., Stachowiak A., Tyczewski P., Zwierzycki W.: Research idea and methodology for determining test parameters for the lubricity evaluation of oil/refrigerant mixtures, Tribologia 3/2016, pp. 87–98. DOI: 10.5604/01.3001.0010.7295.
44. Górny K., Tyczewski P., Zwierzycki W.: Description of the experimental method and procedure of model wear test of refrigeration compressors' parts, 2014, Solid State Phenomena, 225, 85. DOI: 10.4028/www.scientific.net/SSP.225.85.