ISSN 0208-7774 TRIBOLOGIA 2/2020 p. 15–24
DOI: 10.5604/01.3001.0014.3736

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SELECTION OF LUBRICANTS FOR REFRIGERATION COMPRESSORS ON THE BASIS OF VARIOUS TRIBOLOGICAL TESTS

DOBÓR OLEJÓW SMAROWYCH DO SPRĘŻAREK CHŁODNICZYCH NA PODSTAWIE ZRÓŻNICOWANYCH BADAŃ TRIBOLOGICZNYCH

Key words: lubricants, oil/refrigerant mixture, Bellinger's method, decision support tool.

Abstract: The article presents a proposal to use a simple and transparent method in aiding the decision making on the selection of lubricants for refrigeration compressors on the basis of various tribological tests. Tribological studies included full lubrication and poor lubrication conditions for both the lubricants themselves and the oil/refrigerant mixtures.
The Bellinger method was chosen as a method to support the selection of lubricants. The decision making aiding process on the selection of lubricants for various mechanisms of mixing lubricating oil with a refrigerant was presented. A mixture of polyester oils with the R452A refrigerant was chosen for the mixing mechanism by simultaneous intermolecular diffusion and natural mass convection. However, for the mixing mechanism only by intermolecular diffusion, a mixture of mineral oils with the R600a was selected.
Simulations were carried out of several decision-making situations depending on the approach of the decision-maker, i.e. economic, qualitative, or sustainable. In each of the options, weightings were subjectively assigned to individual criteria, trying to reflect the approach of decision-maker.

Słowa kluczowe: środki smarne, mieszanina olej/czynnik chłodniczy, metoda Bellingera, narzędzie wspomagania decyzji.

Streszczenie: W artykule przedstawiono propozycję wykorzystania prostej i przejrzystej metody wspomagania decyzji doboru środków smarnych do sprężarek chłodniczych na podstawie zróżnicowanych badań tribologicznych. Badania tribologiczne obejmowały smarowanie pełne oraz skąpe warunki smarowania zarówno dla samych środków smarnych, jak i dla mieszanin olej/czynnik chłodniczy.
Jako metodę wspomagania decyzji doboru środków smarnych wybrano metodę Bellingera. Zaprezentowano proces wspomagania decyzji doboru środków smarnych dla różnych mechanizmów mieszania się oleju smarowego z czynnikiem chłodniczym. Dla mechanizmu mieszania poprzez jednoczesną dyfuzję międzycząsteczkową oraz naturalną konwekcję masową wybrano mieszaninę olejów poliestrowych z czynnikiem chłodniczym R452A, natomiast dla mechanizmu mieszania jedynie poprzez dyfuzję międzycząsteczkową wybrano mieszaninę olejów mineralnych z czynnikiem chłodniczym R600a.
Przeprowadzono symulacje kilku sytuacji decyzyjnych zależnych od nastawienia decydenta: ekonomiczny, jakościowy i zrównoważony. W każdym z wariantów subiektywnie przypisano wagi poszczególnym kryterium, starając się odzwierciedlić nastawienie decydenta.

INTRODUCTION

The use of new ecological refrigerants has been forced in recent years by legal regulations **[L. 1]**. In order to implement these factors, it is necessary to select new or existing lubricating oils correctly. The selection should be based on a number of criteria, including the evaluation of the lubricating properties of oil-refrigerant mixtures.

Until recently, R404A has been a fairly frequently used refrigerant from the HFC group for commercial refrigeration equipment in both small and large installations. However, due to the high value of the

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potential for creating (intensifying) the greenhouse effect (GWP = 3922), a refrigerant with a lower GWP and comparable performance parameters has been sought. One of the most important substitutes for R404A – especially in transport refrigeration units – is R452A. It contains 11% – R32, 59% – R125, and 30% – R1234yf, respectively. R452A is based on hydrofluoroolefins and has a lower potential (GWP = 1945) to create (intensify) the greenhouse effect than R404A. So far, R452A has not been well identified in terms of tribological interactions.

Currently, refrigerants with a high greenhouse effect potential are also being eliminated. Hydrofluorocarbons (HFCs) refrigerants, such as R134a, are still widely used. However, there are future actions aiming at the successive replacement of these agents with natural substances only slightly affecting the climate change. The prospective refrigerants include hydrocarbons (HC) – for instance, isobutane-R600a.

Previous analyses **[L. 2, 3]** made it possible to claim that, in the friction nodes of refrigeration compressors, there is always a mixture of lubricating oil and refrigerant. Its composition depends on the oil temperature, refrigerant pressure, and the time of the interaction of these substances.

Earlier publications concerned the test method and test stand for model tribological tests in refrigeration compressor operating conditions **[L. 4, 5]**. A series of tests was also presented to assess the lubricating properties of lubricating oil mixtures and refrigerants **[L. 6–9]**. The results of these tests apply to both full and poor lubrication conditions and can help one choose the right lubricating oil for a given application.

In paper **[L. 10]**, there was a proposal for using a simple and transparent method to aid the decision-making on the selection of lubricants for refrigeration compressors on the basis of tribological tests of oil/ /refrigerant mixtures with full lubrication for R134a and R290. This work has attempted to modify that method and extend the set of criteria to include the tests concerning poor lubrication.

This work aimed at the following:

– Recommending the use of the Bellinger method to aid the decision on the selection of lubricants for refrigeration compressors on the basis of various tribological tests, and
– Carrying out the process of aiding the decision making on the selection of lubricants for two different mixing mechanisms between lubricating oil and refrigerant.

Diversified tribological tests should be understood as a comprehensive set of tests that includes both the tests on oil at full and poor lubrication, as well as the tests on oil/refrigerant mixtures for these variants of lubrication.

Three mineral oils (MO) intended for use with R600a and three synthetic oils designed to work with R452A were selected for the comparative analysis which took into account the decision-making process. In the first case, the indicated substances mix with each other only by intermolecular diffusion (MO/R600a mixtures); while, in the second case, mixing was performed by intermolecular diffusion and a simultaneous natural convection (POE/R452A mixtures).

In order to compare the tested oils, several decision situations were simulated depending on the approach of the decision-maker, i.e. economic, qualitative, and sustainable. In each of the variants, the weightings were subjectively assigned to individual criteria, trying to reflect the approach of the decision-maker.

DESCRIPTION OF TRIBOLOGICAL RESULTS

Generally, two basic mechanisms of mixing lubricating oil with refrigerant are distinguished **[L. 11, 12]**. In the subject literature **[L. 13–16]**, one can find reports on two cases of refrigerant performance on the oil liquid surface (at the inter-phase boundary):

– The vapour density of the refrigerant increases above the oil density, and penetration occurs through intermolecular diffusion and natural mass convection; and,
– The vapour density of the refrigerant is lower than the oil density, and penetration occurs only through intermolecular diffusion.

In the first case, the mass transfer (particles of the refrigerant into the oil) results from the thermal movement of the particles, while, in the other case, also from the effect of gravity. The impact of these forces significantly accelerates the process of obtaining the mixture.

Two types of oil/refrigerant mixtures corresponding to two types of mixing mechanisms were used for comparative tests:

– One by simultaneous intermolecular diffusion and natural molar convection – POE/R452A mixtures, and
– One only by intermolecular diffusion of MO/R600a mixture.

In tribological studies, the block-on-ring matching of a concentrated contact was used. Samples in the form of a ring were made of EN-GJL-250 grey cast iron, and the block was made of aluminium PA6. These types of materials are used to make sliding friction nodes of the connecting rod bearing shell and the drive shaft of refrigeration piston compressors **[L. 17]**. In order to produce the oil/refrigerant mixture, an amount of oil was used which enabled the creation of an immersion friction node lubrication system (level of half the height of the ring, with full lubrication) and unlimited access of the refrigerant with a previously selected saturation pressure **[L. 8]**. On the other hand, while reflecting the conditions of poor lubrication, one drop of lubricant was introduced into the friction node area **[L. 9]**.

A set of research parameters was used in which the parameters were selected so as to enable measurable material loss to be achieved in a relatively short period of time. In order to achieve the assumed effect, input forces characteristic for the operating conditions of refrigeration compressors were used, i.e. a high oil content, a high node load, and a low relative speed of the elements of the apparatus (parameters corresponding to a compressor start-up after a long standstill) **[L. 7]**. **Table 1** presents a set of series and test parameters for POE and MO oils and for mixtures of POE/R452A and MO/R600a at full lubrication, and **Table 2** presents the test parameters for the tests under poor lubrication conditions. A minimum of three test runs were carried out for each combination of oil with refrigerant and for the oils themselves.

Table 1. Test parameters for POE and MO and for mixtures of POE/R452A and MO/R600a at full lubrication [L. 8]
Tabela 1. Parametry badawcze dla olejów POE i MO oraz dla mieszanin POE/R452A i MO/R600a przy pełnym smarowaniu **[L. 8]**

Lubricant	Load [N]	Sliding velocity [rotation/min]	Pressure [MPa]	Oil – refrigerant mixture formation time [min]	Wear tests duration time [min]
POE	120	500	0.5	0	20
POE/R452A	120	500	0.5	40	20
MO	120	500	0.21	0	40
MO/R600a	120	500	0.21	1200	40

Table 2. Test parameters for POE and MO and for mixtures of POE/R452A and MO/R600a at poor lubrication [L. 8]
Tabela 2. Parametry badawcze dla olejów POE i MO oraz dla mieszanin POE/R452A i MO/R600a przy skąpym smarowaniu **[L. 9]**

Lubricant	Load [N]	Sliding velocity [rotation/min]	Pressure [MPa]	Oil – refrigerant mixture formation time [min]	Wear tests duration time [min]
POE	120	500	0.5	0	10
POE/R452A	120	500	0.5	40	10
MO	120	500	0.21	0	10
MO/R600a	120	500	0.21	1200	10

Tables 3 and **4** summarize the final test results that are the basis for describing the process of aiding the decision making for the selection of lubricants for refrigeration compressors on the basis of various tribological tests. The above-mentioned results relate to the sample wear volume in the tests with oil, the sample wear volume in the tests with the oil/refrigerant mixture, and the average coefficient of friction in tests with the oil/refrigerant mixture when the testing reflected full and poor lubrication. **Table 5** provides additional information which is to assist in the process of lubricant selection. These additional parameters are the fold increase in wear volume (mixture/oil) and the price of lubricating oil.

Table 3. Test results reflecting full lubrication [L. 8]
Tabela 3. Wyniki testów odzwierciedlających pełne smarowanie **[L. 8]**

Parameter	Lubricant					
	MO1	MO2	MO3	POE1	POE2	POE3
Sample volume wear in tests with unlimited oil [mm^3]	0.17	0.32	0.84	0.51	0.56	0.85
Aample volume wear in tests with the oil/refrigerant mixture in unlimited quantity [mm^3]	2.26	2.57	2.89	0.75	0.65	0.99
The mean coefficient of friction in tests with unlimited oil [-]	0.0413	0.0385	0.0433	0.0162	0.0193	0.0189
The mean value of the coefficient of friction in tests with an unlimited amount of oil/refrigerant mixture [-]	0.0655	0.0538	0.0568	0.0331	0.0581	0.0611

Table 4. Test results reflecting poor lubrication [L. 9]
Tabela 4. Wyniki testów odzwierciedlających skąpe smarowanie **[L. 9]**

Parameter	Lubricant					
	MO1	**MO2**	**MO3**	**POE1**	**POE2**	**POE3**
Sample volume wear in tests with unlimited oil [mm^3]	0.46	0.61	0.52	9.50	8.05	10.55
Sample volume wear in tests with the oil/refrigerant mixture in unlimited quantity [mm^3]	1.10	1.50	0.72	13.53	14.19	17.05
The mean coefficient of friction in tests with unlimited oil [-]	0.12	0.10	0.08	0.24	0.09	0.23
The mean value of the coefficient of friction in tests with an unlimited amount of oil/refrigerant mixture [-]	0.13	0.11	0.15	0.42	0.37	0.41

Table 5. Additional information to support the lubricant selection process [L. 8, 9]
Tabela 5. Dodatkowe informacje mające wspomóc proces doboru środka smarnego **[L. 8, 9]**

Parameter	Lubricant					
	MO1	**MO2**	**MO3**	**POE1**	**POE2**	**POE3**
The sample volume wear fold increase (mixture/oil in unlimited quantity) [-]	13.29	8.03	3.44	1.47	1.16	1.16
The sample volume wear fold increase (limited amount of mixture/oil) [-]	2.39	2.46	1.38	1.42	1.76	1.62
The price of lubricating oil (K11) [% of the price in relation to the cheapest oil]	141	102	100	100	120	107

TEST METHOD

The paper **[L. 10]** presented a proposal to use the Bellinger method to aid the decision-making on the selection of lubricants for refrigeration compressors on the basis of tribological tests of oil/refrigerant mixtures with full lubrication for R134a and R290. This work attempts to modify this method and extend the set of criteria with test results related to poor lubrication. It was due to the possibility of contrasting a small number of variants and making it possible to compare the decision variants in relation to all criteria that this method was chosen to support the selection of lubricants for refrigeration compressors on the basis of various tribological tests which take into account both full and poor lubrication conditions.

In the Bellinger method, the objects are ordered based on the total assessment determined from pre-defined partial criteria **[L. 17]**. The method consists in assessing decision options against all criteria, which are then reduced to the same measurement for comparison. The basic dependencies of the Bellinger algorithm apply to the distance between the upper and lower limits of the desired values.

The Bellinger method involves the following eight subsequent stages **[L. 17]**:

- The determination of the requirements and restrictions for variants of solutions to the analysed problem;
- The definition of the decision options available in a given situation;
- A detailed definition of the adopted assessment criteria, adoption of measurement units and desired direction of changes within a given criterion (stimulants and destimulants), as well as the lower and upper limits of changes for the analysed partial criteria;
- The determination of the weighting given by the decision maker to the adopted assessment criteria;
- The development of a matrix containing the actual values of the analysed criteria with individual variants in mind;
- The presentation of all numbers from the matrix from the previous stage as a percentage of "the path from the least to the most desirable state";
- The multiplication of all numbers obtained in the sixth stage by the weighting adopted in the fourth stage; and,
- The determination of the best option based on the sum of the ratings given to individual options while taking into account all the analysed criteria.

In the Bellinger method, the assessment of the decision variant based on the assessment variant $O_{x_{ij}}$ is determined according to the following relationship **[L. 18]**:

– for the stimulant: $$O_{x_{ij}} = \frac{\sup X - X_i}{\Delta j} \cdot 100\%,$$

– for the destimulant: $$O_{x_{ij}} = \frac{\inf X - X_i}{\Delta j} \cdot 100\%,$$

where

$O_{x_{ij}}$ – the assessment of the decision variant based on the assessment variant,

X_i – the numerical value for the given decision option determined by the decision maker,

Δ_j – the distance between the upper and lower limit of the set of values of the j-th criterion for evaluating decision variants,

supX – the most desirable value,

infX – the least desirable value.

The distance between the upper and lower limits of the set of values of the j-th criterion for the assessment of decision variants Δ_j is expressed by the following relationship **[L. 18]**:

$$\Delta j = |\sup X - \inf X|$$

The final assessment of the decision variant O_{x_i} is determined on the basis of the dependence where one takes into account the weighting of a given criterion determined by the decision maker **[L. 18]**:

$$O_{x_i} = \sum_{j=1}^{m} O_{x_{ij}} \cdot w_{j},$$

where

O_{x_i} – the final assessment of the decision variant,

w_i – the weighting of a given assessment criterion according to the decision maker preference.

APPLICATION OF BELLINGER METHOD TO AID THE DECISION ON THE SELECTION OF LUBRICANTS FOR REFRIGERATION COMPRESSORS

Here is the way of applying the Bellinger method to aid the decision on the selection of lubricants for refrigeration compressors on the basis of various tribological tests.

The analysis was performed having in mind the discussed stages of the Bellinger method. First, the requirements and restrictions for solution variants of the analysed problem were established. It was decided to diversify tribological tests of lubricating oils for refrigeration compressors compatible with R452A (polyester oils in the same ISO VG 32 viscosity grade designated POE1, POE2, and POE3, respectively) and with R600a (also in the same ISO VG 32 viscosity grade marked MO1, MO2, and MO3, respectively). Thus, the tested lubricants are the variants of solutions.

The selection will be made from three polyester compressor oils for use with R452A and three mineral oils for use with R600a.

The adopted assessment criteria are as follows:

- Sample volume wear in tests with unlimited oil – ideal working conditions at full lubrication (K1) [mm^3];
- Sample volume wear in tests with the oil/refrigerant mixture in unlimited quantity – real operating conditions at full lubrication (K2) [mm^3];
- The mean coefficient of friction in tests with unlimited oil (K3) [-];
- The mean value of the coefficient of friction in tests with an unlimited amount of oil/refrigerant mixture (K4) [-];
- Sample volume wear in tests with oil in a limited amount – ideal working conditions with poor lubrication (K5) [mm^3];
- Sample volume wear in tests with a mixture of oil/refrigerant in a limited amount – actual operating conditions with poor lubrication (K6) [mm^3];
- The mean value of the friction coefficient in tests with a limited amount of oil (K7) [-];
- The mean coefficient of friction in tests with a limited amount of oil/refrigerant (K8) [-];
- The sample volume wear fold increase (mixture/oil in unlimited quantity) (K9) [-];
- The sample volume wear fold increase (limited amount of mixture/oil) (K10) [-]; and,
- The price of lubricating oil (K11) [% of the price in relation to the cheapest oil].

All of the selected criteria were chosen so as to constitute destimulants within the given criterion. This means that the smallest numerical values within a given criterion are the most desirable. The lower and upper limits of each of the criteria are the smallest and largest numerical values, respectively. Three examples of the approaches of the decision-maker (economic, qualitative, and sustainable) were adopted in which the weighting of individual criteria differ depending on the preferences of the decision-maker. **Table 6** presents a set of weighting for the above-mentioned types of decision makers' approaches.

Table 6. A set of weightings for various types of approaches of the decision-maker

Tabela 6. Zestaw wag dla różnych rodzajów nastawienia decydenta

Criteria	The approaches of the decision-maker		
	economic	qualitative	sustainable
K1	0.05	0.05	0.10
K2	0.14	0.30	0.10
K3	0.05	0.03	0.10
K4	0.08	0.03	0.10
K5	0.05	0.05	0.10
K6	0.14	0.30	0.10
K7	0.05	0.03	0.10
K8	0.08	0.03	0.10
K9	0.03	0.08	0.05
K10	0.03	0.08	0.05
K11	0.30	0.02	0.10

While making decisions in the economic variant, the main emphasis was on the price criterion K11 (30% impact on the decision). The next in line was the criterion of consumption in the mixture of oil and refrigerant with its unlimited amount of K2 and with poor lubrication conditions, i.e. with a limited amount of K6 mixture (14% decision impact). For the criteria determining the mean value of the coefficient of friction for the tests of the oil/refrigerant mixture in a limited and unlimited amount, the weighting was assigned which represented 8% decision impact (criteria K4 and K8, respectively). The criteria for testing oil exclusively were assigned the weighting of 5% decision impact (criteria K1, K3, K5, and K7). The remaining criteria concerning the multiplicity of volume wear (K9, K10) were assigned the least influence on the selection decision (3% each).

The main emphasis while making decisions in the qualitative variant was put on the volume wear criteria in the mixture of oil and refrigerant – K2 and K6 (30% decision impact). The next criteria were those regarding the multiplicity of volume wear of K9 and K10 (8% decision impact each). In turn, the criteria for volume wear in the oil itself (K1 and K5) were given the weighting of 5%, and the remaining criteria – from 2 to 3% (**Table 4**).

In the qualitative variant, the main emphasis in making the decision was on the volume wear criteria in the mixture of oil with the refrigerant – K2 and K6 (30% influence on the decision). The next criteria were those regarding the fold volume wear of K9 and K10 (8% influence on the decision each). In turn, the criteria for volume wear in the oil itself (K1 and K5) were given the weighting of 5%, and the remaining criteria – from 2 to 3% (**Table 4**).

In the sustainable variant, the weighting for the criteria was determined in the same way for nine criteria (K1-K8 and K11), each having a 10% influence on the decision. For the criteria concerning the multiplicity of the volume wear of K9 and K10, the weighting of 5% was determined.

In the next stage, a matrix was developed containing the actual values of the analysed criteria in terms of individual variants, resulting from the combination of information from **Tables 3–5**. **Table 7** presents a summary of the actual values of the analysed criteria for the problem of selection from the group of mineral oils for R600a and polyester oils for R452A.

In the next stage, a compilation of all numbers from the matrix of real values of the analysed criteria in terms of individual variants as a percentage of "the the path from the least desirable to the most desirable state" was made (**Table 8**). In order to make the summary, the appropriate formulas for the destimulants were used.

Next, the final calculations were made to aid the selection of lubricants for refrigeration compressors based on tribological tests. **Tables 9–11** show the products of the weightings of individual criteria and the percentages of the path from the least desirable to the most desirable state for the three exemplary approaches of the decision maker. Then, the best variant was selected on the basis of the addition of the assessment given to individual variants while taking into account all the analysed criteria, and the variants for individual approaches of the decision maker were arranged in rankings.

Table 7. The matrix of the actual values of the analysed criteria for individual variants

Tabela 7. Macierz rzeczywistych wartości analizowanych kryteriów pod kątem poszczególnych wariantów

Criteria	**Lubricant**					
	MO1	**MO2**	**MO3**	**POE1**	**POE2**	**POE3**
K1	0.17	0.32	0.84	0.51	0.56	0.85
K2	2.26	2.57	2.89	0.75	0.65	0.99
K3	0.0413	0.0385	0.0433	0.0162	0.0193	0.0189
K4	0.0655	0.0538	0.0568	0.0331	0.0581	0.0611
K5	0.46	0.61	0.52	9.50	8.05	10.55
K6	1.10	1.50	0.72	13.53	14.19	17.05
K7	0.12	0.10	0.08	0.24	0.09	0.23
K8	0.13	0.11	0.15	0.42	0.37	0.41
K9	13.29	8.03	3.44	1.47	1.16	1.16
K10	2.39	2.46	1.38	1.42	1.76	1.62
K11	141	102	100	100	120	107

Table 8. The matrix of the actual values as a percentage of the so-called paths from the least to the most desirable state

Tabela 8. Macierz rzeczywistych wartości jako procent tzw. drogi od stanu najmniej do najbardziej pożądanego

Criteria	Lubricant					
	MO1	**MO2**	**MO3**	**POE1**	**POE2**	**POE3**
K1	100.00	77.61	0.00	100.00	85.29	0.00
K2	100.00	50.79	0.00	70.59	100.00	0.00
K3	41.67	100.00	0.00	100.00	0.00	12.90
K4	0.00	100.00	74.36	100.00	10.71	0.00
K5	100.00	0.00	60.00	42.00	100.00	0.00
K6	51.28	0.00	100.00	100.00	81.25	0.00
K7	0.00	50.00	100.00	0.00	100.00	6.67
K8	50.00	100.00	0.00	0.00	100.00	20.00
K9	0.00	53.40	100.00	0.00	100.00	100.00
K10	6.48	0.00	100.00	100.00	0.00	41.18
K11	0.00	95.12	100.00	100.00	0.00	65.00

Table 9. The ratings given to individual variants, taking into account all the analysed criteria with the economic approach of the decision maker

Tabela 9. Oceny przyznane poszczególnym wariantom z uwzględnieniem wszystkich analizowanych kryteriów przy ekonomicznym nastawieniu decydenta

Criteria	Lubricant					
	MO1	MO2	MO3	POE1	POE2	POE3
K1	5.00	3.88	0.00	5.00	4.26	0.00
K2	14.00	7.11	0.00	9.88	14.00	0.00
K3	2.08	5.00	0.00	5.00	0.00	0.65
K4	0.00	8.00	5.95	8.00	0.86	0.00
K5	5.00	0.00	3.00	2.10	5.00	0.00
K6	7.18	0.00	14.00	14.00	11.38	0.00
K7	0.00	2.50	5.00	0.00	5.00	0.33
K8	4.00	8.00	0.00	0.00	8.00	1.60
K9	0.00	1.60	3.00	0.00	3.00	3.00
K10	0.19	0.00	3.00	3.00	0.00	1.24
K11	0.00	28.54	30.00	30.00	0.00	19.50
Total score	37.46	64.63	63.95	76.98	51.50	26.31
Final ranking	3	1	2	1	2	3

For the R600a, the economic option is to choose MO2 (the score 64.63). The subsequent oils in the comprehensive decision-making assessment of this variant are MO2 (the score 63.95) and MO2 (the score 37.46). In the economic approach, the order is not identical to the order resulting from the criterion of consumption of samples in the mixture of oil with the K2 refrigerant. It should also be noted that, in this variant, the compared oils (MO1 and MO2) obtained relatively similar ratings and the choice of the first oil was not determined by the price criterion K11.

For R452A, the economic decision is POE1 (score 76.98). The next oils in the comprehensive decision-making assessment of this variant are POE2 (51.50 evaluation result) and POE3 (26.31 evaluation result). It should be noted that the assessments of individual variants differ significantly and the final ranking is not subject to discussion. In the economic approach, the order is also not identical to the order resulting from the K11 price criterion, which was assigned the highest weighting.

Table 10. The ratings assigned to individual variants while taking into account all the analysed criteria with the qualitative approach of the decision-maker

Tabela 10. Oceny przyznane poszczególnym wariantom z uwzględnieniem wszystkich analizowanych kryteriów przy jakościowym nastawieniu decydenta

Criteria	Lubricant					
	MO1	MO2	MO3	POE1	POE2	POE3
K1	5.00	3.88	0.00	5.00	4.26	0.00
K2	30.00	15.24	0.00	21.18	30.00	0.00
K3	1.25	3.00	0.00	3.00	0.00	0.39
K4	0.00	3.00	2.23	3.00	0.32	0.00
K5	5.00	0.00	3.00	2.10	5.00	0.00
K6	15.38	0.00	30.00	30.00	24.38	0.00
K7	0.00	1.50	3.00	0.00	3.00	0.20
K8	1.50	3.00	0.00	0.00	3.00	0.60
K9	0.00	4.27	8.00	0.00	8.00	8.00
K10	0.52	0.00	8.00	8.00	0.00	3.29
K11	0.00	1.90	2.00	2.00	0.00	1.30
Total score	58.65	35.79	56.23	74.28	77.96	13.78
Final ranking	1	3	2	2	1	3

For R600a, MO1 was selected in the qualitative variant (the score 58.65). The next oils in the comprehensive decision maker assessment from this variant are MO3 (the score 56.23) and MO2 (score 35.79). In the qualitative approach, the sequence is, in this case, identical to the order resulting from the wear criterion in the oil-refrigerant mixture under the conditions of poorly lubricated K6, but it differs from the order determined by the wear criterion in the tests with the oil/refrigerant mixture with full lubrication K2. It is worth noting that the ranking is different from the one in the economic approach, which may indicate the selection of an oil with worse lubricating properties, if only on the basis of the price of the product.

On the other hand, for R452A the decision in the qualitative variant is the choice of POE2 (the score 77.96). The next oils in the comprehensive decision maker's assessment from this variant are POE1 (the score 74.28) and POE3 (the score 13.78). In the qualitative approach, the order is, in this case, the same as the one resulting from the wear criterion in the oil-refrigerant mixture with full K2 lubrication, but it differs from the order determined by the wear criterion in the oil-refrigerant mixture under the poorly lubricated K6 conditions.

Table 11. The ratings assigned to individual options, taking into account all the analysed criteria with a sustainable approach of the decision-maker

Tabela 11. Oceny przyznane poszczególnym wariantom z uwzględnieniem wszystkich analizowanych kryteriów przy zrównoważonym nastawieniu decydenta

Criteria	Lubricant					
	MO1	MO2	MO3	POE1	POE2	POE3
K1	10.00	7.76	0.00	10.00	8.53	0.00
K2	10.00	5.08	0.00	7.06	10.00	0.00
K3	4.17	10.00	0.00	10.00	0.00	1.29
K4	0.00	10.00	7.44	10.00	1.07	0.00
K5	10.00	0.00	6.00	4.20	10.00	0.00
K6	5.13	0.00	10.00	10.00	8.13	0.00
K7	0.00	5.00	10.00	0.00	10.00	0.67
K8	5.00	10.00	0.00	0.00	10.00	2.00
K9	0.00	2.67	5.00	0.00	5.00	5.00
K10	0.32	0.00	5.00	5.00	0.00	2.06
K11	0.00	9.51	10.00	10.00	0.00	6.50
Total score	44.62	60.02	53.44	66.26	62.73	17.52
Final ranking	3	1	2	1	2	3

In the sustainable variant (for R600a), MO2 was selected (the score 60.02). The next oils in the comprehensive decision maker's assessment from this variant are MO3 (the score 53.44) and MO1 (the score 44.62).

For R452A, the decision in the sustainable variant is to choose POE1 (the score 66.26). The next oils in the comprehensive decision maker's assessment from this variant are POE2 (the score 62.73) and POE3 (the score 17.52). In the sustainable approach, the sequence, in this case, is identical to the sequence in the economic approach. The differences in the assessment of the first two oils are insignificant.

Summarizing the results of the rankings given to individual variants with all types of the decision-makers' approaches (**Table 12**), the following can be stated:

Table 12. Summary of the results of the rankings assigned to individual variants for all types of the decision maker's approaches

Tabela 12. Podsumowanie wyników rankingów przyznanych poszczególnym wariantom przy wszystkich rodzajach nastawienia decydenta

	Lubricant					
	MO1	MO2	MO3	POE1	POE2	POE3
Ranking in economic approach	3	1	2	1	2	3
Ranking in qualitative approach	1	3	2	2	1	3
Ranking in sustainable approach	3	1	2	1	2	3

– For R600a, the ranking in the economic and sustainable variants overlaps, while the ranking in the qualitative variant indicates a completely different selection of the best oil.
– For the R600a, in each of the analysed decision makers' approaches, the oil that came second in the ranking was MO3.
– For R452A, POE3 was definitely the worst option, which confirms its last place in the ranking, with all the analysed settings of the decision maker.
– For R452A, the ranking in the economic and sustainable variant overlaps, while the ranking in the qualitative variant indicates a completely different selection of the best oil.

SUMMARY

The article presents proposals for the use of the Bellinger method to aid the decision on the selection of lubricants for refrigeration compressors using ecological refrigerants on the basis of various tribological tests. A lubricant selection decision aiding process was also carried out for two different mixing mechanisms of the lubricating oil and the refrigerant. The analysis included test results reflecting various operational situations in refrigeration compressors, i.e. full and poor lubrication of friction nodes with both oils themselves and their mixtures with the refrigerant. Three mineral oils for use with R600a (the mixing mechanism by intermolecular diffusion) and three synthetic oils for use with R452A and R600a (the mixing mechanism by intermolecular diffusion, simultaneous intermolecular diffusion and natural convection) were analysed.

There are many advantages to using the Bellinger method. The calculation algorithm consists of simple, uncomplicated calculations. The decision maker does not need extensive knowledge in the field of multi-criteria optimization or specialized software. Due to its simplicity and speed of calculation, the Bellinger method can be successfully used to aid decision making on the selection of lubricants for refrigeration compressors on the basis of various tribological tests.

When choosing the oil for R452A in each of the analysed variants (economic, quality and sustainable), by far the worst variant was POE3, which is confirmed by its last position in the ranking of all the analysed decision-maker approaches. For this agent, the ranking in the economic and sustainable variant overlaps, and the ranking in the qualitative variant indicates a completely different choice of the best oil.

When choosing the oil for the R600a, the ranking in the economic and sustainable variant overlaps and successively indicates MO2, MO3, and MO1, and the ranking in the qualitative variant indicates a completely different choice of the best oil – MO1. In each of the analysed decision-maker approaches, the oil that came second in the ranking was MO3.

The above-presented approach to the decision-making on the selection of lubricating oil for cooperation with a specific refrigerant exemplifies the use of test results obtained in the previous studies on the wear of friction node elements in oil-refrigerant mixtures under conditions of full and poor lubrication. It should be noted that the result indicated by the Bellinger method strictly depends on the preferences of the decision-maker and the resulting weightings of individual criteria.

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