ISSN 1232-3829
tts 10/2013
Technika Transportu Szynowego koleje ▪ tramwaje ▪ metro

TYCZEWSKI Przemysław

WEAR OF ELEMENTS OF MACHINES OPERATING IN AGGRESSIVE MEDIA

Abstract

This paper presents the attempt to learn mechanical, corrosive and abrasive wear mechanisms and wear mechanisms in refrigerating compressor systems.

The range of own examinations includes electrolytic liquids with abrasive material occurring in the food industry especially in the sugar industry and lubricating oils polluted with refrigerant occurring in stationary and carrying refrigerating compressor systems.

On the basis of carried out experiments with the use of the mathematical methods for the experimental designs, they formulated a statistical model describing the complex process of simultaneous wear. This model enables forecasting the wear and indicates that the abrasive wear is of dominating character.

Refrigerants create, with compressor oils, compounds causing the accelerated wear of the refrigerating compressors. The complex dependencies, in case of the compound oil – refrigerant, cause that the lubricating and anti-wear properties are much worse than in case of pure oil. In case of exceeding their mutual miscibility a part of the agent is absorbed by oil. More stringent regulations concerning the protection of the ozone layer caused the appearance of new agents creating new compounds with oils. In order to examine the influence of the compounds on the wear processes in the refrigerating compressors, they made a test stand. The stand is built of real elements of the refrigerating system consisting of, among others, the dismountable half-hermetic compressor. There is just being built the stand for testing the model wear processes occurring in the refrigerating compressors; the stand will be used for tribological tests in the atmosphere of refrigerants in the conditions of regular loads.

The purpose of the performed examinations is to be the elaboration of methods of wear phenomena modelling in the complex service conditions in the sectors of production and refrigerating storage of food.

The range of own examinations includes electrolytic liquids with abrasive material occurring in the food industry especially in the sugar industry and lubricating oils polluted with refrigerant occurring in stationary and carrying refrigerating compressor systems.

INTRODUCTION

The carried out tests on the wear mechanisms in complex service conditions show that the total wear occurring in tribological pairs due to simultaneous occurrence of destructive processes: frictional, corrosive and abrasive is not a simple superposition of their individual effects occurring in conditions of their independent interactions (Fig 1a). In the compressor refrigerating systems, the system oil – refrigerant characterizes with complex dependences. Refrigerants create, with compressor oils, compounds causing the accelerated wear of the refrigerating compressors. The complex dependencies, in case of the compound oil – refrigerant, cause that the lubricating and anti-wear properties are much worse than in case of pure oil (Fig 1b).

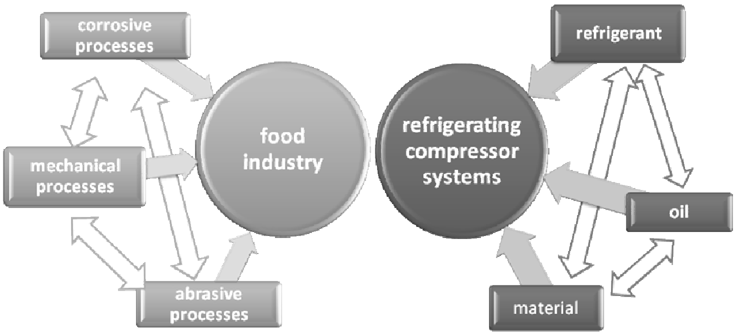

Fig 1. a) electrolytic liquids with abrasive material, b) lubricating oils polluted with refrigerant occurring

1. ELECTROLYTIC LIQUIDS WITH ABRASIVE MATERIAL

In numerous connections of instruments and machines in food industry occur tribological processes characterizing with simultaneous occurrence of interaction effects of abrasive and corrosive factors [8]. The subject of simultaneous abrasive and corrosive wear lies, for years, in the sphere of interest of scientists. Tests were carried out among others in Great Britain, USA, China and RSA [2, 10]. The majority of authors used sulphur acid H_2SO_4 as the active environment whereas sand as the abrasive factor. The models of connections were made of acid resistant steel. Due to the fact that tests were carried out in different countries (different acid resistant steels) with the use of different experimental positions (diversified kinematics pair) the results obtained by individual authors could not be compared in a simple and explicit way. The literature review showed also that the scientists firsts of all formulated conclusions of descriptive, qualitative character. The lack of quantitative models can be distinctly seen.

The authors of this work decided to perform empirical tests using the model connections, hitherto not applied, type ring – ring.

1.1. Methodical conception of tests

The theoretical model describing the wear intensity can be presented as the sum of components being the effect of mechanical (I_M), corrosive (I_K), abrasive ($I_{\acute{S}}$) interactions and their mutual interactions (I_Δ):

$$I_C = I_M + I_K + I_{\acute{S}} + I_\Delta \tag{1}$$

The interaction component I_Δ requires a detailed explanation. The effects of interactions of processes such as the abrasive and mechanical ($I_{\Delta \acute{S} M}$), abrasive and corrosive ($I_{\Delta \acute{S} K}$) ones and the simultaneous influence of abrasive and corrosive and mechanical process ($I_{\Delta \acute{S} KM}$) (formula No. 2) control over relations among all the components.

$$I_\Delta = I_{\Delta \acute{S} M} + I_{\Delta KM} + I_{\Delta \acute{S} K} + I_{\Delta \acute{S} KM} \tag{2}$$

The abrasive and mechanical interaction depends on the influence of the abrasive factor on mechanical processes and of the mechanical factor on abrasive processes:

$$I_{\Delta \acute{S} M} = I'_{\Delta \acute{S} M} + I'_{\Delta M \acute{S}} \tag{3}$$

The corrosive and mechanical interaction depends on the influence of the corrosive factor on the mechanical processes and of the mechanical factor on the abrasive processes:

$$I_{\Delta KM} = I'_{\Delta KM} + I'_{\Delta MK} \tag{4}$$

Also the abrasive and corrosive interaction depends on the influence of the abrasive factor on the corrosive processes and of the corrosive factor on the abrasive processes:

$$I_{\Delta \acute{S} K} = I'_{\Delta \acute{S} K} + I'_{\Delta K \acute{S}} \tag{5}$$

Placing the formulated dependences to the equation (1) you obtain a model of the most general form:

$$I_C = I_M + I_K + I_{\acute{S}} + I'_{\Delta\acute{S}M} + I'_{\Delta M\acute{S}} + I'_{\Delta KM} + I'_{\Delta MK} + I'_{\Delta\acute{S}K} + I'_{\Delta K\acute{S}} + I_{\Delta\acute{S}KM} \qquad (6)$$

The graphic form of the model is additionally presented in the figure 2a.

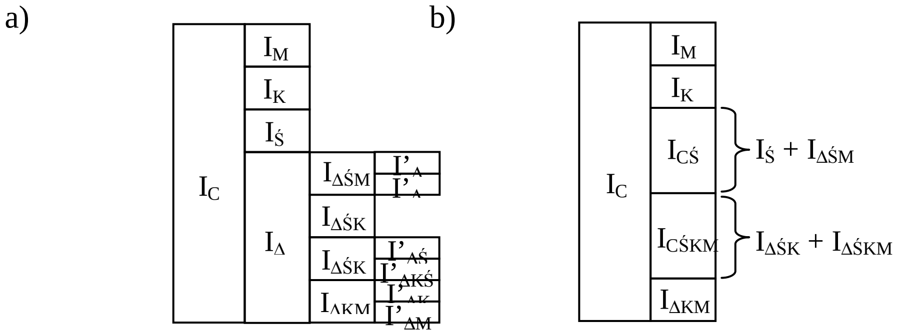

Fig. 2. Theoretical components of the mutual interactions among abrasive-corrosive-mechanical processes; a) individual components, b) the simplified distribution of components

Determination of the mechanical (I_M) and corrosive (I_K) components can be carried out when making experimental tests ensuring force functions of only mechanical or chemical character. The occurrence of abrasive wear requires introduction of abrasive material to co-acting surfaces. In case of the discussed model of tribological connection type ring – ring the contact of the abrasive material with the co-acting surface can be realised only with the simultaneous presence of mechanical forces. So one should regard wear $I_{\Delta\acute{S}}$ as the sum of abrasive factor interactions and the abrasive factor influence on the mechanical wear intensity:

$$I_{C\acute{S}} = I_{\acute{S}} + I_{\Delta\acute{S}M} \qquad (7)$$

It is worth to point out that the presence of the abrasive material can also influence the corrosive wear as well as corrosive and mechanical wear processes which is presented below in the formal dependence:

$$I_{C\acute{S}KM} = I_{\Delta\acute{S}K} + I_{\Delta\acute{S}KM} \qquad (8)$$

To make further analysis easier they gave up the separation of individual interactions: abrasive and mechanical ($I_{\Delta\acute{S}M}$), corrosive and mechanical ($I_{\Delta KM}$), abrasive and corrosive ($I_{\Delta\acute{S}K}$).

So, the simplified model describing wear with simultaneous interaction of abrasive, corrosive and mechanical processes will have the following form (the graphic interpretation is presented in the figure 2b):

$$I_C = I_M + I_K + I_{C\acute{S}} + I_{\Delta KM} + I_{C\acute{S}KM} \qquad (9)$$

1.2. Measuring position and test methods

The tests were carried out on the modernized abrasive machine UMT-2168. The friction connection type ring – ring is chosen for tests (carbon steel 45).

In order to find the individual components of abrasive and corrosive wear they considered carrying out independent experiments following the scheme presented in the table 1. They assumed the corrosive tests to be carried out in the aggressive fluid so there was no need to take into account the atmospheric influence on wear. Experiments in version II and VI, as it was mentioned before, will not be realised due to the influence of the abrasive material on surfaces not being in motion.

Thus, the tests were made according to the schemes I, III, IV, V and VII. The experiment I was made in the distilled water with cathodic protection. For abrasive tests they used purified, dried sand subjected to sieve analysis of fraction 0.1 – 0.2 [mm]. For corrosive tests they used 4% dilution of sulphuric acid H_2SO_4. The process lasted 1800 s.

Experimental test results shown in Table 2 and Figure 3.

Tab 1. Characteristics of experiments

Experiment	Factor			Model
	mechanical	abrasive	corrosive	
	20[N], 75[rpm]	d = 0,2 [mm]	m = 4 % H_2SO_4	
I	X	-	-	$I_{II} = I_M$
II	-	X	-	-
III	X	X	-	$I_{IV} = I_M + I_Ś + I_{\Delta ŚM}$
IV	-	-	X	$I_V = I_{K1}$
V	X	-	X	$I_{VI} = I_M + I_K + I_{\Delta MK}$
VI	-	X	X	-
VII	X	X	X	$I_{VIII} = I_C = I_M + I_K + I_Ś + I_\Delta$
X – factor occurring in a given test - – factor not occurring in a given test				

Tab 2. Experimental test results (variable corrosive factor)

0,2 [mm]	2%		4%		6%		8%	
	I [g]	[%]	I [g]	[%]	I [g]	[%]	I [g]	[%]
I_M	0,0030	7	0,0030	6	0,0030	6	0,0030	6
$I_{CŚ}$	0,0141	35	0,0141	29	0,0141	27	0,0141	26
I_K	0,0056	14	0,0058	12	0,0062	12	0,0062	11
$I_{\Delta KM}$	-0,0010	-2	0,0013	3	0,0014	3	0,0024	4
ΔJ	0,0184	46	0,0250	50	0,0281	52	0,0284	53
I_C^E	0,0401	100	0,0492	100	0,0528	100	0,0541	100

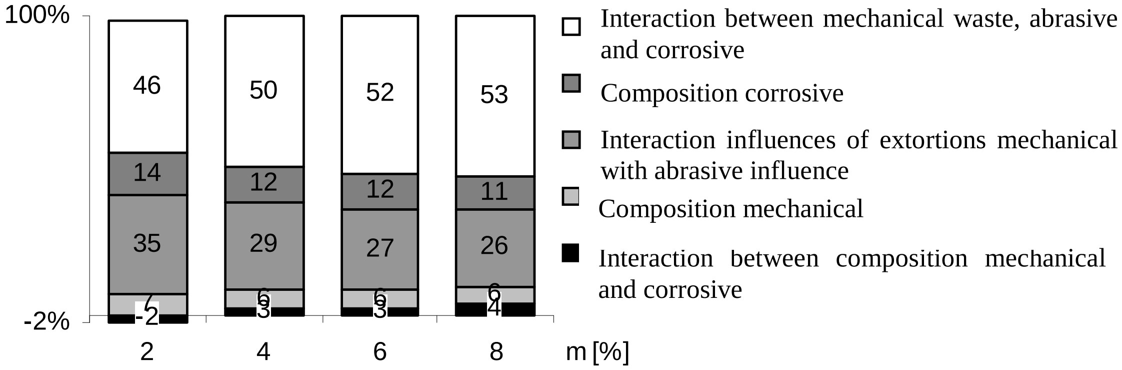

Fig. 3. Values composition wear at variables corrosive extortions caused with differentiation of content of corrosive factor

1.3. Statistic plan of the experiment

They decided to use possibilities of mathematical methods of planning the experiments [7] for the analysis of results of multifactor tribological experiment. They used the CADEX software. They have chosen the statistical determined polysectional orthogonal plan. This plan, in relation to other acceptable test plans, ensures the max. simplification of calculations of model coefficients and their statistical evaluation [7]. In the tests, they have taken into account four initial factors which were changing in four levels.

They decided to verify the general orthogonal model of II order in the following form:

$$I = b_0 + \sum_{i=1}^{4} b_i X_i + \sum_{\substack{i=1 \\ j=1}}^{4} b_{ij} X_i X_j + \sum_{i=1}^{4} b_{ii} X_i^2 , \qquad (10)$$

where: b_{ij} – coefficients, X_{ij} – coded variables.

For the model they assumed the following designations: Initial factors: x_1 – number of rotations [rpm] ($0<x_1<150$), x_2 – pressing force [N] ($0<x_2<40$), x_3 – size of grains [mm] ($0<x_3<0.3$), x_4 – composition of environment [%] ($0<x_4<8$). The exit factor: I – weight-wear.

1.4. Test results

From amongst many possible to be applied formal regressive models in the considered problem they used the second model of the mentioned ones. This choice was imposed by the initial evaluation of the correlation link of the multidimensional correlation coefficient R. The obtained results were the most advantageous for the linear-square model with interaction components. So, in the following experiment they assumed that the initially verified model would have:

$$I = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + b_{44}x_4^2 + b_{12}x_1x_2 + b_{13}x_1x_3 + \\ + b_{14}x_1x_4 + b_{23}x_2x_3 + b_{24}x_2x_4 + b_{34}x_3x_4, \quad (11)$$

Making the reliable verification required the representative test of the test results to be obtained. The list of test parameter values for individual variants together with mean wear values author presents in another publication [9]. For approximation of function of the test object they chose an algebraic multinomial (linear-square-interactive). To simplify calculations in order to find connections between the initial factors and the exit factor they introduced the new coded variable X_i.

One counted approximation errors, i.e. ralations between exit values (I) being the measurement results and the respective approximized exit values ($\hat{I}$) calculated from the determined approximation function are as follows. Making use of the relation normalization they made variable decoding. For verification of essence of individual coefficients in the model they applied the test of t-Student. They calculated for the individual coefficients bj the standard deviation S(bj) and the value of the test statistics t(bj). The new model should be proposed, without unessential coefficients. Using the normalization relations they replaced the coded variables obtaining the equation describing variability of complete wear in case of simultaneous interactions of mechanical, abrasive and corrosive constraint.

$$I=-0.01613+0.00047x_1+0.00156x_2+0.02521x_3+0.00563x_4-0.000003x_1^2-0.00003x_2^2-0.00042x_4^2 \quad (12)$$

The initial model – the approximative multinomial, for the discussed four variables (x_1, ..., x_4) included 15 components. The calculated value of the correlation coefficient was 77%. Using the t-Student they made a formal essence evaluation of the influence of coefficients at the decisive variables and their combination in the tested model. The calculation results showed that at the decreased value of the correlation coefficient to 76% it was possible to simplify the model to the form of eight-component multinomial. The analysis of the form of this equation shows that the initial the initial arbitrary choice of decisive variables (rotational speed, stresses, dimensions of abrasive, concentration of corrosive medium) is reasonable as all the variables (x_1, ..., x_4) occur in the model. The evaluation of the influence of changes of values of decisive variables on complete wear is difficult when the model in its final form is considered. In order to formulate conclusions it is easier to analyse the same model in the form containing the normalized variables.

1.5. Application of artificial neural networks

The artificial neural network is a system which is to simulate the work of brain, so it is used for recognizing, forecasting, controlling. The neural networks are a modern calculating system with which one can process data effectively and without fail [9]. From the point of view of functioning, the multilayer neural network can be treated as a system for the approximation of the nonlinear function of several variables. Four input signals (pressure, velocity, abrasive material fraction and corrosive medium concentration) and one output signal (wear value) were assumed in the elaborated neural model.

Two networks were built. The first one – unidirectional, one-layer (in fact three layers: input, output and one hidden) – with six neurons in the layer. The other one – unidirectional, two-layer (four layers: input, output and two hidden between them); there are 8 neurons in the first layer and 6 neurons in the second layer.

Figures 4 present the application of created one layer networks for forecasting purposes. The figure presents the forecasting wear values for input data not taking part in the experimental tests. The obtained forecast results with the use of models basing on one- and two-layer neural networks turned out to be very similar. The application of "complicated" multilayer networks seems to be groundless. So, in tests aiming to forecast the wear the application of one-layer network is sufficient. The results of the performed verification prove that it is possible to apply artificial neural networks for the analysis of effects of the complicated wear processes, i.e. when simultaneous abrasive, corrosive and mechanical interactions take place. The obtained results show that the obtained models can be used to forecast the wear values for the complicated values of decision variables.

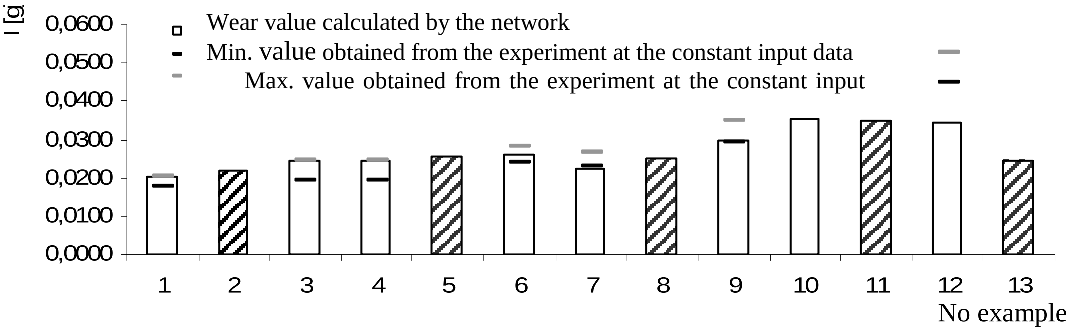

Fig. 4. The application of artificial one layer NN for forecasting purposes (the forecasting value are grey coloured: 2 (v=0,095[m/s], P=20[N], d=0,05[mm], m=2[%]); 5 (v=0,095[m/s], P=30[N], d=0,075[mm], m=2[%]); 8 (v=0,074[m/s], P=23[N], d=0,1[mm], m=4[%]); 11 (v=0,104[m/s], P=20[N], d=0,2[mm], m=4[%]); 13 (v=0,087[m/s], P=15[N], d=0,15[mm], m=3[%])).

2. LUBRICATING OILS POLLUTED WITH REFRIGERANT OCCURRING

Motion elements of refrigerating compressors are subjected to various kinds of wear processes depending on the applied oils and refrigerants [3, 4]. The reasons of mechanical damages of compressors are oil deficiency, compressor overheating, liquid impact, flooded compressor starting and flooding with liquid refrigerant. Improper lubrication is usually caused by the application of oil chosen inadequately to the refrigerant. Then, the mixture oil-refrigerant is created.

Oils applied in refrigerating systems are, apart from basic requirements (compressor lubrication and cooling), required to be resistant to solidification in low temperatures occurring in the evaporator as well as miscible and compatible with refrigerants. Oils must have suitable lubricating properties ensuring the creation of the oil film on the friction elements as well as the ability to return from the refrigerating system to the compressor.

In the refrigerating system, the system oil-refrigerant characterizes by complex relationships. In case of exceeding their mutual miscibility a part of the refrigerant is absorbed by oil. Solubility of refrigerant in oil depends, among others, on the oil base. Depending on the mixture composition, temperature and pressure, the mixture of oil and refrigerant can be of single-phase or diphase character. The complex relationships, in case of the oil-refrigerant mixture, cause that the lubricating and anti-wear properties are much worse than in case of pure oil. As it is possible to dilute oil with refrigerant, oils of higher viscosity are applied.

Due to changing regulations concerning the application of substances weakening the ozone layer there are introduced new refrigerants to the refrigerating machines and systems. The refrigerants create with compressor oils the mixtures causing the accelerated wear of the refrigerating compressors [1, 5, 6]. For the sake of the complexity of problems, now, there are no determined international standards concerning the requirements for oils applied in the refrigerating compressors. Nowadays, there is no universal oil for refrigerating compressors. Oil should be chosen for the suitable compressor and refrigerant.

Mechanical damages of refrigerating compressors and thus wear processes of compressors friction pairs are mainly influenced by the mixture of oil and refrigerant [4]. So the wear processes of the refrigerating compressors (A) depend on the mixture of oil (B) and refrigerant (C):

$$A = B \leftrightarrow C \tag{13}$$

The component (B) in the equation (13) changes depending on the oil kind, base and also additives. The component (C) changes depending on the refrigerant. Depending on the application of oil, refrigerant and also kind of materials used for the friction pair and the operation conditions (temperature, pressure, load) you can expect different wear processes of the motion elements of the refrigerating compressors.

2.1. Test stand

In order to investigate the influence of the unfavourable operation conditions of the refrigerating installation on the tribological wear of the surface of the motion elements of the compressor they made the test stand (fig. 5).

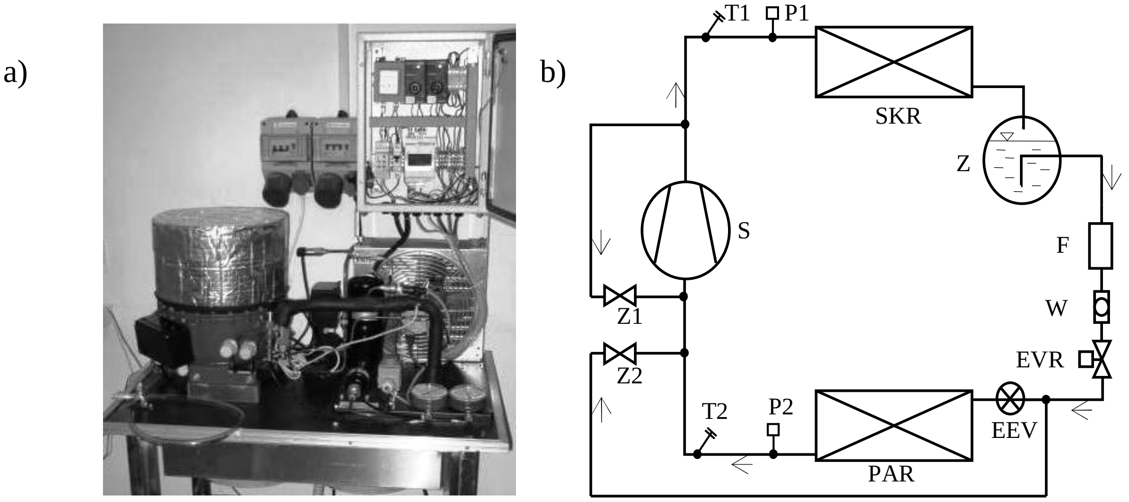

Fig. 5. Stand for testing wear processes of refrigerating compressors: a) stand view, b) scheme where: S – semi-hermetic compressor, SKR – condenser, PAR – evaporator, Z – refrigerant tank, F – dehydrator, W – inspection opening, EVR –electro-magnetic valve, EEV – electronic programmer controlled expansion valve, EVD, Z1 – valve (hot operation), Z2 – valve (wet operation), T1, T2 – temperature sensors, P1, P2 – pressure sensors

The stand was built as a real refrigerating system consisting of the compressor, evaporator, filter, inspection openings, electronic expansion valve, electromagnetic valve and condenser. Using the control system one can control rotation speed of fans on the evaporator and the condenser, the overheating value and the opening extend of the extension valve. The most important element of the stand is the refrigerating compressor situated in the dismountable body. The semi-hermetic casing enables the replacement of the compressor for the evaluation the wear degree of its motion elements. The set of inspection openings enables the oil control in the body. The stand elements are matched to ensure the most universal installation for various refrigerants and oils. The scheme of the stand is shown in the figure 4b. The stand enables simulation of the following unfavourable service conditions of the installation: compressor operation at high temperature and pressure; compressor flooding by liquid refrigerant; supplying hot gases to the compressor; system operation with air and humidity; compressor operation with various oil quantities; compressor operation at oil deficiency; operation with various refrigerants; operation with various oils.

There is just being built the stand for testing the model wear processes occurring in the refrigerating compressors; the stand will be used for tribological tests in the atmosphere of refrigerants in the conditions of regular loads (fig. 6). On the stand you can measure pressure inside the chamber, apply pressure force for samples, control the sample speed.

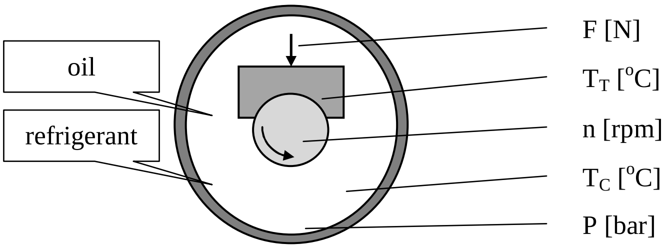

Fig 6. The chamber for testing the model wear processes occurring in the refrigerating compressors

SUMMARY

The analysis of the given test results shows that the wear effects are not the simple superposition of interactions between individual components. One can say that dominating reasons of wear are forcing functions caused by abrasive material interactions.

In the effect of making the multifactor experiment planned according to the rules resulting from the mathematical theory of experiment planning they obtained a mathematical model presenting the quantitative description of the investigated process. The analysis of the formulated detailed remarks shows that abrasive interactions influence in the dominant way on the complete wear in the described complex case of simultaneous tribologic and corrosive wear.

The effect of the application of the artificial neural network is a neural model describing the complex process of simultaneous mechanical, abrasive and corrosive wear. This model has been verified with the use of data not taking part in the network creation process. After the analysis of effects of the network operation one can find out that it is possible to use the artificial neural networks for the analysis of effects of interactions of tribologic processes.

The built stand for testing the model wear processes occurring in the compressors together with the stand for testing the wear processes occurring in the real refrigerating compressors should contribute to the elaboration of methods concerning wear phenomena modelling in the compex service conditions in the sector of the refrigerated food storage.

REFERENCES

1. Allison Y. Suh, Jayesh J. Patel, Andreas A. Polycarpou, Thomas F. Conry: Scuffing of cast iron and Al390-T6 materials used in compressor applications, Wear, 260 (7-8), 2006, s. 735-744
2. Assi F., Böhni H., Study of wear – corrosion synergy with a new microelectrochemical technique, Wear, 233 – 235, 1999, 505 – 514.
3. De Melloa J.D.B., Binderb R., Demasc N.G., Polycarpouc A.A., Effect of the actual environment present in hermetic compressors on the tribological behaviour of a Si-rich multifunctional DLC coating, Wear 267 (2009) 907–915

4. Górny K., Tyczewski P., Zwierzycki W., Characteristics of stands for wear tests of materials for refrigeration compressors elements, Tribologia, 3/2010, s. 75-84
5. Górny K., Tyczewski P., Zwierzycki W., Specification of lubricating oil operation in refrigeration compressors, Tribologia, 3/2010, s. 63-73
6. Hong-Gyu Jeon, Se-Doo Oh, Young-Ze Lee, Friction and wear of the lubricated vane and roller materials in a carbon dioxide refrigerant, Wear 267 (2009) 1252–1256
7. Mańczak K., Technika planowania eksperymentu, WNT, 1976.
8. Nadolny K., Tyczewski P., Test Results Concerning Mechanical - Abrasive Corrosive Wear, Solid State Phenomena Vol. 113 (June 2006) pp. 353-358
9. Rymarczyk M., Decyzje sieci neuronowe, Wyd. WSB, Poznań 1997.
10. Watson S.W., Friedersdorf F.J., Madsen B.W., Cramar S.D., Methods of measuring wear – corrosion synergism, Wear, 181 – 183 (1995) 476 – 484.

ZUŻYWANIE ELEMENTÓW MASZYN PRACUJĄCYCH W ŚRODOWISKACH AGRESYWNYCH

Streszczenie

W pracy przedstawiono próbę poznania mechanizmów zużywania mechaniczno-korozyjno-ściernego oraz mechanizmów zużywania w sprężarkowych układach chłodniczych.

Zakres własnych badań obejmuje ciecze elektrolityczne ze ścierniwem występujące w przemyśle spożywczym a w szczególności w cukrownictwie oraz oleje smarowe zanieczyszczone czynnikiem chłodniczym występujące w sprężarkowych układach chłodniczych stacjonarnych i transportowych.

Z wykonanych eksperymentów przy użyciu matematycznych metod planowania doświadczeń, sformułowano model statystyczny opisujący złożony proces jednoczesnego zużywania. Model ten pozwala na dokonywanie prognoz zużywania i wskazuje na dominujący charakter zużywania ściernego.

Czynniki chłodnicze z olejami sprężarkowymi tworzą mieszaniny powodujące przyśpieszone zużycie sprężarek chłodniczych. Złożone zależności w przypadku mieszaniny olej – czynnik chłodniczy powodują, iż właściwości smarne i przeciwzużyciowe są dużo gorsze niż oleju czystego. W przypadku przekroczenia wzajemnej mieszalności część czynnika jest zaabsorbowana przez olej. Zaostrzenie przepisów prawnych dotyczących ochrony warstwy ozonowej spowodowało pojawienie się nowych czynników, które wraz z olejami tworzą nowe mieszaniny. W celu zbadania wpływu mieszanin na procesy zużyciowe w sprężarkach chłodniczych powstało stanowisko badawcze. Stanowisko zbudowane jest z rzeczywistych elementów układu chłodniczego składające się miedzy innymi z rozbieralnej sprężarki – półhermetycznej. W trakcie budowy jest stanowisko do badań modelowych procesów zużyciowych zachodzących w sprężarkach chłodniczych, które będzie służyło do badań tribologicznych w atmosferze czynników chłodniczych w warunkach obciążeń normalnych.

Celem przeprowadzonych badań ma być opracowanie metod modelowania zjawisk zużyciowych w złożonych warunków eksploatacji w sektorze produkcji i przechowalnictwa chłodniczego żywności.

***Autor*:**

dr inż. **Przemysław Tyczewski –** Politechnika Poznańska, Instytut Maszyn Roboczych i Pojazdów Samochodowych