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BERNARD NOWAK*, RAFAŁ ŁUCZAK*

THERMAL POWER OF THE TS-300B REFRIGERATOR IN THE ASPECTS OF STATISTICAL RESEARCH

MOC CIEPLNA CHŁODZIARKI TS-300B W ASPEKCIE BADAŃ STATYSTYCZNYCH

The article discusses the improvement of thermal working conditions in underground mine workings, using local refrigeration systems. It considers the efficiency of air cooling with direct action air compression refrigerator of the TS-300B type. As a result of a failure to meet the required operating conditions of the aforementioned air cooling system, frequently there are discrepancies between the predicted (and thus the expected) effects of its work and the reality. Therefore, to improve the operating efficiency of this system, in terms of effective use of the evaporator cooling capacity, quality criteria were developed, which are easy in practical application. They were obtained in the form of statistical models, describing the effect of independent variables, i.e. the parameters of the inlet air to the evaporator (temperature, humidity and volumetric flow rate), as well as the parameters of the water cooling the condenser (temperature and volumetric flow rate), on the thermal power of air cooler, treated as the dependent variable. Statistical equations describing the performance of the analyzed air cooling system were determined, based on the linear and nonlinear multiple regression. The obtained functions were modified by changing the values of the coefficients in the case of linear regression, and of the coefficients and exponents in the case of non-linear regression, with the independent variables. As a result, functions were obtained, which were more convenient in practical applications. Using classical statistics methods, the quality of fitting the regression function to the experimental data was evaluated. Also, the values of the evaporator thermal power of the refrigerator, which were obtained on the basis of the measured air parameters, were compared with the calculated ones, by using the obtained regression functions. These statistical models were built on the basis of the results of measurements in different operating conditions of the TS-300B refrigerator, both on the test stand in the manufacturer's laboratory and in the workings of underground mines. The evaluation of the measurement data distributions, as well as an analysis of the basic descriptive statistics of the mentioned variables were carried out, determining their measures of central tendency, location, dispersion and asymmetry.

Keywords: local cooling systems, direct action refrigerator, air conditioning in mines, evaporator thermal power, multiple regression

* AGH UNIVERSITY OF SCIENCE AND TECHNOLOGY, FACULTY OF MINING AND GEOENGINEERING, DEPARTMENT OF UNDERGROUND MINING, AL. A. MICKIEWICZA 30, 30-059 KRAKOW, POLAND

Artykuł dotyczy poprawy cieplnych warunków pracy w wyrobiskach górniczych kopalń podziemnych stosujących lokalne systemy chłodnicze. Rozważa się w nim skuteczność schładzania powietrza chłodziarką sprężarkową bezpośredniego działania typu TS-300B. Bardzo często, w wyniku niedotrzymania wymaganych warunków pracy wymienionego systemu chłodzenia powietrza, występują rozbieżności między prognozowanymi, a więc oczekiwanymi efektami jego pracy a rzeczywistością. Dlatego, dla poprawy skuteczności pracy tego systemu, opracowano, pod kątem efektywnego wykorzystania mocy chłodniczej parownika takiej chłodziarki, łatwe w zastosowaniu praktycznym kryteria jakości. Otrzymano je w postaci modeli statystycznych określających wpływ zmiennych niezależnych, tj. parametrów powietrza wlotowego do parownika (temperatury, wilgotności i wydatku objętościowego) oraz parametrów wody chłodzącej skraplacz (temperatury i wydatku objętościowego) na moc cieplną chłodnicy powietrza traktowaną jako zmienna zależna. Równania statystyczne opisujące pracę rozważanego systemu chłodzenia powietrza wyznaczono na podstawie wielorakiej regresji liniowej i nieliniowej. Utworzone funkcje zmodyfikowano poprzez zmianę wartości współczynników w przypadku regresji liniowej oraz współczynników i wykładników w przypadku regresji nieliniowej, przy zmiennych niezależnych. Otrzymano w ten sposób funkcje dogodniejsze w praktycznych wykorzystaniach. Korzystając z metod statystyki klasycznej oceniono jakość dopasowania funkcji regresji do danych eksperymentalnych. Porównano także wartości mocy cieplnych parownika chłodziarki otrzymane na podstawie pomierzonych parametrów powietrza z obliczonymi przy wykorzystaniu utworzonych funkcji regresji. Powyższe modele statystyczne utworzono na podstawie wyników pomiarów w różnych warunków pracy chłodziarki TS-300B, zarówno na stanowisku badawczym w laboratorium jej producenta jak i w wyrobiskach górniczych kopalń podziemnych. Dokonano oceny rozkładów danych pomiarowych oraz przeprowadzono analizę podstawowych statystyk opisowych wymienionych zmiennych określając ich miary przeciętne, pozycyjne, rozrzutu i asymetrii.

Słowa kluczowe: lokalne systemy chłodnicze, chłodziarka bezpośredniego działania, klimatyzacja kopalń, moc cieplna parownika, regresja wieloraka

1. Introduction

Exploitation of natural resources conducted at the increasingly lower mining levels, and the associated increase in natural hazards, have a significant impact on the deterioration of thermal working conditions of a mining crew. They are improved primarily through intensive ventilation of mine workings. In many cases, the ventilation methods are insufficient. Therefore, the improvement of climatic conditions at miners' workplaces is achieved by additional use of active cooling of the air flowing through the workings. For this purpose, local cooling systems with direct or indirect action air coolers, multiple air conditioning or central air conditioning are used. For the air treatment at workplaces, the Polish underground mining most commonly makes use of local direct refrigeration equipment, having the thermal capacity of 290 kW, 300 kW or 350 kW. These include compression refrigerators, i.e. air cooling systems comprising an evaporator, compressor, condenser and expansion valve. The practical effects of air cooling with such systems often deviate from the expected ones (Nowak & Filek, 2007; Nowak et al., 2010c; Nowak & Kuczera, 2012). This is due to failure to meet the required working conditions, where a detailed diagnosis and a quick response to such a situation in a mine is difficult. Therefore, what emerges is a need to develop this issue in the form of a criterion of the performance quality of the discussed system, easy-to-use by ventilation services of mines, thus allowing for a more efficient use of the available thermal power of the refrigeration equipment. The evaluation of the effectiveness of air cooling with direct action refrigerators, cooperating with evaporative water coolers, was carried out, among others, in the works of (Nowak et al., 2010a,b,c, 2012). Thermal powers of the coolers in these refrigerators were given as a function of air parameters at the inlets to their evaporators and on the inlets of evaporative water coolers. The air cooler is meant to be the evaporator of a direct action compression refrigerator, in which there is a removal of heat from the cooled air. In this article and in the work by (Łuczak, 2012), thermal power of a cooler was made dependent on the inlet parameters of both the air in the evaporator and the water cooling a condenser. In this way, cooling capacity of a compression system was described by the functional dependence of the input parameters to an air cooler and to the machine assembly of a direct action refrigerator. This description relates to the TS-300B refrigerator. Its performance efficiency assessment, in terms of using the capacity of an evaporator, was based on the criteria established in the form of statistical models. They include linear and nonlinear statistical equations. In these equations, the dependent variable (explained) is the thermal power of an evaporator (N_p). In contrast, the independent variables (explanatory) are: air temperature (t_{s2}), its relative humidity (φ_2) and volumetric flow rate (Q_p) at the evaporator inlet, and the temperature (t_{w1}) as well as the volumetric flow (Q_w) of the water cooling the condenser. These air and water parameters are mostly well known or easily measurable by the ventilation and power-mechanical services in a mine. Therefore, efficiency assessment criteria for the TS-300B refrigerator, given in this article, can be useful in forecasting, planning and analysis of the actual status of the discussed air cooling system.

In the statistically developed criteria, extensive research material was taken into account. It comprises the results of earlier measurements of the evaporator of the TS-300B refrigerator, and the above-mentioned basic parameters of the air and the water cooling a condenser, made available by the company Termospec, and partly presented in (Nowak et al., 2010, 2010a), as well as the results of an experimental research in the mines and on the test stand in the laboratory of the manufacturer of these refrigerators (Łuczak, 2012), carried out for different operating conditions of the discussed refrigerator. The statistical analysis also takes into account the nominal operating parameters of the refrigerator.

Earlier measurements of the discussed refrigerator performance efficiency were carried out for three different (510 m^3/min, 575 m^3/min, 660 m^3/min) volumetric flow rates of the air at its evaporator inlet, also changing the temperature of this air from 29°C to 32.8°C and its relative humidity from 75.9% to 92.7%. This yielded 18 different variants of operation of the TS-300B refrigerator. The above-mentioned change in the air parameters corresponded to a change in the power of the evaporator and condenser, respectively from 249.0 kW to 346.0 kW, and from 315.0 kW to 415.8 kW.

On the test stand, the experimental research on the performance efficiency of the TS-300B refrigerator was carried out in conditions similar to the conditions in mine workings, for 101 different variants. The air temperature at the evaporator inlet was changed from 25.6°C to 33.4°C, its relative humidity from 49.2% to 95.7%, and its flow rate from 425 m^3/min to 654.1 m^3/min. Calculated for the analyzed number of variants, the minimum and maximum values of the power of the evaporator and condenser were respectively: 222.5 kW and 326.7 kW and 263.9 kW and 402.4 kW.

The performance of the TS-300B refrigerator was assessed *in situ* for 44 different variants in five workings of the mines: "Sośnica-Makoszowy" Ruch "Makoszowy", "Marcel" Coal Mine and in "Pniówek" Coal Mine. The calculated thermal power of the evaporator changed here in the range of 210.3 kW÷276.3 kW. The lower and upper limits of this range corresponded to the thermal power of the condenser, of respectively 258.6 kW and 345.5 kW.

To sum up, it can be concluded that the air cooling efficiency of the analyzed refrigerator was tested for 164 different variants of its operation. The measurement results of the basic parameters of the air and water, respectively at the inlet of the evaporator and the condenser, as well as the calculated thermal powers of the air cooler for all 164 variants (model 1), have been shown in Figure 1. Taking into consideration cooling capacity of the evaporator and the compressor of the TS-300B refrigerator, it can be concluded that in the considered 164 variants assessing its air cooling efficiency, the condenser ensured sufficient heat removal from the air cooler.

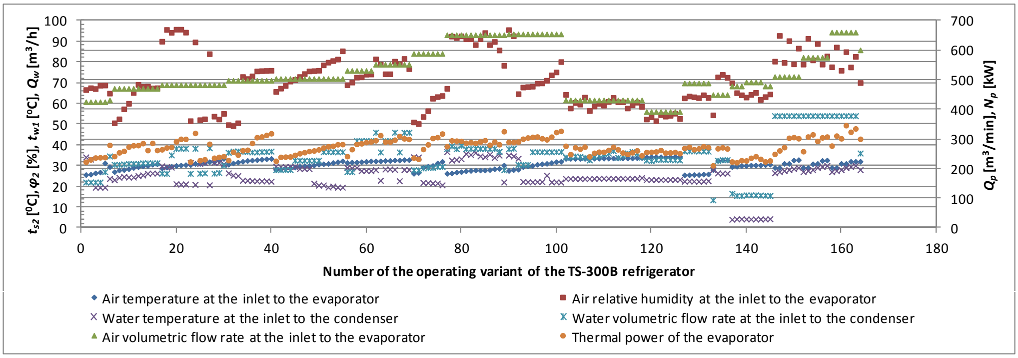

Fig. 1. Capacity of the evaporator and parameters of the air and water used in the statistical analysis

2. Analysis of basic statistical parameters

As shown in Figure 1, in the research material on the efficiency of cooling the air with the TS-300B refrigerator, an analysis of the basic descriptive statistics of the dependent variable and the explanatory variables was carried out, determining their measures of central tendency, location, dispersion and asymmetry. The analyzed parameters included: arithmetic mean, geometric mean, median, mode, minimum and maximum values, standard deviation, coefficient of variation, kurtosis and skewness (Aczel, 2000; Stanisz, 2006, 2007). They have been summarized in Table 1. It shows that the arithmetic mean of particular independent variables and the dependent variable is slightly different from the geometric mean. Also, for these variables, the difference between the arithmetic mean and the median is very small. It only does not apply to the volumetric flow rate of the air, where the difference is 21.97 m^3/min, which represents about 4% of the arithmetic mean. The variation coefficient which is the ratio of the standard deviation and the arithmetic mean defines the percentage variation of the value of the analyzed variable. The highest values (about 26%) it takes for the variables at the inlet to the condenser, i.e. for the temperature (t_{w1}) and the volumetric flow rate of water (Q_w).

When assessing the measures of concentration and dispersion, or during the inference regarding the normality of distribution of the studied independent variables and the dependent variable, kurtosis and skewness are noteworthy. The analysis of the measures of skewness (asymmetry of the distribution) and kurtosis (flattening of the distribution) allows to assess the value concentration of the test characteristics around the mean, and conclude that the test variables are either normally distributed, or close to normal (Aczel, 2000; Domański & Pruska, 2000; Stanisz, 2006; Theil, 1979). The values of skewness of all the studied variables are close to zero. The only exception is an independent random variable, which is the temperature of the water (t_{w1}) cooling the condenser. The calculated skewness index is –1.379, indicating a left-sided asymmetry in the

TABLE 1

Descriptive statistics of the explanatory variables and the dependent variable in a 164-element research sample, evaluating the efficiency of cooling the air with the TS-300B refrigerator

Descriptive statistics						
Parameter	**Air temperature, t_{s2}**	**Air humidity, φ_2**	**Volumetric flow rate of the air, Q_p**	**Water temperature, t_{w1}**	**Volumetric flow rate of the water, Q_w**	**Thermal power of the evaporator, N_p**
Arithmetic mean	30.59	70.88	519.37	24.99	35.20	272.61
Geometric mean	30.50	69.79	513.52	23.40	33.92	271.15
Median	30.80	69.75	497.40	24.42	35.91	272.10
Mode	Multiple	Multiple	431.1	28	54	290.5
Mode Cardinality	9	3	18	8	18	3
Minimum	25.5	49.2	391.9	4.05	13.4	210.3
Maximum	34.4	95.7	660.0	36.7	54.0	346.0
Standard deviation	2.34	12.50	79.62	6.57	9.15	28.13
Coefficient of variation	7.66	17.64	15.33	26.27	26.00	10.32
Skewness	–0.41	0.24	0.52	–1.38	0.24	0.04
Kurtosis	–0.66	–0.82	–0.79	3.35	0.61	–0.70

distribution of this variable. Analyzing the measures of distribution flattening, it can be seen that the distribution of the air parameters at the inlet to the evaporator (t_{s2}, φ_2, Q_p), the distribution of volumetric flow rate of the water at the inlet of the condenser (Q_w) and the distribution of the dependent variable (evaporator cooling capacity N_p) are similar to a normal distribution. Kurtosis coefficient of the independent variable, which is the water temperature at the condenser inlet (t_{w1}), takes the value of 3.35. Thus, the distribution of this variable is steeper, compared with the normal distribution. Modal value, which is a dominant, it is the value that occurs most frequently, with the greatest probability. The distributions of air temperature and humidity exhibit multiple mode characteristics. Multimodality is common, in fact, many physical phenomena have multi-modal distribution (Theil, 1979). Such regularity occurs frequently in measurement procedures, in which the decisive role is played by the human factor and the recurrence of a given phenomenon. The largest cardinality of the mode relates to volumetric flow rate of the air and water, providing for the repeatability of measurements for specific values.

Nature of the distributions of the measurement data were visually examined on the basis of the prepared histograms and using for this purpose, at a significance level of 0.05, the statistical Kolmogorov-Smirnov test modified by Lilliefors, and Shapiro-Wilk test. Figures 2÷7 present histograms of the dependent variable and the independent variables. In the descriptions to these drawings, the results of the conducted tests of normality of distributions were also given, and the symbols used are as follows: K-S – Kolmogorov-Smirnov test, d – the value of the K-S test statistics, S-W – Shapiro-Wilk test, W – the value of the S-W test statistics, p – the probability of making errors of the Ist type.

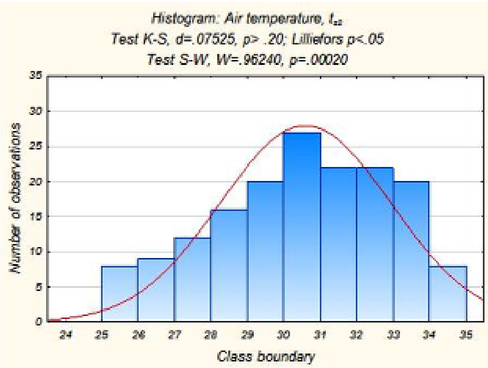

Fig. 2. Distribution of the air temperature at the inlet to the evaporator

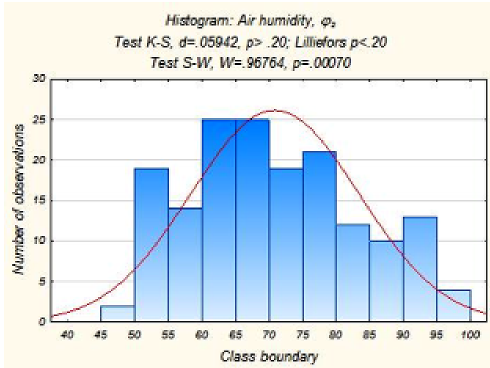

Fig. 3. Distribution of the air relative humidity at the inlet to the evaporator

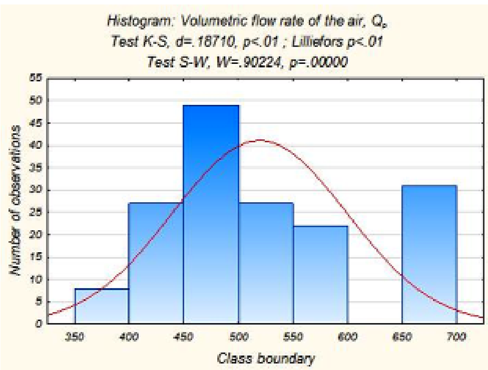

Fig. 4. Distribution of the volumetric flow rate of the air at the inlet to the evaporator

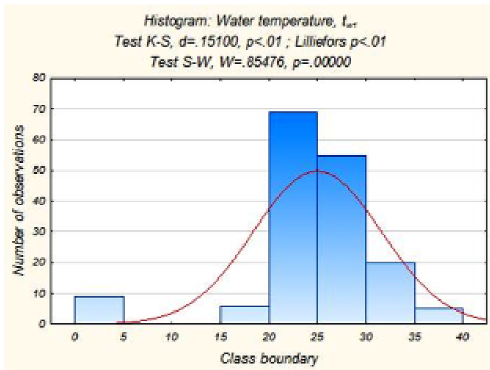

Fig. 5. Distribution of the water temperature at the inlet to the condenser

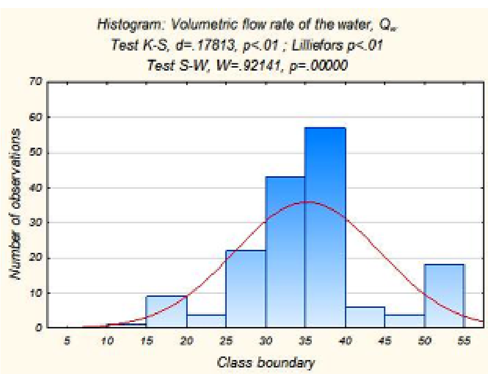

Fig. 6. Distribution of the volumetric flow rate of the water at the inlet to the condenser

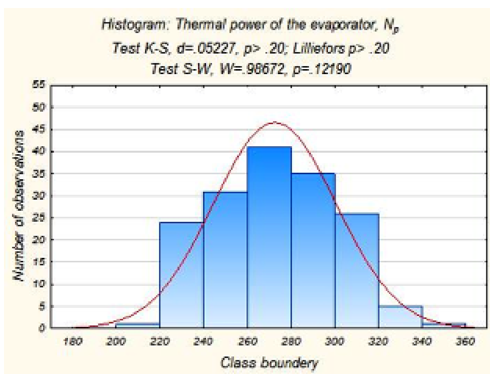

Fig. 7. Distribution of the thermal power of the evaporator

Analyzing the distributions presented in Figures 2÷7, it can be seen that the Shapiro-Wilk test confirms the normal distribution only for the thermal power of the evaporator. For all other variables, the H_o hypothesis of normality of distribution should be rejected. The results of the Kolmogorov-Smirnov test for the variables t_{s2}, φ_2 and N_p do not allow to reject the H_o hypothesis, stating a strong tendency of these variables to the normal distribution. In the case of independent variables Q_p, t_{w1} and Q_w, none of the applied tests allows to accept the null hypothesis of normality of their distributions. While assessing both the values of the obtained tests and the shapes of the histograms for these variables, we can conclude a similarity of distributions of these variables to a normal distribution in a certain range of values. For the variable Q_p, the values in the range of 450-500 m^3/min dominate. The flow of the air through a cooler with such a volumetric flow rate was ensured by one mine ventilation fan. It is also confirmed by the studies carried out in mines. Air volumetric flow values over 650 m^3/min distort a curve fitting to a normal distribution. For the temperature distribution of the water cooling a condenser, the values in the range of 20-30°C dominate, while the temperature of water measured for a refrigerator operating in the "Pniówek" coal mine, stand out in the histogram of the basic values. A histogram drawn up for the volumetric flow rate of the water cooling a condenser represents the dominant values Q_w, corresponding to the nominal flow capacity of water in the condenser circuit.

In the PhD dissertation (Łuczak, 2012), for the considered 164 performance variants of the TS-300B refrigerator, equation of linear regression of the cooler thermal power was determined as a function of parameters of the air at the evaporator inlet and parameters of the water at the condenser inlet. This equation was subjected to the evaluating of fit. 8 outlier variants were identified. These were variants numbered 24, 40, 76, 89, 146, 147, 152 and 158 (Fig. 1). These variants were eliminated from the considered measurement series, thus yielding a basic, 156-element sample. For this sample, a repeated statistical analysis was performed, and its results have been shown in Table 2. In the basic sample, just as in the 164-element sample, very small differences between the arithmetic mean and the geometric mean, and between the arithmetic mean and the median, could be seen for all the variables. The absence of, or insignificance of, the differences between the arithmetic mean and the median of a given population proves that the distribution of the random variable is symmetric, or close to symmetric.

TABLE 2

Descriptive statistics of the explanatory variables and the dependent variable in the 156-element research sample, evaluating the effectiveness of cooling the air with the TS-300B refrigerator

Descriptive statistics – basic sample						
Parameter	**Air temperature, t_{s2}**	**Air humidity, φ_2**	**Volumetric flow rate of the air, Q_p**	**Water temperature, t_{w1}**	**Volumetric flow rate of the water, Q_w**	**Thermal power of the evaporator, N_p**
1	**2**	**3**	**4**	**5**	**6**	**7**
Arithmetic mean	30.61	70.43	517.33	25.03	34.77	271.67
Geometric mean	30.51	69.34	511.45	23.37	33.55	270.26
Median	30.90	68.85	497.40	24.41	35.36	271.80
Mode	Multiple	91.10	431.10	28.00	54.00	290.50

1	2	3	4	5	6	7
Mode Cardinality	8	3	18	8	14	3
Minimum	25.5	49.2	391.9	4.1	13.4	210.3
Maximum	34.4	95.7	660.0	36.7	54.0	346.0
Standard deviation	2.37	12.52	79.75	6.70	8.84	27.68
Coefficient of variation	7.76	17.77	15.42	26.77	25.42	10.19
Skewness	–0.43	0.30	0.55	–1.38	0.19	0.02
Kurtosis	–0.68	–0.77	–0.76	3.20	0.85	–0.66

In the process of inference regarding the shape of the measurement data distributions, coefficients of kurtosis and skewness are significant. They allow to evaluate the asymmetry and the slenderness of the Gaussian. On the basis of the measures of skewness and kurtosis (Table 2) it can be concluded that the distributions of the independent variables and the dependent variable are normal or close to normal (|skewness|≤1) (Stanisz, 2006), the coefficient of kurtosis, only for the temperature of the water at the inlet of the condenser, is quite high at 3.2. Indices of skewness of all variables, except the water temperature, do not exceed 0.6. For t_{w1}, this ratio is equal to -1.38, indicating a left-sided asymmetry in the distribution of this variable. Analysis of the measures of the distribution flattening of all the studied random variables showed that the distributions of the variables t_{s2}, Q_p, t_{w1}, Q_w and N_p in this respect are similar to a normal distribution. The distribution of the variable t_{w1} is steeper, compared with the normal distribution. Multiple modality only refers to the temperature of the air at the evaporator inlet. Other variables are unimodal. The value of the parameter, most commonly occurring in the data set, is determined by the modal number. Multiple cardinality of the modal value expresses several variants, which in a given population are repeated most often. In the basic sample, cardinality of the mode for volumetric flow rate of the air and for the temperature of the water in the condenser circuit have not changed. However, for the volumetric flow rate of water, they have decreased to 14, and for the air temperature at the inlet to the evaporator – to 8 variants.

In this article, due to a lack of relevant, from a statistical point of view, differences between the histograms of the 164-element sample and the basic sample (156 elements), the histograms of the latter have not been included.

3. Analysis of linear and nonlinear multiple regression

As it has already been mentioned in Chapter 1 of this article, in order to evaluate the performance efficiency of the analyzed air refrigerator, for the basic research sample, linear and nonlinear statistical equations were determined. With multiple regression analysis, using Statistica 9.0 and Gretl in the 1.9.9 version softwares, a mutual relationship of the input parameters of the air in the evaporator (t_{s2}, φ_2, Q_p) and of the water in the condenser (t_{w1}, Q_w) were determined at a confidence level of $1 - \alpha = 0.95$, as well as their impact on the power of the evaporator (N_p).

A general form of a linear regression function of the evaporator power N for the considered five explanatory variables is represented by the following equation (1):

$$N = \alpha_1 \cdot t_{s2} + \alpha_2 \cdot \varphi_2 + \alpha_3 \cdot Q_p + \alpha_4 \cdot t_{w1} + \alpha_5 \cdot Q_w + \alpha_0 \tag{1}$$

The parameters $\alpha_0 \div \alpha_5$, called regression coefficients, determine the average change in the value of the dependent variable per unit of the increase in the value of the independent variable.

The best results of a built model using multiple linear regression are obtained on the assumption that the relationship between the dependent and independent variables is linear, and that the residues (the difference between the observed value and the value calculated from the regression equation) are normally distributed. Improving the regression function fitting can be achieved through increasing the number of independent variables in the equation. Elimination of outliers from the model changes the value of the regression coefficients, thereby improving functional representation. In the regression analysis, homoscedasticity is expected from explanatory variables, i.e. the same finite variance. Heteroscedasticity of these variables (unstable residual component variance for subsequent observations) is an undesirable feature. Another feature which is essential for the best fitting of regression function coefficient values is the lack of mutual collinearity of explanatory variables (Koronacki & Mielniczuk, 2001; Seber & Lee, 2003; Stanisz, 2007; Theil, 1979).

Having met the above requirements, when building a linear regression model, which determines the impact of the explanatory parameter variability (t_{s2}, φ_2, Q_p, t_{w1}, Q_w) on the value of the explained variable (N_p), a well-fitting function should be expected.

The power of an evaporator, resulting from the applied statistical methods of multiple regression, for a basic research sample, is represented by the relation (2). It was designated as N_L, to be differentiated from the value of the power of an evaporator of a given refrigerator N_p, resulting from the measurements.

$$N_L = 2.0355 \cdot t_{s2} + 0.4788 \cdot \varphi_2 + 0.1468 \cdot Q_p - 0.6095 \cdot t_{w1} + 1.6012 \cdot Q_w + 59.2943 \tag{2}$$

Building a multiple regression model is conducted *post factum,* since a thorough analysis of the assumptions described above shall be carried out after the assumed model has been built. In the obtained model there is no problem of collinearity of the explanatory variables. This is evidenced not only by the presented in Table 3 values of the partial correlation coefficients (lack of a very strong correlation), but also the values of the coefficients (at most, equal to 2.11) of the conducted VIF tests (*Variance Inflation Factors*). The values of partial correlation coefficients between the explanatory variables and the power of an evaporator have been marked in bold.

TABLE 3

The values of partial correlation coefficients

The values of partial correlation coefficients *r*						
Parameter	**Air temperature, t_{s2}**	**Air humidity, φ_2**	**Volumetric flow rate of the air Q_p**	**Water temperature, t_{w1}**	**Volumetric flow rate of the water, Q_w**	**Thermal power of the evaporator, N_p**
1	**2**	**3**	**4**	**5**	**6**	**7**
Air temperature. t_{s2}	1.000	–0.202	–0.359	–0.184	0.203	**0.110**
Air humidity. φ_2	–0.202	1.000	0.538	0.272	0.490	**0.619**
Volumetric flow rate of the air Q_p	–0.359	0.538	1.000	0.363	0.396	**0.626**

1	2	3	4	5	6	7
Water temperature. t_{w1}	–0.184	0.272	0.363	1.000	0.476	**0.276**
Volumetric flow rate of the water. Q_w	0.203	0.490	0.396	0.476	1.000	**0.750**
Thermal power of the evaporator. N_p	0.110	0.619	0.626	0.276	0.750	1.000

Based on the tests of White and Breusch-Pagan, no heteroskedasticity of the explanatory variables was identified. A similarity in distribution of the residual component to the theoretical distribution was verified using the χ^2 test.

Given the best functional representation, in the equation (2) the values of the coefficients $\alpha_0 \div \alpha_5$ were modified to give, in the form which is more convenient for practical use, the equation given below (3).

$$N_{LZ} = 2 \cdot t_{s2} + 0.5 \cdot \varphi_2 + 0.15 \cdot Q_p - 0.6 \cdot t_{w1} + 1.6 \cdot Q_w + 57 \tag{3}$$

Figure 8 shows a relationship between the measured and the calculated values of the thermal power of the analyzed refrigerator, and the power determined by the correlation linear equation, before and after the modification of its coefficients.

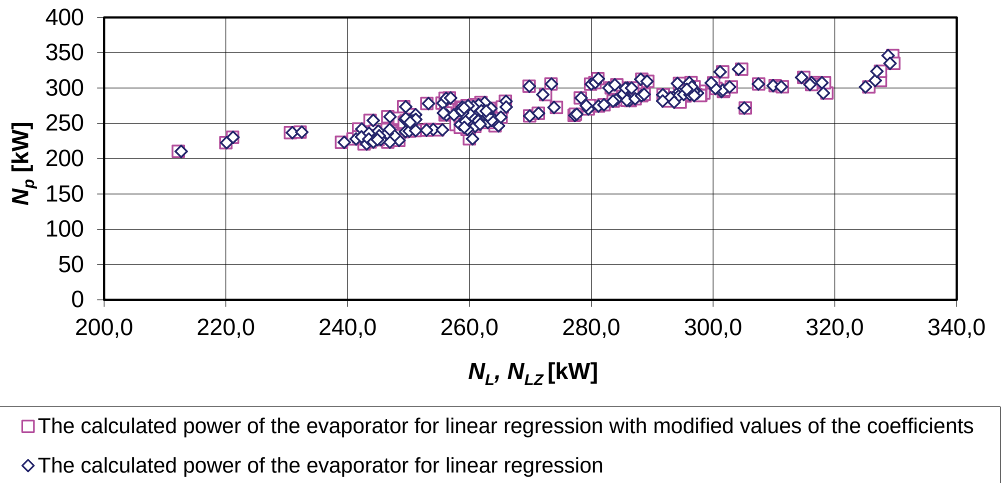

Fig. 8. Interdependence of the evaporator thermal powers, resulting from the measurements and the predicted ones, for the linear regression before and after the modification of its coefficients

Analyzing the obtained results it can be noticed that the largest difference of the evaporator power resulting from the measurements and calculations, given either by the equation (2) or by the equation (3) applies to the 142 measurement variant. It is –33.3 kW and –33.4 kW, respectively, which is –12.3% of the evaporator power obtained from the measurements. The outliers of the measurement variants also include variants 28 and 72. These are, however, individual cases which do not affect significantly the functional representation of the refrigerator power. This is evidenced by the values of the correlation coefficients of both analyzed statistical models, which are not changing. Each of them is equal to 0.87. The coefficients of determination in both cases take the value of 0.76. Standard estimation errors in the linear model, both with and without modification of the coefficients of the explanatory variables, are 13.8 kW. Mean relative estimation errors equal to 5.1% correspond to these values. In Figure 8, small differences can be seen in the calculations of the evaporator thermal powers, determined from statistical relationships before and after the modification of the function coefficients.

A general form of the curvilinear regression function of the evaporator power (N_K) was given by the equation (4). It results from earlier works (Nowak et al. 2010a; Nowak, Ptaszyński, Łuczak, 2012), evaluating the efficiency of using thermal power of evaporators in mining direct action refrigerators.

$$N_K = A \cdot t_{s2}^{\alpha} + B \cdot \varphi_2^{\beta} + C \cdot Q_p^{\chi} + D \cdot t_{w1}^{\gamma} + E \cdot Q_w^{\eta} \tag{4}$$

where:

A, B, C, D, E — non-linear regression function coefficients,
$\alpha, \beta, \chi, \gamma, \eta$ — exponents of non-linear regression function

The procedure of estimating the cooling capacity of the evaporator was performed by Hooke-Jeeves pattern moves. It was dictated by a high fit of the regression function and the speed of the iterations run by this module. Thanks to the obtained results, the estimated nonlinear regression equation can be written in the form given below:

$$\begin{aligned} N_K = 0.0497 \cdot t_{s2}^{1.7971} + 0.4232 \cdot \varphi_2^{1.0361} + \\ + 1.2825 \cdot Q_p^{0.7188} - 0.0041 \cdot t_{w1}^{2.5094} + 20.5757 \cdot Q_w^{0.4854} \end{aligned} \tag{5}$$

As in the case of linear regression, and for the same reasons, in the equation (5), not only were the coefficients of the independent variables modified, but also the values of their exponents. This form of the modified equation (5), which is more convenient to use in practice, is given by the equation (6). N_{KZ} is the evaporator thermal power determined from the equation that is based on the nonlinear estimation of Hooke-Jeeves pattern moves, after the modification of the function coefficients and exponents.

$$N_{KZ} = 0.05 \cdot t_{s2}^{1.8} + 0.4 \cdot \varphi_2 + 1.3 \cdot Q_p^{0.72} - 0.01 \cdot t_{w1}^{2.2} + 20.1 \cdot Q_w^{0.5} \tag{6}$$

Using (5) and (6), for each of the 156 performance variants of the air refrigerator, the calculations of the evaporator thermal power (N_K, N_{KZ}) were performed and compared with the power of this evaporator *in situ*. The results of these calculations have been presented in a graphical form in Figure 9. Very little differences can be noticed in the evaporator capacity, calculated with the non-linear regression equation, before and after the modification of its coefficients and exponents.

Analyzing the statistics assessing the fitting quality of the obtained nonlinear correlation equations of the evaporator power of the TS-300B refrigerator, we can conclude that the curvilinear model is better fitting to the experimental research results than the model obtained by linear estimation. The multiple correlation coefficients R and the determination coefficients R^2 in the nonlinear statistical equation, before and after its modification, take the values of: $R = 0.90$ and $R = 0.89$, $R^2 = 0.81$ and $R^2 = 0.80$, respectively. These values prove a very strong influence

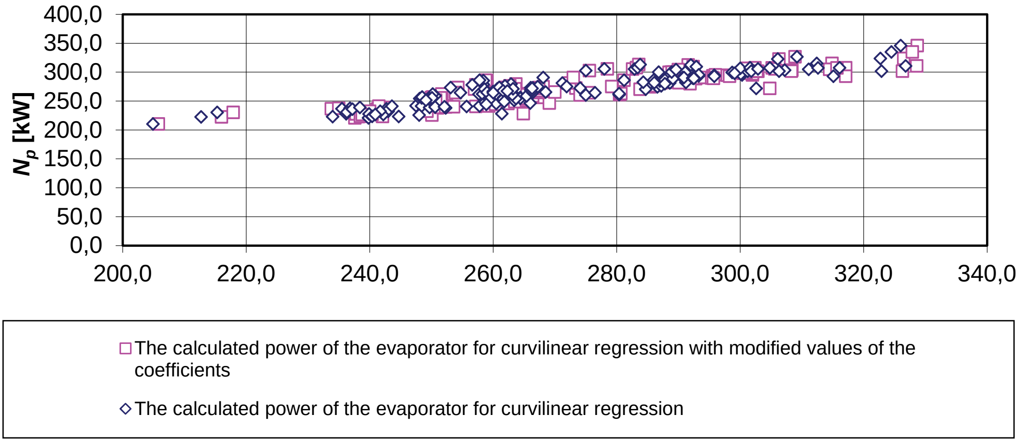

Fig. 9. Interdependence of the evaporator thermal powers resulting from the measurements and the predicted ones, for nonlinear regression before and after the modification of its coefficients and exponents

of the explanatory variables on the dependent variable. On the basis of the calculated values of the coefficients of convergence in both nonlinear models, it can be written that 19% variation of the average power of the air cooler is not explained by the correlation equation (5). In the case of the equation (6), 20% of power variability remains unexplained. The significance of fit of the above nonlinear regression equations to the measurement results are confirmed by the results of the F-Snedecor test for the assumed significance level of 0.05. Standard errors of estimation of the curvilinear model, before and after its modification, are 12.2 kW and 12.6 kW, respectively. They correspond to the relative errors of estimation equal to 4.5% and 4.6%. Normality of the distribution of the residues in both non-linear models are confirmed by the results of the χ^2 test, used for this purpose.

In the calculations, by the formulas (5) and (6), of the evaporator thermal power of the discussed refrigerator, carried out for the individual variants of its operation, it is possible to identify the variants in which this power is significantly different from the power determined on the basis of the measurements. This mainly refers to the variant 30, where the maximum absolute deviation of the evaporator power, calculated by the formula (5) is –33.3 kW, which is –14.6% of its power resulting from the measurements. In the calculations by the modified model, the maximum deviations are: –36.8 kW and –16.1%, respectively.

4. Calculation example

Correlation equations with the modified values of the coefficients (3), and with the modified values of the coefficients and exponents of the explanatory variables (6), through a strong correlation and good representation of the evaporator power, as compared with its power determined on the basis of the *in situ* measurements, allow to assess the efficiency of air cooling with the TS-300B refrigerator. The provided calculation example refers to the performance of the analyzed refrigerator. It compared the capacity of its evaporator, calculated by the formulas

(3) and (6), changing the parameters of the air at its inlet and the parameters of the water at the inlet of its condenser. The results of the calculations have been presented in Table 4. The values of the independent variables, highlighted in gray, are nominal values provided by the refrigerator manufacturer.

TABLE 4

The results of modeling the evaporator thermal power of the TS-300B refrigerator

Lp.	t_{s2}, [°C]	φ_2, [%]	Q_p, [m^3/min]	t_{w1}, [°C]	Q_w, [m^3/h]	N_{LZ}, [kW]	N_{KZ}, [kW]
1.	28	60	450	24	20	228.1	228.9
2.	28	60	450	24	36	253.7	259.6
3.	28	60	600	24	36	276.2	283.9
4.	28	70	600	24	36	281.2	287.9
5.	32	70	600	24	36	289.2	293.4
6.	32	70	600	28	36	286.8	289.0

For the explanatory variables, smaller than the nominal values (listed in the first row of Table 4), the cooling capacity, calculated by the modified linear equation and the modified non-linear equation, are 228.1 kW and almost 229 kW, respectively. An increase by 16 m³/h of the volumetric flow rate only of the water cooling the condenser, results in an increase in the cooling capacity of the evaporator by about 26 kW and 31 kW, calculated by the formulas (3) and (6), respectively. The calculated cooling capacity of the refrigerator, which are respectively $N_{LZ} = 276.2$ kW, $N_{KZ} = 283.9$ kW, were achieved by increasing the volumetric flow of the cooled air to the nominal value, i.e. to 600 m³/min. The increase in the relative humidity of the air by 10% results in a further increase in the thermal power of the refrigerator, to the values of 281.2 kW and 287.9 kW, respectively. The highest values of the evaporator cooling capacity ($N_{LZ} = 289.2$ kW, $N_{KZ} = 293.4$ kW) were obtained for the nominal volumetric flow of the cooled air, its relative humidity of 70%, and the nominal temperature (32°C) before it was cooled. In those calculations, volumetric flow rate of the water cooling the condenser and its temperature were 36 m^3/h and 24°C, respectively. A further increase only in the temperature of the water cooling the condenser by 4°C, i.e. to its nominal value (28°C) results in a slight decrease in the calculated evaporator thermal powers of the TS-300B refrigerator to the values of 286.8 kW and 289 kW, respectively, for both statistical models considered in this paper.

5. Summary

The article discusses the performance efficiency of the direct action TS-300B refrigerator in terms of making use of its evaporator cooling capacity. For its evaluation, criteria in the form of linear and nonlinear statistical equations have been developed. They determine the impact of changes in the temperature, relative humidity and volumetric flow rate of the air at the inlet of the evaporator, as well as the temperature and volumetric flow rate of the water cooling the condenser, on the thermal power of the evaporator. These equations were obtained using multiple regression methods of the research results of the analyzed air refrigerator. By modifying the values of the coefficients and the exponents in these equations, new, less complex, and therefore more convenient in practical use, criteria were obtained. Using the proposed criteria, sample calculations regarding the evaporator power were carried out, paying attention to the influence of the parameters of the air at the inlet to the evaporator and of the parameters of the water at the inlet to the condenser of the TS-300B refrigerator, on the capacity of its cooler.

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