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Design of centrifugal radial fans using regression analysis methods

Abstract. With the development of scientific and technological progress in agriculture, the use of operational and mathematical modelling for effective solution of problems and resource conservation in the field of agricultural engineering is relevant. Therefore, the purpose of the study was to determine the optimal parameters of the centrifugal radial fan of a pneumatic precision seed drill by constructing a new mathematical model of the process of its operation. This was achieved by applying mathematical modelling methods when planning multi-factor experiments. As a result, a complex of automated experiments has been defined, which leads to a significant increase in the productivity of scientific work. A statistical representation of the experiment is established, which allows moving to a multi-factor active experiment, in which it is possible to separate the influence of factors from the noise background and make a transition to statistical methods for analysing the results. This allowed predicting the optimal characteristics of the centrifugal radial fan of the precision seed drill. In the course of this study, a new regression equation was compiled in the form of a first-degree polynomial, which determines the influence of each of the factors on the magnitude and value of the response. The coefficients of the polynomial are determined, the significance of the coefficients is estimated, and the adequacy of the proposed model is checked. After obtaining the regression equation, it became possible to graphically construct the dependence of the response function on impact factors. A fractional factor experiment was also performed, which determined the values of the parameters of the object's state Y for all possible combinations of levels of variation of the factors X_i. Based on the established functional relationship between the output parameter of the fan, a regression equation of the following form is obtained: $P_v = P_v\,(n, \beta_1, \beta_2, z)$. This predicted the receipt of the total pressure P_v(Pa), when setting different values of independent quantities n, β_1, β_2 and z. The application of the obtained analytical dependencies significantly simplified the determination of optimal design parameters of pneumatic systems for the development and construction of modern technical seed drills

Keywords: mathematical model; multi-factor process; pressure; frequency of rotational motion; installation angles; number of blades

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INTRODUCTION

Improving agricultural products and optimising the use of resources is an urgent issue. Pneumatic seed drill systems, in particular fans, play an important role in the sowing process, affecting seed distribution and crop cultivation. Optimisation of their operation involves selecting the optimal geometric parameters of various system components, including the impeller, stator, pipes, and other elements. D.C. Montgomery *et al*. (2023) define a model as an artificial system that reflects, with a certain degree of accuracy, the main properties of the object under study – the original. The model is in a certain correspondence with the object under study can replace it during research, and allows getting information about it. The paper notes that when studying an object, two problems are set: extreme and interpolation. When solving an extreme problem, the conditions of the process are determined to ensure that the optimal value of the selected parameter is obtained (the existence of an extremum of a certain function). When studying a multi-factor process, setting up all possible experiments to obtain a mathematical model is associated with a huge complexity of the experiment, since the number of all possible experiments is large.

Methods of mathematical planning of an experiment allow simultaneously considering the influence of several factors on the object under study. They are based on the mathematical theory of the experiment, which determines the conditions for optimal behaviour of the object under study, including incomplete knowledge of the physical essence of the phenomenon. Mathematical methods of experiment planning allow considering and optimising complex systems and processes, ensuring high efficiency of the experiment and accuracy in determining the factors under study. These methods were used by such researchers as J. Frost (2020), who made significant contributions to the interpretation of experimental results and verification of the correctness of initial prerequisites, planning techniques in laboratory and industrial settings, as well as block planning in the methodology for building scientific research.

F. Tanzim *et al*. (2022) present the developed model for predicting the width of the fan used in the sprayer. The researchers developed a complete factor experiment with a broad analysis of factors affecting the dynamic sputtering index. Based on this, a linear regression model was obtained to calculate the fan width, which varies within 2.5 cm to maintain the production tolerance. The model was tested statistically and experimentally so that it could eliminate trial and error to save time and money. However, the technical parameters of the working bodies that perform this technological process are not considered. Effectiveness is evaluated only by the final result, and therefore, research and the suggestion of broad boundaries are rather questionable here.

Y. Wang *et al*. (2022) applied the Fourier random feature method to detect nonlinear relationships between data samples. In addition, when studying the regression coefficient matrix, the low-rank components of this explicit feature space are simultaneously extracted to reduce the redundancy effect. It is also not possible to use this method to study the optimal parameters of technical systems. The possibility of introducing an appropriate surrogate model for modelling objective functions, subject to its solution, was presented by V.T. Nadikto (2019), S. Nitri Asomani *et al*. (2020). In this study, a sampling method was used to obtain the values of the objective function, and an artificial neural network and a generalised regression neural network were used as surrogate models for approximating the objective function in the design space. This study has all the features of modern analytical research, but it will be quite difficult to optimise the parameters of any technical system using a surrogate model.

And only in the paper by X. Ping *et al*. (2021), based on experimental studies, theoretical analysis, and machine experiments, a controlled model for predicting isoentropic efficiency for a multi-stage centrifugal pump is constructed. The S-fold cross-validation algorithm is used to improve model data analysis and control capabilities. In addition, the accuracy of model prediction is improved by smoothing coefficient circulation screening technology. Based on this, the prediction accuracy of the optimised model and the unoptimised model is determined. Thus, the results of the study presented in this paper can be partially applied to the analytical study of centrifugal fans.

Thus, a brief analysis of literature sources indicates the widespread use of methods for constructing mathematical models that work based on random processes and the use of correlation analysis in the study of complex technical systems. The purpose of the study was to obtain by constructing a new mathematical model of a computational experiment to determine the optimal parameters of the studied workflow carried out by a centrifugal radial fan.

To build a new mathematical model of the fan, it was necessary: to determine the design and analyse the operation of the pneumatic system of the seed drill, in particular the fan; to substantiate the choice of the most influential input factors and the most significant output variables of the experiment; to make a choice of the mathematical model by which experimental data will be provided; to substantiate the choice of the optimality criterion; to substantiate the choice of the experiment plan; to conduct an experiment and process the results; to analyse the work performed.

MATERIALS AND METHODS

An experimental factor mathematical model was used to optimise the parameters. The experimental factor mathematical model, unlike the theoretical ones, is not based on physical laws describing the processes that occur in objects, but represents some formal dependences of the initial parameters on the internal and external parameters of design objects (Nadikto, 2019).

When constructing the experimental factor model, the technical system that was designed was presented in the form of a cybernetic system, the so-called "black box" system (Fig. 1), which was fed with some vectors $X=(X_1, X_2, .., X_k)$ and $W=(W_1, W_2, .., W_l)$ of independent values, and variable values were observed and recorded at the output $y_1, y_2, ..., y_m$ of vector components $Y=(Y_1, Y_2, .., Y_m)$ of dependent values, where k, l, m – number of elements, respectively, of vectors X, W and Y.

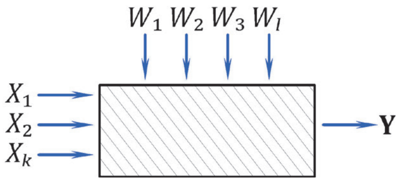

Figure 1. "Black box" system
Source: H. Beloev *et al.* (2021)

During experiments, changes in the values of $x_1, x_2, ..., x_k$ and $W_1, W_2, ..., W_l$ of the quantities X_α, $(\alpha=1, 2, ..., k)$ and W_β, $(\beta=1, 2, ..., l)$ led to a change in the original dependent values $y_1, y^2, ..., y_m$ of components Y_γ, $(\gamma=1, 2, ..., m)$ of vector Y. To build a factor model, these changes were recorded and their necessary statistical processing was performed to determine the model parameters.

During a physical experiment with variables X_α, it was possible to control them by changing their values x_α according to the specified law. Variables W_β, – unmanaged ones that acquired random values W_β. Values x_α and W_β of variables X_α and W_β, can be monitored and registered. Variables X_α, $(\alpha = 1, 2, ..., k)$ are actually controlled manageable factors, and the parameters W_β, $(\beta = 1, 2, ..., l)$ are controlled unmanageable factors. Factors X_α are controlled and changed as deterministic variables, factors W_β, – unmanageable and randomly changed over time. Space of controlled variable factors X_α, $(\alpha = 1, 2, ..., k)$ and uncontrolled W_β, $(\beta=1, 2, ..., l)$ created a factor space as a result of the study (Arkes, 2023).

Output vector Y was a vector of dependent variables of the modelled object, i.e., it is a vector of response functions. Dependency of each component Y_γ, $(\gamma = 1, 2, ..., m)$ vector Y from factors X_α, $(\alpha=1, 2, ..., k)$ and W_β, $(\beta=1, 2, ..., l)$ was a response function. The geometric representation of the response function in this paper forms the response surface. Accordingly, the number of response functions was equal to the number of vector components Y.

In computational experiments, the object of this research was a theoretical mathematical model, based on which it is necessary to obtain an experimental factor model. To determine it, the type of mathematical relations between factors X_α, W_β and a review Y_γ were determined, and numerical parameter values were set. Here, the parameters are coefficients of the equations of the factor model. The problems of determining model parameters were fully formalised and solved by regression analysis methods.

To obtain an adequate mathematical model, certain experimental conditions were met. It was assumed that the model will then be adequate, due to the fact that in a reasonable interval of variation of factors X_α, $(\alpha = 1, 2, ..., k)$ obtained using the value model y_γ, response functions Y_γ, $(\gamma = 1, 2, ..., m)$ differ from the true ones by no more than a given amount. The purpose of planning the experiment was also to obtain maximum information about the properties of the object under study with a minimum of experiments (time and resources spent).

In addition, the following provisions were immediately noted: a complete picture of the properties of the response surface can only be obtained if a dense discrete grid of factor values is used, covering the entire factor space. The choice of the structure of the factor model is based on postulating a certain degree of smoothness of the response surface. Therefore, to reduce the number of experiments, a small number of points of the plan were taken, according to which the implementation of the experiment is carried out.

However, the sets $\{y_1\}, \{y_2\}, ..., \{y_m\}$ of values of response functions Y_γ, $(\gamma = 1, 2, ..., m)$ in experiments conducted at one point of the plan (with fixed values $x_1, x_2, ..., x_k$ factors X_α, $(\alpha = 1, 2, ..., k)$, with a large level of random disturbances, can have large discrepancies. Therefore, the lower the perturbation level, the more accurate the factor model is. In other words, $y_1, y_2, ..., y_m$ is not the same as Y_α, $(\alpha = 1, 2, ..., m)$. Value $w_1, w_2, ..., w_l$ ov unmanaged parameters W_β, $(\beta = 1, 2, ..., l)$ are inherently random. So for fixed values $x_1, x_2, ..., x_k$ due to variation $w_1, w_2, ..., w_l$ in each repetition of the experiment, it is possible to get different values $y_1, y_2, ..., y_m$ of response functions Y_γ, $(\gamma = 1, 2, ..., m)$. That is, a fixed set of parameters $\{x_\alpha\}$, $(\alpha = 1, 2, ..., k)$ will correspond to two sets of sets $\{w_1\}, \{w_2,\} ..., \{w_l\}$ and $\{y_1\}, \{y_2\}, ..., \{y_m\}$, where the number of elements in each set $\{w_\beta\}$ and $\{y_\gamma\}$ is equal to the number of repeatability of the experiment.

Here, separately, it was necessary to focus on the features of computational and full-scale experiments. Unmanaged parameters in a field experiment W_β, $(\beta = 1, 2, ..., l)$ change in accordance with objective processes, and therefore, at the same fixed values of input factors $\{x_\alpha\}$, $(\alpha = 1, 2, ..., k)$ in each new repetition of the experiment, a new unique set of values $\{w_\beta\}$ and $\{y_\gamma\}$ will be obtained. Moreover, there are two possible options in a computational experiment. The first option is implemented if, first, the values of $\{w_\beta\}$ are justified in a certain way and always remain fixed, and, secondly, the algorithm of the computational experiment itself is completely deterministic and does not contain a pseudo-random component. In this case, the repetition of the experiment did not make sense, because the random component was completely excluded. The second option was implemented when at least one condition was met, or an algorithm of a computational experiment containing a pseudo-random component or values $\{w_\beta\}$ are modelled in a pseudo-random way. In this case, the second option was implemented, although the specifics of applying methods of mathematical modelling of random variables were not considered separately.

Further, these provisions of the improved methodology were implemented for their further application in solving a specific problem. First of all, in the general case, it can be argued that there is a functional relationship between independent variables and the output of the process of the following type:

$$(Y\gamma = f(X, W), (\gamma = 1, 2, ..., m). \quad (1)$$

The least squares method was used to solve this problem (to approximate experimental data). This method allows constructing an optimal estimate of the moments of the distribution of the experimental error in a certain sense and solving the question of whether the resulting model is adequate (i.e., one that properly corresponds to reality).

Since the study introduced restrictions in the context of searching for only one response function $Y \in \{Y_\gamma\}$ from the full set of functions $\{Y_\gamma\}$, $(\gamma = 1, 2, ..., m)$ vector components Y, and given that the parameters W_β, $(\beta = 1, 2, ..., l)$ are not manageable and, moreover, it was not planned to fix them, it became possible to further simplify the idea of functional dependence (1) to the following form:

$$Y = f(X). \quad (2)$$

Thus, the number of objective functions was limited to one and a limit was introduced on the number of parameters that were considered and, accordingly, included in the mathematical model that was planned to be obtained.

A mathematical model of the process was constructed from experimental data. The process of determining the explicit type of regression equation is called regression analysis. For different mathematical plans of the experiment, regression equations may contain different components. Namely:

1) for first-order plans, the regression equation includes effects and paired interactions:

$$y = b_0 + \sum_{i=1}^{k} b_i\, x_i + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} b_{ij}\, x_i x_j\,, \quad i, j = 1,2, \dots, k, \quad i < j, \quad (3)$$

2) for second-order plans, the regression equation includes effects, pairwise interactions, and quadratic effects:

$$y = b_0 + \sum_{i=1}^{k} b_i\, x_i + \sum_{i=1}^{k} \sum_{j=i}^{k} b_{ij}\, x_i x_j\,, \quad i, j = 1,2, \dots, k, \quad i \le j, \quad (4)$$

where b_0 – free term of the regression equation; b_i, b_{ij} – coefficients of the regression equation; x_i, – value of factors; k – now and in the future, in accordance with the Pareto principle, this is the number of significant controlled manageable factors considered during the experiment, which is less than the total number of controlled manageable factors, according to the previous definition k.

The resulting expressions (3) and (4) were analysed. Thus, coefficients for independent variables indicate the strength of the influence of factors. The larger the numerical value of the coefficient, the more the factor affects. If the coefficient has a plus sign, then the optimisation parameter increases as the factor value increases, and if it is negative, then, on the contrary, it decreases. The value of the coefficient corresponds to the contribution of this factor to the value of the optimisation parameter when the factor moves from zero to the upper or lower level. Sometimes it is convenient to evaluate the contribution of a factor during the transition from the lower to the upper level. The contribution defined in this way is the effect of a factor and is sometimes referred to as the main or main effect.

RESULTS AND DISCUSSION

Initially, a physical model of the impeller of a centrifugal radial fan was built, which has an outer diameter of 400 mm, the inner diameter of the impeller air inlet – 135 mm, and the width of the impeller itself – 35 mm. The direction of rotational movement with the angular speed of the impeller is shown by an arrow. The blades of the impeller itself have a curved shape, which is regulated by the angles at the inlet and outlet of the blade. These angles were measured between two tangent lines: the first – to the contour of the blade, and the second – to the circle of rotation. Figure 2 shows the angles, respectively, at the input, which is 70° and the output is equal to 140°. The thickness of the blades was 1 mm. In the future, in the process of constructing a regression model of a centrifugal radial fan, the angles of installation of the impeller blades, the number of blades installed on it, and the speed of rotational motion were supposed to change.

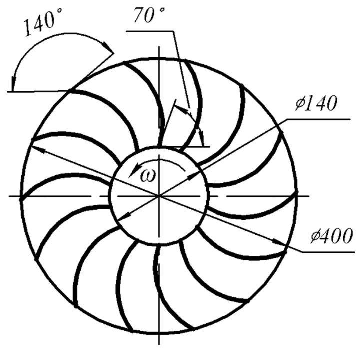

Figure 2. Centrifugal radial fan impeller
Source: compiled by the authors

Next, a mathematical model of the fan impeller was constructed. According to the above method, the following factors were selected as independent variables to investigate the operation process and the dependence of the geometric parameters of a centrifugal radial fan: X_1 – fan impeller rotation frequency, rpm; X_2 – blade installation angle at the impeller inlet, deg.; X_3 – blade installation angle at the impeller outlet, deg; X_4 – number of impeller blades, pcs.

Now, when considering the operation of a centrifugal radial fan, the influence of many factors $\{X_\alpha\}$, $(\alpha = 1, 2, ..., k)$ on the response function Y was first analysed (2). The Box-Wilson method was chosen to solve this optimisation problem. Among the plans of an extreme experiment, the simplest is the plan of a complete factor experiment, the implementation of which determines the value of the response function Y for all possible combinations of levels of variation of factors X_i, $(i = 1, 2, ..., k)$. First, the number of experiments that needed to be conducted in order to carry out a pilaf factor experiment was determined. It is equal to:

$$N = 2^k = 2^4 = 16, \quad (5)$$

where k – the number of experimental factors that are considered in the developed model, 2 – the number of levels.

Two values were set for each factor: maximum and minimum. In this value field, each factor can change continuously or discretely. The boundaries of factor values form a region in a multidimensional space – a hypercube, i.e., the value x_i of factors X_i lie inside this area. For the convenience of processing the results of the study, coding of independent input factors was introduced X_i:

$$x_i = \frac{X_i - X_i^{(0)}}{\Delta X_i}, \; i = 1, 2, \dots, k, \quad (6)$$

where $X_i^{(0)}$ – basic level.

$$X_i^{(0)} = 0.5(X_i^{min} + X_i^{max}), \; i = 1, 2, \dots, k, \quad (7)$$

where X_i^{min} and X_i^{max} – the lower and upper values of the input factors of the experiment; ΔX_i – variation interval of i-th factor:

$$\Delta X_i = \frac{x_i^{max} - x_i^{min}}{2}, \; i = 1, 2, \dots, k. \quad (8)$$

Variation interval ΔX_i of input factors X_i was selected within 0.05...0.3 of the possible range of variation of the i-th factor. In encoded form, the value of factors x_i acquire normalised values: +1 or –1. It is established that in order to build a response surface, it is necessary to conduct N (5) experiments. For the convenience of planning the experiment, it was necessary to draw up a plan and a planning matrix for the four-factor experiment in accordance with which the research was conducted.

At the beginning, a detailed study of the process was not required, and the local area of the experiment around the main level was used as a start for moving to the extremum region. Therefore, initially, instead of a complete factor experiment, a fractional factor experiment was used. Using a fractional factor experiment, the linear terms of the regression equation were estimated. The plan of a fractional factor experiment is actually a fractional replica of a complete factor experiment. The number of experiments that needed to be performed for semi-replicas was determined using the following expression:

$$N = 2^{k-p} = 2^{4-1} = 8, \quad (9)$$

where p – number of linear effects. Thus, the number of experiments is reduced by half compared to the full factor experiment, according to calculations based on expression (5).

To obtain a linear model, it was recommended to choose fractional replicas with a higher resolution, i.e., replicas that have linear effects mixed with interaction effects close to zero. When choosing a fractional replica, it is important to consider the saturation of the plan, that is, the ratio between the number of experiments and the number of coefficients that are determined based on the results of these experiments. The number of experiments in the matrix of a saturated fractional replica is equal to the number of coefficients of the linear model. Next, a semi-replicas of the fractional factor experiment type 2^{4-1} with a generating ratio $x_4 = x_1x_2x_3$ was used. Then the defining contrast and the corresponding score were given by the following relations:

$$\begin{aligned} &1 = x_1x_2x_3x_4, && x_1 = x_2x_3x_4, \\ &x_2 = x_1x_3x_4, && x_3 = x_1x_2x_4, \\ &x_4 = x_1x_2x_3, && x_1x_2 = x_3x_4, \\ &x_1x_3 = x_2x_4, && x_1x_4 = x_2x_3. \end{aligned} \quad (10)$$

This planning provided a rating system of this type:

$$\begin{aligned} &b_1 \to \beta_1 + \beta_{234}, && b_2 \to \beta_2 + \beta_{134}, \\ &b_3 \to \beta_3 + \beta_{124}, && b_4 \to \beta_4 + \beta_{123}, \\ &b_{12} \to \beta_{12} + \beta_{34}, && b_{13} \to \beta_{13} + \beta_{24}, \\ &b_{14} \to \beta_{14} + \beta_{23}, \end{aligned} \quad (11)$$

where the sample coefficients of the process model parameters b_1, b_2, b_3, b_4, b_{12}, b_{13} and b_{14} are only estimates for theoretical coefficients $\beta_1, \beta_2, \beta_3, \beta_4, \beta_{12}, \beta_{13}, \beta_{14}, \beta_{123}, \beta_{124}, \beta_{134}, \beta_{23}, \beta_{24}, \beta_{234}, \beta_{34}$, which are the mathematical expectation for the relevant factors.

Triple and higher-order interactions are much more likely than double interactions to be zero, and they are usually ignored, respectively. The semi-replication of the type 2^{4-1}, defined by the generating relation $x_4 = x_1x_2x_3$, allowed obtaining separate estimates of four linear effects and three joint estimates of paired interactions. Separate estimates are b_1, b_2, b_3, and b_4, and triple interactions – β_{234}, β_{134}, β_{124} and β_{123} are neglected due to their insignificance. In the future, such a replica will be designated as for a fractional factor experiment 2^{4-1}_{IV}.

The initial conditions of the experiment were established and, accordingly, the intervals of variation of independent variables (input factors) were set (Table 1), which were used to determine the transition from natural variables X_1, X_2, X_3 and X_4 to code variables x_1, x_2, x_3, and x_4, which were accepted at the ends of the value intervals +1 or –1.

Table 1. Intervals of variation of independent variables, initial conditions of the experiment

Name and designation of values		Controlled parameters (factors): actual and encoded value							
		X_1	x_1	X_2	x_2	X_3	x_3	X_4	x_4
Variation interval	ΔX_i	350	–	20	–	30	–	6	–
Upper level	X_i^{max}	5,350	1	70	1	140	1	26	1

Continued Table 1.

Name and designation of values		Controlled parameters (factors): actual and encoded value							
		X_1	x_1	X_2	x_2	X_3	x_3	X_4	x_4
Main level	$X_i^{(0)}$	5,000	0	50	0	110	0	20	0
Lower level	X_i^{min}	4,650	–1	30	–1	80	–1	14	–1

Source: compiled by the authors

After selecting the experiment plan, the main levels and intervals of varying factors, the transition to the experiment was made. Each row of the matrix is an experimental condition. To avoid systematic errors, it is recommended to conduct experiments provided for by the matrix in a random sequence. The procedure for conducting experiments should be selected from the table of evenly distributed random numbers. In general, experiments are recommended to be conducted randomly. However, to reduce the time spent on conducting experiments, they are sometimes grouped, that is, several experiments are performed simultaneously. Conditions for conducting experiments (experiment plan) for a fractional factor experiment $2_{4\text{-}1IV}$ are shown in Table 2. In this table, according to the sequence of experiments u, combinations of factors are ordered at two levels.

Table 2. Conditions for performing a fractional factor experiment $2^{4\text{-}1}{}_{IV}$ – combinations of factor values (encoded and actual) for all experiments

u	x_1	X_1	x_2	X_2	x_3	X_3	x_4	X_4
1	–1	4.650	–1	30	1	140	1	26
2	1	5.350	–1	30	1	140	–1	14
3	–1	4.650	1	70	1	140	–1	14
4	1	5.350	1	70	1	140	1	26
5	–1	4.650	–1	30	–1	80	–1	14
6	1	5.350	–1	30	–1	80	1	26
7	–1	4.650	1	70	–1	80	1	26
8	1	5.350	1	70	–1	80	–1	14

Source: compiled by the authors

The results of the experiments are shown in Table 3, where y_{u1}, y_{u2}, y_{u3} and y_{u4} – value of the response function Y (2) for $n = 4$ repetitions of experiments (parallel observations) in each u-th point in the experiment planning matrix; $\bar{y}_u$ – average value of the response function (optimisation parameter) for the experiment by number u; $\sigma_2\{y_u\}$ – sample variance for the experiment by number u, which is calculated using the equation:

$$\sigma^2\{y_u\} = \frac{1}{(n-1)} \sum_{i=1}^{n} (\bar{y}_u - y_{ui})^2. \qquad (12)$$

Table 3. Results of the fractional factor experiment $2^{4\text{-}1}{}_{IV}$

u	y_{u1}	y_{u2}	y_{u3}	y_{u4}	$\bar{y}_u$	$\sigma^2\{y_u\}$
1	10.020	10.060	10.780	10.920	10.445	222.233
2	12.860	12.390	12.270	11.980	12.375	134.167
3	10.160	10.530	10.240	10.650	10.395	54.166.7
4	13.350	14.030	14.160	14.420	13.990	208.333
5	9.730	9.279	9.089	8.970	9.260.25	103.317
6	12.900	12.530	12.440	12.100	12.492.5	108.092
7	8.588	8.276	8.190	7.986	8.260	62.605.3
8	13.290	13.770	13.920	14.020	13.750	104.600
					Σ→	997.514
					max→	222.233

Note: Σ – the sum of sample variance values for all experiments; max – the maximum value of the sample variance
Source: compiled by the authors

Values $\sigma^2\{y_u\}$ were calculated for all points of the matrix plan, and the calculation results were entered in Table 3. Since the number of repetitions of experiments (parallel observations) in each u-th point in the matrix, the planning of the experiment is the same and equal to n, then the uniformity of variance at each level of factors can be checked by the Cochrane criterion. To do this, it was necessary to compare the calculated value G^a of the Cochrane criterion with its tabular value G^b, which is found from the reference table for known values of the total variance value N and the number of degrees of freedom. If the following condition:

$$G^a < G^b, \tag{13}$$

is performed, then there are grounds to assert that the variances are homogeneous and, accordingly, the experiments are reproducible. The calculated value G^a of the Cochrane criterion was calculated by the formula:

$$G^a = \frac{\max\{\sigma^2\{y_u\}\}}{\sum_{u=1}^{N}\sigma^2\{y_u\}}, \tag{14}$$

where N – total number of points in the plan of the experiment matrix ($u = 1, 2, ..., N$); max $\{\sigma^2\{y_u\}\}$ – maximum value of the sample variance from the set N of experiments; $\sum_{u=1}^{N}\sigma^2\{y_u\}$ – sum of sample variances for N experiments. As a result, the following numeric value G^a of the Cochrane criterion was obtained:

$$G^a = 0.22279. \tag{15}$$

Tabular value G^b could also be approximated by the Fischer distribution. To determine the tabular value G^b of the Cochrane criterion, p level of significance was initially selected. The following value is obtained:

$$p = 0.05 \qquad 16)$$

and the calculated number of degrees of freedom f has the following value:

$$f = n - 1 = 3. \tag{17}$$

Further, considering that the number of experiments (points in the plan of the experiment matrix) is:

$$N = 8, \tag{18}$$

the corresponding value G^b of the Cochrane criterion was calculated or selected from the reference table:

$$G^b = G(p; f; N) = 0.43075. \tag{19}$$

Given the value G^a, according to expression (15) and G^b according to expression (19), it was found that the condition $G^a < G^b$ according to expression (13) is fulfilled, which means that there is every reason to assert that the variances are homogeneous and, accordingly, the experiments are reproducible. Further, according to Table 3, the overall average variance was determined, that is, the variance of the reproducibility of the experiment:

$$\sigma^2\{\bar{y}\} = \frac{1}{N}\sum_{u=1}^{N}\sigma^2\{y_u\} = 124{,}689. \tag{20}$$

The error of the experiment (root-mean-square deviation) was determined as follows:

$$\sigma^2\{\bar{y}\} = \frac{1}{N}\sum_{u=1}^{N}\sigma^2\{y_u\} = 124{,}689. \tag{21}$$

The coefficients of the desired regression equation (4) were calculated using the following equations:

$$b_0 = \frac{1}{N}\sum_{u=1}^{N}\bar{y}_u, \tag{22}$$

$$b_i = \frac{1}{N}\sum_{u=1}^{N}\bar{y}_u x_i\,,\ i = 1, 2, 3, 4, \tag{23}$$

$$b_{1i} = \frac{1}{N}\sum_{u=1}^{N}\bar{y}_u x_1 x_i\,,\ i = 2, 3, 4, \tag{24}$$

where x_i – encoded values of experimental factors. The calculation results are shown in Table 4.

Table 4. Calculated values of the coefficients of the regression equation, according to expression (4)

b_i	Value	b_i	Value
b_0	11,370.97	b_4	–74.09
b_1	1,780.91	b_{12}	490.34
b_2	227.78	b_{13}	–390.66
b_3	430.28	b_{14}	163.47

Source: compiled by the authors

Further, it was defined that: $\sigma^2\{b_i\}$ – variance of the regression coefficient error b_i provided that ($i = 0, 1, ..., 14$), and also considering that the number of experiments n (number of repetitions) at all points of the plan of the experiment matrix are the same and are equal to:

$$\sigma^2\{b_i\} = \frac{\sigma^2\{\bar{y}\}}{Nn} = 3{,}896.54. \tag{25}$$

Standard deviation $\sigma\{b_i\}$ of the error variance of regression coefficient b_i was determined by the equation:

$$\sigma\{b_i\} = \sqrt{\frac{\sigma^2\{b_i\}}{Nn}} = 62.42, \tag{26}$$

calculated value of the root-mean-square deviation of the variance $\sigma\{b_i\}$ is the same applies to all regression coefficients.

The significance of the regression coefficients was determined using t^b – the Student's tabular t-test and its value is compared with the calculated value t^a. Values were calculated for each regression coefficient t^a using equation:

$$t_i^a = \frac{|b_i|}{\sigma\{b_i\}}\,,\ i = 0, 1, \dots, 4, 12, 13, 14, \tag{27}$$

where $|b_i|$ – calculated values of the regression coefficient (Table 4), which were taken modulo; $\sigma\{b_i\}$ – root-mean-square deviation of the variance of regression coefficients.

Tabular t^b value of the Student's t-test for the level of significance $q = 5\%$ and the degrees of freedom were determined using the following expression:

$$f_{St} = N(n-1) = 24, \quad (28)$$

next: $t^b = 2.1199$. For each regression coefficient, the values t^a were determined and compared to t^b. It was found that if the calculated value is $t^a > t^b$, then the regression coefficient is statistically significant and can be used in the future calculations. If the calculated value is $t^a < t^b$, then the regression coefficient is statistically insignificant and is discarded without recalculating other coefficients. Calculated values t^a of the regression coefficients according to expression (27) were entered in Table 5.

Table 5. Calculated values t^a

t_i^a	Value	t_i^a	Value
t_0^a	182.162	t_4^a	1.18698
t_1^a	28.53	t_{12}^a	7.85527
t_2^a	3.649	t_{13}^a	6.40246
t_3^a	6.89307	t_{14}^a	2.61876

Source: compiled by the authors

From the data in Table 5, it can be seen that all calculated values of the regression coefficient t_i^a, except for t_4^a, are significant. Instead, $t_4^a = 1.18698$ is an insignificant, and therefore, corresponding term $b_4 x_4$ in equation (4) was ignored. Statistical insignificance of the regression coefficient b_i can be caused by the following factors:

1) factor variation interval ΔX_i is selected small;

2) main level of the factor X_{0i} is close to the point of partial extremum;

3) big error of the experiment due to unaccounted factors;

4) there is no connection of factors with the initial value $\bar{y}_u$.

Interpretation of the regression equation is important both for understanding the process and for making decisions during optimisation. A special case occurs when using saturated plans. With the significance of all regression coefficients, nothing can be said about the adequacy or inadequacy of the model. A function whose coefficient values do not differ significantly is called symmetric with respect to the coefficients. However, it should be noted that a successful choice of variation intervals can make any linear function symmetric for significant factors. But at the first stage of planning, it is not always possible to get a symmetric function. If the function is sharply asymmetric (the coefficients differ by an order of magnitude), then it is more profitable to run the experiment again, changing the variation intervals, rather than moving along a gradient. As a result of the conducted research, the regression equation is further obtained in the form of a polynomial of the following form:

$$\hat{Y} = 11{,}370.97 + 1{,}780.91 \cdot 1 + 227.78 \cdot x_2 + \\ + 430.28 \cdot x_3 + 490.34 \cdot x_1 x_2 - 399.66 \cdot x_1 \cdot x_3 + \\ + 163.47 \cdot x_1 \cdot x_4, \quad (29)$$

where $\hat{Y}$ – mathematical expectation of the optimisation parameter indicator; x_1, x_2, x_3, and x_4 – process factors that were studied. The mathematical model obtained has the form of a first-degree polynomial (29) (Kononyuk, 2010). The coefficients of the polynomial, according to expression (29), are known. Next, the adequacy of the model was checked in accordance with the obtained regression equation according to the form of expression (29). For this purpose, the variance of the adequacy of the model was determined using the following equation:

$$s_{ag}^2 = \frac{n}{N-l} \sum_{u=1}^{N} (\bar{y}_u - \hat{y}_u)^2 = 326{,}594.47, \quad (30)$$

where N – total number of points in the plan of the experiment matrix; l – number of significant coefficients; $\bar{y}_u$ – arithmetic mean with n experiments (Table 3) at the point with the number ($u = 1, 2, \ldots, N$); $\hat{y}_u$ – the mathematical expectation of the optimisation parameter calculated by the regression equation according to expression (29).

The adequacy of the model was checked by comparing the calculated value F^a of Fischer's criterion with a tabular value F^b according to this equation (Kononyuk, 2010):

$$F^a < F^b(f_1; f_2), \quad (31)$$

where f_1 and f_2 – degrees of freedom. Further, the degrees of freedom were determined using the following expressions:

$$f_1 = N - l = 1, \quad (32)$$
$$f_2 = N(n-1) = 24. \quad (33)$$

Calculated value F^a and tabular value F^b of the Fischer criterion, respectively:

$$F^a = 2.619267. \qquad F^b = 4.259677. \quad (34)$$

As can be seen from the numeric values of expressions (34) calculated value of the Fischer criterion F^a turned out to be less than the tabular value F^b and, accordingly, the hypothesis of adequacy of the model according to expression (29) is accepted. After substituting expressions (6) into equation (29), the return to natural variables X_i was made, and the obtained regression equation in explicit (decoded) form, which has such a relationship between the factors:

$$Y = -11{,}817.78 + 4.21 \cdot X_1 - 338.61 \cdot X_2 + 204.34 \cdot X_3 - 390 \cdot X_4 + \\ + 0.07 \cdot X_1 \cdot X_2 - 0.038 \cdot X_1 \cdot X_3 + 0.078 \cdot X_1 \cdot X_4. \quad (35)$$

The regression equation (35) was rewritten, considering that: Y corresponds to the pressure generated by the fan P_v(Pa); X_1 – fan impeller rotation frequency n (rpm); X_2 – blade installation angle at the impeller inlet β_1 (deg.); X_3 – blade installation angle at the impeller outlet β_2 (deg.); X_4 – number of impeller blades z (pcs). As a result, the following equation was obtained:

$$P_v = -11{,}817.78 + 4.21 \cdot n - 338.61 \cdot \beta_1 + 204.34 \cdot \\ \cdot \beta_2 - 390 \cdot z + 0.07 \cdot n \cdot \beta_1 - 0.038 \cdot n\beta_2 + 0.078 \cdot n \cdot z. \quad (36)$$

Further, it was established to what extent each of the factors n, β_1, β_2 and z affects the pressure generated by the centrifugal radial fan P_v. The value of each coefficient in equation (36) is a quantitative measure of this effect. The higher the coefficient, the stronger the influence of the factor. "Plus" sign at n indicates that with an increase in the values of this factor, the value P_v increases, and the "minus" sign at β_1 and z indicates that when they increase, the pressure P_v decreases. The effects of the interaction of factors are important. In the obtained equation (36), such an interaction is significant and has a positive sign for the interaction ($n \cdot \beta_1$) and ($n \cdot z$). With the effect of interaction of factors ($n \cdot \beta_2$), there is a negative sign that reduces the final pressure value P_v.

The condition was accepted that P_v according to expression (36), is a function n, that is $P_v = P_v(n)$, where n – an independent variable, and β_1, β_2 and z – parameters. From the full set of properties, the common between the variable n and parameters β_1, β_2 and z is that they can all change, and the difference is that n changes continuously, and β_1, β_2 and z – discretely. In this case, expression (36) was rewritten as a linear equation of the following form:

$$P_v(n) = A \cdot n + B, \quad (37)$$

where

$$A = 4.21 + 0.07 \cdot \beta_1 - 0.038 \cdot \beta_2 + 0.078 \cdot z, \quad (38)$$

$$B = 11{,}817.78 + 338.61 \cdot \beta_1 - 204.34 \cdot \beta_2 + 390 \cdot z, \quad (39)$$

$$\{\beta_1, \beta_2, z\} = \text{const}. \quad (40)$$

Now previously independent variables β_1, β_2, and z have all the features as parameters included in linear equation (37) and, accordingly, determine the value of the coefficients A according to expression (38) and B according to expression (39). Expression (37) was then analysed. The coefficient A according to expression (38) indicates that: firstly, P_v grows regardless of its size B according to expression (39), it is proportional to growth n provided that $A > 0$; secondly, P_v decreases regardless of the value B according to expression (39), it is proportional to growth n provided that $A < 0$; and finally, thirdly, P_v does not depend on the value n provided that $A = 0$, and the value B according to expression (39), it indicates the value of P_v. It can be concluded that the first option is physically justified and it was further considered. To investigate the relationship between β_1 and P_v, the regression equation (36) was rewritten in the same way as the previous case (38-40) in the following form:

$$P_v(\beta_1) = C_1 \cdot \beta_1 + D_1, \quad (41)$$

where:

$$C_1 = 0.07 \cdot n - 338.61, \quad (42)$$

$$D_1 = -11{,}817.78 + 4.21 \cdot \text{n} + 204.34 \cdot \beta_2 - 390 \cdot \text{z} - \\ - 0.038 \cdot \text{n} \cdot \beta_2 + 0.078 \cdot \text{n} \cdot \text{z}, \quad (43)$$

$$\{n, \beta_2, z\} = \text{const}. \quad (44)$$

The calculations performed have established that in the case when $C_1 = 0$ according to the expression (42) n will have the following meaning:

$$n|_{C1=0} = 4{,}837.286 \text{ rpm}. \quad (45)$$

Value P_v does not depend on β_1 and it is fully defined by a set of parameters:

$$\{\text{n}, \beta_2, z\}. \quad (46)$$

When:

$$n < n|_{C1=0} \text{ and } C_1 < 0, \quad (47)$$

relationship between β_1 and P_v is inversely proportional, and in the case when:

$$n > n|_{C1=0} \text{ and } C_1 > 0, \quad (48)$$

– directly proportional.

Further, a graphical dependency analysis was performed using a personal computer (36). For this purpose, a number of surfaces were considered that illustrate the dependence P_v from n, β_1, β_2 and z, provided that two of the four factors listed remain fixed. When considering the first option, when the value of factors $\beta_2 = 110°$ and $z = 20$ pcs. remain fixed, values n varies from 4,650 to 5,350 rpm, and β_1 varies from 30° to 70° (Fig. 3).

From expression (36) and from the surface shape $P_v(n, \beta_1)|_{\beta2=110°;\ z=20}$ (Fig. 3) it follows that within the full range of angle values $\beta_1 \in [30;70]$ deg, value P_v monotonically increases and proportional to the value $n \in [4650; 5350]$. When β_1 is fixed, the relationship between n and P_v is linear. A fixed speed of rotation of the impeller within $n \in [4{,}650; n|_{C1=0}]$ increasing the angle $\beta_1 \in [30; 70]$ leads to a decrease in the value P_v, and at $n \in [n|_{C1=0}; 5{,}000]$, and when the $\beta_1 \in [30; 70]$ increases, P_v alsoincleases. Therefore, the surface $P_v(n, \beta_1)|_{\beta2=110°;\ z=20}$ (Fig. 3) has a rectilinear product parallel to the plane ($P_v n$), but its angle of inclination relative to the horizontal varies depending on $\beta_1 \in [30; 70]$ and is defined as follows:

$$\arctan\left(\frac{\partial}{\partial n} P_v\right) = \arctan(C_1). \quad (49)$$

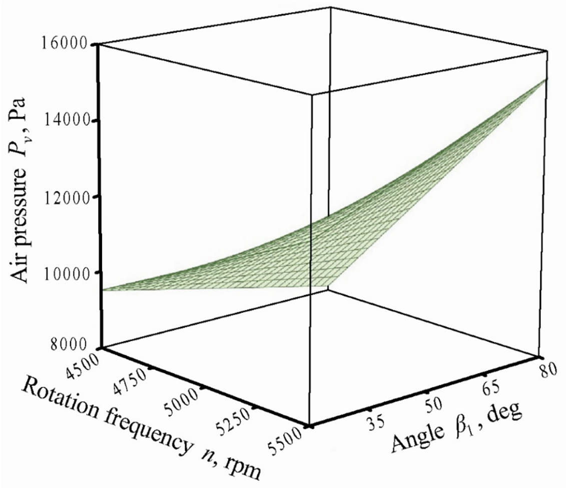

Figure 3. Dependence of the pressure generated by the fan on the impeller rotation speed and the angle of installation of the impeller blades at the inlet, with a fixed value of the angle of installation of the impeller blade at the outlet, and the number of blades

Note: P_v (Pa) – pressure, $n \in [4{,}650;\ 5{,}350]$ (rpm), $\beta_1 \in [30;70]$ deg, $\beta_2 = 110°$, $z = 20$ pcs

Source: compiled by the authors

The second option was considered, when the value of factors $\beta_1 = 50°$ and $z = 20$ pcs. remain fixed, value n varies from 4,650 to 5,350 rpm, and β_2 varies from 80° to 140° (Fig. 4).

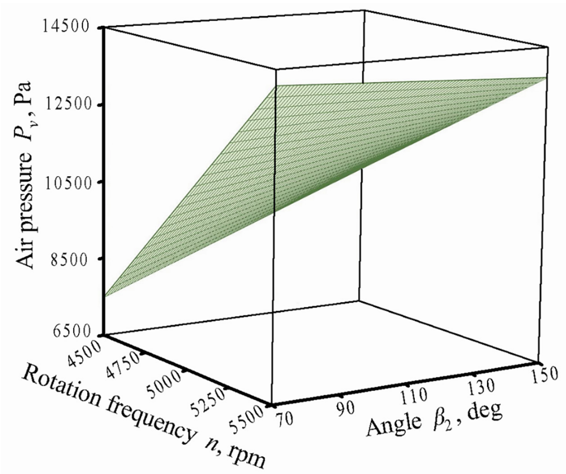

Figure 4. Dependence of the pressure P_v (Pa) generated by the fan on the impeller rotation speed and the angle of the impeller blades at the outlet at a fixed value of the impeller blade angle at the inlet, and the number of blades

Note: P_v (Pa) – pressure, $n \in [4{,}650;\ 5{,}350]$ (rpm), $\beta_2 \in [80;140]$ deg, $\beta_1 = 50°$, $z = 20$ pcs

Source: compiled by the authors

From the expression (36), as well as from the shape of the surface $P_v(n, \beta_2)|_{\beta 1=50°;\ z=20}$ (Fig. 4) it follows that the value P_v monotonically increases in proportion to the growth of $n \in [4{,}650;\ 5{,}350]$ for each fixed $\beta_2 \in [80;\ 140]$. In this case, the relationship between n and P_v is linear. The surface $P_v(n, \beta_2)|_{\beta 1=50°;\ z=20}$ (Fig. 4) has a straight line parallel to the plane $(P_v n)$, as in the previous case.

Next, the regression equation (36) is rewritten in linear form as before:

$$P_v(\beta_2) = C_2 \cdot \beta_2 + D_2, \tag{50}$$

where

$$C_2 = 204.34 - 0.038 \cdot n, \tag{51}$$

$$D_2 = -11{,}817.78 + 4.21 \cdot n - 338.61 \cdot \beta_1 - 390 \cdot z + \\ + 0.07 \cdot n \cdot \beta_1 + 0.078 \cdot n \cdot z, \tag{52}$$

$$\{n, \beta_1, z\} = \text{const}\,. \tag{53}$$

In the case when $C_2 = 0$, equation (50) and, accordingly, $n|_{C2=0}$=5,377.368 rpm value P_v is independent of $\beta_2 \in [80;\ 140]$. When $n < n|_{C2=0}$ and $C_2 > 0$, the relationship between β_2 and P_v is directly proportional, and in the case of $n > n|_{C2=0}$ and $C_2 < 0$ – inversely proportional (Chobal *et al.*, 2023). This is exactly the picture shown in Figure 4. Comparing the current situation with the previous Figure 3, it can be seen that the influence of angles β_1 and β_2 by the amount of P_v in a qualitative sense, it is a mirror image. Further, the third option was considered, when the value of factors $n = 5{,}000$ rpm and $z = 20$ pcs. remain fixed, values β_1 change from 30° to 70°, and β_2 – varies from 80° to 140° (Fig. 5).

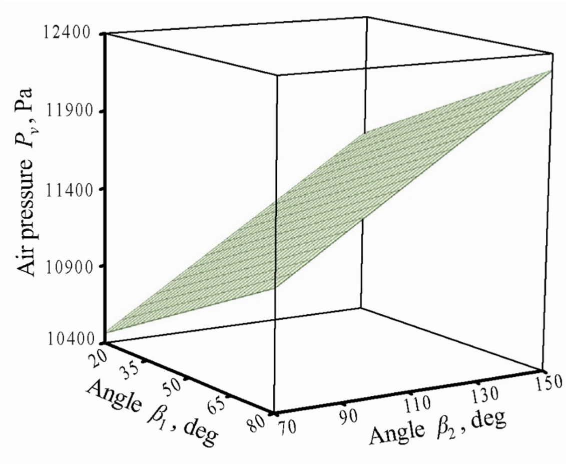

Figure 5. Dependence of the pressure P_v(Pa) generated by the fan on the angle of the impeller blades at the inlet and outlet at a fixed value of the fan impeller rotation frequency, and the number of blades

Note: P_v(Pa) – pressure, P_v deg, $\beta_2 \in [80;140]$ deg, $n = 5{,}000$ rpm, $z = 20$ pcs

Source: compiled by the authors

From the expression (36) and from the shape of the surface $P_v(\beta_1, \beta_2)|_{n\,=\,5000;\,z=20}$ (Fig. 5) it follows that the value P_v monotonically increases in proportion to the increase in both angles $\beta_1 \in [30; 70]$ and $\beta_2 \in [80; 140]$. This situation fully corresponds to the patterns that were identified during the analysis of the surfaces shown in Figures 3 and 4. In the current case, the surface $P_v(\beta_1, \beta_2)|_{n\,=\,5000;\,z=20}$ has a rectilinear line parallel to the plane ($P_v\,\beta_1$). The fourth option was considered as follows, when the value of factors $\beta_1 = 50°$ and $\beta_2 = 110°$ remained fixed, values n varied from 4,650 to 5,350 rpm, and the number of blades z changed from 12 to 28 pcs. The results obtained are shown in Figure 6.

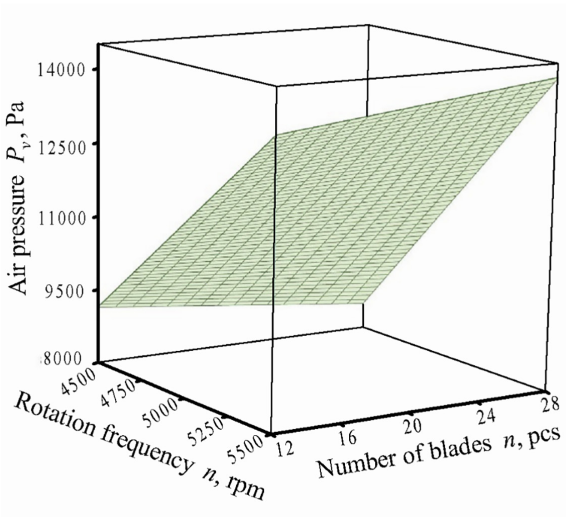

Figure 6. Dependence of the pressure P_v(Pa) generated by the fan on the impeller rotation speed and the number of blades at fixed values of the installation angles of the impeller blades at input and output

Note: P_v(Pa) – pressure, $n \in [4{,}650; 5{,}350]$ rpm, $z \in \{12, 16, \ldots, 28\}$, $\beta_1 = 50°$, $\beta_2 = 110°$

Source: compiled by the authors

From the expression (36) and from the shape of the surface $P_v(n, z)|_{\beta 1\,=\,50°,\,\beta 2\,=\,110°}$ (Fig. 6) it follows that in the qualitative sense, the nature of the influence of quantity z of impeller blades by the amount of pressure generated by it

P_v is similar to the regularities of the relationship between the angle β_1 and P_v, shown in Figure 3. At $n < 5{,}000$ rpm, the effect of the number of blades z on the pressure generated by the fan P_v is inversely proportional, and at $n > 5{,}000$ rpm – directly proportional. At $n = 5{,}000$ rpm, the impact of z on P_v is not observed.

Ultimately, the presented analysis of the obtained graph dependencies shown in Figures 3-6 gives grounds to assert that the obtained regressive model (36) is adequate to the working processes of a centrifugal radial fan of the considered design. Thus, precise and aggregated analytical dependencies and their graphical interpretations are found, which allow efficient and low-cost selection of optimal parameters of a centrifugal radial fan for any pneumatic seed drill.

Building a theoretical model involves conducting large and long-term research, since it is necessary to find out the nature of the microprocessors that the object has and describe them mathematically. R.B. Darlington & A.F. Hayes (2016) present the process model as a complex system of equations (a system of algebraic, ordinary differential equations, or partial differential equations). These systems of equations allow describing the processes occurring in the object very accurately and allow extrapolation at a point in the factor space where direct observation is impossible. Statistical models are obtained as a result of statistical processing of experimental data collected during the study.

Comparing the obtained scientific results with the results of known previous studies, it should be noted that G.J. Peng *et al*. (2021) also optimised the geometric parameters of the impeller of a multi-stage fan (pump) based on a rather complex and expensive experimental study. The obtained similar parameters, such as a smaller impeller diameter and fewer blades, require the use of a multi-stage design, which significantly increases the complexity and cost of the design.

H.C. Ding *et al.* (2020) also took a centrifugal fan as the object of research and installed five models of an impeller with different angles of release of the blades. Here, using computational hydrodynamics, the external characteristics of a centrifugal fan and the internal characteristics, including velocity, pressure, and turbulent energy distribution were obtained and compared in the middle plane of the fan impeller. In addition, pressure fluctuations around the impeller outlet as a function of external parameters were also analysed. However, there is no reason to consider the indicators obtained in this paper optimal, since the main methods of regressive analysis are not used here.

S.Q. Zhou *et al*. (2019) and Z.H. Li *et al*. (2020) considered a multi-blade centrifugal fan, which is characterised by a large number of blades (> 48) and their spiral installation on the drive shaft. It is established that the fluidity and noise characteristics of such a centrifugal fan depend on the type of spiral line and the geometry of the tongue at the spiral outlet. The origin and influence of a complex vortex structure near the spiral outlet of a multi-blade centrifugal fan are also investigated here. Due to the wide blade and short blade channel, the air flow maintains a large radial velocity in the blade channel. This continuous radial partial velocity causes vortices to form in the spiral release zone. A secondary flow close to the impeller is then generated from the centre to the sides along the volume. It is obtained that the current lines are divided into two parts (reverse and output) at the exit of the spiral. Although vortices near the spiral exit are complex, the main features of the flow behaviour caused by the vortex are clear. However, these obtained design and kinematic parameters of fans are not optimal, since they were also calculated without using correlation analysis. It is likely that even when developing specific designs of these centrifugal fans based on the application of the obtained parameters, it is necessary to conduct additional thorough experimental studies. And the application of the results obtained no longer requires any additional theoretical or experimental studies. This greatly simplifies obtaining fairly accurate design and kinematic parameters of the fan under study.

Many bladed centrifugal fans with different designs of impellers, blade profiles, grooves at the tip of the blade, etc., are considered in the papers by M. Kharati-Koopaee & H. Moallemi (2019), Z.Q. Xu *et al*. (2022) and F.N. Meng *et al*. (2023). Although correlation analysis methods are used here, their application is quite complex, expensive, and does not guarantee a fairly simple and accurate method proposed in this study. S. Tong *et al*. (2020), E.Ö. Aydın *et al*. (2022) considered a method for optimising the hydraulic efficiency of a ten-stage centrifugal pump. In accordance with the hydraulic loss model, a multi-criteria method for calculating optimisation based on constructed surrogate models is proposed. To determine the nonlinear relationship between key design variables and values of external characteristics of a centrifugal pump, this paper constructed a quadratic response surface, a radial basis Gaussian response surface, and three Kriging surrogate models using computer hydrodynamic modelling analysis. It is quite possible to switch from the study of a centrifugal pump to a centrifugal fan, but it still gives the effect that is used in this particular study. The authors of this well-known study have also built several models, but they are overwhelmingly based on hydraulic losses and applying them to generate air pressure will require significant additional transformations.

Based on the conducted comparative analysis, it can be argued that the developed method of designing centrifugal radial fans allows quite simply but also accurately determine the optimal design and kinematic parameters, which can be effectively used in the development and construction of various pneumatic systems that are widely used in the field of agricultural mechanisation.

CONCLUSIONS

The dependence of the total pressure P_v of the pneumatic system of the seed drill on the parameters of the main external factors present in its main body – the impeller – is analytically determined. For this purpose, a regression equation was derived that obeys the law of the first-degree polynomial equation. The high efficiency of applying the statistical theory of experiment planning in conducting computational studies instead of full-scale ones is proved.

In particular, the method of interpolation computational experiment is given. As a result, a functional relationship was established between the value of the total pressure generated by the fan P_v and independent variables: n – fan impeller rotation frequency; angles β_1 and β_2 of installations of each blade, respectively, at the inlet and outlet of the impeller; z – the number of impeller blades.

The resulting regression equation $P_v = P_v(n, \beta_1, \beta_2, z)$, Pa, shows that within the studied intervals, changes in independent quantities ($n \in [4{,}650; 5{,}350]$, rpm; $\beta_1 \in [30; 70]$, deg; $\beta_2 \in [80; 140]$, deg; $z \in [12, 16, \ldots, 28]$, pcs.) function $P_v = P_v(n, \beta_1, \beta_2, z)$ retains monotony, and therefore, the minimax optimisation experiment does not make sense. To obtain the required value of the total pressure generated by the fan P_v is enough to assign the corresponding values of independent values n, β_1, β_2 and z. Such a regression equation allows predicting response values based on the specified values of factors. The obtained analytical results allow effectively designing and constructing centrifugal radial fans with various technical indicators. In the future, the proposed methodological approach provides for the use to study and optimise processes in pneumatic systems not only in seed drills of various purposes and design in their development or improvement, but also in the study and design of pneumatic systems of other agricultural machinery and equipment of modern technical level.

The next stages in further research are the development of new physical models of pneumatic systems used in machines of various branches of agriculture and a fairly correct and accurate formalisation of their functioning depending on the input and output parameters, which will form the basis of their regression models built in the future. At the same time, there is a primary need to detail and establish the significance of individual factors, depending on the specific goals and features of further mathematical modelling.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Проєктування відцентрових радіальних вентиляторів із застосуванням методів регресивного аналізу

Анотація. З розвитком науково-технічного прогресу в сільському господарстві актуальним є застосування операційно-математичного моделювання для ефективного вирішення завдань та ресурсозбереження в галузі сільськогосподарського машинобудування. Тому метою дослідження було визначення оптимальних параметрів відцентрового радіального вентилятора пневматичної сівалки точного висіву шляхом побудування нової математичної моделі процесу його роботи. Досягнення цього було здійснене шляхом застосування методів математичного моделювання при плануванні багатофакторних експериментів. В результаті визначено комплекс автоматизованого експерименту, що призводить до суттєвого підвищення продуктивності наукової роботи. Встановлено статистичне уявлення про експеримент, що дозволяє перейти до багатофакторного активного експерименту, в якому є можливість відокремити вплив факторів від шумового фону та здійснити перехід до статистичних методів аналізу результатів. Саме це дозволило отримати можливість прогнозування оптимальних характеристик відцентрового радіального вентилятора сівалки точного висіву. У процесі даного дослідження складено нове рівняння регресії у вигляді полінома першого ступеня, яке визначає вплив кожного із факторів на величину та значення відгуку. Визначено коефіцієнти полінома, проведено оцінку значущості коефіцієнтів та перевірку на адекватність запропонованої моделі. Після отримання рівняння регресії виникла можливість графічної побудови залежності функції відгуку від чинників впливу. Також проведено дробовий факторний експеримент, реалізуючи який визначено значення параметрів стану об'єкта Y при всіх можливих поєднаннях рівнів варіювання факторів X_i. На підставі встановленого функціонального взаємозвязку між вихідним параметром вентилятора одержане рівняння регресії наступного вигляду: $P_v = P_v(n, \beta_1, \beta_2, z)$. Це дало підстави прогнозувати отримання повного тиску P_v, (Pa), при заданні різних значень незалежних величин n, β_1, β_2 та z. Застосування отриманих аналітичних залежностей суттєво спростило визначення оптимальних конструктивних параметрів пневматичних систем для розробки та конструювання сівалок сучасного технічного рівня

Ключові слова: математична модель; багатофакторний процес; тиск; частота обертального руху; кути установки; кількість лопаток