STUDY OF THE DEPENDENCE OF PRODUCTIVITY OF SMOKE AND HEAT REMOVING MEANS ON THEIR TECHNICAL CHARACTERISTICS (IN UKRAINIAN CONTEXT)

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Abstract: The paper examines the tactical and technical characteristics that affect the performance of smoke and heat removal devices, and it is proposed to investigate the determined effect. To study the influence of tactical and technical characteristics, the use of two parameters (the angle of inclination of the fan blades and the total active surface area of the blades of the fan impeller) is justified, and the range of these two parameters is determined. The study is devoted to the issue of revealing the dependence of productivity, as a characteristic that directly affects the duration of tactical ventilation by fire and rescue units, on the technical parameters of the smoke and heat removal means. The creation of a mathematical model of the description of the performance indicators of smoke and heat removal devices based on their technical characteristics allows establishing the range of values of the specified parameters, which are accepted during further experimental studies in order to find the optimal values of these parameters. The obtained mathematical model makes it possible to evaluate the effect on the technical parameters of the smoke and heat removal device under different operating conditions, namely: independent operation, simultaneous operation with the supply of finely sprayed water and simultaneous operation with a foam generating unit. The regularity of the dependence of the productivity of smoke and heat removal devices on their technical characteristics has been established as a scientific basis for the improvement of these devices.

Keywords: Means of smoke and heat removal; tactical ventilation; technical characteristics; angle of inclination of the blades; total active area of the blades.

1 Introduction

The analysis of statistical data shows that during firefighting, gas and smoke protection units are used in the vast majority to protect rescuers from dangerous factors, in particular, high temperatures and smoke, and to effectively eliminate fires [3; 13]. In Ukraine, up to 30 firefighters get injures of various types every year while extinguishing fires related to the work of gas and smoke protection service units.

An important tactical way to reduce such an impact on the personnel of fire and rescue units is to control the heat and smoke flows of a fire with the help of portable smoke and heat removal devices [6; 11], which are functionally designed to increase the local air pressure by injecting air into the personnel's work area or removing combustion products from premises in fire conditions to normalize the temperature and air environment.

The analysis of operational and rescue work of the rescue services in different countries of the world indicates the high tactical significance of the use of portable fire extinguishers, which have acquired innovative changes. To date, 471 portable smoke and heat removal devices are in operation in Ukraine, of which 350 units are outdated models. Statistical data indicate a low level of their use. One of the reasons is the insufficient parameter of the smoke and heat removal means - productivity, which is from 5000 to 7000 cubic meters per hour.

According to the results of analytical studies, it was established that the average productivity of modern equipment is from 11,000 to 24,000 cubic meters per hour. Our research involves improving the means of smoke and heat removal to increase the effectiveness of extinguishing fires in conditions of high temperature and smoky conditions by enhancing its individual elements.

2 Literature Review

The problems of enhancing technical solutions aimed at improving the operation of smoke and heat removal devices were studied by scientists such as Paul H Wiedorn, Jurgen Bader, William L. Jackman, Konz Lufttechnik, and others [2; 5; 8; 19]. Their work was aimed at modifying structural elements, improving the performance characteristics of these devices. In these works, most of the technical solutions relate to the direction of the air flow created by the fan blades are covered. Ukrainian scientists also conducted research aimed at the deposition of combustion products, lowering the temperature and increasing the visibility in smoky rooms with the use of smoke and heat removal tools - these are scientists V.V. Kovalyshina [4], Gulida E.M. [7], Lusch V.I. [11], Shtangereta, N.O. [17], and others.

However, it should be noted that the researchers did not investigate the question of establishing the regularity of the dependence of the productivity of smoke and heat removal devices on changes in their technical parameters, in particular, the area and angle of the fan blades.

The purpose of the work is to reveal the regularities of smoke and heat removal devices productivity dependence on their technical characteristics as a scientific basis for the improvement of such devices.

To achieve the goal, the following tasks must be solved:

- To establish technical characteristics that affect the effectiveness of removing dangerous fire factors from premises and buildings using smoke and heat removal means;
- To build a mathematical model that allows investigating the dependence of productivity, as a characteristic that directly affects the duration of tactical ventilation by fire and rescue units, on the technical parameters of the means of smoke and heat removal;
- To establish the dependence of the effectiveness of removing dangerous fire factors on the technical characteristics of smoke and heat removal devices.

3 Methods

The following research methods are used in the work: mathematical modeling, which makes it possible to investigate the dependence of productivity, as a characteristic that directly affects the duration of tactical ventilation by fire and rescue units, on the technical parameters of the means of smoke and heat removal and is based on a complete system of Navier-Stokes differential equations; experiment planning method (approximation of experimental data); the method of assessing the adequacy of the obtained polynomial model with the detection of discrepancies between the variances of research results (Fisher); the method of evaluating the reproducibility of experiments (Cochren).

4 Results and Discussion

4.1 Study of the parameters of smoke and heat removal devices characterizing their effectiveness

The main characteristic of the effectiveness of the functioning of portable smoke and heat removal devices is their productivity. This characteristic directly affects the duration of tactical ventilation by fire and rescue units, as a result of which the probability of saving people and extinguishing fires increases.

The performance of the fan depends on the main parameters: the fan diameter, speed, the total area of the blades and the installation angle of the blade profile [14]. The selection of the list of parameters in relation to which their influence on the performance of the smoke and heat removal device will be further investigated is based on the significance of the influence of the selected parameter on the performance of the device and economic indicators regarding the production, operation, and maintenance of the device in the event of a change in the considered parameter.

Parameters such as the diameter of the fan and speed affecting the performance of the fan create a linear relationship between such parameters and the performance of the smoke and heat removal agent. At the same time, the larger the values of the fan diameter and the number of revolutions, the greater the productivity of the device; along with this, the economic indicators for the production, operation, and maintenance of such a device increase. Therefore, improving the characteristics of smoke and heat removal devices at the expense of increasing their cost is defined as impractical in this work. At the same time, the change in the diameter and number of revolutions of the fan can be taken into account during the design and manufacture of a new fan.

In the existing means of smoke and heat removal, the parameter of the angle of inclination of the fan blades profile varies within the limits from 0.6 to 0.96 radians. Therefore, during further research, we accept the minimum value of the angle of inclination of the fan blade profile as 0.6 radians, the average value as 0.78 radians, and the maximum value as 0.96 radians. The second indicator, which also significantly affects performance (air flow, $m^3 \cdot s^{-1}$) and has a relatively small effect on the economic indicators (cost) of the fan, is the total active surface area of the fan impeller blade, which is described by the formula:

$$S = b \cdot \frac{D(1 - v_h)}{2} \cdot n_b \text{, м2,} \qquad (1)$$

where: b – the average chord length of the blade section, which is taken according to the recommendations [4] at a point at a distance of the effective radius r_{mid} from the axis of the hub of the impeller according to the formula:

$$r_{mid} = \frac{\sqrt{2}}{4} \cdot D\sqrt{1 + v_h^{\ 2}} \text{, m,} \qquad (2)$$

where: D – is outer diameter of the grid of the blades of the fan impeller, m;

vk = $D_b \cdot D^{-1}$ = 0.4 - the relative diameter of the sleeve on which the blades are installed (according to measurements of an unimproved means of smoke and heat removal);

D_b – diameter of the sleeve of the fan impeller, m;

n_b – the number of blades of the fan impeller.

Thus, during the study of the performance of the smoke and heat removal means, the effect on the specified characteristic of such a parameter as the total active surface area of the blades of the fan impeller should also be investigated.

Data on the range of parameters of the angle of inclination of the fan blade profile and the total active surface area of the blade of the fan impeller are given in Table 1.

Table 1: The range of parameters of the blade angle and the area of the fan blade

Parameter name	**Parameter value**		
	Minimal	**Average**	**Maximum**
Angle of inclination of the blade β, radians	0.6	0.78	0.96
Blade area S, m^2	0.075	0.127	0.18

These two indicators, namely, the angle of inclination of the fan blade profile and the total area of the blades of the fan impeller, were chosen for further research in order to find the optimal values of these values, which ensure the maximum value of productivity (air flow, $m^3 \cdot s^{-1}$) of the means of smoke- and heat removal in this work.

The criterion for an improved smoke and heat removal device can be taken as the ratio of the performance of an improved smoke and heat removal device to the performance of unimproved smoke and heat removal device, which can be expressed in the form of an equation:

$$K = \frac{Q_{imp}}{Q} \qquad (3)$$

where: K – criterion of performance of smoke and heat removal means;

Q_{imp} – performance of the improved means of smoke and heat removal;

Q – performance of an unimproved means of smoke and heat removal.

4.2 Creation of a mathematical model describing the performance indicators of smoke and heat removal devices depending on their technical characteristics

The mathematical model makes it possible to establish a range of parameter values (the angle of inclination of the fan blades and the total active surface area of the blades of the fan impeller), which are adopted during further experimental studies in order to find the optimal values of these values. Obtaining a mathematical model makes it possible to assess the effect on the technical parameters of the smoke and heat removal device under different operating conditions, namely: independent operation, combined operation with the supply of finely sprayed water, and combined operation with a foam generating unit.

When creating a mathematical model, the theory of profile grids was also used, and the following assumptions and simplifications were adopted [16]:

- The simplified scheme does not provide for the presence of a guiding device that corresponds to the accepted initial conditions during design;

- It is assumed that the flow in the working cavity of the pump is axisymmetric;

- It is considered that the thermodynamic process taking place in the pump cavity is isothermal (as a result of small values of pressure changes characteristic of an axial fan);

- The angle of inclination of the chord of the blade to the area of rotation of the blade impeller β_m depending on the radius of the intersection of the blade grid varies according to the following law:

$$r \cdot tg(\beta_m) = const \text{, m,} \qquad (4)$$

where: r – is the radius at the intersection of the blade grid;

β_m – the angle of inclination of the chord of the blade, which varies depending on the point of measurement.

Using the scheme of the grid of axial fan profiles (Figure 1), the compatible plan of velocities and forces (Figure 2), and the plan of the speeds of the impeller grid (Figure 3), the main kinematic parameters of the flow passing through the grid were introduced. The strength characteristics of the grid (Figure 4) of the profiles were calculated based on the formulas for the lifting force of the blade:

$$dP_y = c_y \cdot \rho \cdot b \cdot \frac{w^2}{2} \cdot dr; dP_x = c_x \cdot \rho \cdot b \cdot \frac{w^2}{2} \cdot dr, \qquad (5)$$

where: c_y, c_x – coefficients of lift and frontal aerodynamic resistance;

b – blade width, m;

ρ – air density, kg·m^{-3};

dr – blade length element, m;

w – air speed along the blade, according to the speed plan of the impeller grid.

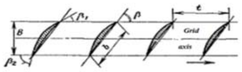

Figure 1. A grid of axial fan profiles, unfolded on a plane

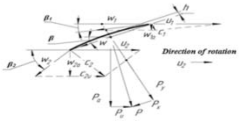

Figure 2. Combined plan of speeds and forces

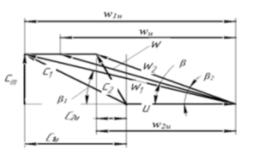

Figure 3. Speed plan of the impeller grid

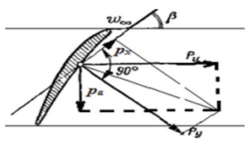

Figure 4. Forces acting on the flow from the side of the blade

We have derived the formula for the functional dependence between the static pressure of the grid of profiles on the amount of air flow (air mixture) and the fan parameters:

$$p(Q,b,h,\beta) = ..$$
$$= \left\{A \cdot \left[ctg\left(\beta - arctg\left(\frac{2\cdot h}{b}\right)\right) - ctg\left(\beta + arctg\left(\frac{2\cdot h}{b}\right)\right)\right]\cdot Q - B\cdot Q^2\right\}\times ..$$
$$..\times \frac{1-\mu\cdot ctg(\beta - arctg(C\cdot Q))}{1+\mu\cdot ctg(\beta - arctg(C\cdot Q))}, \text{ Pa} \quad (6)$$

where: μ = 0.03 – reverse profile quality;

Q – the amount of productivity, or air flow, m^3·s^{-1}.

In this formula, the complexes used: A, B, and C are chosen in such a way that the values included in them remain unchanged in the chosen direction of modernization of the existing fan model:

$$A = 2\cdot\sqrt{2}\cdot\frac{\sqrt{1+v_h^2}}{D\cdot(\sqrt{1-v_h^2})}\cdot\rho\cdot n, \text{kg}\cdot\text{m}^{-4}\cdot\text{s}^{-1}$$

$$B = \frac{8}{\pi^2}\cdot\frac{\rho}{D^4\cdot(1-v_h^2)}, \text{kg}\cdot\text{m}^{-7} \quad (7)$$

$$C = \frac{8}{2\cdot\pi^2}\cdot\frac{1}{D^3\cdot(1-v_h^2)\cdot\sqrt{1+v_h^2}\cdot n}, \text{s}\cdot\text{m}^{-3}$$

where: D – outer diameter of the blades of the fan rotation wheel, m;

ρ – density of air (mixtures), kg/m^3;

v_h – the relative diameter of the hub of the fan impeller.

The developed mathematical model provides the calculation of the main characteristics of smoke and heat removal devices [16], taking into account the peculiarities of the field of application in relation to conventional fans, namely: air injection (Figure 5) and air injection with simultaneous supply of finely sprayed water (Figure 6), as well as air injection with simultaneous foam supply (Figure 7).

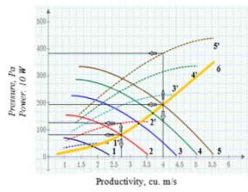

Figure 5. Diagram for calculation under air supply conditions

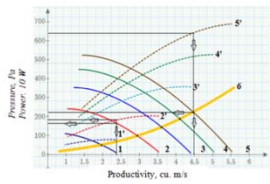

Figure 6. Diagram for calculation under the conditions of simultaneous operation with the supply of finely sprayed water

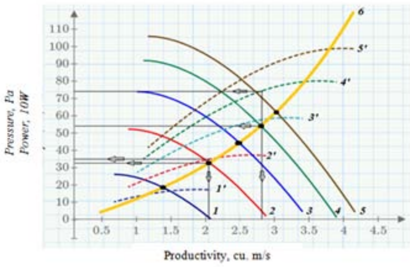

Figure 7. Diagram for calculation under the conditions of compatible operation with a foam-generating unit

Based on the practice of designing and manufacturing axial fans, it is known that theoretical calculations do not provide the required accuracy, so the data for the modernization of the existing fan model were refined based on the use of experimentally determined characteristics of the smoke and heat removal means.

In order to carry out improvements and corresponding changes in the design of the existing fan model, a decision was made to select the necessary parameters, the optimization of which will ensure the maximum increase in productivity. The task of finding a maximum or a minimum by means of a complete factorial experiment must assume the existence of a maximum point of the response surface, but it cannot have a maximum or minimum point using a first-order plan. In this case, it is necessary to switch to plans of the second order, with variation of two possible factors on three levels (quadratic model). To solve the problem of constructing a second-order polynomial using [1], an experimental plan for two factors was constructed, using an orthogonal plan of the first order as a kernel, on which the construction of the second-order plan was completed, shown in Table 2. The formula of the response surface was chosen as follows:

$$Q(\beta,S) = b_0 + b_1\cdot\beta + b_2\cdot S + b_3\cdot\beta^2 + b_4\cdot S^2 + b_5\cdot\beta\cdot S, \quad (8)$$

The normalization of factors was carried out according to the formula:

$$X_1 = \frac{2\cdot\beta - \beta_{\min} - \beta_{\max}}{\beta_{\max} - \beta_{\min}}, X_2 = \frac{2\cdot S - S_{\min} - S_{\max}}{S_{\max} - S_{\min}}, \quad (9)$$

Table 2: Orthogonal plan of the second order

No of the experiment	X_1	X_2	$X_1^2 - \varphi$	$X_2^2 - \varphi$	$X_1 \cdot X_2$	y
1	-1	-1	1/3	1/3	+1	y_1
2	+1	-1	1/3	1/3	-1	y_2
3	-1	+1	1/3	1/3	-1	y_3

4	+1	+1	1/3	1/3	+1	y_4
5	-1	0	1/3	-2/3	0	y_5
6	+1	0	1/3	-2/3	0	y_6
7	0	-1	-2/3	1/3	0	y_7
8	0	+1	-2/3	1/3	0	y_8
9	0	0	-2/3	-2/3	0	y_9

In our case (at the set maximum frequency of rotation of the fan impeller), the following factors were chosen: the angle of inclination of the blade of the middle line of the grid of profiles and the total active area of the blades. Using a previously developed mathematical model, the values of the physical values of the selected factors were determined. The obtained data are displayed in Table 3.

Table 3: Working planning matrix and research results

No. of the experiment	Angle of inclination, rad.	Area m^2	Productivity, 1st measurement, $m^3 \cdot h^{-1}$	Productivity, 2nd measurement, $m^3 \cdot h^{-1}$	Productivity, 3rd measurement, $m^3 \cdot h^{-1}$	Average productivity, $m^3 \cdot h^{-1}$	Unbiased sampling variance
	β	S	Q_1	Q_2	Q_3	Q	σ^2
1	0.60	0.0750	9938	10192	10254	10128	28036
2	0.96	0.0750	10480	11659	9895	10678	807327
3	0.6	0.1800	12493	11173	10018	11228	1533675
4	0.96	0.1800	10532	10562	10493	10529	1197
5	0.6	0,1275	10880	12299	10973	11384	630081
6	0.96	0,1275	11008	11042	10893	10981	11008
7	0.78	0.0750	10008	11192	10828	10676	367792
8	0.78	0.1800	10638	11492	11104	11078	182836
9	0.78	0.1275	12495	11223	10698	11472	853803

The reproducibility of the performance measurement experiments was confirmed using the Cochren criterion:

$$G = \frac{\sigma^2_{max}}{\sum_{i=1}^{n} \sigma^2} = 0.348 < G95\%\ (n.m-1) = 0.4775 \quad (10)$$

where: m = 3 – the number of factors;

n = 9 – the number of experiments.

After calculating the regression coefficients in the formula for normalized factors, and taking into account formula (6), we will get the values of the regression coefficients of the response surface for the physical values of the factors. Then the formula of the response surface in physical (β, S) variables is written as follows:

Q(β,S) = 56.1660997+81831.5193 β + 15931.4153 S – 7839.5062 · β2 – 202993.1973 · S2 – 33042.3280 · β · S (11)

The adequacy of the obtained model was confirmed using Fisher's test.

Reproducibility variance:

$$\sigma^2_y = \frac{\sum_{i=1}^{n} \Delta Q_i^2}{n} = 4336.861 \quad (12)$$

Adequacy variance:

$$\sigma^2_{ad} = \frac{\sum_{i=1}^{n} \Delta Q_i^2}{n-k-1} = 6505.292 \quad (13)$$

Let us calculate Fisher's adequacy criterion:

$$F = \frac{\sigma^2_{ad}}{\sigma^2_y} = 1.5 < F95\%(g,h) = 8.9406, \quad (14)$$

where: F95%(f, g) - the tabular value of Fisher's test, which corresponds to a confidence level of 95% according to [10]:

f = n – k – 1 = 6 – the number of degrees of freedom of the adequacy variance;

g = n – 0.5·(k+2)·(k+1) = 3 – the number of degrees of freedom of the dispersion of reproducibility.

The results of the calculation of deviations are shown in Table 4.

Table 4: Results of calculation of deviations

Deviation	**Obtained values**
Cochren criterion	0.4775
Fisher's criterion	8.9406
Reproducibility variance	4336.861
Adequacy variance	6505.292

The desired performance maximum corresponds to the function maximum. To find the values of the parameters that will ensure the maximum performance of the smoke and heat removal means, we find the derivatives of the two-dimensional function Q (β, S) (according to formula (6)) with respect to the independent variables β and S:

$$\frac{\partial Q(\beta,S)}{\partial \beta} = -15679 \cdot \beta - 33042.3 \cdot S + 15.931.4,$$
$$\frac{\partial Q(\beta,S)}{\partial S} = -33042.3 \cdot \beta - 405986 \cdot S + 81834.5. \quad (15)$$

Equating the right-hand sides of both equations to zero, we get a system of equations:

$$\begin{cases} -15679 \cdot \beta - 33042.3 \cdot S + 15931.4 = 0 \\ -33042.3 \cdot \beta + 405986 \cdot S + 81.834.5 = 0 \end{cases} \quad (16)$$

Having solved this system of equations, we will obtain the values of the angle of attack of the fan blade profile and the active surface area of the blades, which ensure the maximum productivity of the smoke cleaner:

Optimal parameters:

the angle of attack of the fan blade profile x = 0.71 radians, which corresponds to β = 41°;

active surface area of the blades y = 0.143 m^2, which in our case corresponds to S = 0.143 m^2 and the following value of the width of the blade:

$$b = \frac{2 \cdot S}{n_b \cdot D \cdot (1 - v_h)} = 0.1103, \text{ m} \quad (17)$$

Based on the results of the approximation of experimental data for more significant parameters using a mathematical model, the values of the optimal values of the angle of inclination of the blade profile (x) and the total active surface area of the blades (y) were obtained, and the formula for the maximum productivity Q (x, y) of the smoke and heat removal device was obtained, which was used during its improvement, having the form:

Q (x, y) = -7840 x2-33040 x y+15930 x-203000 y2+81830 y-56.17 (18)

The resulting three-dimensional graph based on the results of the approximation is shown in Figure 8.

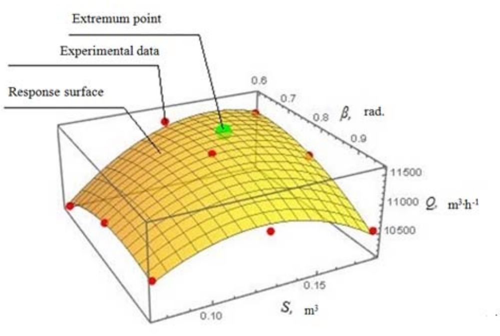

Figure 8. Three-dimensional graph showing the approximation results

4 Conclusion

As a result of the research, a mathematical model was built that allows investigating the dependence of productivity, as a characteristic that directly affects the duration of tactical ventilation by fire and rescue units, on the technical parameters of the smoke and heat removal means.

A list of parameters that have the most significant influence on the performance of the smoke and heat removal device, taking into account economic indicators regarding the production, operation, and maintenance of the device in the event of a change in the considered parameter, is established, namely: the angle of inclination of the fan blade profile and the total active area of the working fan wheel' surface.

On the basis of the mathematical model, the range of values of the parameters, which are accepted during further experimental studies in order to find an approximation formula, and that for the angle of inclination of the fan blade range from 0.6 to 0.96 radians for the total active surface area of the fan impeller from 0.075 to 0.18 m2 was established.

After performing a series of experiments (the reproducibility of which was confirmed with a confidence level of 95% according to the Cochren criterion), an approximation polynomial of the second order was obtained (the adequacy of which was confirmed with a confidence level of 95% according to the Fisher criterion), that reflects the dependence of the performance of the smoke and heat removal means on the angle of inclination of fan blade (β, rad.) and the total active surface area of the blades (S, m):

$$Q(\beta,S) = 56.1660997+81831.5193\ \beta + 15931.4153\ S - 7839.5062 \cdot \beta2 - 202993.1973 \cdot S2 - 33042.3280 \cdot \beta \cdot S$$

Based on the obtained approximation formula of the dependence of the smoke and heat removal device productivity on the angle of inclination of the fan blade and the total active surface area of the blades, by finding the maximum value, the optimal values of these parameters were found, namely: the angle of inclination of the fan blade is 0.71 rad. and the active surface area of the fan impeller from 0.143 m^2, which correspond to the maximum performance of the smoke and heat removal means. The found values are used as a basis for the improvement of the smoke and heat removal means.

On the basis of a mathematical model, the characteristics of the smoke and heat removal device were built, demonstrating characteristic changes in their parameters (engine power and air supply or air mixture performance) for a room with a certain aerodynamic characteristic, when smoke and heat removal is provided in different operating conditions, namely: air injection, air injection with simultaneous supply of finely atomized water, and air injection with simultaneous supply of foam.

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