На основі диференціальних рівнянь, що представляють газоповітряний тракт виробничого обладнання і характеризують його процеси, з використанням закону збереження маси і балансу тисків, розроблена методика для визначення розподілу газоповітряних потоків на виході технологічного тракту. Розроблена математична модель для встановлення механізму впливу на швидкість газоповітряного потоку і визначення місця розташування гвинта генератора у газоповітряному потоку для вироблення газоповітряною енергетичною установкою максимальної електроенергії

Ключові слова: газоповітряна енергетична установка, газоповітряні потоки, технологічний тракт, електроенергія, лабораторний стенд

На основе дифференциальных уравнений, представляющих газовоздушный тракт производственного оборудования и характеризирующих его процессы, с использованием закона сохранения массы и баланса давлений, разработана методика для определения распределения газовоздушных потоков на выходе технологического тракта. Разработана математическая модель для установления механизма влияния на скорость газовоздушного потока и определения местоположения винта генератора в газовоздушном потоке для выработки газовоздушной энергетической установкой максимальной электроэнергии

Ключевые слова: газовоздушная энергетическая установка, газовоздушные потоки, технологический тракт, электроэнергия, лабораторный стенд

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SIMULATION OF A GAS AND AIR FLOW EXHAUSTED BY PRODUCTION EQUIPMENT

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1. Introduction

A market economy requires an increase in the efficiency of electricity consumption by production facilities, which corresponds to the economic interests of the supplier and consumer of electricity. Searching for alternative sources of energy in an enterprise is the main task of modern production. As an energy source, gas and air flows exhausted in the process can be used. One of the ways of solving this problem is to obtain electricity from the consumer by removing the kinetic energy of the exhaust gas flow at the exit from the production equipment. For this purpose, gas and air power units (GAPUs) are introduced. Electricity in a GAPU is obtained by converting the mechanical energy of the generator's propeller rotation into electrical power. The expediency of developing new GAPUs with modern control systems complies with Ukraine's energy strategy for the period up to 2030 [1]. Therefore, this particular direction should provide part of the overall energy saving of the consumer. A GAPU requires increasing the efficiency of work to obtain the maximum electrical energy. This is achieved with sufficient power and kinetic energy of the gas and air flow. At the same time, the gas and air flow rate is proportional to the cross-sectional area of the flow, density and velocity in the third stage.

In this direction, extensive scientific work is carried out all over the world to produce new developments, which can be seen in studies devoted to research findings that have a significant impact on the efficiency of power units [2, 3].

According to the theory of the ideal propeller actuated by the gas and air flow, its useful work becomes part of the kinetic energy. Therefore, it is necessary to conduct additional research on the influence of gas and air flows to determine the conditions for ensuring maximum efficiency of the GAPU. This testifies that the topic of research devoted to the process of distributing exhaust gas streams at the exit from the technological channel of production equipment for the effective operation of the GAPU is an important scientific and practical problem.

2. Literature review and problem statement

Study [4] shows that an autonomous wind power unit uses mine airflows. However, the efficiency of this installation is small, as the air flow in underground iron ore mines is not intense.

The use of wind energy in the work of wind power units depends on the speed of the wind flow. However, the wind flow changes during the day, during the month and season of the year [5]. Therefore, the kinetic energy of the wind has a low efficiency. To eliminate this disadvantage, the authors propose to use wind power units and solar energy installations [6, 7], or low potential air, thermal and hydraulic flows [8, 9]. In scientific work [10], research is aimed at developing mathematical models for determining the impact of a turbulent air flow on the operation of the wind turbine. For this, it is suggested to perform computer and physical simulations. In other articles, authors use genetic algorithms [11]. Meanwhile, the European Academy of Wind Energy solves wind power problems in a long-term research program [12]. However, while studying the construction of modern automated wind power unit control systems, researchers underestimate the impact of gas and air flows on the work of the GAPU to obtain the maximum amount of electricity. Despite the obvious, obtaining additional electricity by removing the kinetic energy of the exhaust gas flux from the production equipment in general is not considered by the researchers. This imposes certain restrictions on the use of a GAPU.

At the same time, the development of wind power units of small and ultra-high power is noted in [13–15]. However, for such installations there is not enough research for the conditions of ensuring the maximum efficiency of their work. Paper [16] shows ways to improve the efficiency of air power units, though not for GAPUs, which work on exhaust gas fluxes of production equipment. The known methods of alternative power generation can include the approach that involves transforming thermal energy into mechanical work in a gas turbine unit [17]. However, this method of generating electricity requires additional costs for compressing air and combusting hydrocarbon fuels. In this case, it is necessary to mix the products of combustion with water vapour and cool the gas and steam mixture. This significantly reduces the efficiency and involves additional equipment, which is expensive. Another well-known method is to obtain electricity in the subway [18], which includes operations for creating and using air streams. Mechanical energy is transformed into electrical by artificial creation of air flows from the movement of electrical trains. The torque of the air propeller simultaneously drives the shaft of the generator, producing electricity. The disadvantage of this method is that the air mass flow that occurs as a result of the electrical train movement is not fully utilized, which reduces the efficiency of electricity generation. The implementation of this method requires an additional air mass flow on the generator's propeller blades. This significantly reduces the efficiency of converting air masses into mechanical energy. The implementation of this method additionally requires material and financial expenses.

Modern research is aimed at improving the design and systems of controlling wind power units [19–21]. A wind power unit is a very complex electromechanical facility, and its control system needs improving. The given task improves devices [22, 23] that use a stream of gas and air masses, worked out, released or blown by technological equipment. Such devices have a manageable control system. It is powered by an electrical network and the electrical energy derived from the conversion of the kinetic energy of the mass flow of gases and air. The devices work from technological equipment containing a technological channel for the separation of the gas and air flow. Inside the duct, there is an air fan propeller. The GAPU consists of a generator, the generator propeller, a microcontroller, switches, gas and air flow sensors, a frequency converter, and a control unit. This reduces the amount of electricity used by industrial equipment. However, the work of the GAPU depends on the availability of the required stable flow in the technological channel. This prevents the GAPU from using the flow energy in its entirety. In addition, this control requires choosing the optimal angle of the generator propeller blades, which greatly complicates the design of the GAPU. The problem of distributing exhaust gas flows at the exit from the technological channel of production equipment is also unresolved. The issue of determining the place of the greatest intensity of gas and air flows at the exit from the technological channel has not been considered either. It is necessary to define these conditions for developing maximum electrical energy by the GAPU.

3. The aim and objectives of the study

The purpose of this work is to simulate the gas and air flow exhausted by industrial equipment so that the gas and air power unit could produce the maximum electrical energy.

To achieve this aim, the following tasks are set and solved:

– to develop a methodology for calculating the gas and air flow rate at the exit from the technological channel;

– to develop a mathematical model for determining the distribution of gas and air flows at the exit from the technological channel;

– to verify the adequacy of the results obtained on the mathematical model using a laboratory facility.

4. Research on the distribution of gas and air flows

4. 1. A method of calculating the velocity of the gas and air flow during the fan operation in the process channel

To answer the question about calculating the velocity of the gas and air flow when it is generated by the fan and at the exit from the technological channel of production equipment, it is expedient to use mine fans of local VMEVO ventilation types. These fans are designed to ventilate deadlock coal and ore mines, including those that are hazardous in terms of gas and dust. The gas and air flow is provided through a flexible or rigid process pipeline with a diameter of 0.6 to 1.2 meters and a length of more than 25 meters. For calculations, five models of mine fans were selected. Their specifications are provided in Table 1.

To calculate the velocity of the gas and air flow in the process channel, its output power, the influence of the parameters of the technological channel and its other indicators, it is necessary to obtain appropriate mathematical expressions. An important step in this case is to determine the power of the air stream at the exit from the technological channel, that is, what amount of electricity we can get, for example, using the VMEVO types of fans. Thus, the power at the exit from the technological channel is determined by the formula [24]:

$$P_{out} = C_p \frac{p \cdot V^3}{2} \cdot D \cdot H \cdot \eta_{tot}, \qquad (1)$$

where C_p is the power factor equal to the ratio of the power of the flowing gas and air to the power of the rotor shaft; V is the velocity of the gas and air flow, m/s; ρ is the density of the gas and air, kg/m^3; η_{tot} is the pre-set efficiency; H is the height of a blade; D is the diameter.

Table 1

Specifications of the fans

Parameters \ Name	VMEVO-5-15	VMEVO-6-25	VMEVO-8-45	VMEVO-10-110	VMEVO-12-110
Nominal diameter, mm	500	600	800	1,000	1,200
Nominal supply, m^3/s	3.6	7	9	14	23
Nominal full pressure, Pa	2,300	2,500	3,500	5,200	3,300
Maximum efficiency	0.66	0.7	0.7	0.67	0.7
Power of the electrical drive, kW, max	15	25	45	110	110
Rotation frequency, min^{-1}	3,000	3,000	3,000	3,000	1,500
Height, mm, max	770	895	1,105	1,160	1,385
Width, mm, max	600	775	1,000	1,100	1,200
Length, mm, max	950	1,035	1,190	1,530	1,961

Before determining the output power, it is necessary to calculate the gas and air flow rate for each fan model. The velocity of the gas flux created by the fan is found according to the known formula:

$$V = \frac{Q}{S}, \quad (2)$$

where Q is the volume flow of gas and air through the fan; S is the area of the technological channel.

The area of the technological channel can be calculated by the formula [25]:

$$S = 2\pi rl + 2\pi r^2 = 2\pi r(l + r), \quad (3)$$

where r is the radius; l is the length of the technological channel.

For the calculations, the following dimensions of the technological channel are taken: $r=50$ mm$=0.05$ m as the radius; l equals one meter of the length of the technological channel.

The maximum useful energy is obtained using the generator's propeller. It is kinematically associated with the rotor of the generator. The energy value is estimated by the coefficient of energy use of the gas and air stream, the maximum value of which can be equal to 0.593. In addition, as the practice shows, the existing range of speed of the gas and air flow is not fully utilized by the existing structures of the GAPU. At the rate of the air flow below the minimum, the working power of the propeller is not enough even to rewind the frictional forces in its knots. Formula (2) is used to calculate the gas and air flow rates for each type of the fan.

4. 2. Development of a mathematical model for the distribution of gas and air flows at the exit from the technological channel

To determine the distribution of the gas and air flow produced by the fan in the process channel and the efficiency of using the kinetic energy of the exhaust gas flux for the production of electrical energy, we shall develop a mathematical model. To do this, we deduce the differential equations for describing the technological channel and the elements of the GAPU, which is presented in Fig. 1.

Let us note the variables (control values): ω_{eng} is the speed of rotation of the blower fan; ω_{gen} is the speed of the generator propeller rotation; Q_{in} and Q_{out} are input and output variables (regulated quantities) of the gas and air flow through the generator's propeller.

The physical equation that characterizes the processes of the gas and air channel through the law of mass conservation is as follows:

$$\frac{dm}{dt} = Q_{in} - Q_{out}. \quad (4)$$

The difference between the air flow at the inlet and exit is accumulated in the working field of the generator's propeller location.

The equation of state, as is known from the courses of thermodynamics, has the form:

$$PV = \frac{m}{\mu} RT, \quad (5)$$

where $V=V_t$, and $m=V_t=V\rho$.

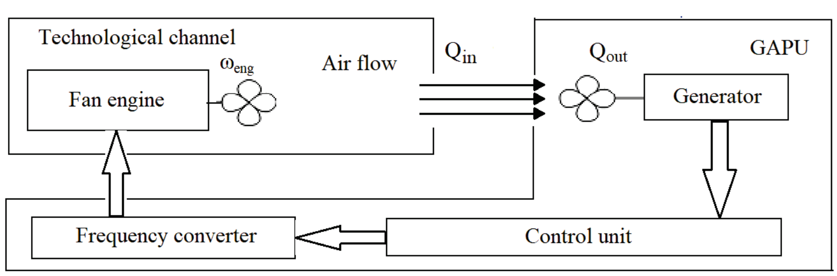

Fig. 1. The technological channel and the GAPU elements

Equation (4) produces a correlation that connects the mass and pressure in this case: $m=k_{cor}P$. Substituting the correlation in the law of conservation of mass (4), we obtain the formula for measuring the pressure:

$$k_{cor}\frac{dp}{dt}=Q_{in}-Q_{out}. \qquad (6)$$

The low-level rarefaction in the working field before and after the generator's propeller is taken into account in the system of equations using the pressure balance. Let us record the balance of pressures [26] in the form of a system of differential equations for the section before and after the generator's propeller operation:

$$\begin{cases}\frac{l_p}{S_p}\frac{dQ_{in}}{dt}=P_{eng}-P_p-P_{resp};\\ \frac{l}{S}\frac{dQ}{dt}=P_{gp}-P_p-P_{respg}.\end{cases} \qquad (7)$$

By introducing the assumption that the air and gas flows are laminar, we shall write the equations of hydrodynamics, which establish the relation between the use and loss of pressure to the resistance:

$$\begin{cases}P_{resp}=\xi_{resp}Q_{in};\\ P_{respg}=\xi_{respg}Q_{out}.\end{cases} \qquad (8)$$

Let us rewrite differential equations (7) taking into account (8) in the form:

$$\begin{cases}\frac{l_p}{S_p}\frac{dQ_{in}}{dt}=P_{eng}-P_p-\xi_{resp}Q_{in};\\ \frac{l}{S}\frac{dQ}{dt}=P_{gp}-P_p-\xi_{>B3}Q_{out}.\end{cases} \qquad (9)$$

The equation of the blower fan and the work of the generator propeller in the assumption are written so that the pressure in them depends linearly on the speed of the engine rotation:

$$\begin{cases}P_{eng}=k_{eng}\omega_{eng};\\ P_{gp}=k_{gp}\omega_{gp}.\end{cases} \qquad (10)$$

After the transformations, the resulting differential equations will be combined into a system that characterizes the gas and air channel as an object of regulation [27]:

$$\begin{cases}Q'_{in}=-\xi_{resp}\frac{S_{resp}}{l_{resp}}Q_{resp}+k_{resp}\frac{S_{resp}}{l_{resp}}\omega_{resp}+\frac{S_{resp}}{l_{resp}}P_p;\\ Q'_{out}=-\xi_{respg}\frac{S_{pg}}{l_{pg}}Q_{out}+k_{pg}\frac{S_{pg}}{l_{pg}}\omega_{pg}+\frac{S_{pg}}{l_{pg}}P_p;\\ P'_p=\frac{1}{k_{cor}}Q_{in}-\frac{1}{k_{cor}}Q_{out}.\end{cases} \qquad (11)$$

For modelling in SolidWorks Flow Simulation [28], we obtain the necessary system of equations. The system of equations takes into account the conservation of mass, momentum, and energy of the non-stationary spatial flow in the Cartesian coordinate system (x_i, $i=1, 2, 3$). The coordinate system rotates with an angular velocity Ω around the axis passing through its beginning [29]:

$$\begin{cases}\frac{\partial\rho}{\partial t}+\frac{\partial}{\partial x_k}(\rho u_k)=0;\\ \frac{\partial(pu_i)}{\partial t}+\frac{\partial}{\partial x_k}(\rho u_i u_k-\tau_{ik})+\frac{\partial}{\partial x_i}=S_i;\\ \frac{\partial(pE)}{\partial t}+\frac{\partial}{x_k}((pE-P)u_k+q_k)-\tau_{ik}u_i=S_k u_k+Q_H,\end{cases} \qquad (12)$$

where t is time, u is the speed of the gas and air flow; ρ is the density of the gas and air flow; P is the pressure of the gas and air flow; S_i means the external mass forces acting on the unit mass of the gas and air flow: S_{res} is the effect of the resistance of the porous body; S_{gr} is the effect of gravitation; S_{csr} is the effect of the coordinate system rotation. $S_i=S_{res}+S_{gr}+S_{csr}$; E is the total energy of the unit mass of the gas and air flow; Q_H is the heat released by the heat source in the unit volume of the gas and air flow; τ_{ik} is the tensor of viscous shear stresses; q_i is the diffuse heat flux, where lower indices mean summation over three coordinate directions.

For Newtonian fluids, the tensor of viscous shear stresses is determined as follows:

$$\tau_{ij}=\mu\left(\frac{\partial u_i}{\partial X_j}+\frac{\partial u_j}{\partial X_i}-\frac{2\partial u_i}{3\partial X_i}\right)-\frac{2}{3}\rho k\delta_{ij}, \qquad (13)$$

where $\mu=\mu_l+\mu_t$, μ_l is the coefficient of dynamic viscosity; μ_t is the coefficient of turbulent viscosity; δ_{ij} is the Kronecker delta function ($\delta_{ij}=1$ at $i=y$, $\delta_{ij}=0$ at $i\neq y$); k is the kinetic energy of turbulence. Accordingly, $k-\varepsilon$ is a model of turbulence, and μ_t is determined by the values of the kinetic energy of turbulence k and the dissipation of this energy ε:

$$\mu_t=f_\mu\frac{C_\mu\rho k^2}{\varepsilon};$$

$$f_\mu=\left(1-\exp(-0.025R_y)\right)^2\cdot\left(1+\frac{20.5}{R_t}\right);$$

$$R_y=\frac{\rho\sqrt{ky}}{u_i};\quad R_T=\frac{\rho k^2}{u_i\varepsilon};$$

where $f_\mu=\left(1-\exp(-0.025R_y)\right)^2\cdot\left(1+\frac{20.5}{R_t}\right);$

$$R_y=\frac{\rho\sqrt{ky}}{u_i};\quad R_T=\frac{\rho k^2}{u_i\varepsilon};$$

y is the distance from the surface of the wall; $C_\mu=0.09$.

The kinetic energy of turbulence k and the dissipation of this energy ε are determined by solving the following two equations [30]:

$$\frac{\partial\rho k}{\partial t}+\frac{\partial}{\partial X_k}(\rho u_k k)+\frac{\partial}{\partial X_k}\left[\left(\mu_i+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial X_k}\right]+S_k, \qquad (14)$$

$$\frac{\partial\rho\varepsilon}{\partial t}+\frac{\partial}{\partial X_k}(\rho u_k\varepsilon)+\frac{\partial}{\partial X_k}\left[\left(\mu_i+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial X_k}\right]+S_\varepsilon, \qquad (15)$$

where

$$S_k=\tau_{ij}^R\frac{du_i}{dx_j}-\rho\varepsilon+\mu_l P\ ;$$

$$S_\varepsilon=C_{\varepsilon1}\frac{T}{k}\left(f_1\tau_{ij}^R\frac{du_i}{dx_j}+\mu_t C_B P_B\right)-C_{\varepsilon2}f_2\frac{\rho\varepsilon^2}{k}, \quad (16)$$

$$\tau_{ij}^R=\mu_t\left(\frac{du_i}{dx_j}+\frac{du_j}{dx_i}-\frac{2}{3}\frac{du_l}{dx_l}\delta_{ij}\right)-\frac{2}{3}\rho k\delta_{ij};$$

$$P_B=-\frac{g_i}{\sigma_B}\frac{1}{p}\frac{dp}{dx_i}, \quad (17)$$

where g_i is the component of gravitational acceleration in the coordinate direction. x_i, σ_B=0.9; C_B=1 at P_B>0 and C_B=0 at $P_B\leq 0$, $f_1=1+(0.05/f_\mu)^3$, $f_2=1-\exp(-R_T^2)$; $C_{\varepsilon1}=1.44$; $C_{\varepsilon2}=1.92$; σ_ε=1.3; σ_k=1.

The diffusion heat flux is modelled using the equation:

$$q_k=\left(\frac{\mu_l}{p_r}-\frac{\mu_t}{\sigma_c}\right)c_p\frac{dT}{dx_k},\ k=1, 2, 3, \quad (18)$$

where σ_c=0.9 Pr is the Prandtl number; c_p is the specific heat at constant pressure; T is the temperature of the gas and air flow.

4. 3. The laboratory facility for studying the distribution of gas and air flows at the exit from the technological channel

To verify the adequacy of the results obtained through the mathematical model, the developed resources are information data and software, an automation scheme and a laboratory facility that is connected via the USB-2 interface to the computer. The facility contains a technological channel. At the entrance to the technological channel, a fan propeller is installed. The GAPU manages the work of the fan. At the exit from the process channel, a propeller is installed to be kinematically connected to the generator. The output voltage of the generator is accumulated in the GAPU. The technical characteristics of the fan, the technological channel and the generator propeller are given in Table 2.

Table 2

Specifications of the fan, the technological channel, and the generator propeller

Fan DeepCool GS120	Technological channel	Generator propeller
Fan diameter: 110 mm	Length: 500 mm	Fan diameter: 110 mm
Number of blades: 11	Diameter: 110 mm	Number of blades: 3; the blades' inclination angle: 32.73.
Diameter: 38.5 mm	Thickness of the walls: 4 mm	Diameter: 38.5 mm
Material: polypropylene	Material: polypropylene	Material: polypropylene
Air flow: 61.93 cfm (1.754 m^3/min)	–	–

A virtual computer model was installed to identify the patterns of electricity consumption, the confirmation of technical indicators and the efficiency of the proposed method of obtaining electricity using the GAPU. This model is developed in the LabVIEW software environment. Experimentally, the energy characteristics of the GAPU are recorded when changing the speed of the fan rotation. The obtained data are summarized in Table 3.

Table 3

Characteristics of the GAPU performance when changing the speed of the fan blades rotation

U_f, V	ω, rpm	U_g, V	I, A	P, W	Q_{in}, m/s	Q_{out}, m/s
23.45	4,300	4.55	0.406	9.5	5.4	4.5
22.08	3,507	4.41	0.39	8.6	4.6	3.7
21. 22	3,280	3.8	0.37	7.85	4.0	3.1
20.46	3,001	2.12	0.36	7.36	3.6	2.7
18.6	2,512	0	0.35	6.51	3	2.1

Table 2 shows that when the power supply voltage U increases, the fan speed increases. At the same time, the voltage U_f and current I increase at the output of the generator. The gas and air flow to the generator propeller Q_{in} decreases at its Q_{out} to 30 % when the speed of the fan rotation decreases. The experiment and the model of calculation confirmed the main characteristics of the GAPU work.

5. Results of studying the distribution of the gas and air flow at the exit from the process channel

Mathematical expressions (1)–(3) were used to construct the dependencies of output power on the air flow velocity for different types of mine fans. The characteristics are presented in Fig. 2, *a*. As the analysis of these characteristics shows, in order to increase the air flow rate at the exit from the technological channel, it is necessary to increase the output power of the fan. We have practically linear dependencies, except for one fan model type VMEVO-12-110 (Fig. 2, *a*). The size of the propeller blade increases the air flow rate at the exit from the process channel (Fig. 2, *b*). Increasing the speed of the air flow by the area (Fig. 2, *c*) and the length (Fig. 2, *d*) of the technological channel leads to a decrease in the air flow velocity at the exit from the process channel.

Mathematical expressions (4)–(18) are used to simulate the air distribution process in the SolidWorks Flow Simulation software environment. The simulation is performed when air is blown by the fan towards the exit from the technological channel.

Fig. 3 shows the result of simulating the distribution of air flows outside the technological channel. The generator propeller is located at a distance of 400 mm (Fig. 3, *a*) and 1,000 mm (Fig. 3, *b*) from the technological channel exit. In this case, the fan speed in the test was roughly 4,300 rpm.

The change in the speed of the air flow at the edge and in the middle of the diameter at the exit from the process channel, respectively, is presented in Fig. 4, *a*, *b*. In these cases, the fan speed is roughly 4,300 rpm. When reducing the speed of fan rotation down to 2,500 rpm at various distances of the generator propeller in the middle of the diameter of the process channel, the nature of the relationship remains unchanged (Fig. 5).

The air pressure at the exit from the technological channel at the edge of the diameter and in the middle of the technological channel, respectively, is presented in Fig. 6, *a*, *b*. The change in the air temperature and the number of blade turns of the generator at the exit from the technological channel are given in Fig. 7, 8.

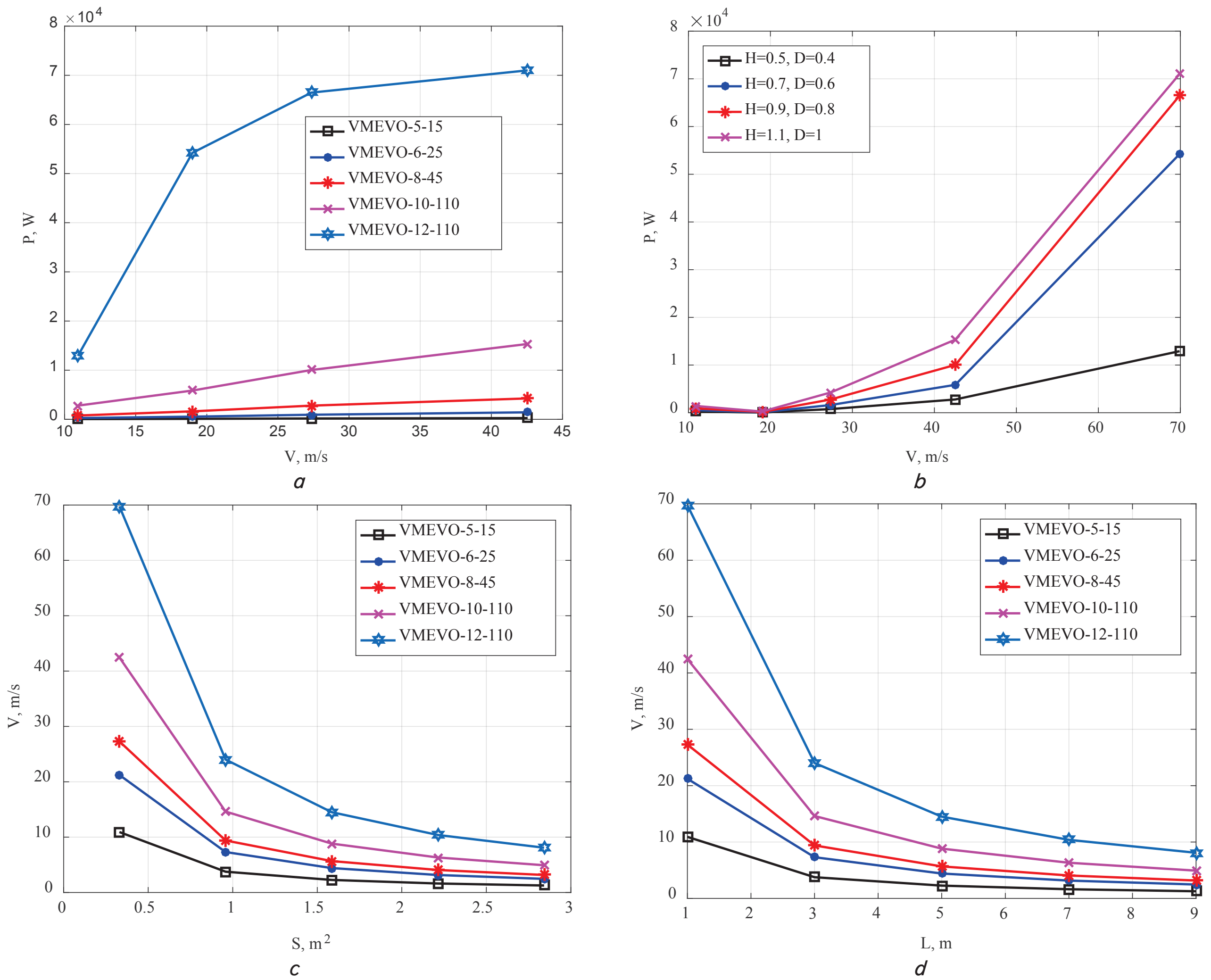

Fig. 2. Dependences of the output electricity of the fans: *a* – on the velocity of the gas and air flow; *b* – with different sizes of the propeller blade; *c* – the flow velocity depending on the area; *d* – on the length of the technological channel

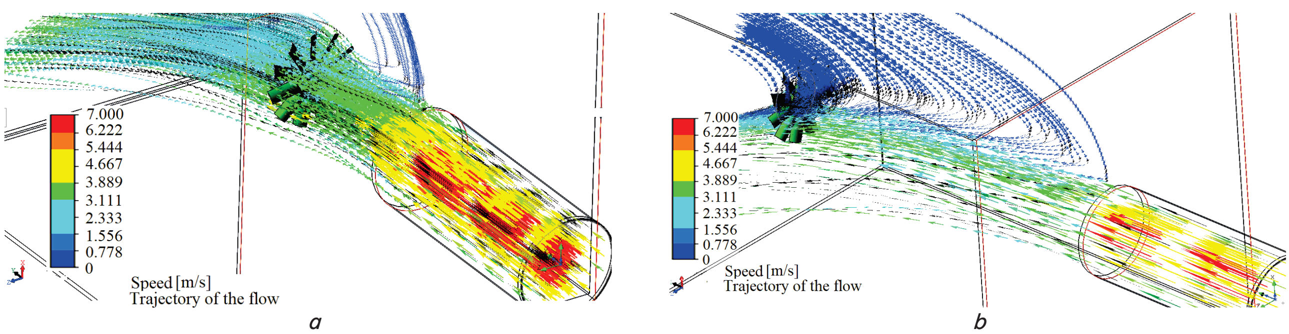

Fig. 3. Simulation of the process of the air flow distribution at distances from the technological channel exit before and after the generator's propeller: *a* – 400 mm; *b* – 1,000 mm

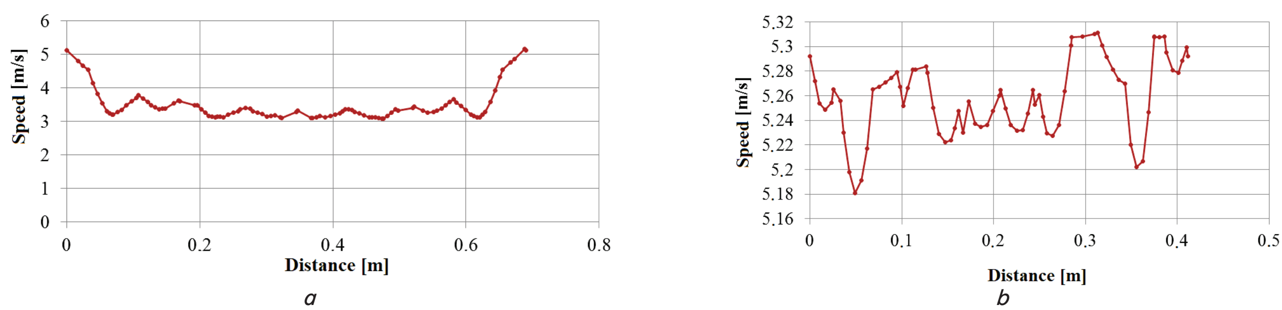

Fig. 4. Changes in the air flow velocity with the fan speed of rotation being 4,300 rpm: *a* – at the edge and *b* – in the middle of the diameter of the technological channel

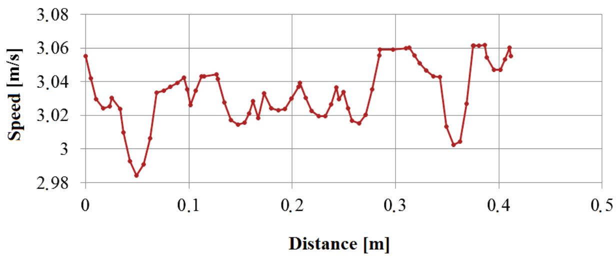

Fig. 5. A change in the air flow velocity with the rotation speed of the fan's blades being 2,500 rpm in the middle of the diameter of the technological channel

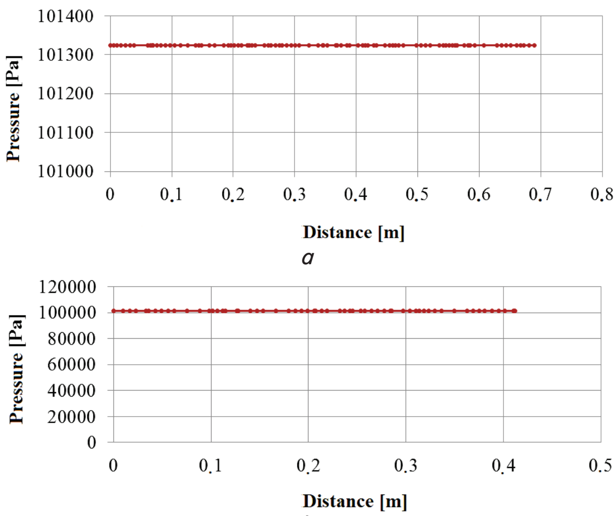

Fig. 6. A change in the air pressure at the exit from the technological channel: *a* — at the edge of the diameter of the technological channel; *b* — in the middle of the diameter of the technological channel

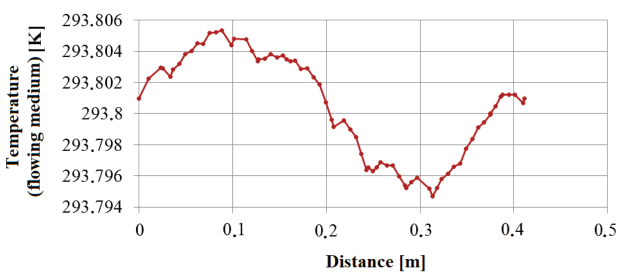

Fig. 7. A change in the air temperature at the exit from the technological channel

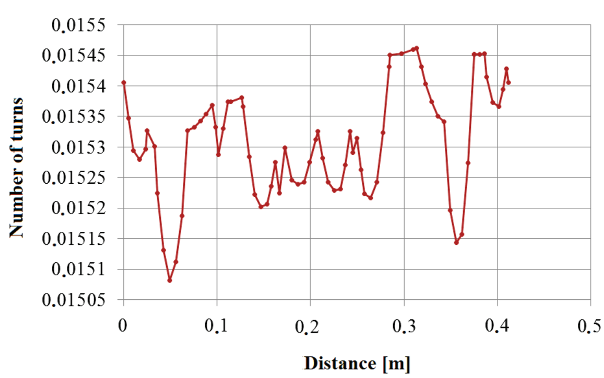

Fig. 8. A change in the number of turns of the generator's blades at the exit from the technological channel

To verify the adequacy of the results obtained with the help of the mathematical model, the characteristics of the GAPU were recorded using a laboratory facility. To do this, we used the LabView software application and an anemometer, a device for measuring the air flow velocity.

The comparative characteristics are given in Fig. 9.

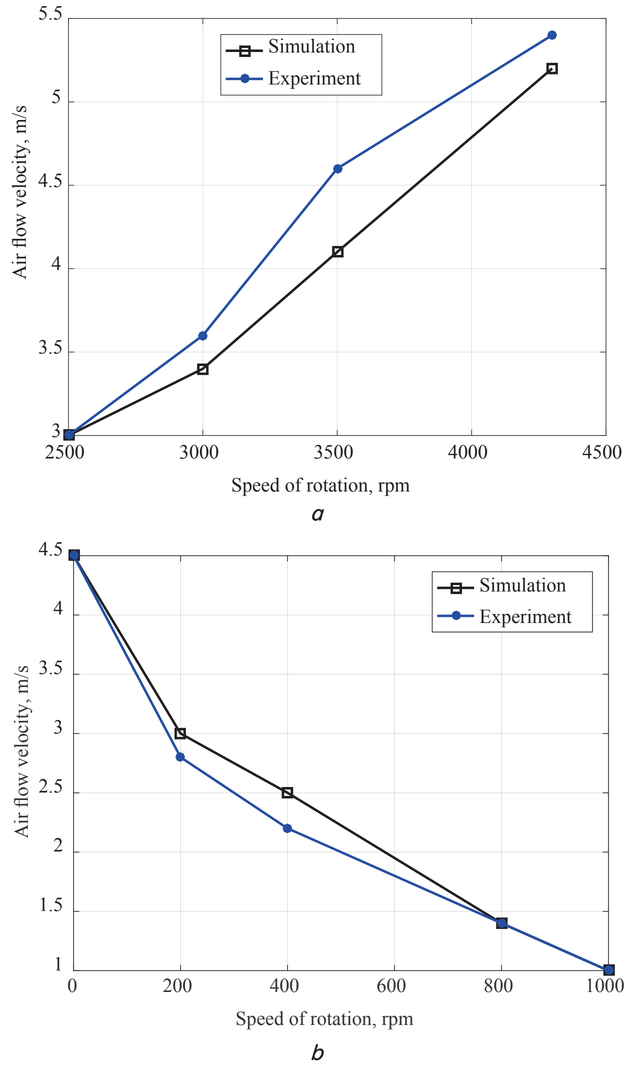

Fig. 9. Graphs of changes in the velocity of the gas and air flow in the function of the rotation speed of the fan propeller blades: *a* — at the exit from the technological channel; *b* — after the propeller of the generator

A fan DeepCool GS120 was used in the technological channel to obtain data on the work of the laboratory facility. The electrical drive of the fan contains a DC motor. It has permanent magnets of type RK-370ca-11490, a voltage of 24 V, a current of 350 mA, and a rotation speed of 4,300 rpm. The air flow is accumulated by the fan in a technological channel of 110 mm in diameter. Electrical energy is generated by a DC generator with permanent magnets of type RS-545ph. The operating range of the oscillator is from 32 V to 42 V, at a current of 0.04 A and a speed of 3,940 rad/min. In the process channel, the battery is constantly charged by the generator. The load on the battery, with a sufficient voltage level at its terminals, is the electric motor of the fan.

6. Discussion of the results of studying the process of distribution of exhaust gas fluxes

The analysis shows (Fig. 1, *a*) that the rate of the air flow at the exit from the technological channel is proportional to the power of the fan. The size of the blades of the fan propeller affects the speed of the air flow. This implies that with larger propeller blades, the output power increases at the same speed of the gas and air flow. At the speed from 11 to 42.5 m/s (Fig. 1, *b*), the first two models of the fans (VMEVO-5-15 and VMEVO-6-25) have practically the same performance, that is, the difference in the power that the propeller provides at the output when using these fan models is insignificant. With respect to other models (VMEVO-8-45, VMEVO-10-110, and VMEVO-12-110), with a change in the fan power, the output energy of the air stream increases, and the difference in the productivity becomes more and more visible. For example, at a speed of 42.55 m/s, the VMEVO-10-110 fan produces 3.5 times more power than the previous fan model.

As a result of the research, it has been determined that the especially important factors are the dimensions of the technological channel such as the area and length, which influence the speed of the air flow. Several values of the area and length of the technological channel were taken for calculations, which were made using formulas (2) and (3). Based on the graphs that are given in Fig. 1, *b*, *c*, it has been established that the larger the diameter and dimensions of the blade of the fan propeller, the greater the power value obtained at the exit. In this case, the overall dimensions, diameter and power consumption vary considerably. It is worth noting that at a speed of 11 to 27 m/s there is practically no difference in power, despite the different sizes of the propeller blade. However, at a speed of 70 m/s, a significant difference is observed in the power of the fans with the dimensions of the propeller blade being $H=0.5$ and $D=0.4$ as well as $H=0.7$ and $D=0.6$, which indicates a more purposeful use of the latter. As a result of analysing the dependencies presented in Fig. 1, *d*, the following conclusion is made: with an increase in the length of the technological channel, the air flow velocity decreases. It is worth noting that the longer the length of the process channel, the less the difference in the speed between different fan models is. Thus, with the length of the technological channel ranging from 7 to 9 meters, the difference in the speed between the different models of fans is not significant, and at a length of 9 meters it does not exceed 3–4 m/s.

The simulation of the distribution of the air flow before and after the generator propeller shows, in Fig. 3, that the influence of the air flow on the work of the generator's propeller is more effective at a distance of 400 mm from the technological channel exit.

The simulation results presented in Fig. 4, *a*, *b* show that the velocity of the air flow at the edge and in the middle of the diameter of the technological trajectory changes significantly. When the speed of rotation of the fan propeller blades increases from 2,500 rpm to 4,300 rpm, the speed of the air flow increases, too (Fig. 4, *c*).

The velocity of the air flow in the middle of the diameter of the process channel, regardless of the speed of rotation of the fan propeller blades being 2,500 rpm or 4,300 rpm, fluctuates significantly. The air pressure at the exit from the technological channel varies from the edge of the diameter towards the middle of the technological channel (Fig. 6). Depending on the speed of the air flow, the air temperature (Fig. 7) and the number of the blade turns of the generator propeller change (Fig. 8) at the exit from the process channel.

The value of the conducted research consists in obtaining the distribution of the gas and air flow before and after the generator propeller. One of the difficulties in the attempt to develop this study was the lack of a sufficient base of experimental facilities for researching such a technological process. This resulted in significant changes in the velocity of the air flow at the edge and in the middle of the diameter at the exit from the technological channel. It has been established that fluctuations of the gas and air flow vary from 0.16 % to 39 % in relation to its average value. The results of the tests have shown that when changing the speed of rotation of the fan propeller blades several times with a length of the technological channel being up to 500 mm and a diameter of 110 mm, the velocity of the gas and air flow at the exit varies proportionally, but the pressure remains unchanged.

A limitation of the study is that the tests were performed using only one configuration of the technological channel.

The obtained results are useful for determining the optimal location of the generator's propeller in the gas and air flow for to develop a gas and air power unit of maximum electrical energy capacity.

The research on the distribution of the gas and air flow at the exit from the technological channel of production equipment was not carried out before. Further improvement of this study may be in the direction of changing the configurations of the technological channel.

7. Conclusions

1. To obtain the gas and air power unit of the maximum electrical energy production capacity, a method has been developed for calculating the velocity of the gas and air flow at the exit from the technological channel. This helps determine the optimal location of the generator propeller in the working area of the process channel. The method consists of physical equations that characterize the gas and air flow through the law of mass conservation as well as accounts for a balance of pressures in the form of a system of differential equations for the section before and after the generator's propeller, representing the gas and air channel as an object of regulation. Using the proposed physical equations, the dependencies of the air flow velocity on the output power of different types of fans have been calculated. As the results of the study show, the location of the generator's propeller is influenced by the air flow, which depends on the fan's power, varies over the diameter of the process channel and is a function of the diameter and parameters of the blades of the fan and the technological channel. Fluctuations of the gas and air flow at the edge and in the middle of the diameter of the technological channel vary up to 39 % in relation to its average value. When the fan speed of rotation is changed several times, the velocity of the gas and air flow at the exit varies proportionally, but the pressure remains unchanged.

2. To analyse the distribution of gas and air flows, a mathematical model has been constructed. The model includes the equation of conservation of mass, momentum and energy of a non-stationary spatial flow in the Cartesian coordinate system. This system rotates at an angular velocity around the axis passing through its start. The mathematical model

includes equations on the kinetic energy of turbulence and the dissipation of this energy. The computer simulation of the technological process of distributing gas and air flows blown by the fan of the production unit is performed using the SolidWorks Flow Simulation software environment. The distribution of gas and air flows at the exit from the technological channel before and after the generator propeller is made at a distance of 400 mm and 1,000 mm away from the technological channel exit. Using the model, it was possible to determine changes in the air flow velocity after the generator at the exit from the process channel, depending on the fan speed changing from 2,500 to 4,300 m/s. In this case, the number of the propeller blades in the generator was 11, and the diameter of the propeller of the generator was 110 mm.

3. Experimental tests were carried out on a laboratory facility. The tests helped verify the adequacy of the results obtained in the computer simulation of the process of air blowing by the fan and their distribution at the exit from the technological channel. The change in the speed of the air flow at the technological channel exit that was obtained experimentally differs most noticeably from the result of the simulation – by 12 % with a fan speed of rotation being 3,500 rpm. However, after the generator's propeller, this parameter differs only by 8 % at a fan speed of rotation of 400 rpm. The experimental results of the GAPU were obtained using the SCADA system. To do this, a virtual model was developed in the LabVIEW software environment and installed on the computer. Through the USB-2 interface, the laboratory facility was connected to the computer.

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