A study of flow characteristics in a low-pressure ejector installation

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Abstract. Production processes sometimes are accompanied by the release of hazardous substances, the composition and volume of which is determined by the production technology. When designing ventilation systems for paint departments, special attention is paid to safety concerns, since all paint coatings are corrosive and flammable substances. Besides, solvent vapors are explosive. For local ventilation of painting chambers, it is rational to use safe exhaust systems with an ejector, which works sturdily, regardless of the release of flammable and explosive impurities. The ejector is simple in design and can operate in a wide range of changes in the parameters of the state of airflow. The model of the ejection unit is synthesized using the universal modeling package ChemCad, which contains a highly developed database of airflow parameters, which allows for solving various applied problems. Numerical modeling was carried out using the software package - FLUENT. In work, a calculation was carried out and a low-pressure ejector was designed for a typical painting booth. The calculation results are presented in the form of graphs and tables of pressures, velocities, flow rates in characteristic sections, pressure losses in the sections of the ejector installation.The ejection coefficient was also calculated.
Keywords: Heat supply, ventilation, air conditioning, gas supply, and lighting.

1 Introduction

There are known studies in which to stabilize the operation of the exhaust ventilation system of buildings for various purposes it is proposed to design modular ejection systems [1-6].

When designing industrial ventilation, supply and exhaust systems are used based on the operation of fans. Such solutions are quite sufficient in assembly, packaging, and filling shops of industries that are not associated with the release of pollutants, and where the main task of ventilation is the comfortable stay of the working personnel in the room. If the production process is associated with the release of a large amount of heat, moisture, dust, flammable and explosive substances, then when designing ventilation systems, it is

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necessary to take into account the peculiarities of the production technology [7-9] and the danger of using fans. In cases where the exhaust air contains explosive or destructive impurities acting on the fan, for example, in painting booths or in chamber dryers, when it is required to create insignificant dynamic pressures for the circulation of airflow, it is rational to use safe exhaust systems with an ejector. At the same time, ejection systems have low efficiency and therefore are used when other solutions are not possible. In the studies [10-11], a description and study of exhaust ventilation systems is given, where ejector installations have been used that work reliably, regardless of the volume of released flammable, explosive, and abrasive impurities.

Methods for calculating ejectors are well developed, but they do not allow for designing optimal solutions with minimal energy consumption. Problems of this kind are effectively solved using various modeling applications. In particular, the use of the ChemCad universal modeling program (UMP) allows for the calculating of the thermophysical properties of air flows with various contaminants. In [12-13] examples of solving applied problems using the UMP ChemCad are considered.

Computational fluid dynamics methods using the ANSYS (FLUENT) software package are also widely used to solve such applied problems [14-18]. Numerical methods make it possible to quickly and visually simulate the flow of air flows in characteristic sections of an ejector installation and design more efficient industrial ventilation systems [19-22].

2 Materials and methods

In this work, the object of research is a low-pressure ejector unit (Fig. 1). The ejection effect consists in the fact that the ejected stream (active), of high pressure, moves at a high speed, carries along with it the ejected stream (passive) of low pressure. Clean air, blown by a high-pressure fan 5 located outside the ventilated room, flows out of nozzle 1 into the mixing chamber 3, into which air from the receiving chamber 2 of the manned room is sucked in due to the pressure difference. Further, the mixture of active and passive streams flows through the diffuser 4, and the air duct and is discharged into the atmosphere.
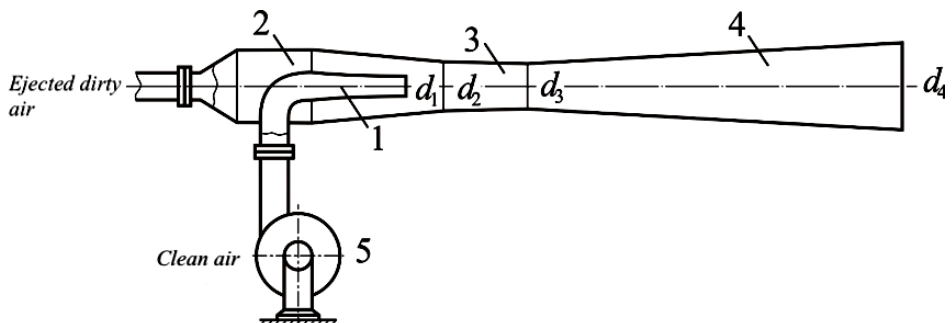
Fig. 1. Scheme of the ejector installation: 1 – nozzle; 2 – receiving chamber;3 – mixing chamber; 4 – diffuser; 5 – fan.

For painting a variety of products - from small parts to large-sized products, paint booths are designed. When simulating a low-pressure ejector, a painting booth with a size of 5.4 * 3.4 * 2.5 m^3 was considered. The air is supplied from the top, evenly over the entire area of the false ceiling. Air suction is carried out in the center of the chamber, through the floor, which is equipped with floor grilles throughout the entire area. The inlet and outlet pass through a cleaning system. The minimum temperature is 20-25 °C (in the drying mode up to 50°C). Air movement in the painting area is 20-25 cm/s. The air pressure in the chamber is slightly higher than the standard 100 kPa (atmospheric pressure or outside pressure).

For the calculation, the amount of air supply was taken as 6600 m³/h. To ensure the back pressure, it is required to remove 6000 m³/h of air with the resistance of the suction network Δp_2 = 230 Pa; the resistance of the pressure head of the ejector Δp_3 = 80 Pa; stirring factor w = 1.

When designing equipment based on the principles of ejection, it is necessary to determine the optimal shape and geometric dimensions of the ejector, as well as the characteristics of the fan, taking into account that the power consumed by its electric drive determines a significant share of the costs of the painting process.

The main design parameter of the ejector is the ejection coefficient, which is understood as the ratio of the flow rate of the active (blown by the fan) stream to the flow of the passive stream (sucked in from the painting chamber). The higher the ejection coefficient, the lower the flow rate of the supplied active stream, and, thus, the less electricity is consumed by the fan. The ejection coefficient itself is a function that depends on the geometric characteristics of the ejector, therefore, finding the optimal geometry of the ejector will reduce both operating and capital costs for installing the ventilation system.

The main purpose of calculating the ejector installation in this work is to obtain the values of pressures and velocities at any point of the model, flow rates at the boundaries, and also to calculate the ejection coefficient:

$$. \beta = G_C/G_D, \tag{1}$$

Where G_D - flow rate of the ejected (dirty) air; G_C - flow of ejecting (clean) air, kg/s.

2.1 Low-pressure ejector simulation

In the simulation, the ejector is divided into three parts: a nozzle, a mixing chamber, and a diffuser (Fig. 1).

The pressure and temperature at the nozzle exit are determined by the equations (2) and (3):

$$\frac{P_1}{P_2} = \left[1 + \frac{\gamma-1}{2}M^2\right]^{\frac{\gamma}{\gamma-1}}, \tag{2}$$

$$\frac{T_1}{T_2} = 1 + \frac{\gamma-1}{2}M^2. \tag{3}$$

The main equation used in the simulation of the ejector:

$$\frac{A_2}{A_c} = \sqrt{\frac{\left[\left(\frac{2}{1+\gamma_1}\right)\left(1+\frac{\gamma_1-1}{2}M_2^2\right)\right]^{\frac{\gamma_1+1}{\gamma_1-1}}}{M_2^2}}. \tag{4}$$

The nozzle outlet pressure is calculated as follows:

$$P_2 = \frac{P_1}{\left[\frac{\gamma_1-1}{2\eta_c}M_2^2+1\right]^{\frac{\gamma_1}{\gamma_1-1}}}. \tag{5}$$

Nozzle outlet temperatures:

$$T_2 = \frac{T_1}{1+\frac{\gamma_1-1}{2\eta_c}M_2^2}. \tag{6}$$

The speed of sound:

$$C_2 = \sqrt{\gamma_1 R_1 T_2}. \tag{7}$$

Actual flow rate:

$$V_2 = C_2 M_2. \tag{8}$$

The Mach number before mixing the active and ejected streams in the nozzle is expressed by the formula:

$$M_{v_2} = \sqrt{\frac{2}{\gamma_2-1}\left[\left(\frac{P_v}{P_2}\right)^{\frac{\gamma_2-1}{\gamma_2}}-1\right]}. \qquad (9)$$

In general, to obtain the critical Mach number in any section i, the following equation can be used:

$$M_i^* = \sqrt{\frac{M_i^2(\gamma+1)}{M_i^2(\gamma-1)+2}}. \qquad (10)$$

If we take into account equation (10), then the critical Mach number at the nozzle exit is calculated by the formula:

$$M_2^* = \sqrt{\frac{M_2^2(\gamma_2+1)}{M_2^2(\gamma_2-1)+2}}. \qquad (11)$$

By definition, the ratio for the ejection coefficient is calculated by the formula:

$$w = \frac{m_v}{m_1}. \qquad (12)$$

The critical Mach number of the moving stream at the outlet from the nozzle before mixing with the ejected stream:

$$M_{v_2}^* = \sqrt{\frac{M_{v_2}^2(\gamma_1+1)}{M_{v_2}^2(\gamma_1-1)+2}}. \qquad (13)$$

When simulating the mixing process, one-dimensional continuity equations in combination with the equations of motion and energy can be combined into the following relations to calculate the critical Mach number and Mach number in the diffuser:

$$M_4^* = \frac{M_2^* + wM_{v_2}^*\sqrt{\frac{T_v}{T_1}}}{\sqrt{(1+w)\left(1+w\frac{T_v}{T_1}\right)}}, \qquad (14)$$

$$M_4 = \frac{\sqrt{2}M_4^*}{\sqrt{(\gamma_3+1)-M_4^{*2}(\gamma_3-1)}}. \qquad (15)$$

To calculate the mixed active and ejected flow before the exhaust, the following equation is used:

$$T_4 = \frac{T_2}{1+\frac{\gamma_3-1}{2}M_4^2}. \qquad (16)$$

Mach number at the entrance and exit of the diffuser:

$$M_5 = \sqrt{\frac{M_4^2+\frac{2}{\gamma_3-1}}{\frac{2\gamma_3}{\gamma_3-1}M_4^2-1}}, \qquad (17)$$

$$M_3 = \sqrt{\frac{M_5^2+\frac{2}{\gamma_3-1}}{\frac{2\gamma_3}{\gamma_3-1}M_5^2-1}}. \qquad (18)$$

It should be noted that the following equations are used to calculate the temperature and pressure at the diffuser inlet:

$$T_3 = \frac{T_2}{1+\frac{\gamma_1-1}{2}M_3^2}, \qquad (19)$$

$$P_3 = \frac{P_2}{\left(1 + \frac{\gamma_3 - 1}{2} M_3^2\right)^{\frac{\gamma_3}{\gamma_3 - 1}}}. \tag{20}$$

The speed of sound and the actual speed are determined by the following relationships:

$$C_3 = \sqrt{\gamma_3 R_3 T_3}, \tag{21}$$

$$C_4 = \sqrt{\gamma_3 R_3 T_4}, \tag{22}$$

$$V_3 = C_3 M_3, \tag{23}$$

$$V_4 = C_4 M_4. \tag{24}$$

The temperature and pressure at the outlet of the diffuser are calculated as follows:

$$T_5 = \frac{1 + \frac{\gamma_3 - 1}{2} M_4^2}{1 + \frac{\gamma_3 - 1}{2} M_5^2}, \tag{25}$$

$$P_5 = \frac{1 + \gamma_3 M_4^2}{1 + \gamma_3 M_5^2} P_4. \tag{26}$$

In order to calculate the outlet pressure from the ejector, we can use the following equations:

$$\frac{A_1}{A_d} = \frac{P_6}{P_1} \left(\frac{1}{(1 + w)\left(1 + w \frac{T_v}{T_1}\right)}\right)^{1/2} \cdot \frac{\left(\frac{P_2}{P_6}\right)^{\frac{1}{\gamma_1}} \cdot \left(1 - \left(\frac{P_2}{P_6}\right)^{\frac{\gamma_1 - 1}{\gamma_3}}\right)^{1/2}}{\left(\frac{2}{\gamma_1 + 1}\right)^{\frac{1}{\gamma_3 - 1}} \cdot \left(1 - \frac{2}{\gamma_3 + 1}\right)^{1/2}}, \tag{27}$$

$$P_6 = P_5 \left(\eta_d \frac{\gamma_3 - 1}{2} M_5^2 + 1\right)^{\frac{\gamma_3}{\gamma_3 - 1}}. \tag{28}$$

Thus, the output stream from the ejector is:

$$m_6 = m_1 + m_v. \tag{29}$$

Equations (2) - (29) allow to calculate the ejector for a given performance. Problems of this kind are effectively solved using various modulating application programs. In particular, the use of the ChemCad universal modeling program (UMP) makes it possible to calculate the thermophysical properties of air streams with volatile components of various paints and varnishes. In [12-13] examples of solving applied problems using the UMP ChemCad are considered.

Equations (2)–(29) were inputted into the ejector calculation algorithm for various operating modes (using the DataMap toolkit).

## 2.2 A numerical study of the flow in a low-pressure ejector system

A numerical study of the flow in a low-pressure ejector system was carried out using the licensed software package ANSYS® Academic Research Mechanical and CFD, Release 18.2. The system of differential equations of turbulent motion is closed using the «standard» $k - \varepsilon$ model (k - kinetic energy of turbulent pulsations, ε - specific dissipation of turbulent energy). For modeling the boundary layer near impermeable surfaces, *the Standard Wall Function* is adopted.

Limit conditions:

- at the inlet of the ejected (dirty) air, the flow rate G_D was set, kg / s;

- at the inlet of the ejecting (clean) air, the excess pressure P_n, created by the pump was set, Pa;

- excess pressure P_{out}, Pa was set at the outlet from the ejector unit.

3 Results

In fig. 2 the design diagram of the ejector in the UMP ChemCad is shown. Square contours denote flows, where 1 – passive stream (PS); 2 – gas at the suction pipe of the ejector; 3 – a mixture of AS and PS; 4 – gas at the outlet of the ejector; 5, 6 – active stream (AS). Circular contours indicate the modules of the calculation scheme that simulate an ejector and a fan, where module 3 (Mixer) is a mixer that mixes the input flows at a given outlet pressure; module 1 (Pump) – fan; module 2 (Valve) – simulates the pressure drop across the suction line; Module 4 (Valve) – simulates an increase in pressure in the ejector outlet cone.
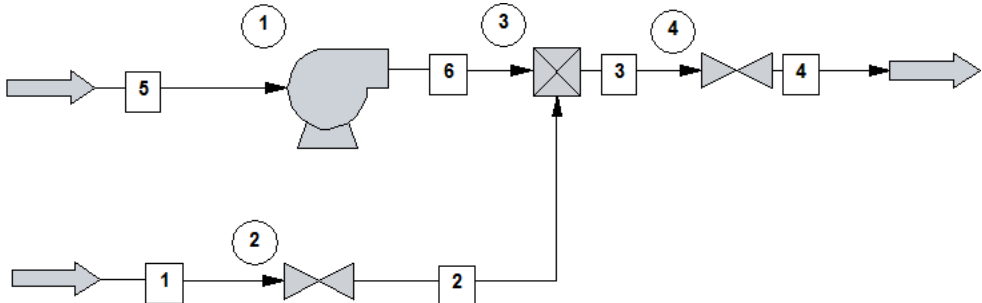
Fig. 2. Design scheme of the ejector in the UMP ChemCad.

The table shows the geometrical dimensions and parameters of the ejector for a capacity of 6000 m^3 / s, which can be recommended for ventilation of a painting booth with a size of 5.4 * 3.4 * 2.5 m^3:

Table 1. Ejector parameters.

Ejector parameter	Geometric size, mm
Diameter of the outlet section of the nozzle, d_1	211
Diameter of the beginning of the mixing chamber, d_2	470
Ejectorthroatdiameter, d_3	376
Diffusermouthdiameter, d_4	800
Suctiondiameter, d_{suc}	560
Pressurepipelinediameter, d_p	500
Mixingchamberlength, l_{chem}	1320
Diffuserlength, l_{dif}	4240
Height of the cylindrical part of the nozzle, G	106
Nozzleconfuserheight, E	422
Distance from the center of the pressure air duct to the bottom of the receiving chamber, Z	500
Receivingchamberheight, K	1000
Receivingchamberdiameter, L	1000
Intake chamber diffuser length, M	560
Length of the confuser of the receiving chamber, I	528

It is proposed to install a fan of the VTs5-35-8V1.01 brand, an AIM132M4 electric motor, and power consumption of 11 kW to the ejector. The rotational speed is 1500 rpm, the developed total pressure is 2900 - 2060 Pa.

Table 2. Calculation of low pressure ejector.

Parameter name	Designation	Value	Unit
Secondary volume of evacuated air	L2	1.6667	m³/s
Second volume of ejected air	L1	1.6667	m³/s

Mixed air volume per second	L3	3.3333	m³/s
The efficiency of the diffuser is η_{diff} = 0.65, which at β = 1 corresponds to the optimal speed ratio	n	0.4	
Air velocity U3 after mixing flows in the ejector	U3	20.6	m/s
Air velocity in the throat of the ejector	U`3	27.8	m/s
Air velocity when leaving the nozzle	U1	44.5	m/s
Mixingflowrate	U2	11.15	m/s
The area of the outlet section of the nozzle	f1	0.0375	m²
Diameter of the outlet section of the nozzle	d_1	0.2187	m
Annular cross-sectional area between the mixing chamber wall and the nozzle	f`2	0.1495	m²
Sectional area at the beginning of the mixing chamber	f2	0.1869	m³
Mixingchamberstartdiameter	d_2	0.4886	m
Ejectorthroatarea	f3	0.1199	m²
Ejectorthroatdiameter	d_3	0.3913	m
Mixingchamberdiameter	l_{chem}	1.9345	m
Mixingchamberfrictionresistance	Δp_{chem}	2.5467	kg/m²
The diameter of the diffuser mouth is taken from the speed conditions of 4-8 m / s	d_4	0.8	m
Diffusermouthspeed	U4	6.6348	m/s
Diffuserlength	l_{dif}	4.0871	m
Diffuserfrictionresistance	Δp_{dif}	2.4237	kg/m²
Total resistance of the pressure head of the ejector	Δp_3	6.9304	kg/m²
Back-up pressure in case of installation of an exhaust shaft	Δp_{shaft}	1.0696	kg/m²
Nozzleheight	G	0.1093	m
Nozzleconfuserheight	E	0.4374	m
Radius of curvature of the pressure air duct at the entrance to the receiving chamber	$r = d_p$	0.5	m
The speed of the ejected air in the pressure air duct	U_p	8.4926	m/s
Distance from the center of the pressure air duct to the receiving chamber	$Z=d_p$	0.5	m
Length of the confuser of the receiving chamber	$I = 2,5d_1$	0.5467	m
Receivingchamberheight	$K = J+3 = 2d_н$	1	m
Receivingchamberdiameter	$L = K = 2d_н$	1	m
Intakechamberdiffuserlength	$M = d_{in}$	0.56	m
The speed of the ejected air in the intake duct	$U_{в2}$	6.7702	m/s
Dynamic pressure in the annular section of the chamber	Δp_{dyn2}	7.75	kg/m²
Vacuum at the beginning of the mixing chamber	Δp_{vac}	27.75	kg/m²
Dynamic pressure at the outlet of the nozzle	Δp_{dyn1}	123.77	kg/m²
Full pressure at the outlet of the nozzle	Δp_1	96.016	kg/m²
Pressure network resistance to nozzle	$\Delta p_{to\ noz.}$	25.25	kg/m²
Total pressure generated by the fan	Δp_{fan}	139.83	kg/m²
Static efficiency of the ejector	n_{st}	29.162	%

We convert the pressures in Pascal (table 3).

Table 3. Converted pressure values.

Parameter name	Designation	Value	Unit
Mixingchamberfrictionresistance	Δp_{chem}	24.974	Pa

Diffuserfrictionresistance	Δp_{dif}	23.768	Pa
Total resistance of the pressure head of the ejector	Δp_3	67.964	Pa
Back-up pressure in case of installation of an exhaust shaft	Δp_{shaft}	10.489	Pa
Dynamic pressure in the annular section of the chamber	Δp_{dyn2}	76.001	Pa
Vacuum at the beginning of the mixing chamber	Δp_{vac}	272.134	Pa
Dynamic pressure at the outlet of the nozzle	Δp_{dyn1}	1213.769	Pa
Full pressure at the outlet of the nozzle	Δp_1	941.595	Pa
Pressure network resistance to nozzle	$\Delta p_{\text{to noz}}$	247.617	Pa
Total pressure generated by the fan	Δp_{fan}	1371.263	Pa

We select the fan according to the pressure created by the fan. In our case, V4-10D and V3-10a are suitable, which create a pressure of 140 kg/m².

The results of the numerical calculation of the ejector installation are presented in tables 4-6 and Fig. 3. The purpose of the calculation was to determine the pressure, velocities, flow rates in characteristic sections, pressure losses in the sections of the ejector installation, and also to calculate the ejection coefficient. The calculation results are presented in Tables 2-4 and Figs 2-3.

Table 4. Values of the found parameters in the characteristic sections of the ejector installation.

N	Boundaries	Flow rate G, kg/s	Speed V, m / s	Excess static pressure, P, Pa	Excess dynamic pressure, P_d, Pa	Excess total pressure, P_t, Pa
1.	Dirtyairinlet	2	4.3	0	11.36	11.36
	Cleanairinlet	2.4	5	1470	15	1485
	Cleanairoutlet	4.4	57.8	-759.40	2051.5	1292.10
	Flowmixingline	4.4	47.78	-898.48	1459.26	560.78
	The beginning of the diffuser	4.4	59.53	-1625.69	2185.05	559.36
	Exit	4.4	27.7	0	500	500
2.	Dirtyairinlet	2	4.3	0	11.64	11.64
	Cleanairinlet	2.64	5.1	1784	16	1800
	Cleanairoutlet	4.64	60.42	-668.41	2240.82	1572.41
	Flowmixingline	4.64	47.77	-800.10	1523.12	723.02
	The beginning of the diffuser	4.64	59.53	-1470.24	2156.84	686.60
	Exit	4.64	27.7	0	500	500
3.	Dirtyairinlet	2	4.3	0	11.09	11.09
	Cleanairinlet	2.15	2.56	1196	4	1200
	Cleanairoutlet	4.15	55.2	-856.17	1867.73	1011.56
	Flowmixingline	4.15	47.8	-1002.76	1526.07	532.31
	The beginning of the diffuser	4.15	59.5	-1774.96	2280.78	505.82
	Exit	4.15	27.7	0	500	500

A fan is selected according to the specified pressure at the inlet of clean air (Table 2) according to the designer's manual. In the performed numerical experiments, fans of models V-Ts14-46-4-04 and V-Ts4-70-4-01 can be used.

**Table 5.** Values of the ejection coefficients of the installation.

Dirty air flow rate G_D, kg / s	Clean air flow rate G_c, kg / s	Ejectioncoefficient β
2	2.4	1.2
2	2.64	1.32
2	2.15	1.08

Table 6. Losses of total pressures in the sections of the ejector installation.

N	Section	Total pressure loss, ΔP, Pa
	Pressure pipeline (from inlet to outlet of dirty air)	193
1.	Intake duct (from dirty air inlet to mixing line)	74.81
	Inthediffuser	59.36
	Pressure pipeline (from inlet to outlet of dirty air)	227.59
2.	Intake duct (from dirty air inlet to mixing line)	70.55
	Inthediffuser	186.6
	Pressure pipeline (from inlet to outlet of dirty air)	188.44
3.	Intake duct (from dirty air inlet to mixing line)	79.56
	Inthediffuser	5.82

Fig. 3 shows a qualitative picture of the distribution of velocies and pressures in the ejector.
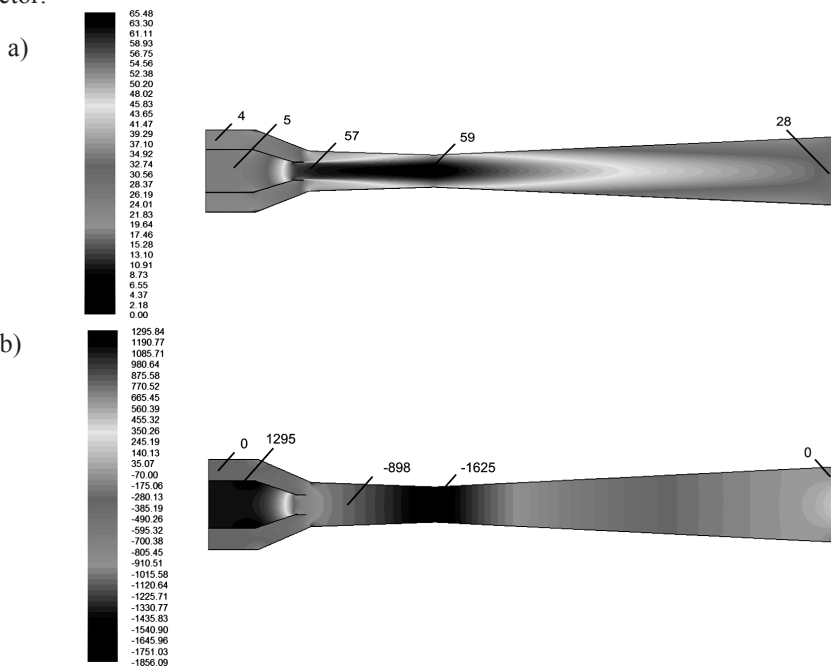
Fig. 3. Distributed characteristics of the ejector installation (illustration by the authors): velocity distribution, m / s; b) the distribution of excess static pressure, Pa.

4 Discussion

The unit is used to house a painting booth with internal dimensions of 5.4x3.4x2.5 m, where mechanical exhaust ventilation is provided by the ejection method. The flow rate of the removed dirty air is 2 kg/s, which corresponds to 6000 kg/h. From the designer's handbook «Internal sanitary devices. Ventilation and air conditioning», a typical ejection installation was selected, the geometric dimensions of which are presented in table 1 and several variants of centrifugal fans have been selected for it.

The β coefficient turned out to be slightly more than one, which indicates a fairly efficient operation of the ejection installation. In the case of β> 1, the dirty air is purified by mixing in a significant amount of clean air. The optimal ejection coefficient lies in the range from 0.5–1, which corresponds to the high efficiency of the ejection device.

5 Conclusions

1. Since all paints and varnishes are flammable substances, it is advisable to use an ejection exhaust ventilation system when designing ventilation for painting chambers (both new and those to be reconstructed).

2. Using the DataMap toolkit (an embedded function of the UMP ChemCad), which connects the universal simulator with a user file, it is possible to integrate the thermophysical properties of flows into formulas (2) – (29), thereby automating the calculation process.

3. In the work, a numerical study of the airflow in a low-pressure ejector installation has been carried out. Changes in pressures, velocities, and flow rates at the inlet and outlet of the low-pressure ejector and pressure losses in different sections of the ejector were determined.

4. The ejection coefficient β was determined, it turned out to be slightly more than one, which indicates a fairly efficient operation of the ejector installation. Anaccurately calculated ejection coefficient significantly increases the energy efficiency of the room ventilation system.

5. The results obtained in the article can be recommended for calculation in the design of ejector installations of industrial ventilation systems, including the optimal operating mode of the fan based on the pressure losses found.

List of designations
P – pressure, kPa; T – temperature, ^{o}K; A – cross–sectional area, m^2; γ – adiabatic index; C – speed of sound, m/s; V is the actual speed, m/s; M – Mach criterion; R – universal gas constant, kJ/(kg ^{o}K); w – ejection coefficient; η – efficiency; m – mass flow rate, kg/s.
Indexes
v – parameters of the passive stream; 1 – parameters of the active stream; 2 – parameters at the nozzle exit; 3 – parameters of the mixed stream; 4 – parameters before entering the diffuser; 5 – parameters at the outlet of the diffuser; 6 – parameters at the outlet of the ejector; c – parameters related to the nozzle; d – parameters related to the diffuser; * – critical parameters.

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