Received: 4 September 2023 | Revised: 18 October 2023 | Accepted: 28 January 2023 | Published online: 4 February 2024

RESEARCH ARTICLE

Green and Low-Carbon Economy
2024, Vol. 00(00) 1–7
DOI: 10.47852/bonviewGLCE42021598

Increasing Economic Efficiency When Creating a Dynamic Microclimate in Compressed Conditions of Production Premises

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Abstract: This work is devoted to increasing economic efficiency when using two-stream air distributors that form a swirled and flat stream while providing a dynamic microclimate in compressed conditions of industrial premises. The design of a two-jet air distribution (TJAD) is proposed, which forms a swirled and flat laying air jet that provides intensive attenuation of air flow velocity and temperature in stationary and variable mode. Measures aimed at saving cold energy are considered, namely, air supply in a variable mode, use of the flooring effect, and use of devices for intensification of tidal flow turbulence. A set of optimal measures for obtaining the maximum economic effect is determined. A method of development and calculation of inflow mechanical ventilation systems based on the specified air distributors is proposed. The economic evaluation of the use of air distribution devices proved that the use of a TJAD makes it possible to obtain some economic effect.

Keywords: air distribution, swirled air jet, flat air jet, dynamic microclimate, energy saving

Working conditions, efficiency, and reliability of the equipment largely depend on the conditions of the air environment of production and technological premises, which must be provided by ventilation systems. The means for this is a proper air distribution system in the room.

1. Introduction

In technological premises of a small volume, scattered sources of harmful substances are observed [1, 2], minor thermal excesses [3], high CO_2 concentration [4], and fixed workplaces. In this situation, tidal flows have a decisive influence on the formation of the internal microclimate [5, 6]. Solving this problem is complicated by limited distances to the working area, since air is supplied through vertical currents and possible transfer of harmful substances by horizontal tidal currents [7, 8].

Studies in the premises of both public and industrial buildings indicate that there are variable factors that have a beneficial effect on a person's thermal sensation [9]. The variable flow mode of tidal currents means the creation of a dynamic microclimate and has a positive effect on the thermal regulation of the human body. For example, it can be cited well-known developments for welding shops of the system of blowing workplaces with pulsating air flows with the frequency of their oscillations per minute in the working zone $n = 6–15$ 1/min and the period $T = 4–10$ s. The device is suitable, which is an air duct separated by a longitudinal partition (damper). Its installation makes it possible to ensure a periodic change in the speed of the stream exiting the nozzles. This happens due to the change in the amount of air entering each of the two parts of this air duct.

Determining the dynamic and thermal parameters of the jet when creating a dynamic microclimate in the room makes it possible to quantitatively assess the energy efficiency of the microclimate maintenance system.

In this regard, there is a need to develop new constructive air distribution solutions that would simultaneously ensure the creation of the necessary microclimate and the saving of material and energy resources.

Rational methods of air distribution are the supply of tidal air both directly to the working zone and to the upper zone. A characteristic feature of inflow air jets in small volume rooms is increased turbulence compared with straight-flowing jets in large rooms.

At the same time, it is advisable to propose the use of air distributors with a high intensity of extinction of the speed and temperature of the supply air. Such devices ensure intensive mixing of the supply air with the surrounding [10]. One of the methods of increasing the turbulence of air flows is the use of swirled inflow jets [11].

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2. Literature Review

Comfortable conditions are the main task in creating heating, ventilation, and air conditioning (HVAC) systems for various industrial premises [12]. Proper microclimate in premises of various purposes ensures satisfactory well-being of people and increases work productivity [13]. It should be noted that the dynamic microclimate in the room creates a more comfortable well-being of people. In addition to improving the well-being state of people, an economic effect is achieved. It consists in saving heat energy for the needs of the consumer and electric energy of the fan motors of HVAC systems. At the same time, there is a difficulty in the calculation, since the process is non-stationary and there is a dependence of air parameters on time.

Different ventilation schemes in different purpose rooms and efficiency of air distribution have been considered. However, an analysis of the provision of air exchange in small-sized premises has shown that this is quite a challenge [14]. This primarily applies to small rooms in which air jets flow out in compressed conditions. The characteristics of an air jet in compressed conditions differ from free conditions primarily by the presence of a compression ratio. This coefficient affects the long range of the jet and the attenuation of its speed and temperature. It should be noted that both longitudinal and transverse compression are distinguished. There is a difficulty in the analytical description of compressed jets, so it is advisable to apply experimental studies of compressed jets [15].

Air distributors are characterized by the attenuation coefficient of air speed and temperature. In the compressed conditions of small rooms, it is necessary to use devices with the lowest possible speed damping coefficient. In this regard, air distributors that form swirled jets deserve attention. Such jets have a high intensity of turbulence.

One of such effective devices is a two-jet air distribution (TJAD). In small rooms, its 3D dimensions, locations of equipment, heat sources, and workplaces should be taken into account. But, this issue still remains unresolved. In such rooms, when a large amount of air is supplied, it is difficult to ensure its normalized speed. A separate role should be given to the economic efficiency of HVAC systems [10], including energy saving [16], exhaust ventilation, acoustic properties, mathematical models [17–19], etc.

After the literature review, it may be claimed: it is necessary to create a methodology for calculating the swirled jet in the compressed conditions of the production premises, provided that a dynamic microclimate is created.

The aim of the article is to increase the economic efficiency of air distribution by swirled and flat laying air jets in compressed conditions of small production premises with their outflow in a variable mode.

2.1. Theoretical framework

The main characteristics of air jets are velocity and temperature. These parameters characterize the air jet on the axis of the flow and at arbitrary points of the direct flow. To describe the axial velocity and temperature of a swirled air jet, it is proposed to use traditional formulas for compact jets with the introduction of the flow twisting coefficient, which is an experimental value.

Therefore, air velocity and excess temperature of the swirled air flow should be determined according to the following dependencies Equations (1) and (2):

$$v_x = v_o \cdot k_{tw} \cdot m \frac{\sqrt{F_o}}{x} \tag{1}$$

where v_x and v_0 – axial and initial air velocity, respectively, m/s; k_{tw} – twisting coefficient; m – coefficient of air velocity attenuation; F_0 – aperture square, m^2; and x – running coordinate.

$$\Delta t_x = \Delta t_o \cdot k_{tw} \cdot n \frac{\sqrt{F_o}}{x} \tag{2}$$

where Δt_x and Δt_0 – axial and initial air excess temperature, respectively, °C; n – coefficient of air temperature attenuation.

In addition, it should be noted the expediency of using a two-stream device to create time-varying parameters, in particular with the help of an automation system. When using the air supply in a variable mode due to the appropriate device, the initial velocity of the jet exit from the nozzle will fluctuate according to the periodic law: that is, it will vary within $v_{0_{min}} - v_{0_{max}}$, and excess temperature Δt_o – in the range from $\Delta t_{0_{min}}$ to $\Delta t_{0_{max}}$:

$$v_0 = \overline{v_0} + A_1 \cdot \sin \omega\tau \tag{3}$$

$$\Delta t_0 = \Delta \bar{t}_0 + A_2 \cdot \sin \omega\tau \tag{4}$$

where $\overline{v_0}$ – the average value of v_0 during the oscillation period, m/s; $\Delta \bar{t}_0$ – the average value of Δt_o during the oscillation period, °C; A_1 and A_2 – respectively, the amplitude of oscillation of quantities v_0, m/s and Δt_o, °C; ω – cyclic (circular) frequency of oscillations, s^{-1}; τ – period, *s*.

At the same time, the values $\overline{v_0}$, $\Delta \bar{t}_0$, A, and ω are determined by the following formulas:

$$\overline{v_0} = 0.5\left(v_0 0_{max_{min}}\right) \tag{5}$$

$$\Delta \bar{t}_0 = 0.5\left(\Delta t_0 0_{max_{min}}\right) \tag{6}$$

$$A_1 = 0.5 \cdot \left(v_0 0_{min_{max}}\right) \tag{7}$$

$$A_2 = 0.5\left(\Delta t_0 0_{min_{max}}\right) \tag{8}$$

$$\omega = \frac{2\pi}{T} \tag{9}$$

where T – period of oscillation, *s*.

2.2. Air distribution by TJAD

Maintenance of the necessary microclimate in the production premises, especially in the warm period, is carried out by ventilation and air conditioning systems. The choice of the ventilation scheme and the method of air distribution depend on the technological processes taking place in the room.

The series of air distributors that form a swirled and flat laying jet are proposed for use, the productivity of which ranges from 135 to 4060 (m^3/h) depending on the air velocity and the dimensions of the devices.

The use of swirled air jets makes it possible to obtain small values of the velocity of air movement in the working area of the premises at high multiples of air exchange [11]. This is due to the fact that there is an intensive mixing of the supply air with the air of the room and a rapid attenuation of the velocity and excess temperature of the supply air flow.

The initial data for the calculation of air distribution are the previously accepted ventilation scheme, the method of air supply, as well as its quantity and parameters, calculated according to the thermal balance of the room. The task of air distribution calculation is to maintain the necessary air mobility and temperature difference in the working area, to choose the standard size of the air distributor with known initial data, and to assess the quality of the selected air distribution method. On the basis of the conducted theoretical and experimental studies of air distribution by swirled jets, it is possible to assert the expediency of their use when arranging supply air both in the upper zone of the ventilated room and in the working zone [11, 20].

For the further creation of a computer program, an algorithm for engineering calculation of the parameters of the air distribution device is proposed.

The implementation of the algorithm was carried out for a room with a plan size of 5 × 4.5 m, a height of 3 m with two windows oriented to the South, measuring 2 × 1.6 m.

It is necessary to supply L m^3/h ($L = 1350$ m^3/h) air to the room through the ventilation system. Two air distributors with a diameter of 125 mm with an open annular gap of 40 mm are pre-accepted for installation.

3. Research Methodology

This article proposes several means of increasing the technical, aerodynamic, and thermal efficiency of air distribution in small-volume technological premises. In particular, the use of TJAD (Figure 1) in air conditioning systems, the use of a variable mode of air flow into the room, and the effect of air jet laying deserve attention.

To evaluate economic efficiency, traditional formulas for determining annual specific costs (SC – EUR/year) were chosen based on the sum of two terms: one-time capital investments for the TJAD device (CI – EUR) and annual operating costs during the year (OC – EUR/year). At the same time, an important parameter is the coefficient of variable costs (VC – 1/year), which allows to combine one-time costs (CI, Eur) and costs lasting throughout the year (OC, Euro/year). This is reflected in Formula (10):

$$SC = OC + CI \cdot VC \tag{10}$$

Figure 1
Air distributor with twisting plates for a swirled air jet

3.1. Research design

The results of the study of air distribution with a TJAD device (Figure 1) showed that the positive effect of creating a proper microclimate in the compressed conditions of the production premises due to intensive turbulence of the inflow flow, reducing the damping coefficient of the air jet speed, and therefore the possibility of supplying the premises is obtained a significant amount of incoming air while ensuring standardized microclimatic conditions.

Limitations of the research: the air jets are isothermal; the air flow rate in the experiments was within: $L = 180 - 540$ m^3/h; angles of twisting plates were 30°, 60°, 90°; initial velocity of air was: $v_0 = 2 - 10$ m/s.

It should be noted that the TJAD device is able to supply air inflow jets in an alternating direction, thanks to the adjustment of the angle of inclination of the twisting plates. The rotary plates can be installed at different angles and create the appropriate initial conditions for the outflow of the air jet. Smaller swash plate angles provide a higher flow swirl factor and a lower velocity damping factor, allowing more supply air to be supplied in the compressed conditions of a small production facility. At the same time, smaller tilt angles increase the aerodynamic resistance of the system. With larger angles of inclination of the rotary plates, there is a decrease in the aerodynamic resistance of the system, a decrease in the swirl coefficient, and an increase in the range of the swirled jet, but the supply of a larger amount of supply air into the room is complicated.

It is possible to change the angle of inclination of the rotary plates using the automation system and optimize it depending on the purpose and dimensions of the production room. In addition, it is advisable to change the initial conditions of outflow of the inflow jet, creating additional local supports, in particular, turning the air duct to a certain angle, using louvered grids, etc. These measures increase the turbulence of the inflow flow and reduce the attenuation coefficient of the jet velocity but do not affect the twisting coefficient of the flow. But under these conditions, it is possible to supply a larger amount of supply air and ensure standardized values of air velocity and temperature in the working area of the production premises.

3.2. Creating a dynamic microclimate

Since the dynamic microclimate has a favorable effect on the well-being of people, it is advisable to consider the outflow of the inflow air jet in a variable mode.

The results of the study of air distribution in the variable mode proved that, in this case, savings in cold energy are obtained due to a decrease in the volumetric flow rate of supply air.

Let us consider the air supply in a variable mode in the air conditioning system with a jet developing in free space and determine its parameters. Let the flow be axisymmetric, for which the axial velocity v_x and the excess temperature Δt_x at the calculation point A with the coordinate x_A in the case of steady motion (without using the pulsating mode) are determined by Formulas (1) and (2) for the calculation of the axial velocity v_x and the excess temperature Δt_x at known initial v_o and Δt_o.

When using the air supply in variable mode due to the appropriate device, the initial velocity v_0 of the jet exit from the nozzle will oscillate according to the periodic law: that is, it will vary within the range of $v_{0_{min}}$ to $v_{0_{max}}$, and excess temperature Δt_o – within the range of $\Delta t_{0_{min}}$ to $\Delta t_{0_{max}}$. These values are determined by Formulas (3) and (4).

At the same time, the values $\overline{v_0}$, $\Delta\bar{t}_0$, A, and ω are determined by Formulas (5)–(9).

Similarly, it is written down the expression for the oscillations of the axial velocity v_x and the axial excess temperature Δt_x taking into account $\omega = 2\pi/T$:

$$v_x = \overline{v_x} + B_1 \cdot \sin\left(\frac{2\pi}{T_1}\tau - \phi_1\right) \tag{11}$$

$$\Delta t_x = \Delta\bar{t}_x + B_2 \cdot \sin\left(\frac{2\pi}{T_2}\tau - \phi_2\right) \tag{12}$$

Since the axial velocity v_x and the excess temperature Δt_x lag in phase compared to v_o and Δt_o, the initial phases φ_1 and φ_2 are included in expressions (11) and (12) with a negative sign.

The average value of the axial air velocity $\overline{v_x}$ and the excess temperature $\Delta\bar{t}_x$, as well as the amplitudes of their oscillations B_1 та B_2 are determined similarly to the initial parameters Equations (13), (14):

$$\overline{v_x} = 0.5 \cdot \left(vx_{min\,x_{max}}\right);\; \Delta\bar{t}_x = 0.5\left(\Delta t_x x_{min_{max}}\right) \tag{13}$$

$$B_1 = 0.5 \cdot \left(vx_{min\,x_{max}}\right) B_2 = 0.5\left(\Delta t_x x_{min_{max}}\right) \tag{14}$$

Based on Equations (5)–(14), we obtain, respectively, Equations (15) and (16):

$$\overline{v_x} + B_1 \cdot \sin(\omega\tau - \phi_1) = \overline{v_0}\frac{m\sqrt{F_0}}{x} + A_1\frac{m\sqrt{F_0}}{x} \cdot \sin\omega\tau \tag{15}$$

$$\Delta\bar{t}_x + B_2 \cdot \sin(\omega\tau - \phi_2) = \Delta\bar{t}_o\frac{n\sqrt{F_0}}{x} + A_2\frac{n\sqrt{F_0}}{x} \cdot \sin\omega\tau \tag{16}$$

Since the steady state is a partial case of the variable state with amplitudes of oscillations $A = 0$ and $B = 0$, Equations (15) and (16) are transformed into Equation (17) and are similar to Equations (3) and (4):

$$\overline{v_x} = \overline{v_0}\frac{m\sqrt{F_0}}{x};\; \Delta\bar{t}_x = \Delta\bar{t}_o\frac{n\sqrt{F_0}}{x} \tag{17}$$

Considering Equations (15) and (16), it is got:

$$B_1 \cdot \sin\left(2\pi\frac{\tau}{T_1} - \phi_1\right) = A_1\frac{m\sqrt{F_0}}{x} \cdot \sin 2\pi\frac{\tau}{T_1} \tag{18}$$

$$B_2 \cdot \sin\left(2\pi\frac{\tau}{T_2} - \phi_2\right) = A_2\frac{n\sqrt{F_0}}{x} \cdot \sin 2\pi\frac{\tau}{T_2} \tag{19}$$

from where the amplitudes B_1 and B_2 are determined:

$$B_1 = A_1\frac{m\sqrt{F_0}}{x} \cdot \frac{\sin 2\pi\tau/T_1}{\sin(2\pi\tau/T_1 - \phi_1)};$$

$$B_2 = A_2\frac{n\sqrt{F_0}}{x} \cdot \frac{\sin 2\pi\tau/T_2}{\sin(2\pi\tau/T_2 - \phi_2)} \tag{20}$$

Note that the amplitude B_1 of axial velocity oscillations and B_2 of excess temperature oscillations are time-varying, which corresponds to the conditions of a dynamic microclimate. Let us determine the initial phase φ_1, that is, the initial moment of time for the point A. To do this, we schematically consider the dependence of the average axial speed $\overline{v_x}$ together from the current coordinate x ($\overline{v_x} = f_1(x)$) and from time τ ($\overline{v_x} = f_2(\tau)$) in the initial and main sections of the stream development.

Time of movement τ_A of the elementary volume of the jet from the nozzle to the calculation point A with the coordinate x_A will be the initial moment of time of oscillation of the axial velocity v_x, which is determined:

$$\tau_A = \frac{x_A}{v_A} \tag{21}$$

and the average velocity v is calculated by integrating Equation (22) on the intervals of the initial and main sections:

$$v = \frac{\overline{v_0}x_{in} + \int_{x_{in}}^{x_A}\frac{v_0 m\sqrt{F_0}}{x} \cdot dx}{x_A} \tag{22}$$

As a result of integration, we get an expression for the average speed of the stream v:

$$v = \frac{\overline{v_0}}{x_A}\left(x_{in} + m\sqrt{F_0} \cdot ln\frac{x_A}{x_{in}}\right) \tag{23}$$

Therefore, taking into account Equations (21) and (23), the initial moment of time τ_A is:

$$\tau_A = \frac{x^2{}_A}{\overline{v_0}\left(x_{in} + m\sqrt{F_0} \cdot ln\frac{x_A}{x_{in}}\right)} \tag{24}$$

The value of τ_A, which is determined from Equation (24), is the phase delay time of the axial velocity oscillations v_x; therefore, the initial phase $\varphi 1$ is obtained from Equations (2) and (24):

$$\phi_1 = \frac{2\pi \cdot x^2{}_A}{T_1 \cdot \overline{v_0}\left(x_{in} + m\sqrt{F_0} \cdot ln\frac{x_A}{x_{in}}\right)} \tag{25}$$

Similarly, it is got the initial phase φ_2 of excess temperature oscillations delay Δt_x:

$$\phi_2 = \frac{2\pi \cdot x^2{}_A}{T_2 \cdot \Delta\bar{t}_0\left(x_{in} + n\sqrt{F_0} \cdot ln\frac{x_A}{x_{in}}\right)} \tag{26}$$

Thus, all values necessary for the calculation of time-dependent variables of the axial velocity v_x and excess temperature Δt_x in point A have been determined. Along with this, the energy assessment of the air conditioning system is of interest. At the same time, it should be considered that the temperature of the exit of the air stream from the nozzle t_{ext} and the internal temperature t_{in} are also time-varying.

The amount of cold Q_c, necessary for air conditioning needs in the room in stationary mode, is as follows:

$$Q_c = v(\bar{t}_{in} - \bar{t}_0)_{0_{max}} \tag{27}$$

where $v_{0_{max}}$, ρ, c – respectively, the maximum speed of air exit in the stream, m/s; its density, kg/m^3 and specific heat, kJ/(kgK); F – air outlet area, m^2; $\bar{t}_{in}$, $\bar{t}_0$– respectively, the average air temperatures in the room and at the exit from the air outlet, $^{\circ}$C.

The cooling capacity of the air conditioning system at variable mode is as follows:

$$\overline{Q}_c = \overline{v}_0 \cdot F \cdot \rho \cdot c\left(\left(\bar{t}_{in} - \bar{t}_0\right) + \left(A_{in}\sin\omega_B\tau - A_0\sin\omega_0\tau\right)\right) \tag{28}$$

where A_{in} and A_0 – amplitudes of their oscillations.

The capacity of the air conditioning system decreases by α times, where $\alpha = \frac{Q_c}{Q_c}$, i.e., $\alpha = 1 + \frac{A}{\overline{V}_0}$, subject to simplification: $\frac{t_a - t_0}{\left(\bar{t}_{in} - \bar{t}_0\right) + (A_{in}\sin\omega_B\tau - A_0\sin\omega_0\tau)} \approx 1$.

The economy of cold is determined by the initial velocity of the flow stream $\overline{v}_0$ and the amplitude of its oscillation A under the condition of ensuring comfort in the room, as well as the necessary thermal regulation of the body. If we take into account that the temperature of the exit of the air jet from the nozzle is variable in time $t_0 = var$, then on the basis of Equation (27) we state that the saving of cold energy is obtained.

3.3. Energy saving due to the effect of the air jet laying

An effective air distribution scheme using a TJAD device, which forms a swirled and flat laying air jet, was considered.

If the air jet is placed on a solid surface, for example, on the ceiling (horizontal air supply) or on the wall (vertical supply), then the Coanda effect is observed: the range of the jet increases almost 1.5 times. In addition, additional heat exchange is created between the air jet and the surface. During the study, the amount of cold energy perceived by the surface jet when it is laid on the surface of the enclosing structure was determined.

At the same time, criterion equations of convective heat exchange were applied. On the basis of thermotechnical and aerodynamic air parameters (temperature, speed, kinematic viscosity coefficient, thermal conductivity coefficient, etc.) the Reynolds and Nusselt criteria and the convective heat transfer coefficient and the amount of cold energy were determined.

The results showed that due to the heat transfer during the forced longitudinal flow around a flat surface, according to the calculations, 5% of the amount of heat Q, W, which is transferred from the air to the enclosing surface, is saved.

This means that the actual initial air temperature t_{0a} may be slightly higher than the calculated temperature t_{0c} by an amount $\Delta t = t_{0a} - t_{0c}$.

3.4. Technical and economic efficiency of air distribution systems in industrial premises

The effectiveness of ventilation systems was determined by the following economic factors: the cost of materials, transportation costs, wages of key employees, operating costs, etc.

Let us consider the definition of these components. The investment costs of the ventilation system (Table 1) was determined by the expression:

$$IC = DC + GPC + EP \tag{29}$$

where IC – investment costs; DC – direct costs; GPC – general production costs; EP – estimated profit.

Direct costs represent the sum of the cost of materials (the cost of air ducts, fans, fittings, loading and unloading costs, transport costs, procurement, and storage costs) M, the wages of the main workers WMW and the costs of operating the ventilation system OC (the cost of lubricants, electricity, wages of employees who maintain the system), and amortization costs AC (costs for all types of repairs, etc.) (Table 1).

The investment costs of air ducts of the ventilation system depend on the material, diameter, length, cost of installation, and insulation work. For the most part, many components of the investment costs depend on the diameter of the air duct, others are almost independent of it.

Annual operating costs include costs for maintenance and repair of ventilation system air ducts; costs for depreciation of ducts C_d; costs for the wages of the personnel who serve the ventilation network C_w; electricity costs C_{el}; costs of fan action C_f; costs for maintenance and repair of ventilation units (individual units) C_{vu}; costs for depreciation of ventilation units C_{dvu}; and unaccounted expenses C_{ue} (Table 1).

The costs of maintenance and repair of air ducts were assumed to be proportional to their estimated cost. An increase in the diameter of air ducts leads to an increase in maintenance and repair costs:

$$C_r = r_1 \cdot IC \tag{30}$$

where r_1 – coefficient of deductions for repairs and maintenance; IC – investment cost of air ducts of the ventilation system.

Pipeline depreciation costs were also assumed to be proportional to the estimated cost of ventilation system pipelines:

$$C_d = r_2 \cdot IC \tag{31}$$

where r_2 – coefficient of deductions for depreciation of air ducts.

Table 1
Parameters of different air distributors

No.	Parameters	Air distributors: DPU-M-Ø250 (conical and incomplete fan jets)	4 APR 600 × 600 (laying on ceiling fan jets)	1VPT 900 × 595 (combined jets)	TJAD 250 (two-jet device)
1	2	3	4	5	6
1	The cost of equipment and materials, Eur.	69.75	77.3	80.95	58.05
2	The cost of installation works, Eur.	25.35	20.22	19.83	15.53
3	Capital investments, Eur.	95.1	97.55	100.78	73.58
4	Annual expenses, Eur/year	14.28	14.63	15.13	11.05
5	Electricity costs, Eur/year	2.48	2.48	2.48	2.48
6	Service, Eur/year	9.6	9.23	8.98	8.68
7	Operating costs, Eur/year	12.08	11.7	11.45	11.15
8	Annual specific costs, Eur/year	26.35	26.33	26.58	22.2
9	Economic effect, Eur/year	4.15	4.13	4.38	–

Wages costs for personnel who maintain air ducts of ventilation systems depend on their length and on the diameters of the pipelines:

$$C_{wad} = r_3 \tag{32}$$

where r_3 – wages of personnel who maintain air ducts of the ventilation system.

Since labor costs depend on the performance of the ventilation system and the number of units in it, they do not affect the choice of the diameter of the air ducts:

$$C_{wvu} = r_4 \tag{33}$$

where r_4 – wages of personnel who maintain ventilation units.

Electricity costs were determined by the formula:

$$C_{el} = \sigma \cdot t \tag{34}$$

where σ – specific cost of electricity for air volume transportation per unit of time; t – operation time of the ventilation system throughout the year.

Since σ depends on the installed capacity N_{ic}, on the tariff and cost of electricity, on the reliability class of the ventilation system, on the number of fans in the group, etc., then:

$$\sigma = \left(\sigma_{aue} \cdot \frac{N_a}{N_{ic}} + C_{ip}\right) N_{ic} \tag{35}$$

where σ_{aue} – the specific cost of the used electricity; C_{ip} – cost of 1 kW of installed power; N_a – the actual power used by the operating units; N_{ic} – total passport power of installed electric motors.

The investment cost of the IC_v ventilation unit was assumed to be proportional to the installed capacity of the working units:

$$IC_v = f \cdot N_{ic} \tag{36}$$

where f – the investment cost of the ventilation installation, which refers to the unit of installed capacity.

The costs of maintenance and repair of the ventilation unit were assumed to be proportional to its investment cost:

$$C_{rm} = r_{11} \cdot IC_v \tag{37}$$

where r_{11} – coefficient of deductions for repair and maintenance of the ventilation installation.

Depreciation costs of the ventilation unit were assumed to be proportional to its estimated cost:

$$C_d = r_{22} \cdot IC_v \tag{38}$$

where r_{22} – coefficient of deductions for depreciation of the ventilation installation.

Unaccounted costs were accepted in the amount of 3% of the sum of all operational costs.

Therefore, the annual operational costs (Table 1) associated with ventilation units will amount to:

$$OC = \begin{pmatrix} (r_1 + r_2)IC + r_3 + r_4 + (r_{11} + r_{22})fN_{ic} + \\ + \left(\sigma_{aue} \frac{N_a}{N_{ic}} + C_{ip}\right) N_{ic} \cdot t \end{pmatrix} 1.03 \tag{39}$$

On the basis of the conducted research, technological solutions have been developed that ensure the possibility of supplying the necessary amount of air to the production premises. When evaluating the economic efficiency of the measures proposed in the work, the following were taken into account: the need for costs for the creation of an air distribution device, the cost of installation work, and the cost of operating costs.

The specific annual economic effect of the introduction of energy-saving technologies is 165–175 UAH/(year thousand m^3/h) compared to alternatives, and based on 1 room (10–20 thousand m^3/h), respectively, 2.5–3.0 thousand UAH/year.

4. Discussion

The results of theoretical and experimental studies of compressed air inflow swirling jet were obtained. The technical, aerodynamic, and economic efficiency of the use of the TJAD air distributor is shown. Besides, economical effect scientific work has social consequences, as it leads to the improvement of working conditions at workplaces and the reduction of the impact of technological processes on occupational diseases.

Since the studies were performed for the swirled and compact laying air jets, the results for other air streams would be interesting. So there would be also numerical modeling of the tidal compressed air jets and exhaust ones.

In future, research on air jets will be continued. In particular, special initial conditions should be investigated.

5. Conclusion

The design of a TJAD is proposed, which forms a swirled and flat laying air jet that provides intensive attenuation of air flow parameters in stationary and variable mode.

The theoretical and practical consequences are: creation of a methodology for engineering calculation and selection of ventilation systems using TJAD; the possibility of designing energy-saving air distribution schemes in ventilation and air conditioning systems in small-volume production premises with the provision of standard temperatures and air velocities in both stationary and variable modes.

Air distribution schemes with the use of laying air jets are effective, as they make it possible to save energy costs for the AC system by the amount of about 5%, and therefore the actual initial temperature of the supply air can be slightly higher. When using air distribution in a non-stationary mode, it is possible to achieve additional savings in cold energy, which is determined by the initial velocity of the inflow stream and the amplitude of its oscillations.

The economic evaluation of the use of air distribution devices proved that the use of TJAD makes it possible to obtain a specific annual economic effect of UAH 165–175/ (year thousand m^3/h) compared to alternative options and based on 1 room (10–20 thousand m^3/h), respectively, 2.5–3.0 thousand UAH/year.

Recommendations

It is advisable to use TJAD in small-sized production premises, especially in variable mode and with the effect of laying an air jet.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

The data that support the findings of this study are openly available in AKJounals at https://doi.org/10.1556/606.2021.00419, in Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu at https://doi.org/10.33271/nvngu/2021-2/104, and in Sciendo at https://doi.org/10.30657/pea.2021.27.22

Author Contribution Statement

Orest Voznyak: Conceptualization, Data curation, Writing – original draft, Supervision, Project administration. **Nadiia Spodyniuk:** Validation, Formal analysis, Writing – review & editing. **Iryna Sukholova:** Methodology, Investigation, Resources. **Olena Savchenko:** Software, Formal analysis, Visualization. **Oleksandr Dovbush:** Data curation, Visualization. **Mariana Kasynets:** Investigation, Resources.

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How to Cite: Voznyak, O., Spodyniuk, N., Sukholova, I., Savchenko, O., Dovbush, O., & Kasynets, M. (2024). Increasing Economic Efficiency When Creating a Dynamic Microclimate in Compressed Conditions of Production Premises. *Green and Low-Carbon Economy*. https://doi.org/10.47852/bonviewGLCE42021598