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DEVELOPMENT OF ENERGY-SAVING AIR SUPPLY IN SMALL-SIZE ROOMS WITH HIGH-HEAT LOCATIONS

It is well known that the most effective method of air distribution in high-heat areas is displacement ventilation with a variable air loss according to changeable operating conditions. Dense equipment arrangement makes requirements to air distribution even higher. The necessity of spreading jets till they reach convective flows is shown. To slow down these jets uniform air supply is required at the exit of an air distributor. Modern devices do not fully meet this requirement. The suggested method of air supply ensures uniform air distribution and thorough ventilation of the area at a changed expenditure of inflowing air.

Keywords: **air distribution, high-heat area, displacement ventilation, low-speed air distributor, turbulent jet**

INTRODUCTION

With the development of small and medium business a large number of small-size production enterprises are established. Studies have shown that in industrial rooms specified parameters of air are insufficient. The reason is ineffective air exchange. To increase ventilation energy efficiency and ensure sanitary and hygienic conditions it is necessary to use displacement ventilation with controlled air exchange rate, depending on current needs of the rooms. Displacement ventilation means air supply directly to working zone with low initial velocity and differential temperature [1-5]. Special air distributors are used for this type of ventilation [6]. Their drawback is inability to ensure uniform air distribution, which leads to higher initial velocity of the jet and consequently violates the displacement ventilation principle. The authors suggest low-velocity two-chamber air distributors [7], which provide uniform distribution of initial velocity along the height of air-distribution surface. The structure of these air distributors ensures effective control of air distribution with almost unaltered outgoing air velocity. This also ensures a constant jet range.

1. LITERATURE ANALYSIS

Fundamentals of displacement ventilation using, indoor air temperature distribution along room height, characteristics of convective flow development and indoor pollutant diffusion, the effectiveness of displacement ventilation and ways of organizing air exchange for it are described in many studies [1-5]. It is commonly believed that in high-heat locations the distribution of indoor environment parameters is dependent only on convective flows. Therefore, the effect of ventilation air jets and air exchange organization in such locations are studied insufficiently. The most profound research of turbulent ventilation air jets was carried out by G. Abramovych [8], V. Taliev [9], L. Dudyntsev [10] and others. Among modern theories let us note a theory of A. Tkachuk, the professor of Heat Gas Supply and Ventilation Department of Kyiv National University of Construction and Architecture [11].

One of the major problems using displacement ventilation in this type of rooms is insufficient development of air-distribution equipment. Analysis of technical specifications of different producers shows that the majority of air-distribution devices designed for displacement ventilation systems consist of one chamber and do not ensure uniform initial velocity distribution along the height of the air distributor. This leads to higher initial velocities of the jet, equipment airflow and deterioration of sanitary and hygienic conditions and makes it impossible to control air exchange rate. At the lower rate the air jet range becomes shorter and this leads to poor ventilation of certain areas.

2. GOALS OF THIS WORK

To ensure proper sanitary and hygienic conditions it is necessary to analyse the effect of supply air jets on indoor air environment parameters. For effective ventilation it is necessary to ensure a uniform profile of initial air jet velocities and suggest technical solutions which can ensure uniform initial air jet velocity.

3. ANALYTICAL AND EXPERIMENTAL RESEARCH

To analyse the effect of supply air jets on distribution of air environment parameters, an approximate mathematical model of heat and mass exchange processes at air supply directly to working zone has been developed in accordance with the provisions given in study [10].

Four typical areas have been distinguished in the room (Fig. 1): *WZ* - working zone; *C* - supply jet area; ℓ - upper area; *K* - convective jet.

In the convective air jet *K* area 1 is considered within the working zone.

To take into consideration the peculiarities of air jet development, a coefficient of convective flow supply by air jets is introduced as a ratio of jet flow rate $G_{c\to k}$ supplying the convective flow to the total flow rate of this jet $G_c = G_{c\to k} + G_{c\to wz}$:

$$k_S = G_{c\to k} / \left(G_{c\to k} + G_{c\to wz}\right) \tag{1}$$

If the jet does not interact with the convective flow, this coefficient equals zero. Air exchange organization efficiency is determined by non-dimensional air exchange coefficient $k_L = t_\ell - t_{in} / t_{wz} - t_{in}$. An increase of this coefficient means reduction of the necessary air exchange in the location. This allows saving energy for air preparation and moving, saving material for the production of air distribution system and reducing the size of this system.

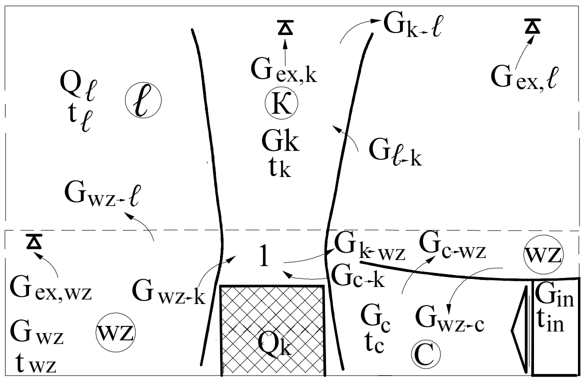


Fig. 1. Computational diagram of heat and mass exchange processes in an industrial room with heat sources

Balance equations according to the diagram in Figure 1 (Tab. 1) provide the value of air exchange coefficient:

$$k_L = \frac{\left(\left(\overline{G}_{\mathbf{ex},\ell} + \overline{G}_{\mathbf{ex,k}}\right) - \left(\Delta\overline{Q}_k + \Delta\overline{Q}_\ell\right)\overline{G}_{\mathbf{ex,wz}}\right)\overline{G}_k - \left(\Delta\overline{Q}_{wz}\overline{G}_{k,\mathbf{wz}} + \Delta\overline{Q}_k\right)\overline{G}_{\mathbf{ex,k}} - \left[\left(\Delta\overline{Q}_{wz} + \Delta\overline{Q}_k\right)\overline{G}_{\mathbf{ex,k}} + \overline{G}_k\right]k_S}{\Delta\overline{Q}_{wz}\left(\overline{G}_k\left(\overline{G}_{\mathbf{ex},\ell} + \overline{G}_{\mathbf{ex,k}}\right) - \overline{G}_{\mathbf{ex,k}}\overline{G}_{\mathbf{k},wz}\right)} \tag{2}$$

where: $\overline{G_i} = G_i / G$; $\Delta\overline{Q_i} = \Delta Q_i / \Delta Q$.

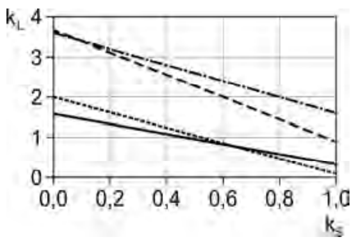
Table 1. **Balance equations**

Area	Mass balance	Heat balance
WZ	$G_{c\to wz} - G_{wz\to c} - G_{wz\to k} - G_{wz\to\ell} - G_{ex,wz} = 0$	$G_{c\to wz}c\Delta t_c - G_{wz\to c}c\Delta t_{wz} - G_{wz\to k}c\Delta t_{wz} - G_{wz\to\ell}c\Delta t_{wz} - G_{ex,wz}c\Delta t_{wz} + \Delta Q_{wz} = 0$
1	$G_{k\to wz} = G_{wz\to k} + G_{c\to k}$	$G_{wz\to k}c\Delta t_{wz} + G_{c\to k}c\Delta t_k - G_{k\to wz}c\Delta t_k + \Delta Q_k = 0$
ℓ	$G_{wz\to\ell} - G_{\ell\to k} + G_{k\to\ell} - G_{ex,\ell} = 0$	$G_{wz\to\ell}c\Delta t_{wz} - G_{\ell\to k}c\Delta t_\ell + G_{k\to\ell}c\Delta t_k - G_{ex,\ell}c\Delta t_\ell + \Delta Q_\ell = 0$
K	$G_k = G_{wz\to k} + G_{\ell\to k} + G_{c\to k} = 0;$ $G_k = G_{k\to\ell} + G_{ex,k}$	$G_{wz\to k}c\Delta t_{wz} + G_{\ell\to k}c\Delta t_\ell + G_{c\to k}c\Delta t_c - G_{k\to\ell}c\Delta t_k - G_{ex,k}c\Delta t_k + \Delta Q_k = 0$
C	$G_c = G_{in} + G_{wz\to c} = G_{c\to wz} + G_{c\to k} = G_{c\to k}k_{эс} + G_{c\to wz}(k_{эс} - 1)$	$G_{in}\cdot 0 + G_{wz\to c}c\Delta t_{wz} - G_{c\to wz}c\Delta t_c - G_{c\to k}c\Delta t_c = G_{c\to k}k_{эс}c\Delta t_c + G_{c\to wz}(k_{эс} - 1)c\Delta t_c = 0$

Analysis of dependence of the air exchange coefficient on the flow supply coefficient (Fig. 2) shows the necessity to minimize the inflow of supply air jets to the convective flow.

To reduce the inflow of supply air jets to convective flows it is necessary to ensure minimum initial velocity of the air jet. For this purpose low-velocity two-chamber air distribution devices are suggested [7], which create a uniform initial velocity profile. The first chamber is distribution chamber equipped with shelf separators of the flow.

At that, the obtained value of air exchange coefficient is the highest.



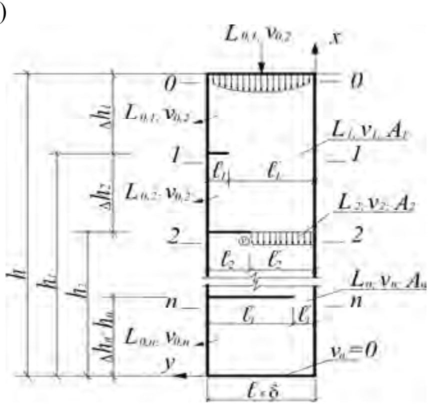
Line	Settings					
	$\Delta\bar{Q}_{w.z}$	$\Delta\bar{Q}_{k}$	$\bar{G}_{ex.w.z}$	$\bar{G}_{ex.k}$	$\bar{G}_{k}$	$\bar{G}_{k.w.z}$
----	0,3	0,6	0,3	0,4	0,8	0,4
—	0,3	0,6	0,4	0,2	0,6	0,3
-·-	0,1	0,8	0,8	0,4	0,8	0,4
– –	0,1	0,8	0,8	0,2	0,6	0,3

Fig. 2. Dependence of air exchange coefficient on flow supply coefficient

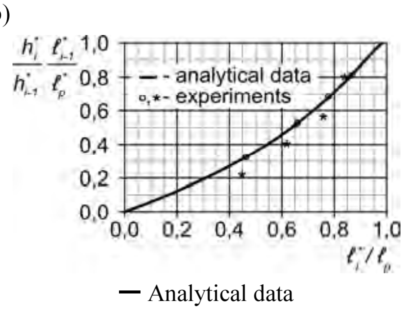
This chamber ensures approximately uniform distribution of excessive static pressure along the height of air distribution device. The second chamber is for stabilization, where excessive non-uniformity (as a result of flow perturbation in the distribution chamber) of the velocity profile is equalized.

A method of calculating the dimensions of distribution chamber of a low-velocity air distributor has been developed to provide equal distribution of excessive pressure. The computational diagram for a short air distributor with a uniform cross-section is given in Figure 3a.

a)



b)



— Analytical data
* Experimental data

Fig. 3. Air distributor with shelf pressure equalizers: a) computational pattern, b) diagram for determining the size of air gaps between shelves

The inlet port area is $A = \ell b$; initial flow rate is L_0 and velocity is v_0. Shelf separators of the flow are local damper-type resistances. Let us designate the number of a shelf separator i. They divide the chamber into n sections. As a result of solving Bernoulli equations for adjacent cross-sections the following recurrent dependence is obtained to determine the passage width ℓ^* related to the width ℓ of the shelf flow separator at the level h_i above the air distributor bottom:

$$\left(h_i / h_{i-1}\right)\left(\ell_{i-1} / \ell\right) = \left(\ell_i / \ell\right) / \sqrt{3{,}1 - \left(\ell_i / \ell\right)\left(2{,}1 + 0{,}54\left(\ell_i / \ell\right)\sqrt{1 - \left(\ell_i / \ell\right)}\right)} \qquad (3)$$

In order to check the adequacy of an air distributor mathematical model, experimental research of such air distributor models has been carried out under laboratory and enterprise conditions [9].

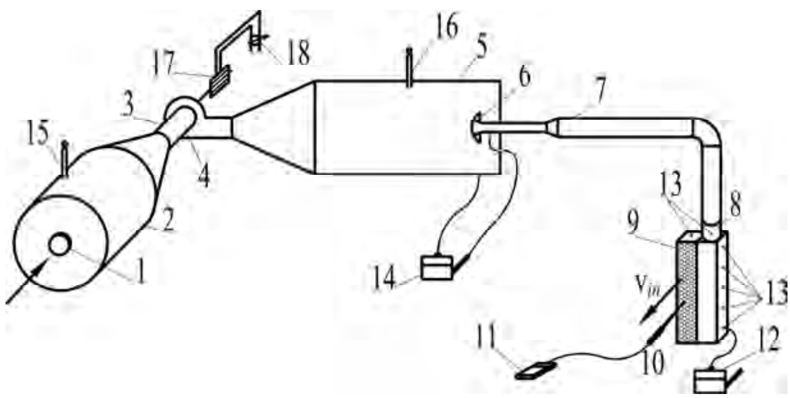


Fig. 4. Diagram for researching a low-velocity panel-section two-chamber air distributor model: 1 - inlet pipe, 2 - pressure chamber, 3 - air channel, 4 - radial fan, 5 - pressure chamber, 6 - flow-measuring collector, 7 - air channel, 8 - inlet nozzle of air distributor, 9 - air distributor model, 10 - thermoelectric wind gauge sensor, 11 - thermoelectric wind gauge «TESTO-405», 12, 14 - micromanometers MMH-2400, 13 - control points (pickup ports) of excessive static pressure measuring, 15, 16 - alcohol thermometers, 17 - motor, 18 - motor rotation control

As a result of experimental research carried out using the test stand (Fig. 4), best sizes of flow separators have been obtained, at which the coefficient of static pressure uniformity reaches its maximum value. Experimental data agree with analytical data (Fig. 3b).

Jet flows formed by an air distributor model under laboratory conditions have been studied (isothermal, Fig. 5) as well as those formed by an air distributor in conditions of an operating production enterprise (non-isothermal, Fig. 6).

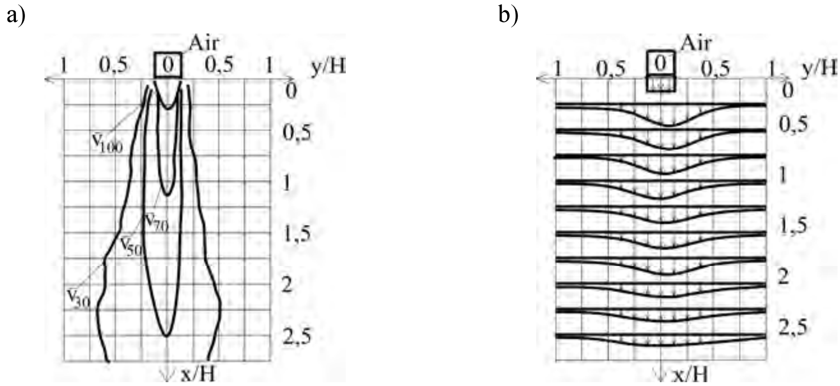


Fig. 5. Development characteristics of isothermal jet formed by at middle level of the air distributor: a) relative isotachs, b) diagrams of relative velocity in cross-sections; H - air distributor analog height

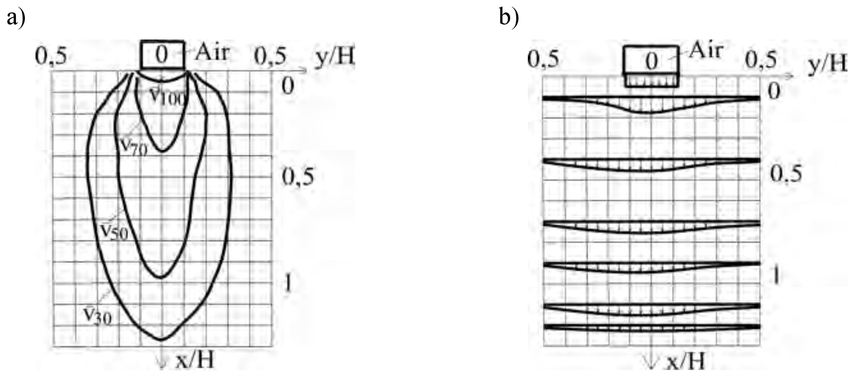


Fig. 6. Development characteristics of jet formed by at middle level of the air distributor: a) relative isotachs, b) diagrams of relative velocity in cross-sections; H - air distributor height

The configuration of the jet formed by air distributor in conditions of a production facility is identical to one formed under laboratory conditions. This proves weak non-isothermality of the jet. Velocity drop coefficient is a universal feature of the jet fade rate: $m = (\nu_x/\nu_0)\sqrt{x/A_0}$; $m = (\nu_x/\nu_0)\sqrt{x/b_0}$, where x - distance to the air distributor; A - area of air distributing surface for compact jet; b_0 - initial width for flat jet. As a result of industrial research of the air jet formed by a one-section air distributor with one-way air supply, constructed a graph of inside-jet velocity drop coefficient for flat jet m dependence on the distance to air distributor (Fig. 7) have been built.

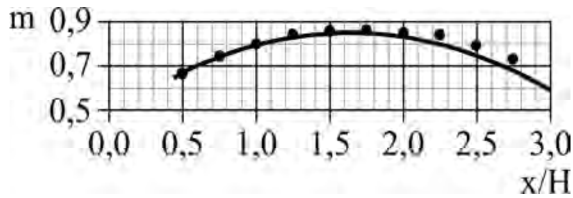


Fig. 7. Inside-jet velocity loss coefficient dependence on distance to air distributor:
▬ - approximation data, ● - research data

Velocity drop coefficient on the basis of the experimental data is:

$$\begin{cases} m = -0.138(x/H)^2 + 0.4514(x/H) + 0.4807 & \text{at } x/H \le 1.6355 \\ m = 0.85 & \text{at } x/H > 1.6355 \end{cases} \tag{4}$$

Velocity error does not exceed 1.2% at $x / H > 1.635$.

Analysis of supply flow development characteristics on the basis of supply coefficient (1) alone is not enough. Therefore, it is necessary to carry out an experiment with a finite-differential mathematical model of heat exchange processes in small-size high-heat room. For this the $k-\varepsilon$ model of turbulent flows has been used as the most tested modern model.

For this purpose a 3-D simulation of the location with an area of 19 x 12 m is created. Air distributors are substituted by solid models with the use of boundary conditions to the air-distributing surface "Air supply with a constant velocity, normal to the surface". Numerical studies of air flows in high-heat room allowed obtaining a new requirement which allows avoiding hot air recirculation from convective flows: areas of dilution between supply jets should be minimized. A model of air exchange arrangement has been discovered which creates favourable conditions for convective flow development due to the absence of convective flow recirculation. The most effective air supply is ensured by air distributors with a convex front panel installed every 3.5 m of the room length. The installation of air distributors with a flat front panel at the same interval lowers air conditioning energy performance requiring extra cooling of the air by 0.5÷1°C. A bigger interval between air distributors considerably deteriorates sanitary and hygienic conditions and makes it impossible to meet the requirements [1].

CONCLUSIONS

An approximate physical and mathematical model of heat and mass exchange processes in small-size high-heat locations has been created on the basis of balance equations of characteristic areas. Jet development characteristics are taken into consideration by the coefficient of convective flow supply by jets. The dependence for determining the air exchange coefficient has been obtained. Analysis of the dependence shows the necessity to minimize the inflow of supply jets to convective flows. Displacement ventilation best meets these requirements.

Low-velocity air distributors ensuring uniform velocities across the entire surface of air supply due to air flow separators in the first chamber are suggested.

A recurrent equation for determining the optimum size of horizontal flow separators of the low-velocity air distributor has been developed. Experimental data confirm it. Characteristics of development of the formed jet flow have been researched.

As a result of numerical simulations it has been obtained that the most effective air supply is ensured by air distributors with a convex front panel installed after every 3.5 m of the length of the location. Such arrangement best meets the requirement of avoiding convective flow recirculation.

A new requirement for avoiding hot air recirculation with convective flows has been obtained: depression areas should be minimized between supply jets. This requirement is especially important for small-size locations.

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OPRACOWANIE ENERGOEFEKTYWNEGO DOPŁYWU POWIETRZA DO POMIESZCZEŃ O NIEDUŻEJ OBJĘTOŚCI ZE ŹRÓDŁAMI CIEPŁA

Wiadomo, że najbardziej skutecznym sposobem nawiewu powietrza do pomieszczeń ze źródłami ciepła jest wentylacja wyciągowa ze zmiennym przepływem powietrza w zmiennych warunkach eksploatacyjnych. Zwiększanie szczelności pomieszczeń podwyższa wymagania do nawiewu powietrza. Aby zmniejszyć prędkość strumieni, należy zapewnić równomierny przepływ powietrza na wyjściu z jednostki nawiewu powietrza. Stosowane metody wentylacji na ogół nie spełniają tego wymogu. Zaproponowany sposób dopływu powietrza pozwala zapewnić równomierność dostarczania powietrza i likwidację nieprzewietrzanych stref przy zmianie wydatku przepływu powietrza.

Słowa kluczowe: **nawiew powietrza, pomieszczenie ze źródłami ciepła, wentylacja wyporowa, dystrybutor powietrza, turbulentny strumień**