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Research of the round convective air jet of the exhaust local ventilation

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ORIGINAL RESEARCH PAPER



ABSTRACT

The article is devoted to research of properties of the round convective air jet. The aim of this work is to establish universal graphical dependencies and empirical formulas for describing velocity and temperature fields over the entire range of development of round convective exhaust ventilation jet; development of an algorithm for solving the transcendent problem of determining the surface temperature of a heat source; introduction of velocity and temperature attenuation coefficients for round convective jet; visualization of its characteristics in the form of a 3D image; achieving reduction of metal consumption of the local exhaust ventilation system due to the overall optimization of the velocity and temperature fields of the round convective air jet.

KEYWORDS

exhaust ventilation, local ventilation, convective jet, round jet, exhaust outlet

1. INTRODUCTION

The Heating, Ventilation, Air Conditioning (HVAC) systems [1, 2] of residential, public and industrial buildings maintain the needed air indoor temperature [3, 4], velocity [5, 6], humidity [7, 8], carbon dioxide concentration [9, 10], level of the noise in a room [11], etc. The HVAC systems should be energy effective [12, 13] in all aspects, for instance building [14, 15], heat insulation [16, 17], heat source [18], heating and heat supply system [19, 20], ventilation tidal [21, 22] and exhaust [23] system, exhaust air heat recovery [24, 25], gas supply system [26, 27], renewable energy sources [28, 29], efficiency of material resources [30], especially metal products, etc.

If it is considered as industrial buildings, restaurant kitchens, etc., the technological processes are usually accompanied by significant heat emissions. In particular, in thermal shops, the production technology involves a large number of furnaces and equipment with high surface temperatures. This emits a significant amount of heat and convective air jets are formed. They are formed over the devices of the heating system [23], over the hot surfaces of the equipment [18] of industrial premises (thermal shops, galvanic shops, boiler rooms, etc.). As a result, the state of the air deteriorates and unfavorable working conditions can be created, which have a negative impact on people's well-being. A local ventilation system is used to deal with excess heat.

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2. PREVIOUS RESEARCH AND PROBLEM STATEMENT

Air supply and exhaust jets (round, compact, flat, annular, swirl, etc.) are characterized by the appropriate shape (depending on the supply or exhaust hole), temperature and velocity profile [31, 32], air volume flow rate. Tidal air jets also have attenuation coefficients for velocity and temperature [33]. Convective (thermal) air jets also have the appropriate shape, velocity and temperature fields [34, 35]. The characteristics of convective air jets are primarily influenced by the thermal power of the heat source, and thus - the surface temperature of the heat source [23]. Obviously, the shape of the convective jet depends on the configuration of the heat source. The most common are round, compact, flat and annular convective jets.

Heat transferred by convective jets is localized by local ventilation devices, usually exhaust outlets [23]. Of interest is the issue of minimizing the metal consumption of these devices. It depends on the volume flow rate of exhaust air in the convective jet. This value is different in different cross sections. The effective air volume flow rate is determined by the value of the velocity in the suction plane of the exhaust outlet. It is necessary to take into account the dependence of air density on the temperature of the entrance to the exhaust outlet and the environment, because in convective jets these temperatures, and therefore the air density differ significantly. The volume flow rate of the local ventilation hood is determined by the formula of continuity [36, 37].

Analysis of the development of convective (thermal) air jet, which is formed above the heat source, shows that there are three areas in the jet: overclocking, transient and main. The section between the acceleration and transition section is called compressed, and between the transition and the main - transition [38]. Since the acceleration and transition zone of convective jets is insufficiently studied, the article proposes the feasibility of experimental study of heat jet in order to further establish universal empirical formulas for describing velocity and temperature fields throughout the range of convective jet development. In addition, it is advisable to use the property of self-similarity and introduce on this basis the attenuation coefficients of velocity and temperature for convective jets. This will unify the calculated dependencies.

An important issue is to determine the surface temperature of the heat source, because this value determines the characteristics of the convective air flow over the entire range of its development. The surface temperature can be determined analytically or experimentally.

3. THE PURPOSE OF THE ARTICLE

The aim of the work is:

- to establish universal graphical dependencies and empirical formulas for describing velocity and temperature fields over the entire range of development of round convective exhaust ventilation jet;

- development of an algorithm for solving the transcendent problem of determining the surface temperature of a heat source; - introduction of velocity and temperature attenuation coefficients for round convective air jet;
- visualization of its characteristics in the form of 3D images to confirm the results of the study;
- achieving reduction of metal consumption of the local exhaust ventilation system due to some optimization.

4. INVESTIGATION OF THE ROUND CONVECTIVE AIR JET OF THE EXHAUST LOCAL VENTILATION

The heat power of the heat source consists of the convective and radiation components [39]. To determine it, the article develops an algorithm for solving the transcendental problem, namely the calculation of the surface temperature of the heat source. What is this transcendent problem?

First of all, it should be noted that it is advisable to operate with the values of heat fluxes, respectively, convective, radiative and total heat (q_c , q_R and q_0 , W m^{-2}). Guided by this thesis and [23], Eq. (1) was obtained to determine the surface temperature of the heat source on the basis of the convective component and Eq. (2) – on the basis of the radiative component of heat released by the source:

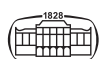
$$\tau = t_0 + \left(\frac{q_c}{2.05} \right)^{0.75}, \quad (1)$$

$$\tau = 100 \left(\frac{q_R}{c_0 \varepsilon} \right)^{0.25} - 273, \quad (2)$$

where c_0 is the coefficient of radiation of an absolutely black body, $c_0 = 5.67 \text{ W}/(\text{m}^2 \text{K}^4)$; ε is the degree of blackness of the heat source (for oxidized steel $\varepsilon = 0.8$); τ is the surface temperature of the heat source, °C or K.

Obviously, the results obtained by Eqs (1) and (2) must match. But the values of q_c and q_R are unknown, so a transcendental problem arises. To solve it, the basis of the algorithm has been developed, which is to operate on the particles of the convective and radiative components of the heat released by the source. The surface temperature of the heat source should be determined by Eqs (1) and (2) by the iterative method. It is expedient to accept in the first approximation the same share of the convective and radiation component, $q_c = q_R = 0.5q_0$, and then to specify this value, carrying out iterations within the desired accuracy.

According to the results of the implementation of the algorithm for determining the surface temperature of the heat source they are approximately: $\tau = 92^\circ \text{C}$ for $Q = 0.4 \text{ kW}$, $\tau = 151^\circ \text{C}$ (424 K) for $Q = 0.8 \text{ kW}$, and $\tau = 197^\circ \text{C}$ (470 K) for $Q = 1.2 \text{ kW}$. The shares of the convective and radiation components are 0.43 and 0.57 (minimum thermal power of the source), 0.48 and 0.52 (intermediate thermal power of the source), 0.48 and 0.52 (maximum thermal power of the source), respectively.



The next step is to determine the optimal location for the installation of the exhaust outlet for the maximum effect of localization of excess heat from the room. To do this, consider the scheme of convective jet over the heat source, which is presented in Fig. 1.

Let us analyze the effect of installing the exhaust outlet at a height with coordinates x_1 , x_2 and x_3 (positions 1, 2, 3 in Fig. 1). It should take into account the volume air flow rate at a certain height, which directly affects the size of the exhaust outlet, and therefore - on its metal content. Installing the exhaust outlet at a lower height (x_1 in Fig. 1) is not effective due to the fact that the useable space is small, and high velocities of air stream cause an increase in air volume flow rate. Since the productivity of the exhaust outlet of local ventilation is determined by the formula of continuity, to reduce it, the priority is to operate in the area of lower velocities, ie at higher altitudes (x_3 in Fig. 1). At the same time the useful space of the room increases. However, in this area it should be taken into account the significant expansion of the convective jet, which results in the need to increase the cross-sectional area. In addition, the convective jet ejects the surrounding air. It is obvious that the expedient place of installation of an exhaust outlet is section with intermediate coordinate x_2 in Fig. 1. The result of this mathematical problem is uncertainty, the analytical solution of which is quite difficult. Instead, it is advisable to choose experimental research as a way to solve this problem.

Experimental investigations have been carried out under following conditions, assumptions and simplifications: shape of heat source was round; the air flow rate in the experiments was within: $L = 170\text{--}50\text{ m}^3\text{ h}$; heat power of the heat source was 0.4 kW ; initial velocity and temperature of the air jet was in the range of $v_0 = 1.0\text{--}1.4\text{ m s}^{-1}$ and $t_0 = 33\text{--}45\text{ }^\circ\text{C}$. During experimental studies [40] the velocity and

temperature of the air on the axis of the convective air jet and in its cross section were measured with a thermal anemometer Testo-405. The position of the piezoelectric element in space was fixed by the coordinate installation.

The results of the study of the characteristics of the convective air jet over the heat source are presented in Figs 2 and 3. Figure 2 shows the distribution of velocities, and Fig. 3 presents the distribution of excessive temperatures on the axis of the air jet depending on the current coordinate and heat power of the heat source.

For the possibility of analytical calculations, these nomograms are approximated by Eqs (3) and (4), respectively:

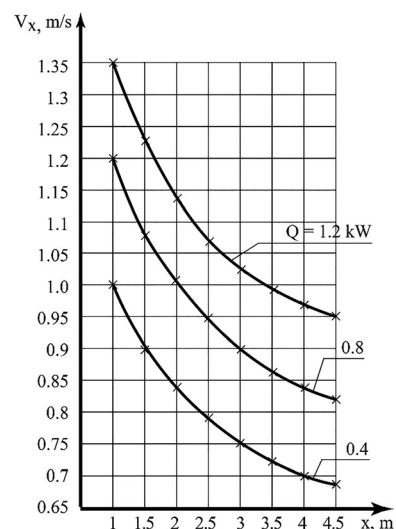


Fig. 2. Velocities of the convective air jet on its axis depending on current coordinate and heat power of the heat source

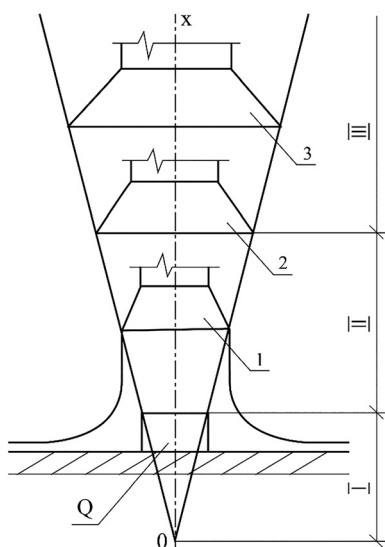


Fig. 1. Scheme of convective air jet over a heat source with thermal power Q : I - acceleration zone, II - transition zone, III - main zone; 1, 2, 3 - position of the exhaust outlet

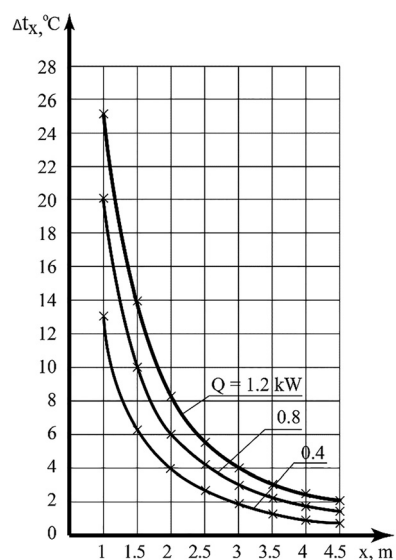


Fig. 3. Excessive temperatures of the convective air jet on its axis depending on current coordinate and heat power of the heat source

$$v_x = \frac{0.75 + 0.69Q_c - 0.15Q_c^2}{x^{0.25}}, \quad (3)$$

$$\Delta t_x = \frac{3.7 + 23.1Q_c - 4.1Q_c^2}{x^{1.7}}, \quad (4)$$

where v_x and Δt_x are respectively axial velocity, m s^{-1} and excessive temperature, $^{\circ}\text{C}$ or K ; x is the current coordinate, m ; Q_c is the current heat power of the heat source, kW .

Research has shown that the product of a certain jet parameter and the current coordinate in some power is a constant value. In particular, the product of the axial velocity and coordinate in the unit-less power of 0.25, as well as product of the excessive axial temperature and coordinate in the unit-less power of 1.7 is constant. Therefore, it is advisable to introduce the attenuation coefficients of velocity and temperature and to unify the formulas for calculating all types of air jets: tidal and convective. But axial velocities and excessive temperatures depend on the heat power of the heat source. Eqs (5) and (6) are obtained to determine the axial velocities and excessive temperatures. They take into account the attenuation coefficients of velocity and temperature, as well as the dimensionless heat power $\bar{Q}$ as the ratio of the current heat power Q_c to the minimum $Q_{\min}$:

$$v_x = \frac{m\sqrt{F}}{x^{0.25}}\bar{Q}c_1, \quad (5)$$

$$\Delta t_x = \frac{n\sqrt{F}}{x^{1.7}}\bar{Q}c_2, \quad (6)$$

where m and n are respectively, the dimensionless attenuation coefficients of velocity and temperature; F is the area of a round heat source, m^2 ; c_1 and c_2 are the dimensionless jet characteristics that depend on the heat power of the heat source.

In the course of research Eqs (7) and (8) were obtained to determine these characteristics of the convective air jet:

$$c_1 = 0.87 - 0.405\bar{Q} + 0.065\bar{Q}^2, \quad (7)$$

$$c_2 = 9.5 - 1.6\bar{Q} + 0.1\bar{Q}^2. \quad (8)$$

Experimental studies were performed under minimum heat power $Q_{\min} = 400 \text{ W}$.

As a result of processing experimental data to confirm the results of the study it was created 3D visualization of velocities (Fig. 4a) and excessive temperatures (Fig. 4b) depending on the current coordinate and heat power of the heat source.

The results of the experiment agree well with the theoretical dependencies. Based on them, it should be stated that it is rational to place the exhaust outlet not higher than the level of the transition section of the air jet, because the convective air stream is stable (v_x exceeds 0.5 m s^{-1}), and the expansion of the air jet and ejection of ambient air are optimal. This allows to minimize the volume flow rate of exhaust air, reduce the productivity of local ventilation and achieve the localization of harmfulness in the form of excessive heat in the place of their release. Together, these

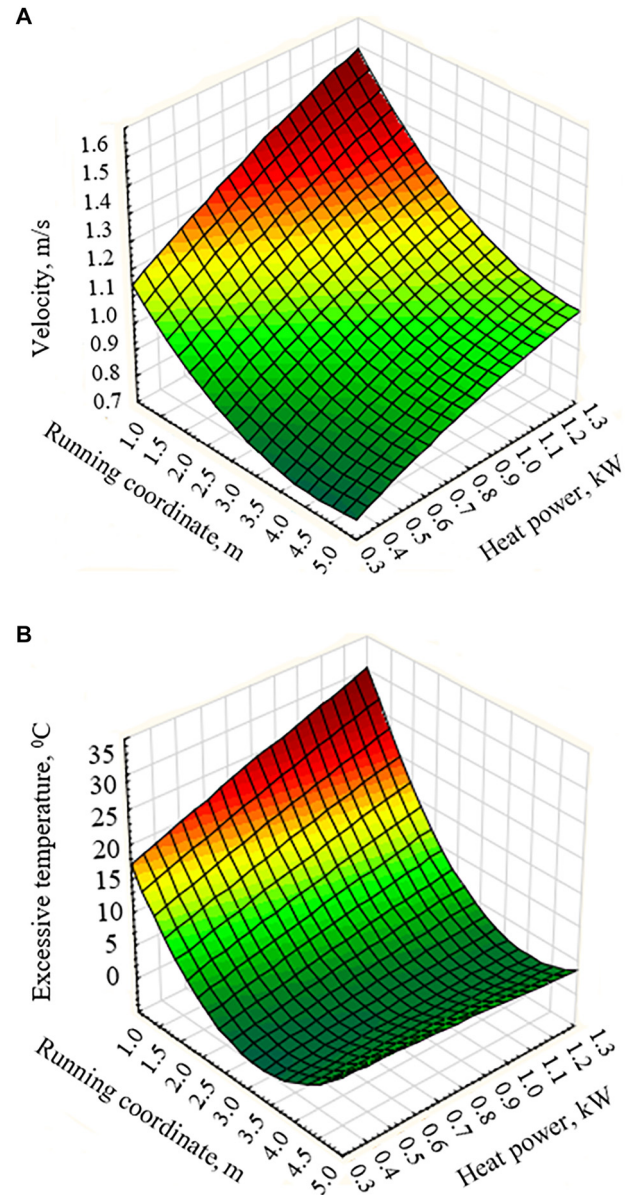


Fig. 4. Visualization of convective round air jet characteristics depending on current coordinate and heat power of the heat source: a) velocities; b) excessive temperatures

factors minimize the size of the exhaust outlet and achieve savings in metal content of ventilation equipment.

5. CONCLUSIONS

1. Universal graphical dependencies and empirical formulas for the description of velocity and temperature fields in the whole range of development of round convective exhaust ventilation jet depending on the current coordinate and heat power of the heat source are established;
2. An algorithm for solving the transcendental problem of determining the surface temperature of a heat source has been developed. They are approximate: $\tau = 92^{\circ}\text{C}$ (365 K) for $Q = 0.4 \text{ kW}$, $\tau = 151^{\circ}\text{C}$ (424 K) for $Q = 0.8 \text{ kW}$ and $\tau = 197^{\circ}\text{C}$ (470 K) for $Q = 1.2 \text{ kW}$;

3. The attenuation coefficients of velocity and temperature of a round convective air jet are introduced and determined, which are respectively equal $m = 1.9$ and $n = 1-5$;
4. 3D visualization of velocities and excessive temperatures of round convective exhaust ventilation jet is created;
5. Due to the combined optimization of the velocity and temperature fields of the round convective air jet and the geometric characteristics of the exhaust outlet, the metal content of the local exhaust ventilation system is minimized. It is rational to place the exhaust outlet not higher than the level of the transition section of the jet, because the convective air stream is stable (v_x exceeds 0.5 m s^{-1}), and the expansion of the air jet and the ejection of ambient air are optimal.

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