DIAGNOSIS OF DAMAGE TO THE VENTILATION SYSTEM

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Abstract

The article is devoted to solving of urgent problem to eliminate damages of two types in ventilation systems for air distribution efficiency increasing in the premises by swirled air flow, compact air jet, flat air stream and rectangular air jet. A mathematical model of air supply with swirled air flow, compact air jet, flat air jet and rectangular air stream in the room has been developed. It is shown that in order to achieve the maximum efficiency of air distribution it is necessary to ensure its supply by jets. Graphical and analytical dependences on the basis of the conducted experimental research are presented. Parameters of swirled air flow, compact air jet, flat air stream and rectangular air jet during the formation of a comfortable indoor climate are determined. The results of experimental studies of air supply to the room by the air distribution devices, which form a swirled air flow, compact air stream, flat air flow and rectangular air jet with adequate turbulence and long range of the supply air flow, are presented. It is established that with the increase of the angle of swirling plates inclination and ratio of the slit sides the air jets long range increases.

Keywords: air distribution, damages, swirled air jet, compact air jet, flat air jet.

1. INTRODUCTION

One of the important tasks of room ventilation is to ensure the effective organization of air exchange [6], in particular air distribution [2, 4, 12]. In this case, the requirements of ensuring the normalized velocity and temperature of the air in the working area [14, 16, 18] and energy efficiency [9, 37, 39] should be followed. Exhaust air utilization by recuperators is usually used [1, 36]. Sometimes the production process takes place in small premises, overloaded with technological equipment and personnel [38]. In this case, there is a need to ensure the supply of a large amount of fresh air in the compressed conditions of these premises. This makes it impossible to provide a normalized air velocity in the working area [17, 21, 27, 33]. The velocity of air flows usually exceeds the normalized values, because it does not provide effective attenuation of the air jets velocity [5, 7, 10]. The rate of attenuation is caused by viscosity as a physical property of air. The quantitative characteristic of the attenuation of the air flow velocity is the corresponding velocity attenuation coefficient, which is denoted by $n$. The attenuation coefficients of velocity and temperature are dimensionless and describe the behavior of the air flow as it flows out of the air distributor at the initial and main section of the air jet. If the values of the attenuation coefficients are high, it indicates insufficient flow turbulence, insufficient attenuation of velocity and temperature, and a significant advantage of dynamic forces over friction forces (viscosity). However, air distributors have a low coefficient of aerodynamic resistance, which is a positive factor in the energy aspect.

The attenuation of the air flow rate is directly related to its long range. The long range of the air stream is the maximum distance that the air flow travels during its development from the air distributor to the point where the velocity of the direct flow becomes equal to the mobility of air in the room, and the air stream is transformed from the direct flow to the reverse one. At the same time the long range of the air jet becomes too high and needs to be reduced. When the normative values of air velocity and temperature are exceeded, the conditions of comfort are violated [24]. This phenomenon means that the ventilation system has a damage type 1.

There is another problem of formation of stagnant unventilated areas in the room due to
insufficient air jets long-range since the intense air velocity attenuation. In this case, the values of the attenuation coefficients are too low. This indicates excessive flow turbulence, excessive attenuation of air velocity and temperature, and a significant advantage of friction (viscosity) over dynamic forces. As a result, air distributors have a high coefficient of aerodynamic resistance, which negatively affects the ventilation system as a whole, as it becomes energy consuming [25]. This results in the fact that the long range of the air jet becomes too low and needs to be increased. The consequence of this is an excessive concentration of CO₂ in the room [13, 15, 19, 20]. This phenomenon means that the ventilation system has a damage type 2.

A progressive direction in overcoming damage to the ventilation system of both types is an adequate choice of air distribution devices [3, 23, 34] with the appropriate coefficients of attenuation of air jet velocity and temperature and also achieving proper air jet long range in a premise. Attention should be paid to the distribution of air by compact, flat, rectangular and swirled air streams. Ensuring comfort conditions and achieving energy efficiency of air distribution by optimizing the attenuation coefficients of air velocity and temperature and also long range through the use of compact, flat, rectangular and swirled air jets and recuperators is an extremely important task.

2. GOAL OF THIS PAPER

The aim of the work is to eliminate damages of two types in ventilation systems due to determine the long range and initial section of flat, compact, rectangular and swirled air jets and to establish graphical and analytical calculation dependences under the condition of creating a comfortable microclimate in the premises.

To achieve this goal it is necessary to perform the following research tasks:
- to analyze the characteristics of flat, compact, rectangular and swirled air jets, their efficiency and design dependencies;
- to generalize and deepen the theory of aerodynamic processes in air supply by flat, compact, rectangular and swirled jet streams;
- to perform experimental studies of air distribution by flat, compact, rectangular and swirled air jets, establish graphical and analytical calculation dependences;
- to determine the long range and length of the initial section of flat, compact, rectangular and swirled air jets;
- to compare the theoretically obtained results with experimental data and establish correction factors for the theoretical solution of indoor air distribution.

3. RESEARCH OF AIR JETS LEAKAGE

Flat [8, 11], compact [36, 37] and swirled [34, 36, 37] air jets are one of the most common in ventilation technology. Flat and compact air jets are usually used as horizontal, and swirled – as vertical [36, 37]. Flat air jets are formed by means of inflow slits with a ratio of length to height \( l/b \geq 10 \), and with a ratio of \( 1 < l/b < 10 \) it is expedient to call jets rectangular. Compact jets are formed by round or square holes. Swirled air jets are formed due to the presence in the cylindrical hole of the swirling plates, which can be deviated at a certain angle \( \alpha \).

This is an important factor that determines the properties and characteristics of these jets. As a result, they have different coefficients of air velocity and temperature attenuation, aerodynamic resistance, acoustic properties of aerodynamic noise [35], and especially the long range of the jet and its initial section. In particular, it would be interesting to compare the long range of flat, compact and rectangular air jets depending on the ratio of the sides of the supply slit \( l/b \) and swirled air stream depending on the angle of the swirling plate’s inclination \( \alpha \).

Based on the analysis, it should be stated that the long range of air jets is directly affected by the air velocity attenuation coefficient, which depends on the aerodynamic resistance. Among them the flat air jets have the highest aerodynamic resistance and compact air jets have the lowest. This is a consequence of a sudden narrowing of the jet when it enters the cross section of the air outlet. Due to this, the attenuation coefficient of the velocity is lower, which results in a decrease in the length of the initial section of the supply air jet. However, the corresponding nature of the change in axial velocity indicates the need to take into account the initial velocity of the jet and the size of the supply nozzle to determine the range [29 - 32]. The aerodynamic resistance of the swirled jets depends on the angle of the swirling plates inclination. At smaller angles of the plates inclination more intense turbulence of the inflow is observed, so the resistance increases, and the attenuation coefficient of velocity decreases.

The article presents a generalization of the calculation dependences for determining the long range \( x_{\text{max}} \) of the flat, compact, rectangular and swirled air jets and bringing them to a universal form.

Taking into account the hypothesis, we assume the dependence (1) to determine the long range of the flat, compact and rectangular air jets:

\[
x_{\text{max}} = b \left( \frac{v_p m}{v_c} \right)^{\frac{1}{\alpha}}
\]

where \( x_{\text{max}} \) – air jet long range, m;
\( b \) – height of a tidal slit, m;
\[ x_{\text{max}} = \frac{v_0 m k_{sw} \sqrt{\pi D}}{2v_x} \]  

where \( x_{\text{max}} \) - air jet long range, m;  
\( D \) - diameter of the inlet nozzle, m;  
\( m \) - air velocity attenuation coefficient, which depends on the angle of the swirling plates inclination \( \alpha \) and is determined from [36];  
\( k_{sw} \) - a swirling coefficient which depends on the angle of the swirling plates inclination \( \alpha \) and is determined from [36];  
\( v_0 \) and \( v_x \) - respectively, the absolute initial and axial velocity of the air stream, m/s.

Experimental studies have been carried out on the installation shown in Fig. 1 under the following conditions and simplifications:  
- the area of openings \( F_0 = 0.009 - 0.010 \text{ m}^2 \);  
- air flow rate was within the range \( L = 100 - 500 \text{ m}^3/\text{h} \);  
- the initial air velocity was within \( v_0 = 2 - 6 \text{ m/s} \);  
- the ratio of the sides of the tidal slit: \( l/b = 10; 5; 2.5; 1 \);  
- angle of swirling plates inclination: \( \alpha = 15^\circ, \alpha = 30^\circ, \alpha = 45^\circ, \alpha = 60^\circ, \alpha = 75^\circ \);  
- diameter of the air distributor with the swirling plates: \( D = 150 \text{ mm}, D = 250 \text{ mm} \).

Air velocity was measured with a thermal electrical anemometer Testo-405 at these values.  
The obtained results with respect to axial velocities are presented in Fig. 2.
The experimental results (Fig. 2) show that directly at the outlet of the nozzle for rectangular air jets close to the flat (increasing of the slit sides ratio) increases the flow turbulence. At the same time the air velocity attenuates more intensively and the ambient air is ejected. As a result, the length of the initial section decreases (Fig. 3). For rectangular air jets close to compact (reduction of the slit sides ratio), the turbulence of the flow is not so intense. In this case, the air velocity attenuates weaker and the ambient air is ejected less intensely, as a result of which the long range of the compact air jet decreases and the length of the initial section increases (Fig. 3).

The graph (Fig. 3) is approximated by a polynomial dependence (3):

\[ x_{in} = 0.1 + 1.1 \frac{b}{l} - 0.6 \left( \frac{b}{l} \right)^2 \]  (3)

For the convenience of the graphic image and analytical approximation, the ratio of the sides dimensions of the flat slit is presented in the form \( b/l \).

The results of the swirled air jet study are presented in Fig. 4. Fig. 4 shows that the effect of swirling is manifested as much as possible at smaller angles: the air jet is most affected by the swirling of the air flow, and the axis of the jet changes the direction as much as possible.

At an angle of the swirling plate’s inclination \( 30^\circ \) in the section from \( \bar{x} = 0.125 \) to \( \bar{x} = 0.250 \) the axis of the tidal jet passes at an angle of 18° to the horizontal, in the section from \( \bar{x} = 0.250 \) to \( \bar{x} = 0.50 \) the axis of the jet passes at an angle of 45° to the horizontal. Starting from the cross section \( \bar{x} = 0.50 \), the axis of the jet runs parallel to the axis of the air distributor and at a distance \( \bar{y} = 0.50 \) from its axis. At an angle of the swirling plate’s inclination \( 60^\circ \) in cross section from \( \bar{x} = 0.125 \) to \( \bar{x} = 0.375 \) the axis of the swirled air jet passes along the axis of the air distributor. In cross section from \( \bar{x} = 0.375 \) to \( \bar{x} = 0.625 \) the axis...
of the jet passes at an angle of 45° to the horizontal.

Starting from the cross section \( x = 0.625 \), the axis of the supply air jet runs parallel to the axis of the air distributor and at a distance \( y = 0.20 \) from its axis.

At an angle of the swirling plates inclination 90°, the axis of the air jet coincides with the axis of the air distributor, so air jet is close in its characteristics to the direct flow. At small angles of inclination, the air jet passes the greatest distance from its exit from the air distributor to the working area entrance. Thus there is the most effective mixing of supply air with surrounding one and therefore at such angle of inclination it is possible to supply air with higher initial velocity at exit from the air distributor.

The swirling effect results in to a significant reduction of the initial section length compared to rectangular air jets in general. Increasing of the swirling plates inclination angle results in to increase the length of the initial section and decreasing – according to decrease.

To determine the long-range of tidal air jets was implemented planning a complete three-factor experiment – Table 1, where the determining factors are:

- \( x_1 = v_0 \) – initial air jet velocity, \( x_2 = 2 – 6 \text{ m/s} \);
- \( x_2 = \alpha \) – the angle of the swirling plates inclination,
  \[ x_2 = 15^0 \quad 75^0 \];
- \( x_3 = D \) – nozzle diameter, \( x_3 = 150 – 250 \text{ mm} \).

The optimization parameter is the long-range of the air jet \( y = x_{max} \), \( m \).

Table 1

| No | \( x_0 \) | \( x_1 = v_0 \) | \( x_2 = \alpha \) | \( x_3 = D \) | \( x_3 \times x_3 \times x_3 \) | \( y = x_{max} \) |
|----|----------|----------------|-----------------|----------------|----------------|---------------|
| 1  | +        | -              | -               | +              | -              | 0.6           |
| 2  | +        | +              | -               | -              | +              | 1.8           |
| 3  | +        | -              | +               | -              | +              | 0.9           |
| 4  | +        | +              | -               | +              | -              | 2.7           |
| 5  | +        | -              | -               | +              | -              | 1.0           |
| 6  | +        | +              | -               | -              | +              | 1.5           |
| 7  | +        | -              | +               | -              | -              | 3.0           |
| 8  | +        | +              | +               | +              | +              | 4.5           |

According to the results of experiment planning, we obtain the regression equation (4):

\[
y = 2.0 + 1.0x_1 + 0.25x_2 + 0.5x_3 \quad (4)
\]

The regression analysis showed that the long-range effect is most affected by the initial air velocity, and the least affected by the angle of the swirling plate’s inclination. Long-range increases with increasing all the determining factors: the initial air velocity, the angle of the swirling plates inclination and the diameter of the nozzle.

According to the results of the experiment, a nomogram was constructed (Fig. 5).

Due to graphical dependence (Fig. 5) the direct problem and three inverse problems are solved (the corresponding solution keys are presented in Fig. 5). This means that any value from the four ones (the initial velocity \( v_0 \), the angle of the swirling plates inclination \( \alpha \), the diameter of the nozzle \( D \) and the air jet long range \( x_{max} \)) is determined if other three are given. This graph (Fig. 5) makes it possible to determine the required long range of the swirled air jet to eliminate damage of both types in the ventilation system.
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For compact, flat and rectangular air jets, a similar experiment planning matrix is composed with the following determining factors:
\[ x_1 = v_0 - \text{initial velocity of the air jet}, \quad x_2 = 2 - 6 \text{ m/s}; \]
\[ x_2 = \frac{b}{l} - \text{the ratio of the slit height to its length}, \quad x_2 = 0.1 - 1; \]
\[ x_3 = b - \text{slit height}, \quad x_3 = 0.03 - 0.10 \text{ m}. \]

According to the results of experiment planning, it was received the regression equation (5) for long-range as an optimization parameter:
\[
y = 6.45 + 3.225x_1 - 2.15x_2 + 3.45x_3 \quad (5)
\]

The regression analysis showed that the smallest effect on long-range is the ratio of the sides of the tidal slit, and the effect of the initial velocity and height of the slit is almost equivalent. Long-range increases with increasing initial velocity and slit height, but decreases with increasing ratio of slit height to its length \( \frac{b}{l} \).

According to the results of the experiment, a nomogram was constructed (Fig. 6).

Similarly, to Fig. 5 due to graphical dependence (Fig. 6) four problems are solved (direct problem and three inverse problems). The corresponding solution keys are presented in Fig. 6. This nomogram (Fig. 6) makes it possible to determine the required long range of the rectangular air jet to eliminate damage of both types in the ventilation system.

CONCLUSIONS

1. On the basis of the conducted research graphic and analytical dependences for determination of long-range and length of initial section \( x_{in} \) of flat, compact, rectangular and swirled air streams are received and they are brought to a universal form. The ability to choose the long range of air jets allows us to eliminate damage type 1 to the ventilation systems.

2. Graphical and analytical dependences for determination of air velocities of the flat, compact, rectangular and swirled inflow air jets under the condition of creating a comfortable microclimate indoors are obtained. This eliminates type 2 damage to ventilation systems.

3. The hypothesis of air jets long range and length of the initial section of the flat, compact, rectangular and swirled air jets is experimentally confirmed.

4. The regression analysis showed that the long range of the swirled jets is most affected by the initial velocity, and the least affected by the angle of the swirling plate’s inclination. Long-range increases with increasing all the determining factors: the initial air velocity, the angle of the swirling plates inclination and the diameter of the nozzle. The smallest effect on the range of rectangular air jets has the ratio of the sides of the tidal slit, and the effect of the initial air velocity and height of the hole is almost equivalent. Long range increases with increasing initial velocity and slit height, but decreases with increasing the ratio of slit height to its length \( \frac{b}{l} \). These results make it possible
to eliminate damage of both types in ventilation systems.
5. The graphical way of the decision of four problems (direct and three inverted) in the form of the corresponding keys of the decision for the swirled, flat, compact and rectangular air streams is presented.

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