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Improvement of Energy Efficiency of Air Distribution in a Room Using Swirled Air Jets

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Abstract

This article investigates the aerodynamic behavior and efficiency of swirled air jets used in modern ventilation systems. The influence of rotational motion on turbulence intensity, mixing efficiency, and air distribution uniformity is assessed. Results confirm that swirled jets enhance air mixing and reduce axial velocity and temperature gradients more effectively than traditional non-swirled jets. Key dimensionless parameters, such as velocity and temperature attenuation coefficients, are introduced to simplify calculations. Velocity and temperature profiles across the jet cross-section are examined in detail. The findings demonstrate that swirled jets provide improved control of indoor air distribution, minimize drafts, and help maintain stable thermal comfort. These insights support the implementation of swirl-based air supply solutions in confined and energy-sensitive environments.

Keywords: air distribution; swirled air jet; air velocity; jet border; air flow turbulence; aerodynamics.

1. Introduction

Contemporary standards regulating indoor environmental quality impose stringent criteria regarding airflow organization, thermal consistency, and the maintenance of a stable and comfortable indoor atmosphere [1]. In scenarios involving frequent occupancy — particularly in administrative, public, or industrial buildings — precise management of air circulation is of critical significance [2]. A pivotal factor in this context is the balanced distribution of air across the space, which helps to eliminate stagnant air pockets and mitigate abrupt thermal variations [3].

Conventional ventilation configurations employing standard air outlets often fail to deliver sufficient airflow uniformity [4], struggle to prevent zones of thermal overload or excessive cooling, and are generally inadequate in minimizing localized draughts [5]. Such deficiencies result in compromised thermal comfort, suboptimal working conditions, and can lead to adverse health implications, including respiratory ailments and reduced occupational performance [6]. Moreover, the ineffective operation of air delivery systems contributes to unnecessary energy expenditure, leading to elevated operational costs for climate control [7].

One of the effective strategies for enhancing indoor air mixing and thermal comfort involves the application of rotational (swirled) airflow patterns [8]. These vortex-type air jets, generated through specially designed inlet geometries, contribute to more intensive and uniform distribution of air throughout the occupied zone. By inducing turbulence and directional variability, swirled flows help to eliminate stratification and reduce the presence of thermally stagnant regions, thereby improving the overall microclimatic balance [9].

Numerical modeling and experimental investigations have demonstrated that swirl-inducing ventilation approaches offer superior control over air momentum and temperature gradients. This method allows for a more

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dynamic interaction between supply air and room air, facilitating enhanced thermal comfort and energy efficiency. The generation of rotational air streams also minimizes localized discomfort by dampening draft effects and promoting even temperature dispersion across diverse indoor environments [10].

2. Analysis of the recent publications and research works on the problem

Modern air distribution strategies increasingly incorporate vortex-forming devices that produce rotational airflows characterized by angular momentum and enhanced turbulence intensity [11]. These swirled jets are highly effective in improving air mixing, reducing temperature gradients, and minimizing zones of thermal stagnation. Depending on the boundary conditions and temperature differentials, such jets can exhibit varied flow regimes, including:

- free swirled jets, developing in open space without interference from nearby surfaces;
- confined swirled jets, influenced by walls, ceilings, or other room boundaries;
- isothermal jets, where inlet and ambient air temperatures are equivalent;
- non-isothermal jets, involving heated or cooled air relative to room temperature;
- laminar vortex flows, observed at low Reynolds numbers (Re < 2,300);
- turbulent vortex flows, dominant at higher Reynolds numbers (Re > 10,000) [12].

Swirled jets typically consist of a vortex core, where rotational velocity remains stable, surrounded by an outer area with increasing mixing and entrainment. A distinct feature of such flows is their ability to generate strong axial and tangential velocity components, which significantly enhance the distribution of thermal energy and reduce stratification effects [13]. This makes them especially suitable for use in spaces with complex air distribution requirements or high occupancy densities.

In the course of experimental investigations of individual swirled jets and their mutual interactions, it was observed that within the main development zone, the jets exhibit a gradual and relatively uniform attenuation in axial velocity v_x and excess temperature $\Delta\ t_x$, defined as the difference between the jet air temperature and the ambient room temperature t_{in}: $\Delta\ t_x = t_x - t_{in}$ [14]. This raises an important question: how does the interaction of multiple swirled jets, generated by a vortex diffuser, influence their aerodynamic behavior and thermal performance?

It is reasonable to hypothesize that the formation of multiple interacting swirled air jets at the outlet of a vortex diffuser significantly increases flow turbulence, promotes more rapid attenuation of axial velocity in the supply stream, and as a result, reduces the velocity attenuation coefficient (Fig.1.) [15].

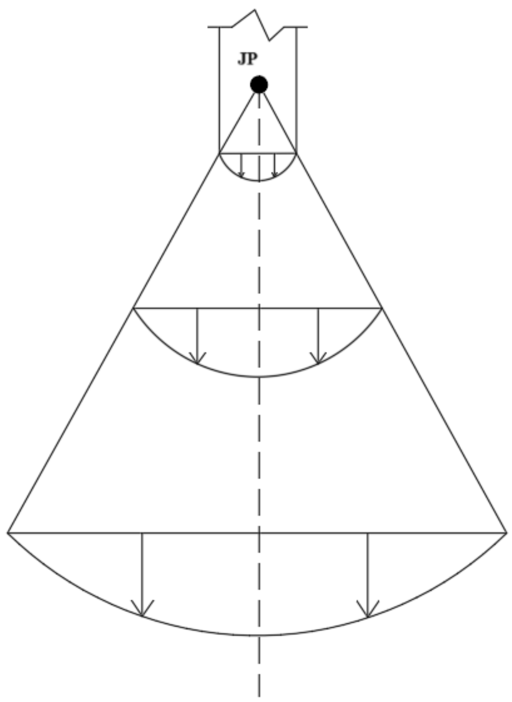

Fig.1. Scheme of a free jet development. Jet pole (JP) is the vertex through which the outer boundaries of the air jet pass.

3. Formulation of the goal of the paper

The aim of this study is to examine the efficiency of using swirled airflow configurations in mechanical ventilation systems, to determine optimal flow parameters, and to evaluate their impact on the uniformity of air distribution and overall microclimate quality within enclosed environments. Special attention is given to the analysis of the aerodynamic behavior of swirled air jets. The methodology combines numerical simulations with experimental investigations, which provides a solid foundation for developing design recommendations for ventilation systems incorporating swirl-inducing air supply components to enhance energy efficiency and indoor comfort.

4. Presentation of research results

In the study of air distribution in indoor environments, swirled jets have gained attention due to their enhanced mixing capabilities and ability to ensure uniform temperature and velocity fields. Unlike plane or compact free jets, swirled flows exhibit complex velocity profiles and increased turbulence, which significantly influence the attenuation of axial velocity and temperature excess in the supply stream.

The axial velocity v_x of an isothermal swirled jet was described by the inverse proportionality law:

$$v_x = \frac{SC}{x}, \tag{1}$$

where x is the axial distance from the outlet, m; SC is the swirl coefficient (a dynamic parameter incorporating both geometric and thermal physical properties of the jet), m^2/s.

The swirl coefficient is determined as follows:

$$SC = \frac{0.66}{\mathrm{tg}\beta}\sqrt{\frac{T_v}{T_o}} \cdot \sqrt[4]{\zeta} \cdot v_o \cdot \sqrt{A_o}, \tag{2}$$

where β is the effective swirl dispersion angle, typically determined by the geometry of the swirl generator (for example, β=45°, so tg$\beta \approx 1$); ζ is the local resistance coefficient associated with the swirl-inducing element; T_o and T_v are the absolute temperatures of the supply air and the room air, respectively, K; v_o is the initial velocity of the flow at the outlet, m/s; A_o is the effective area of the outlet cross-section through which the swirled jet is introduced into the space, m^2.

To simplify practical calculations, a velocity attenuation coefficient s specific to swirled jets is introduced as:

$$s = \frac{0.66}{\mathrm{tg}\beta}\sqrt{\frac{T_v}{T_o}} \cdot \sqrt[4]{\zeta}. \tag{3}$$

Accordingly, the axial velocity at any distance x from the outlet was expressed in a generalized form:

$$v_x = k \cdot v_o \cdot \sqrt{A_o}/x, \tag{4}$$

where k is an empirical constant that may vary depending on the swirl intensity and outlet geometry.

These equations enable a practical estimation of the behavior of swirled air jets, providing a basis for optimizing air distribution strategies in ventilation and air-conditioning systems to improve indoor environmental quality.

The velocity profile of air flow in swirled jets, particularly in the cross-sectional plane, plays a key role in determining the overall distribution efficiency and thermal comfort. The transverse velocity component v_y at any cross-section x and at a radial distance y from the central axis of the jet is defined by Schlichting's empirical formula:

$$v_y = v_x\left[1 - \left(\frac{y}{y_b}\right)^{1.5}\right]^2, \tag{5}$$

where v_x and v_y are the axial and lateral velocity components, respectively, m/s; y_b is the jet boundary defined by the extent of significant momentum transfer, m.

For practical analysis, it is beneficial to express the velocity components in dimensionless form: the relative axial velocity $\overline{v}_x = v_x/v_o$ and the relative lateral velocity $\overline{v}_y = v_y/v_x$.In this context, the dimensionless velocity $\overline{v}_x$ was approximated by:

$$\overline{v}_x = \frac{0.48}{a \cdot x/d_e + 0.145}, \tag{6}$$

where a = 0.078 is an empirical coefficient; d_e is equivalent diameter of the nozzle or outlet.

In the case of non-isothermal swirled jets, buoyancy effects must be considered due to temperature differences between the supply air and the ambient environment. The ratio of buoyancy to inertial forces at the point of ejection is characterized by the Archimedes number Ar_o:

$$\mathrm{Ar}_o = \frac{g\sqrt{F_o}\cdot\Delta t_o}{V_o^2\cdot T_{in}}, \tag{7}$$

where g = 9.81 m/s^2 is gravitational acceleration; F_o is outlet area, m^2; $\Delta t_o = t_o - t_{in}$ is excess initial temperature of the jet over ambient temperature, K; T_{in} is absolute indoor air temperature, K; V_o is initial supply velocity at the outlet, m/s.

Based on the magnitude of the Archimedes number Ar_o, non-isothermal jets are typically classified into two regimes:

- non-isothermal A – where inertial forces dominate and buoyancy effects are negligible;
- non-isothermal B – where buoyancy significantly affects the development and trajectory of the air jet.

Understanding this distinction is essential for accurately modeling the behavior of swirled jets in HVAC systems, especially when maintaining thermal comfort and stratification control in large or thermally sensitive indoor environments.

In the case of horizontally discharged non-isothermal swirled jets classified as **type A** — where buoyancy forces exert a limited influence — the axial excess temperature $\Delta t_x = t_x - t_{in}$ attenuates with distance from the jet origin and was represented as:

$$\Delta t_x = \frac{N}{x}, \tag{8}$$

where x is the axial coordinate, m; N is a thermal parameter describing the initial thermal energy and geometric characteristics of the jet, °C·m.

The thermal parameter is determined as:

$$N = \frac{0.54}{\mathrm{tg}\alpha}\sqrt{\frac{T_{in}}{T_0}}\cdot\frac{1}{\sqrt[4]{\xi}}\cdot\Delta t_o\cdot\sqrt{F_o}, \tag{9}$$

where α = 12°25′ is the effective jet spread angle (with tg$\alpha \approx 0.22$); ξ = 1 is local resistance coefficient; T_0 is absolute temperature at the nozzle outlet, K.

For simplified engineering calculations, a temperature attenuation coefficient n is introduced:

$$n = \frac{0.54}{\mathrm{tg}\alpha}\sqrt{\frac{T_{in}}{T_0}}\cdot\frac{1}{\sqrt[4]{\xi}}. \tag{10}$$

Then, the axial excess temperature may be compactly expressed as:

$$\Delta t_x = n\cdot\Delta t_o\cdot\frac{\sqrt{F_o}}{x}. \tag{11}$$

To describe the temperature field across the jet cross-section at any given distance x, the **transverse excess temperature** $\Delta t_y = t_y - t_{in}$ is given by the following expression:

$$\Delta t_y = \Delta t_x\cdot\exp\left(-0.7\sigma_\mathrm{T}\bar{y}^2\right), \tag{12}$$

where σ_T is the turbulent Prandtl number (typically 0.65÷0.7 for compact jets); $\bar{y} = y/(cx)$ is the dimensionless transverse coordinate (c=0.28 is an empirical constant).

For the analysis and comparison, dimensionless forms of the excessive temperature are often applied:

- axial, $\Delta\bar{t}_x = \Delta t_x/\Delta t_o$;
- transverse, $\Delta\bar{t}_y = \Delta t_y/\Delta t_x$.

These relationships are essential for understanding the thermal diffusion patterns of swirled jets, which are critical in optimizing ventilation systems for temperature uniformity and thermal comfort in enclosed spaces.

In the range of dimensionless axial coordinates x =0.7÷2.2, calculations were performed to determine the relative axial velocities of swirled jets based on equation (6). The obtained results were used to construct a velocity distribution graph specifically for swirled airflow structures, reflecting the characteristic attenuation of velocity along the jet axis (see Figure 2). Fig. 2 represents the theoretical curve and the experimental data points. The velocity was measured at a certain coordinate and plotted on the graph.

The calculation of relative axial velocity was based on equation (6), which describes the inverse dependence of velocity on the axial coordinate x. To align the theoretical results with the experimental data shown in Fig. 2, where the dimensionless coordinate $\bar{x} = x / \sqrt{F_0}$ is used, equation (6) was adapted accordingly. Specifically, the axial distance x was expressed in terms of $\bar{x}$, which allowed the relative velocity $\bar{v}_x$ to be represented as a function of the dimensionless coordinate in a normalized form.

Experimental studies were conducted to determine the distribution of the relative axial velocity in a swirling jet at various distances from the jet axis. A specially designed nozzle with a diameter of D=40 mm, equipped with tangential channels to induce rotational motion of the air at the outlet, was used to generate the swirling jet.

The air was supplied to the setup from a compressor through a pressure stabilization system, which maintained a constant volumetric flow rate. The mean velocity profile was measured in the control cross-section of the jet at various distances from the axis using a single-component constant temperature hot-wire anemometer (CTA type), connected to a digital data acquisition system with a sampling frequency of 5 kHz. The velocity measurement error was ±2%.

The experiments were carried out in a laboratory aerodynamic channel under ambient temperature conditions of T=293±1 K and atmospheric pressure. Measurements were performed in a plane perpendicular to the jet axis, at dimensionless axial coordinates x=0.7÷2.2, $\bar{x} = x / \sqrt{F_o}$. At each coordinate, the results were averaged over 10 independent measurements. The obtained velocity values were normalized with respect to the maximum axial velocity. To smooth the experimental data points and construct the theoretical curve, the least squares method was applied using exponential approximation.

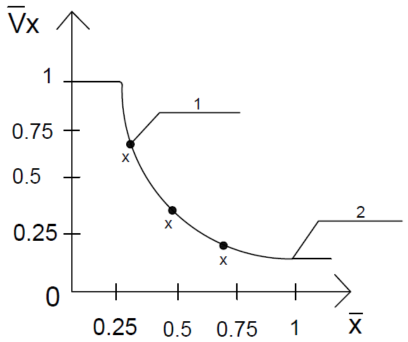

Fig.2. Relationship of relative axial velocity vs dimensionless coordinate x: 1 – experimental data points; 2 – theoretical curve.

5. Conclusion

1) The obtained results confirmed the hypothesis that the introduction of swirl at the jet outlet results in enhanced turbulence and more intensive mixing of air masses.
2) The rotational motion of the air stream significantly accelerates the axial velocity attenuation — by 10–20% depending on the axial position — compared to non-swirled jets.
3) Swirled air jets give a possibility for efficient air supply in confined spaces, distributing airflow more evenly while minimizing the risk of drafts and local discomfort.
4) Due to the vortex structure of the jet, a distinctive velocity profile is formed across its cross-section, characterized by a strong axial core and peripheral rotational zones.
5) The aerodynamic behavior of swirled jets improves air distribution efficiency and provides better control over microclimatic parameters in indoor environments.

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Підвищення енергоефективності повітророзподілу в приміщенні із використанням закручених повітряних струменів

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Анотація

У статті досліджено аеродинамічні характеристики та ефективність закручених повітряних струменів, що застосовуються в сучасних системах вентиляції. У роботі проаналізовано особливості затухання осьової швидкості та надлишкової температури в неізотермічних закручених потоках з урахуванням як теоретичних моделей, так і експериментальних даних. Оцінено вплив обертального руху на інтенсивність турбулентності, ефективність перемішування та рівномірність розподілу повітря. Результати підтверджують, що закручені струмені забезпечують краще перемішування повітря та ефективніше зменшують градієнти швидкості й температури порівняно з традиційними прямолінійними струменями. Запроваджено ключові безрозмірні параметри, такі як коефіцієнти затухання швидкості та температури, що спрощують розрахунки. Детально розглянуто профілі швидкості та температури в поперечному перерізі струменя. Отримані результати свідчать про те, що закручені струмені забезпечують покращене керування повітророзподілом у приміщеннях, мінімізують протяги та сприяють стабільному тепловому комфорту. Отримані висновки підтверджують доцільність використання систем подачі повітря із закрученими струменями у замкнених та енергочутливих просторах.

Ключові слова: розподіл повітря; закручений повітряний струмінь; швидкість повітря; межа струменя; турбулентність повітряного потоку; аеродинаміка.