Flow evolution in the near field of a turbulent annular jet

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Abstract. The results of an experimental study of the flow structure in the near zone of an annular swirling jet are presented. The data were obtained using a two-component laser-Doppler anemometer for the annular jets with a swirl angle of 0–60°. The results of measurements of the average velocity and pulsations in the near jet region (up to 5 diameters of the outer ring) are presented. Based on the analysis performed, it is shown that formation of an internal toroidal vortex near the nozzle plays an important role in the flow dynamics and the process of annular jet mixing. Formation of a stationary toroidal vortex outside the ring is also noted. These structures determine the flow in the near zone of the jet. With the studied Reynolds numbers, this character of the flow in the near zone leads to an increase in the mixing rate, high degree of turbulence, and an increase in the jet ejection capacity.

1. Introduction

Investigation of annular jet aerodynamics is of great interest when studying the fundamental properties of turbulent flows, and existence of large-scale vortex structures in an annular jet makes it attractive for the use in many technical applications.

There are a number of works dealt with the study of both swirling and non-swirling annular jets. For example, in [1] the types and properties of swirlers, formulas for calculating various parameters and characteristics of jets are presented, and the effect of swirl on turbulence characteristics is estimated.

The paper [2] presents the results of experimental investigation of the aerodynamics of impinging swirling and non-swirling jets. The measurements were carried out using PIV with swirl degree \( S = 0–1.0 \) and Reynolds number \( Re = 8900 \). It was shown that the swirling jet had a higher propagation velocity, but a smaller range than the non-swirling one.

In [3], heat transfer was studied experimentally at interaction of an impinging jet with a hemispherical hole. It was found out for swirl parameters \( S = 0.2-0.74 \) and Reynolds number \( Re = 10000-60000 \) that with an increase in swirl intensity, heat transfer decreases due to rapid mixing of the jet with environment.

The experimental results on heat transfer of an annular impinging jet at Reynolds numbers of 12000–36000, distance \( Z \) from the nozzle to the obstacle \( Z/D_0 = 2, 4, 6 \) and height of an annular gap \( D_1/D_0 = 0.51, 0.71 \) are presented in [4]. An increase in heat transfer intensification by 70% and significant increase in the intensity of thermal pulsations, especially for \( Z/D_0 = 2 \), were found.

Paper [5] is devoted to the study of an annular impinging jet with hysteresis behavior and possibility to control this phenomenon by jet swirling. Bistability and hysteresis were experimentally confirmed for the same boundary conditions with Reynolds numbers less than 3000.
Thus, the study of the annular jet behavior is relevant and important, and free distribution of annular jets is poorly understood. Therefore, the purpose of this work is to study complex phenomena occurring in the near zone of the annular jet, as well as to obtain accurate and detailed experimental data that can serve as initial or comparative data for numerical simulation of circular and annular jets.

2. Experimental set-up
The experimental set-up for the study of jet flows was equipped with a two-component laser-Doppler anemometer with an adaptive time selection of orthogonal channels. The range of velocity measurements is \( V = 0–40 \text{ m/s} \). An aerosol formed during recondensation of glycerol vapors under the controlled conditions (with particle diameter of \( \sim 1 \mu\text{m} \)) was used for light scattering. The aerosol generator is designed and developed by the authors. The flow was formed by a nozzle with six holes arranged along the circumference (outer diameter \( D_0 = 22 \text{ mm} \)) (figure 1); the slit length along the circumference was 6 mm, and the swirl angle relative to the center line was 0, 20, 45, and 60 degrees. It was possible to create an additional axial jet with nozzle diameter \( D_1 = 10 \text{ mm} \). The Reynolds number for all versions was Re = 5500.

3. Results and discussion
Experimental results are presented for three versions of nozzles with a swirl angle of 0, 20, 45, 60 degrees along the axial \( V_x \), radial \( V_r \) and tangential \( V_t \) velocity components, as well as their standard RMS deviations in the near jet region (up to \( Z = 5D_0 \)).

3.1 Non-swirling annular jet. Continuous ring
The measured velocity field for an annular non-swirling continuous jet has a pronounced axial toroidal vortex (figure 2), which promotes intensive mixing in the axial region and rapid expansion of the jet. Pulsation characteristics are uniform, and there are no peaks along the jet edges in the profiles of axial pulsations (figure 3), which indicates stable interaction between the jet and the surrounding space and, as a result, formation of stable vortex structures. At distance \( Z = 13 \text{ mm} \) from the nozzle, relatively uniform axial velocity profiles are obtained. Further, the jet develops as a uniform one with a low level of turbulence. We can also note a weak increment in the flow rate of the non-swirling annular jet after the mixing zone \( Z \sim 15 \text{ mm} \) (figure 3). All these facts suggest the possibility of using such a jet for impact cooling of a surface with high uniformity.
3.2 Swirling annular jet consisting of six discrete jets. Swirl angle of 60°

The axial, tangential and radial velocity components were measured. Based on their analysis, it can be said that the ratio of total velocity projection onto the nozzle plane to axial velocity is approximately equal to $\tan(\pi/3)$. This suggests that the jets behave as the separate ones and there is almost no their mixing.

3.3 Annular discrete jets with swirl angle of 0, 20, 45°. Effect of axial injection

The measurement results for a system of six discrete jets located along the circumference are presented in figures 4-6. Two cases were considered: with an additional injection along the axis and without it. For the swirl angle of 20 and 45 degrees, the integral degree of swirl was $S = 0.46$ and 1.7, respectively. The integral degree of swirl is defined as:

$$ s = \frac{\int_0^{\infty} (\rho V_x V_t + \rho V_x' V_t') r^2 dr}{\int_0^{\infty} (\rho u^2 + \frac{1}{2} \rho (V_{t0}^2 - V_t^2)) r dr} $$
With an additional injection along the axis, the flow in the central cross-section was equal to the sum of the flow rates in discrete jets forming a ring.

In the near region of a discrete annular jet with the swirl angles of up to 45°, in contrast to a non-swirling continuous annular jet, there is a vortex nonstationary zone in the center (figure 4), which is much larger than the toroidal vortex in the non-swirling jet (figure 2). We should note that without swirl, this zone is weakly expressed and its length is small, whereas with an increase in the swirl angle, the central region becomes more extended and intensity of vortex mixing increases there. A more than twofold increase in the ejection capacity of the jet is also observed with increasing swirl angle (figure 5).

**Figure 4.** Streamlines and $V_x$ and $V_r$ profiles at distance $Z = 1, 7, 13$ mm from the nozzle outlet, swirl angle of 45°, no axial jet.

**Figure 5.** Flow rate change vs. distance from the nozzle, with axial jet. Different angles of swirl.

**Figure 6.** The field of axial velocity at $Z = 5$ mm, $Re = 5500$ (with axial injection), swirl angle of 20°.

**Figure 7.** The field of axial velocity at $Z = 5$ mm, $Re = 5500$, swirl angle of 20°, no axial jet.
Interaction of a discrete annular jet with an additional axial jet can be seen in figures 6 and 7. Comparison of these figures demonstrates that this interaction is quite small in the initial region. As the flow develops, interaction of the central jet with the peripheral annular jet increases. At that, the axial jet plays a focusing role (figure 8, 9), increasing significantly the long range of the entire jet system (figure 8), whereas in its absence (figure 9) there is symmetrical propagation of six jets with rapid expansion of the jet area.

4. Conclusion
A turbulent flow of various configurations of annular jets was studied using laser Doppler anemometry (LDA). Special attention was paid to the near region of the annular jets. The results of measuring the average velocity and its RMS of velocity demonstrate the important role of a toroidal vortex in the flow dynamics and the mixing process of an annular (continuous or discrete) jet. High recirculation rates are observed in the central part of the vortex. The inner and outer surfaces of the annular jet are characterized by a low intensity of turbulence. For an annular non-swirling jet, the characteristics of the average velocity and RMS of velocity form two zones in the flow field. In the first of them, the toroidal vortex and dynamics of the vortex ring prevail, and the second zone is located upstream and has the characteristics of a continuous weakly turbulent jet. For small swirl angles, a nonstationary vortex is formed in the inner part of the studied region, which ensures rapid mixing of the flow. With an increase in the swirl angle, the vortex zone and nature of jet interaction change significantly. This increases the intensity of ejection dramatically. At very large swirl angles, interaction of jets weakens and, starting from a certain angle, they can be considered as the separate jets. It is also worth noting that there is a qualitative agreement with the literature and we can make a conclusion that the annular jet is able to provide effective and uniform impact cooling over long distances.

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