Experimental investigation of heat and mass transfer of an annular impinging jet

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Abstract. This work presents an experimental study of a turbulent flow and heat transfer of an annular impinging jet for organizing effective surface cooling. Heat and mass transfer of the impinging annular jet was studied at Re = 5500. At that, a distance from the nozzle to the wall was varied. The focus was made on configurations with small nozzle-to-wall distances. It is shown that, depending on the indicated distance, fundamentally different flow regimes with characteristic features of heat transfer distribution are observed.

Introduction
Annular impact jets have become widely used in many modern industrial applications, such as heating, cooling and drying processes due to their significantly higher efficiency in comparison with circular jets [1]. Numerous studies [1–11] of the heat transfer characteristics of an annular impinging jet in various configurations have been carried out over many years. These studies revealed the main characteristics of the flow and heat transfer of annular jets. Heat transfer of an impinging annular jet depends on the Reynolds number, nozzle geometry, and distance between the nozzle and the surface. It should be noted that, in some regimes, the phenomena of bistability and hysteresis, when heat transfer of the annular impinging jet can differ for the same parameters [10], are observed. In addition, the flow field of an annular impinging jet at low Reynolds numbers is asymmetric [8-9]. In this regard, the study of an annular impinging jet is relevant and important also for the construction of a fundamental theory. This work is aimed at studying the aerodynamic and thermal processes in annular impinging jets, taking into account the influence of a large number of factors affecting the structure of turbulence and near-wall heat and mass transfer.

Experimental setup
The experimental setup for studying the aerodynamics and heat transfer (figure 1a) is a two-component laser-Doppler anemometer with adaptive time-gated channels, velocity measurement range \( V = 0-120 \) m/s, and a 3-component KPD (coordinate positioning device) with a moving step of 0.00125 mm. The accuracy of velocity measurement was 2 percent and the accuracy of velocity pulsation measurement was 3 percent. An aerosol formed during recondensation of glycerin vapors using a generator created by the authors was used as a source of light-scattering particles. The compressor injected an air flow through the aerosol generator to the experimental section. Heat transfer was investigated with a testo thermal imager for thermal imaging with a resolution of 1280x800. An annular jet cooled a substrate made of titanium foil of 260x200x0.1 mm, heated
uniformly using a power supply unit (heating power of 36 W). A distance from the jet to the substrate was controlled using a one-component coordinate device with a moving step of 0.2 mm. The experimental section (figure 1b) was an annular impinging jet with a ring width $b = 3$ mm and a jet width $D = 22$ mm. The distance to the $z/D$ plane was varied from 0.5 to 1.5. The Reynolds number was $Re_D = 5000$, $Re_b = 682$. The $Nu_D$ number was calculated as in [12].

Figure 1. (a) experimental setup: 1 – nozzle; 2 – heated surface; 3 – LDA; 4 – thermal imager; 5 – receiver; 6 – compressor; 7 – flow meter; 8 – aerosol generator; (b) experimental section.

Experimental results

1. Aerodynamics of an annular impinging jet

Figure 2. $z/D = 0.5$: (a) streamlines and velocity $V_z$ (b) streamlines and velocity $V_r$. (c) streamlines and pulsations of velocity $V_z$ (d) streamlines and pulsations of velocity $V_r$.

In this paper, we consider the aerodynamics of an annular impinging jet for three distances between the nozzle and the wall $z/D = 0.5$, 1, and 1.5. Area ratio was $\frac{(D-2b)^2}{D^2} \approx 0.5$. With this area ratio, no hysteresis was found. Despite this, two regimes resulting from the changes in $z/D$ were experimentally investigated. The first regime is shown in figures 2 and 3. It is characterized by adhesion of vortex structures to the wall. At $z/D = 0.5$, the highest ejection and the highest negative velocity are observed in the heart of the annular jet (figures 2-4a). Moreover, in the near-wall zone, the radial velocity and
Figure 3. \( z/D = 1 \): (a) streamlines and velocity \( V_z \) (b) streamlines and velocity \( V_r \) (c) streamlines and pulsations of velocity \( V_z \) (d) streamlines and pulsations of velocity \( V_r \).

Figure 4. \( z/D = 1.5 \): (a) streamlines and velocity \( V_z \) (b) streamlines and velocity \( V_r \) (c) \( \pi \) streamlines and pulsations of velocity \( V_z \) (d) streamlines and pulsations of velocity \( V_r \).
pulsations of the axial and radial velocities demonstrate the highest values in comparison with \( z/D = 1, 1.5 \) (figures 2-4bcd). In addition, with symmetric injection, an asymmetry of velocity and pulsations is observed, which is associated with bifurcations at low Re numbers [8-9]. As it can be seen in figure 3, at \( z/D = 1 \), the regime of vortex adhesion to the wall is implemented. The vortices become more elongated, and the magnitude of inverse velocity decreases.

Regime switching occurs at \( z/D = 1.36 \) both with increasing and decreasing \( z/D \). Let us consider the second flow regime. It is characterized by the closure of the axial jet; moreover, the axial velocity field is symmetric, except for the region of the toroidal vortex. The volume of a toroidal vortex is approximately equal to its volume for an annular free jet [11]. According to this, it can be assumed that hysteresis does not form for such a configuration due to the large slot width. The momentum of the outgoing jet is rather large to ensure vortex deformation and faster closure of the annular jet.

2. **Heat transfer of an annular impinging jet**

Let us consider heat transfer for an annular impinging jet (figure 5). The asymmetry in velocity and pulsations affects distribution of the heat transfer coefficient \( \dot{N}u_p \). But for \( z/D = 1.5 \), distribution of the heat transfer coefficient is symmetrical. In general, the heat transfer coefficient for an annular impinging jet \( \dot{N}u_p \) corresponds approximately to the heat transfer coefficient for a circular impinging jet (except for the central region) [12]. The distribution of the \( \dot{N}u_p \) number is characterized by a cavity in the central zone for the first regime, whose area is equal to the area of vortex adhesion. According to the values of the integral heat transfer coefficient \( \dot{N}u_d \), calculated as in [10] (figure 5d), we can observe 2 zones: the near zone, where the second regime efficiency is prevailing, and the far zone, where the values of the wall velocity and pulsations of the integral heat transfer coefficient \( \dot{N}u_d \) are the best for \( z/D = 0.5 \) due to higher ejection.

![Figure 5](image)

**Figure 5.** The heat transfer coefficient \( \dot{N}u_p \): (a) \( z/D = 0.5 \) (b) \( z/D = 1 \) (c) \( z/D = 1.5 \) (d) mean integral Nusselt number \( \dot{N}u_d \) (black color - \( z/D = 0.5 \), red color - \( z/D = 1 \), blue color - \( z/D = 1.5 \)).
4. Conclusion
The paper demonstrates an experimental study of aerodynamics and heat transfer for the annular impinging jets with varying nozzle-to-wall distance. It is shown that when the ratio of the ring area to the nozzle area is $\sim 0.5$ and Re = 5000, no hysteresis and bistability are observed. The transition between the characteristic flow regimes occurs at $H/D = 1.36$. The first of the regimes is characterized by spreading of an annular jet along the surface, which leads to a decrease in heat transfer near the axis of symmetry. In the second regime, the closure of the annular jet into a round one is observed until it reaches the surface. Asymmetry of the fields of the mean and pulsation velocities, noted earlier in [8-9], was observed for all considered distances $z/D$.

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