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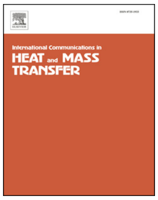

An experimental investigation of flow structure and heat transfer in an impinging annular jet☆

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ABSTRACT

The paper presents the results of an experimental study of flow and heat transfer in an impinging annular jet. Using the PIV-system the distribution of average and pulsation velocities was measured; and heat fluxes and their pulsations were detected using miniature heat flux sensors. The measurement results have been compared at identical mass flow rate of air with similar data for a round jet with a diameter equal to the outer diameter of the annular jet. It is shown that under these conditions of comparison the values of velocity and turbulent pulsations in the annular jet are significantly higher than the same values in the round jet. The heat transfer intensity of the impinging annular jet is also higher than that of the round jet, and the degree of heat transfer enhancement depends on the annular gap size and distance from the nozzle to the obstacle.

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1. Introduction

The impinging jets are widely used in modern cooling systems. In this regard, the issue of increasing their efficiency is important. One of the known ways to increase the intensity of heat removal by impinging jets is to change the geometry of the nozzle through which the cooling medium is supplied. This problem is actively studied in a large number of experimental and numerical works [1–3]. The goal of these studies is the search for possible ways to expand the region of higher heat transfer in the zone of jet stagnation and for a more uniform distribution of the heat transfer coefficient. Such opportunities may be realized for the annular impinging jets. This is evidenced by data of the first experimental work [4], dedicated to the comparative analysis of heat transfer in the annular and round jets. The authors determined that at the same coolant flow rate the impinging annular jets with the ratio of inner to outer diameter $d_2/d_0 = 0.3$ and 0.6 can give a more intense heat transfer than the round ones with an identical external diameter.

It should be noted that even free annular jets have complex flow structures. Even more complex are the impinging annular jets. This follows from the works [5–7], devoted to the experimental study of flow fields and mass transfer of the impinging annular jets at a close location of the nozzle and obstacle ($S/d_0 \leq 2$, where S is the distance between the nozzle and the obstacle), when the vortex structures formed behind the nozzle interact directly with the streamlined wall.

The conditions of experiments [5] were the following: the ratio of the internal diameter of the ring to the outer one was $d_2/d_0 = 0.77$ and 0.95, and the values of the Reynolds number, calculated based on parameters at the nozzle outlet, were $Re = U_0 d_0/\nu_0 = 5\cdot10^3 \div 10^4$. This work showed that two alternative flow patterns (bistability) are possible for the impinging annular jets in the studied conditions. In one case, a rather small region of recirculation was formed behind the central insert of the nozzle, and in the other case, the recirculation region behind the nozzle became much larger and extended all the way to the streamlined wall, forming therein an annular line of stagnation. According to the results of [5,6], bistability occurred only for a narrow annular nozzle (in the experiments [5] it was observed when the ratio of the inner to the outer diameter of the nozzle was $d_2/d_0 = 0.95$) at low values of Reynolds number ($Re \leq 5\cdot10^3$) and small distances between the nozzle and the wall ($S/d_0 \approx 1$). The instability of the flow pattern in the regime of bistability led to a spontaneous transition from one flow pattern to another and to stratification of the pressure and heat transfer distributions.

Similar experimental studies were conducted by the authors of [7]. Conditions of experiments were the following: the ratio of the diameters was $d_2/d_0 = 0.8 \div 0.98$, the Reynolds number $Re = (d_0 - d_2)U_0/2\nu = 1.2\cdot10^3 \div 3.6\cdot10^4$, and U_0 was the mean flow velocity at the nozzle outlet. The authors noted an interesting phenomenon of the impinging annular jets, namely an appearance of a reverse (against the direction of the incident jet) flow in the frontal point. According to the findings of [7], three different variants of the obstacle streamlining are formed depending on the distance S/d_0. They differ in the radial position of the stagnation point on the obstacle and in the heat transfer intensity.

When comparing the efficiency of cooling by the annular and round jets, the conditions of comparison become vital. In terms of technical application it is logical to compare the various nozzles provided at the

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Nomenclature

r	Radial coordinate (mm)
x	Distance from the nozzle to the considered cross-section (mm)
x_p	Distance from the obstacle to the cross-section (mm)
d_0	Diameter of the base round nozzle; the outer diameter of the annular nozzle (mm)
d_2	Inner diameter of the annular nozzle (mm)
S	Distance from the nozzle to the barrier (mm)
T_0, T_w	Flow temperature at the nozzle outlet and temperature of the barrier (°C)
q_i, q_w	Local heat flux density: instantaneous and averaged on data array (W/m^2)
U_{0r}, U_{0an}	Velocity in the outlet section of round and annular nozzles (m/s)
Re_{0r}, Re_{0an}	Reynolds number of the round and annular nozzles ($U_{0r}\, d_0/\nu_0$ and $U_{0an}\, d_0/\nu_0$)
Pr	Prandtl number
Nu_0	Nusselt number for the stagnation point of the obstacle ($\alpha_0 d_0/\lambda_0$)
Greek	
α, (α_0)	Heat transfer coefficient, (heat transfer coefficient in the frontal point of the obstacle) (W/m^2 °C)
λ_0	Coefficient of thermal conductivity of air at temperature T_0 (W/m °C)
ν_0	Coefficient of kinematic viscosity at temperature T_0 (m^2/s)
Subscripts	
0r	Corresponds to the output cross-section of the round nozzle
0an	Corresponds to the exit section of the annular nozzle

same mass flow of refrigerant. If the areas of the outlet cross-sections of the nozzle are the same as well, the velocities at their section and the integral values of the jet pulses, respectively, are also equal. This situation is possible only when the diameter of the round jet and the inner diameter of the annular jet are identical, while its outer diameter should be equal to $d_0 = \sqrt{2} \cdot d_2$. Identical impulses at the nozzle outlet were investigated in [8], where the annular and round impinging laminar jets were studied numerically. The distribution of friction and heat transfer for the annular jet significantly differs from the same distribution for the round jet by the presence of a region of negative friction (the flow is directed from the periphery to the center) and by a substantial decrease in the heat transfer intensity in the axial region for the annular jets. As a result, if the average heat transfer is compared under the above conditions, then its intensity for the annular jet is ≈20% lower than for the round one. This conclusion, at first glance contradicting the data of work [4], where the heat transfer intensity for the annular jet is much higher than that for the round one, indicates the fundamental importance of the conditions of comparison of the impact cooling efficiency. It is appropriate to emphasize that the problem of choosing the governing parameters has not been completely solved even for the classical axisymmetric jet that is noted in particular in [9].

A detailed experimental study of characteristics of flow and heat transfer in the impinging annular jets at small distances from the nozzle to the obstacles $S/d_0 \leq 1$ was made in [10] with the variation of parameter $d_2/d_0 = 0.51 \div 0.9$ with a fixed outer diameter. Measurements taken with thermal anemometer and liquid crystals showed that when reducing the height of the annular gap the intensification of heat transfer takes place. The obtained experimental results were generalized using correlations, describing the distribution of Nu along the radius for different slit parameters. However, these relations are valid only at small distances between the nozzle and the surface.

It should be noted that the problem of flow and heat transfer in the impinging annular jets is of great practical interest to create the burner spray, since the central stagnant zone is a good stabilizer of combustion [11,12]. A special place in this problem belongs to the study of swirling annular [13–15] and coaxial [16,17] jets. With jet swirling the mechanisms of transfer processes become much more complicated, and the intensity of heat and mass transfer largely depends on the level of centrifugal forces. As a rule, an increase in the swirling leads to the suppression of heat exchange due to more intense mixing of the impinging jet with the ambient medium [18]. However, at small distances between the nozzle and the obstacle, the swirl can cause the enhancement of heat transfer as well [14]. In general, this research area is of independent interest, and more details on the issue may be found in several monographs and reviews [19–21].

This article presents the results of experimental studies of flow and heat transfer in the impinging annular jet with variation of the ring parameters, the Reynolds number and the distance from the nozzle to the obstacle. As shown in [22], the annular jet is characterized by a number of features in comparison with the round jets. The most important of them are the presence of the axial separation zone, the development of the internal mixing layer and the resulting global instability of the entire jet.

2. Description of setup and measurement methods

The experiments were carried out on the set-up, whose scheme is shown in Fig. 1. Main elements of the set-up were the system of feeding, adjustment and measurement of air flow, the test section, including the nozzle forming a jet and the barrier, and two instrument units for studying flow fields and heat transfer. The working medium was the air coming from the high-pressure air net. In the experiments, the impinging jets of round and annular cross-sections were studied. Round jets were used to obtain "baseline". It served for comparison with the data for the impinging annular jet that allowed identifying the effects associated with the nozzle geometry. The round nozzle was characterized by: the total length of the nozzle – 72 mm, the length of the tapering part (L_1) – 67 mm, the height of the centering ring (L_2) – 5 mm, the diameter of the nozzle up to tapering (d_1) – 62 mm, tapering of the nozzle 12.1, and the output diameter $d_0 = 17.8$ mm. For forming an annular cross-section the cylindrical rod of varying diameter d_2 (see

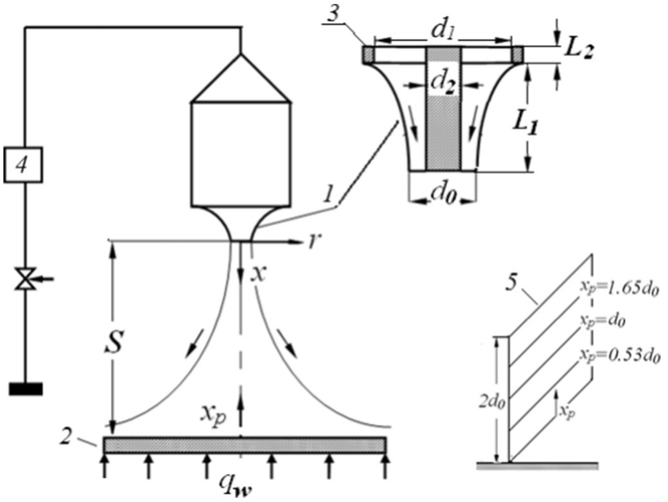

Fig. 1. The scheme of experimental set-up: 1 – nozzle; 2 – obstacle; 3 – centering insert; 4 – flowmeter; and 5 – the measuring plane.

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