The Effect of Swirl Intensity on Heat Transfer of Swirling Coaxial Impinging Jet

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Abstract. The results of numerical simulation of convective heat transfer under coaxial jet impinging on a surface are presented. The effect of jet’s peripheral component swirling on the heat transfer enhancement by changing the number of tangential nozzles for creating jet is analyzed.

1. Introduction
A significant intensification of heat transfer during jet impingement on a surface and relative ease of regulating the distribution of coolant mass flows and heat fluxes define wide application of this method of cooling in various fields of technology, including gas turbine cooling systems.

Swirling the impinging jet [1-7] intensifies heat transfer by 20-30%. In addition, changing the geometry can provide an increase in efficiency of this cooling method.

Swirling jets due to the action of centrifugal forces have a large impact area in the cross section. As a rule, in the central part of the swirling jet, a zone of reverse flows with low velocities and low heat transfer intensities are formed [1, 3, 6, 7]. This can lead to the overheating of the local surface area, or as a result, to burnout. This lack of swirling jet weakened the interest of researchers in this method of heat transfer intensification, as noted in a few experimental studies on the topic.

To solve the problem, a combined coaxial nozzle consisting of a central nozzle from which an axial jet flows and a peripheral ring one forming a swirling jet, is proposed [7,15]. The interaction of axial and swirling jets further turbulizes the flow, resulting in the uniformity of the axial velocity profile of the jet that increases and intensifies the average heat transfer coefficients.

The interaction of impinging jets becomes much more complicated when such a jet has a circumferential component of velocity. Heat transfer and flow structure of the swirling coaxial impinging jets on surfaces are underexplored at the present time. In a few available works [1, 5, 8-14] it is shown that the process of interaction of swirling jets with surfaces is complex and multifactorial. The increase in the swirl of the jet [1] intensifies the mixing processes, as a result of which, at large distances between the nozzle and the surface ($L/d_n > 6$), the heat transfer significantly reduces in comparison with the axial jet. At small distances ($L/d_n < 6$), the pattern can be reversed and additional maxima appear in the radial distribution of the heat transfer coefficient due to the specifics of the formation of vortex jets with different swirl intensities, Reynolds number values and distances between the surface and the nozzle.

Extensive studies of swirling impinging jets were conducted at Lund University, Sweden [6]. To create a swirling jet, screw and blades were used. As a characteristic of the swirl intensity, the ratios of the axial flows of the circumferential and axial pulse were used. The author performed a series of numerical calculations in two-dimensional formulation using several turbulence models: SST k-ω,
V2F, RNG k-ε, RSM. The results of the calculations have shown that the increase in the intensity of the flow swirl near the surface stagnation point leads to the emergence of a stationary recirculation zone. The presence of this zone in the center of the plate leads to an increase in the thickness of the thermal boundary layer and a decrease in the heat transfer coefficient. Verification of the results of calculations from experimental data has shown that the smallest discrepancy in the heat transfer coefficients is obtained using SST k-ω and V2F turbulence models. In paper [6], the influence of the profile of the circumferential velocity on the gas-dynamic flow pattern and heat transfer was analyzed. Four types of circumferential velocity profiles were compared: quasi-solid rotation, rotation as a forced vortex, flow in a rotating tube, and Rankine vortex. A significant influence of the circumferential velocity profile on the flow structure near the flow stagnation point was manifested. Thus, when specifying the law of rotation of the impinging jet corresponding to the Rankine vortex, no stationary recirculation zones were found, and when the jet rotated at a constant circumferential velocity, this zone manifested itself and led to a significant decrease in the heat transfer coefficient.

The paper [2] presents the results of an experimental study of heat transfer in the interaction of vortex jets with plane surfaces. The authors note that the characteristic feature of such jets is the increased ejection properties. As a result the angle of expansion of the jet increases with increasing swirl, whereby the maximum heat transfer is shifted from the center and depends on the degree of swirling and the distance between the nozzle and the surface. At the value of $L/d_n = 2$ it can be pronounced, but at $L/d_n = 10$ it has a smooth appearance. A similar trend occurs in other swirl intensities of the jet. It is important to emphasize that in most experiments, the distribution of local heat transfer along the radius with a change in the Reynolds number has a similar form, and with an increase in the number of Re, the heat transfer intensity increases.

The existing studies do not contain an analysis of the dependence of the heat transfer coefficient on the swirl intensity of the coaxial (partially swirling) impinging jet. This problem determines the relevance of this work aimed at studying the influence of the swirling peripheral component on its heat transfer and features of its interaction with the surface.

2. Formulation of CFD Simulation

The object of the study is a swirling coaxial impinging jet created by the combined nozzle (figure 1). Generation of the coaxial jet is carried out as follows. Air flows through straight cylindrical nozzle in the form of a jet predominantly in the axial direction. Besides, air enters through the tangential holes into the peripheral annular nozzles formed by the outer surface of the straight cylindrical nozzle and the inner surface of the swirling device and starts swirling. Flowing into the space between the wall of the discharge chamber and the surface, the two jets, interacting with each other, flow onto the surface, unfold and leave the study area in the form of a radial flow.

Figure 1. Scheme of swirling coaxial impinging jet [16].

Figure 2. Model of combined nozzle: 1) straight cylindrical nozzle; 2) peripheral annular nozzle; 3) inlet of the straight cylindrical nozzle; 4) inlet of the peripheral annular nozzle.
The gas flow was described by RANS equations with the use of k-ω SST turbulence model. The total temperature at the inlets of the axial and swirling jets was set constant for all calculations $T^*_{in}=293$ K. The total inlet pressure for the axial jet was $p^*_{in,ax}=1.05\cdot p_{out}=106391$ Pa, and for the swirling jet $p^*_{in,sw}=1.2\cdot p_{out}=121590$ Pa. At the outlet of the computational domain, open boundary conditions with the static pressure $p_{out}=101325$ Pa were set. The heat flux of 1kW was set on the wall, where the jet impinges. The other walls were set adiabatic. A grid with a prismatic wall layer with a total volume of 2.5 million elements was used (figure 3). The calculations were stopped after they reached the level of convergence of normalized mean square residuals below $5\cdot10^{-5}$ and the imbalance of the total mass flow was lower than 0.01%.

In order to verify the approach based on applying RANS equations in combination with k-ω SST turbulence model, a calculation of a simple swirling impinging jet was carried out and its results were compared with experimental data published in [11]. The comparison is shown in figure 4 as a radial distribution of Nusselt number $Nu$ over the target surface. Obviously, the usage of the k-ω SST model served to reach satisfactory correspondence of calculated and experimental data which is sufficient to accomplish the goal of this work.

To estimate the influence of mesh parameters of a domain, numerical simulation of flow of the coaxial impact jet on the target surface for five meshes with different total number of elements was performed. An analysis of results was carried out using the area averaged heat transfer coefficient (figure 5). Total number of elements equal to 2.5 million gives the optimal solution after which the results change insignificantly.

![Figure 3. Grid model of the combined nozzle.](image)

![Figure 4. Comparison of Nu number distributions for swirling impinging jets on the target surface: 1 – experimental results from [11] at $H/d = 1.5$; 2 – calculation results at $H/d = 1.5$.](image)

![Figure 5. Dependence of the area averaged heat transfer coefficient on the total number of elements.](image)
3. Results and Discussion
To study the effect of swirl intensity on heat transfer of the coaxial jet, a numerical simulation of impinging on the surface of the nozzle with different number of tangential supplies was performed. The numbers of supplies were equal to 2, 3, 4, 6, and 8.

Two series of calculations were carried out. In the first series, a constant pressure drop in the nozzle was maintained when varying the number of tangential supplies. In the second series, a constant flow rate of the swirling jet was maintained, which was corresponding to the flow rate in the case with four tangential supplies.

The most significant is the comparison of the results of calculations of the heat transfer coefficient of the jets, generated by the nozzles with different number of tangential supplies $N$ and their diameters $d_{tan} = 1 \text{ mm}$ under maintaining a constant mass flow rate.

Analysis of the distributions of the heat transfer coefficient shows that increasing the number of tangential peripheral inlets of the nozzle leads to reducing circumferential unevenness. This occurs when the number of tangential supplies increases from 2 to 4. At $N = 6$ and $N = 8$ the distribution unevenness is almost the same (figure 6 and 7).

Based on the analysis of the results for pressure ratio $\pi^* = p_{in,sw}^*/p_{out} = \text{const}$ (figure 8), it can be concluded that an increase in the number of tangential supplies leads to a rapid release of the jet after its flow in the radial direction, and as a consequence, a more uniform distribution of the parameters on the cooled surface can be obtained.

In the case of $M_{swirl} = \text{const}$ (figure 9) the presence of 6 or more tangential supplies leads to the fact that the velocity of the axial jet exceeds the velocity of the swirling one. As a result, a low flow of swirling is observed ($S < 1$), the zone of influence of the swirling jet is significantly reduced, which then leads to a decrease in the heat transfer, and as a consequence, insufficient cooling of the surface.

The most effective cooling was reached for 2 and 3 tangential supplies when $M_{swirl} = \text{const}$.

![Figure 6. Heat transfer coefficient distributions at $\pi^* = \text{const}$: a) $N=2$; b) $N=3$; c) $N=4$; d) $N=6$; e) $N=8$.](image)
Figure 7. Heat transfer coefficient distributions at $M_{swir}=$const: a) $N=2$; b) $N=3$; c) $N=4$; d) $N=6$; e) $N=8$.

Figure 8. Velocity distributions at $\pi^*=$const: a) $N=2$; b) $N=3$; c) $N=4$; d) $N=6$; e) $N=8$. 
When the number of supplies is equal to or less than 4 (figure 6 c-d and figure 7 c-d) there are two maxima in the heat transfer coefficient distribution, since the reversal zones of the axial and swirling jets coincide. An increase in the number of tangential supplies to 6 or more leads to the appearance of two additional maxima of the heat transfer coefficient due to the collision of a peripheral swirling jet with the surface and an increase in the angle of its release. Comparison of figures 6a and 6e with figure 7a and 7e shows that the flow pattern changes in the opposite direction due to the low velocity in the peripheral nozzle, and as a consequence, the insufficient swirling flow leads to a decrease in heat transfer.

The highest cooling efficiency at $\pi^* = \text{const}$ was achieved by using nozzles with 6 or more tangential supplies.

4. Conclusion
The analysis of the results of numerical simulation of an impinging jet provided the possibility to estimate the effect of the Reynolds number and the number of tangential supplies of the peripheral nozzle on the heat transfer.

An increase in the pressure drop on the swirling jet leads to an increase in the swirl intensity, a decrease in the axial velocity, and as a consequence, its rapid release in the radial direction at the outlet of the nozzle. At the same time ($\pi^*_\text{swirl} > 1.25$), some streamlines do not even reach the cooled surface, and the distribution of the heat transfer coefficients tends to the form of the corresponding axial jet.

In the region of Re > $3.5 \times 10^4$, there are additional maxima located opposite to the output edge of the peripheral nozzle in the distribution of the heat transfer coefficients on the cooled surface. Their appearance is due to an increase in the axial velocity of the swirling jet and its more intense interaction with the surface.

In order to reduce the circumferential unevenness in the distribution of heat transfer coefficients, it is recommended to use nozzles with a number of tangential supplies of at least 6. In this case, the highest heat transfer coefficients are achieved for the case $\pi^* = \text{const}$ when using nozzles with 6 or more tangential supplies. At the constant mass flow $M_{\text{swirl}} = \text{const}$, the most intensive heat transfer can be obtained for 2 and 3 tangential supplies.

The increase in the pressure drop on the swirling jet to 1.4 has little effect on the value of the heat transfer coefficient, since only the circumferential velocity increases while maintaining the area of the tangential supplies, and the axial velocity practically does not increase. Therefore, the peripheral swirling jet practically does not interact with the cooled surface, it flows out of the nozzle and releases under the action of centrifugal forces leaving the domain in the radial direction.

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