Experimental study of heat transfer of impinging swirling jets and jets with chevrons

A S Nebuchinov

Institute of Thermophysics of SB RAS, 630090, Ac. Lavrenyiev ave. 1, Novosibirsk, Russia

E-mail: nebuchinov.alexander@gmail.com

Abstract. The aim of this work is to study the effect of different forms of passive change in the shape of the flow on the intensity of heat transfer in the impinging jet. In this work, a series of experiments was carried out to study an axisymmetric jet flowing normally onto a heated surface. The jet was studied both under the natural conditions and during swirling of the flow (S = 0.4; 0.7; 1.0). It is shown that the intensity of heat transfer on a heated target in the case of a jet with chevrons has a little effect on the heat transfer character, but intensifies it significantly. In the case of a swirling jet, the intensity distribution on the impingement surface changes its character and increases it locally at small distances between the nozzle and the heater.

1. Introduction

In recent years, impinging jets have attracted the attention of researchers more and more due to the wide variety of their applications. Modern energy technologies require a large amount of heat to be removed from the working heat exchange surfaces. The possibilities of classical methods for intensifying heat transfer are almost exhausted by now. Surface cooling is widely used in power engineering and radio electronics, metallurgy, including cooling heating elements of integrated circuits and powerful processors. Aviation equipment can also be attributed to other areas of practical application of impinging jets - these are the systems for protecting aircraft from icing, cleaning runways and roads from snow and ice, preventing their destruction from engines jets; metal hardening; paper drying; cooling turbine blades.

Understanding the dynamics of turbulent flows will not only allow prediction of their evolution, but also development of methods for controlling the spectral composition of turbulence, large-scale and small-scale transport processes; it will ensure modernization of existing and developed new effective technologies that reduce energy consumption and anthropogenic load on the environment in industrial devices and apparatuses.

The flow structure of circular impinging jets is well known [1]. It strongly depends on the nozzle diameter and the distance between the nozzle and the flow surface and can be subdivided into several characteristic zones: the free jet region, the frontal point region, the near-wall region of the jet, the mixing zone, and the region caused by suction from the environment.

Areas of practical application of impinging jets can also be considered in aeronautical engineering. These are systems for protecting aircraft from icing, cleaning runways and roads from snow and ice, preventing their destruction from engines jets; paper drying; cooling turbine blades.
From the point of view of practical significance, methods are of interest since they ensure uniform, but at the same time, intense heat transfer from the wall. Impinging jets with flow swirling and chevron jets are of interest from this point. The turbulent structure of such jets changes significantly. With different degrees of swirl and its generation, different flow regimes can be achieved. With weak swirling and even in its absence, vortex rings appear, and with more intense swirling, spiral vortices of different scales are formed. Many authors regard swirling flows as an effective method for passive flow control.

In steep jets, mixing properties can be improved by placing triangular prongs at the outlet of the nozzle that induce a low velocity region behind them and a high velocity region at each edge of the prong, resulting in a pair of counter-rotating vortices [2]. Similar structures have also been observed in star-shaped nozzle jets [3]. In free jets with chevrons, the mixing process is altered by the generation of counter-rotating longitudinal structures in the chevron slots [4].

The huge range of practical applications of limited jet flows necessitates the study of fundamental physical effects and phenomena accompanying them. In various regions of the flow, there are free and near-wall shear layers with large-scale vortex structures developing in them: sharp curvature of streamlines when the jet flows onto the wall; the area of the stagnation point of the flow with the maximum coefficients of heat and mass transfer; in the near-wall part of the jet, local unsteady flow separation and the development of the near-wall jet take place.

From the point of view of practical significance, methods are of interest since they ensure uniform and intensive heat transfer from the wall. From this point, impinging jets with chevrons are of interest. It is assumed that organization of such jets will allow obtaining high and uniform heat transfer coefficients. Changing the geometry of the nozzle can be attributed to passive methods for heat transfer enhancement in impinging jets. In the study of limited impinging jets, it was shown that the hyperbolic shape of the nozzle leads to more uniform heat transfer on the heated surface. For a distance between the nozzle exit and the surface equal to 4 diameters, a nozzle with triangular protrusions located around the nozzle circumference leads to heat transfer intensification by more than 25% in relation to a round jet. The characteristics of heat transfer in elliptical nozzles with various nozzle to the surface distances were also studied. It is shown that the maximum of heat transfer intensity in the near wall region is reached when the distance between the nozzle outlet and the surface is equal to 4 diameters and is 15% larger than that for a circular jet. In free jets with chevrons, the mixing process changes due to the generation of counter-rotating longitudinal structures in the chevron slots. The aim of this work is to study the hydrodynamics and heat transfer in a jet with chevrons using modern panoramic optical measurement methods.

2. Experimental details

The experiment with an impinging jet was carried out on a setup, which is a closed hydrodynamic circuit consisting of a working section with a test object, a pipeline system, a thermostat, a pump, and a flow meter (figure 1). The walls of the working area were made of plexiglass, = 20 mm thick. Internal geometric dimensions of the working volume were 0.6×0.4×0.4 m. The objects of investigation were the axisymmetric circular, swirl and chevron jets. A jet, organized by a nozzle with a Vitoshinsky profile (the outlet diameter \( D = 15 \) mm), flowed onto a flat obstacle, where a sapphire obstacle, 4 mm thick and 150x150 mm in size, was mounted. On the side in contact with the liquid, a thin transparent in visible light conductive coating made of indium-tin oxide (ITO, \((\text{In}_2\text{O}_3)_{0.9} – (\text{SnO}_2)_{0.1}\)) solid solution 1.2 μm thick at the center and 1.12 μm thick at the corners was applied. A current of 16 A passed through the coating, providing uniform heating of 3.3 W/cm\(^2\). IR imager Titanium HD 570M (FLIR Systems ATS) with spectral ranges of 3.7-4.8 microns detected the temperature of the heating element, which was varied from 27 to 38°C under the test conditions. The temperature of water was controlled using DT5045-50M resistance thermocouples installed in the working section and in the tank. During the experiments, the temperature was kept constant at 25 ± 1°C by cooling the circulating liquid in the tank.
The swirling of the flow was organized using swirlers with different angles of attack placed in the outlet section of the nozzle. The indicated number $S$ was calculated from the geometry of the swirler by formula (1) and was used only to indicate the experimental conditions

\[
S = \frac{2}{3} \left( \frac{1-(d_1/d_2)^3}{1-(d_1/d_2)^2} \right) \tan(\phi)
\]  

(1)

Where $d_1 = 7$ mm is the diameter of the central body of the supporting blade, $d_2 = 27$ mm is the outer diameter of the swirler, and $\phi$ is the angle of inclination of the blades. In this work, we used swirlers corresponding to the following values of swirl: $S = 0.4; 0.7$ and $1.0$.

To change the boundary conditions at the nozzle outlet, special nozzles installed over the main nozzle were used. The attachments were the flat discs $8$ mm thick with radial ditches from the center to the periphery. The ditches were $2$ mm wide and $2$ mm deep (figure 2). The beams are located at equal distances from each other. The number of ditches ranged from zero to eight. As a designation for the number of chevrons, we will use the following designations: $N = 0$ is the nozzle without chevrons (circular jet), $N = 4, 6, 8$ are nozzles with $4, 6, 8$ chevrons, respectively.

The measurement area ran along the ditch. The Reynolds number ($Re = DU_0/\nu$, where $D = 15$ mm was the nozzle outlet diameter) was chosen to be 6000 in all experiments.

![Figure 1. Scheme (left) and photo (right) experimental installation. 1 - working space, 2 - nozzle ($D = 15$ mm), 3 - the heated surface, 4 - power line, 5 - flow meter 6 - pump 7 - thermostat 8 - source of external excitation, 9 - pipeline.](image1)

![Figure 2. Photo of nozzle tips.](image2)
3. Results and discussion

3.1. Circular and swirling jet

For various flow regimes of the jet: the distance between the nozzle and the heated surface, the degree of swirling of the flow, the number of chevron depressions, and the integral Nusselt numbers were calculated with the help of fixation of the distribution of instantaneous temperature on the wall using an IR camera. To obtain the integral temperature distribution on the heated surface, 2000 realizations of the instantaneous temperature were averaged.

Figure 3 shows the integral distribution of the Nusselt number for a circular non-swirling jet. This is the regime with \( Re = 6000 \), the distance between the nozzle outlet and the heated impinging surface is \( h/D = 0.5 - 5.5 \). A characteristic form of the distribution of the intensity of heat transfer on the wall is observed at \( h/D = 0.5 \). The local minimum of the Nusselt number is observed on the central axis of the jet symmetry. Further, a local maximum is found at distance \( r/D \approx 0.8 \). It arises due to the leakage of large-scale eddies onto the obstacle in this area. Due to boundary layer turbulization at distance \( r/D \approx 2.2 \) from the central axis of the jet symmetry, a second maximum appears on the Nusselt number distribution. And, as a consequence of these hydrodynamic effects, there is intensification of heat transfer in these areas.

![Figure 3. Distribution of Nu number depending on h/D.](image)

With an increase in the distance between the heated surface and the nozzle exit, the distribution of heat transfer intensity on the impinging surface decreases monotonically with a distance from the frontal point.

It is also seen that with an increase in the distance to the heated surface, the integral values of the heat transfer intensity decrease.

Figure 4 (a, b, c, d) shows the results for four distances between the wall and the nozzle \( h/D = 0.5; 1; 3; 5.5 \).
Figure 4. Distribution of Nu number depending on S. (a) $h/D = 0.5$; (b) $h/D = 1$; (c) $h/D = 3$; (d) $h/D = 5.5$.

It can be seen that the introduction of a swirl radically changes the character of the distribution of heat transfer intensity on the heated surface in comparison with a circular jet. A swirling jet at small distances between the nozzle and the obstacle is characterized by the presence of a recirculation zone in the air up to the impinging surface, even at a small degree of swirling. On the axis of the jet there is a local minimum. Further there is a significant increase in heat transfer coefficients to $r/D \approx 1.4$, which corresponds to the local maximum, and then the intensity is gradually weakening with distance from the nozzle axis. At these $h/D$ values, the introduction of a swirl intensifies heat transfer in the region $r/D = 0.5 - 3$.

The difference between the integral values of the Nusselt numbers of the swirling jet and the direct-flow jet reaches 27% at $h/D = 0.5$ and 18.3% at $h/D = 1$.

Figure 4 (c, d) shows that the integral values of the distribution of the Nusselt number in a jet with different degrees of swirling decrease, and they become lower almost over the entire heated surface than in a circular jet without swirling. This is due to the fact that the outgoing flow slows down due to the mixing of the swirling jet with the external environment. It is also observed that with an increase in
the distance between the nozzle exit with flow swirling and the impinging surface, the heat transfer intensity decreases significantly.

3.2. Chevron jet.

Figure 5 shows the distribution of the average Nusselt number on the heated surface in the case of a jet with a different number of chevrons \((N = 4, 6, 8)\) at \(Re = 6000, h/D = 3\), in comparison with a circular jet \((N = 0)\). For a jet with chevrons, the maximum \(Nu\) is located on the central axis, which indicates the most intense heat transfer in this region. Further, the values of the heat transfer intensity decrease gradually with a distance from the flow axis, in contrast to the circular jet, which has a characteristic form with two local \(Nu\) maxima. This is due to the fact that the chevrons destroy the toroidal vortices, turbulizing the flow. And the coherent structures in the shear layer, which are generated inside the gap between the chevrons, are the so-called C-shaped vortices.

Figure 5. Distribution of the average Nusselt number with different numbers of chevrons \((N = 0, 4, 6, 8)\), \(h/D = 3\).

![Figure 5](image_url)

It is shown that the heat transfer coefficients increase with an increase in the number of chevrons, which indicates more intense mixing. In the case of a jet with chevrons, the increase in the average intensity of heat transfer reaches 15.5% \((N = 8)\) in comparison with a circular jet.

Moreover, a similar trend persists at all distances between the nozzle and the heater (figure 6). The maximum intensity of heat transfer is observed at \(h/D = 3\) for a jet with 8 chevrons.

Figure 6. Comparison of the distribution of the average Nusselt number of impinging jet with chevrons \((N = 8)\) and without \((N = 0)\) at \(h/D = 1, 2, 3, 4\).

![Figure 6](image_url)
Figure 7 shows a comparison of the distributions of the heat transfer intensity on the impinging surface of a circular \((N = 0)\), chevron \((N = 8)\), and swirling jet \((S = 0.4)\) at \(h/D = 1\). It is seen that in cases of a chevron jet the distribution is more uniform across the surface without local maximums and the average heat transfer rate increases by 13\% as compared with a circular jet. And in the cases of a swirling jet, the distribution of heat transfer coefficients is more uniform, although it has a strongly pronounced local minimum and maximum, but intensification of heat transfer reaches 18\%.

![Figure 7](image_url)

**Figure 7.** Comparison of the distribution of the average Nusselt number of impinging jet with chevrons \((N = 8)\), without them \((N = 0)\) and in a swirling jet at \(h/D = 1\).

4. Conclusion

Experimental data on the heat transfer rate distribution on the heated impinging surface are obtained using thermal imaging method for registering a surface temperature. A comparison is made between circular, swirling, and chevron jets. The different character of the distribution of the average heat transfer on the target is shown. It is also shown that at small distances between the nozzle and the heater a significant increase in the average intensity occurs in the case of a swirling jet, and at large distances, in the case of a chevron jet.

Acknowledgments

This work is funded under the State Contract with IT SB RAS.

References

[1] Meola C. 1, Cardone G. 1, Carmicino C. 1 and Carlomagno G.M. 2000. *The Millennium 9th Int. Symposium on Flow Visualization (Volume: CD Rom Proc)* (Edinburgh, Scotland) pp 429-1–429-14.

[2] Reeder, M.F., Samimy, M. 1996. *Journal of Fluid Mechanics* **311** 73–118.

[3] El Hassan M., Meslem A. 2010. *Journal of Physics of Fluids* **22** (3) 035107.

[4] Bridges, J., & Brown, C. A. 2004. *Collection of Technical Papers - 10th AIAA/CEAS Aeroacoustics Conference* (Manchester, Great Britain) pp 284–300.