Experimental study of hydrodynamics and heat transfer of impact jet with chevrons

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Abstract. Using modern panoramic optical measurement methods, a comprehensive experimental study of the flow structure and heat transfer in a submerged impact jet with and without chevrons was carried out. A detailed study of the influence of the presence of a flat athwart-oriented surface on the structure of the chevron jet flow on convective heat transfer was carried out. In the case of a jet with chevrons, the velocity values at the surface are shown to exceed the values of the standard round jet, and the pulsations are more intense and more uniform near the impact surface, which, accordingly, affects the heat transfer on the target. The increment in the average intensity of heat transfer of the chevron jet reaches 24%, compared with the round jet. The reason for the increment in the heat transfer coefficient is due to an increase in the number of chevrons.

1. Introduction
One of the most common types of jet flows is limited impact jet, i.e. the jet impinging on a solid surface normal or angled. Impact flows are one of the most common forms of organizing efficient heat and mass transfer. The possibilities of classical methods for intensifying heat transfer have been practically exhausted by now. Surface cooling is widely used in metallurgy, energy, power engineering and radio electronics, including for cooling heating elements of integrated circuits and powerful processors. Another area of practical application of impact jets is aeronautical engineering, in particular, systems for protecting aircraft from icing, cleaning runways, and roads from snow and ice, preventing their destruction from jets of jet engines; paper drying; and cooling turbine blades.

Huge range of practical applications of limited jet flows necessitates the study of fundamental physical effects and related phenomena. In various regions of the flow, there are free and near-wall shear layers with developing large-scale vortex structures; 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, where local unsteady flow separation and the development of the near-wall jet take place.

Methods that allow obtaining uniform and intensive heat transfer from the wall are of interest from a practical standpoint. In this context, impact jets with chevrons are of particular interest. It is assumed that the 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 impact jets. In the study of limited impact jets [1] 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 an intensification of heat transfer by more than 25% compared to round jet [2].

The characteristics of heat transfer in elliptical nozzles with various distances to the surface were also studied [3]. It was shown that the maximum heat transfer in the leakage region was achieved when the distance between the nozzle exit and the surface was equal to 4 diameters and was 15% larger than that for a round jet. In free jets with chevrons, the mixing process changes due to the generation of counter-rotating longitudinal structures in the chevron slots [4]. 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

A series of experiments were carried out to measure the flow structure by the PIV method and the temperature distribution on the surface by IR spectroscopy. Experiments were performed using the hydrodynamic stand (see Fig. 1) equipped with a tank, a pump with feedback from a flow-measuring washer, and a thermostat, and including a test section made of Plexiglas. The objects of investigation are axisymmetric round and chevron jets. A jet, generated by a nozzle with a Vitoshinsky profile (the outlet diameter \(d = 15\) mm) impinged upon a flat obstacle, into which a sapphire, 4 mm thick and 150x150 mm in size, was mounted. On the side in contact with the liquid, a thin conductive coating made of indium tin oxide (ITO, \((\text{In}_2\text{O}_3)_{0.9} - (\text{SnO}_2)_{0.1}\) solid solution was applied with the thickness of 1.2 and 1.12 μm at the center and the corners, respectively. The coating was transparent in visible light. 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 a spectral range of 3.7-4.8 microns detected the temperature of the heating element, which in the test conditions varied from 27 to 38 °C. The temperature of the circulating water was controlled using DTS054-50M resistance thermocouples installed in the working section and the tank. During the experiments, the temperature was kept constant at 25 ± 1 °C by cooling the circulating liquid in the tank.

The PIV system consisted of a PhotonicsDM high-speed pulsed laser (pulse energy of 150 μs, up to 8 mJ at a pulse repetition rate of 10 kHz) and a high-speed CMOS camera Photron SA5 (the frequency of capturing full frames of 1024x1024 pixels with a dynamic range of 12 bits reached 7.5 kHz). For PIV measurements, polyamide tracer particles with minimal buoyancy were added to the flow. To detect particles, scattering laser radiation at a wavelength of 532 nm, the camera was equipped with a narrow-band transmission filter of 532 ± 5 nm.

To change the boundary conditions at the exit from the nozzle, special nozzles installed over the main nozzle were used. The attachments were 8 mm thick flat discs with radial ditches from the center to the periphery. The ditches were 2 mm wide and 2 mm deep (see Fig. 2). The beams were located at equal distances from each other. The number of ditches ranged from zero to eight. To designate the number of chevrons, we used the designations: \(N = 0\) - nozzle without chevrons (round jet), \(N = 4, 6, 8\) – nozzles with 4, 6, 8 chevrons, respectively.

![Figure 1. Schematic diagram of the experimental stand.](image)

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.
The measurement area ran along the ditch. The Reynolds number ($\text{Re} = \frac{dU_0}{\nu}$, where $d = 15$ mm was the nozzle outlet diameter) was chosen to be 6000 in all experiments.

3. Results and discussion
As a result of the experimental studies, a comprehensive database of experimental data was obtained. Using the measured instantaneous velocity fields for the impact submerged jet, the fields of statistical moments were calculated. In Fig. 3 (a, b) and Fig. 4 (a, b) the spatial distributions of the average velocity and intensity of pulsations of the longitudinal velocity component are presented at $\text{Re} = 6000$, $h/d = 1$ for a jet without chevrons (Fig. 3, 4 (a)) and with 8 chevrons (Fig. 3, 4 (b)). It is shown that in the case of a jet with chevrons, the velocity values at the surface slightly exceed the velocity of a circular jet, and propagate further from the central axis. At that, the pulsations are more intense and more uniform near the impact surface, which, accordingly, affects the heat transfer at the target.

![Figure 3. Spatial distributions of the average jet velocity: (a) without chevrons; (b) with 8 chevrons.](image)

![Figure 4. Distribution of pulsations of the longitudinal composing velocity for the jet: (a) without chevrons; (b) with 8 chevrons.](image)
Figure 5 presents profiles of the longitudinal component of the average velocity and intensity of the jet pulsations at a distance of $y/d = 0.1$ from the nozzle exit with and without 8 chevrons at $Re = 6000$ and $h/d = 1$ for one of the modes. The velocity profiles for both cases are similar, though differ in the region $r/d = 0.5$, where a slight increase in the velocity values (circled in red) of the chevron jet is observed. We can say that the increase in speed occurs due to the compression of the flow between the chevrons. In the same region, the intensity of pulsations for a jet with chevrons is higher in absolute values than that for a jet without chevrons (see Fig. 5 (b)). Figure 6 shows the downstream velocity profiles for a chevron jet ($N = 8$) at $Re = 6000$ $h/d = 6$. The jet expands with distance from the nozzle exit.

![Figure 5](image1)

(a)

![Figure 5](image2)

(b)

**Figure 5.** Profiles: (a) of the average longitudinal positioning velocity, and (b) the intensity of pulsations at a distance of $y/d = 0.1$ from the nozzle exit with and without 8 chevrons at $Re = 6000$ $h/d = 1$.

![Figure 6](image3)

**Figure 6.** Velocity profiles downstream for the chevron jet ($N = 8$) at $Re = 6000$ $h/D = 6$.

The analysis has shown that the flow structure in the chevron jet, in comparison with the round one, changes its shape and turbulent characteristics. In a free round jet, azimuthal coherent structures (toroidal vortices) are formed in the mixing layer and are caused by the development of the Kelvin-Helmholtz instability. However, in the case of a chevron jet, their development is largely suppressed because the shape of the shear layer at the exit from the nozzle is irregular (non-circular). Chevrons break toroidal vortices, turbulizing the flow. In this flow configuration, the coherent structures in the shear layer represent longitudinal C-shaped vortices generated inside the gap between the chevrons.
Figure 7 shows the average Nusselt number distribution along the surface of the jet heater with different numbers of chevrons (N = 4, 6, 8) at Re = 6000, h/d = 3, in comparison with the round jet (N = 0). For a jet with chevrons, a maximum of Nu is found on the central axis which indicates the most intense heat transfer in this region. Further, the heat transfer intensity gradually decreases with distance from the flow axis, in contrast to a round jet, which has a characteristic shape with two local maxima of Nu approximately at distances of the order of r/d = 0.7 and r/d = 2.8. In the case of a jet with chevrons, the increase in the average intensity of heat transfer reaches 24%, compared to a round jet. Moreover, the heat transfer coefficients grow with an increase in the number of chevrons, which indicates a more intense mixing.

![Figure 7. Distribution of the average Nusselt number over the surface of the jet heater with a different number of chevrons (N = 4, 6, 8) at Re = 6000, h/d = 3, in comparison with the round jet (N = 0).](image)

A similar tendency remains at all distances between the nozzle and the contact surface (see Fig. 8). The maximum intensity of heat transfer is observed at h/d = 3 for a jet with 8 chevrons.

![Figure 8. Comparison of the distribution of the average Nusselt number over the surface of the heater of the round (N = 0) and chevron (N = 8) jets at h/d = 1, 2, 3, 4.](image)

Conclusions
Using the measured fields of instantaneous velocity for an impacted submerged jet, the fields of statistical moments of the jet with and without chevrons have been calculated for different modes.

It is shown that in the case of a jet with chevrons, the velocities at the surface slightly exceed the velocity of a round jet and propagate further from the central axis. At that, the pulsations are more intense and more uniform near the impact surface, which, accordingly, affects the heat transfer at the
target. It is shown that in the case of a jet with chevrons, an increase in the average intensity of heat transfer reaches 24%, compared to that for a round jet.

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