Vortex heat transfer enhancement on energy-efficient surfaces structured by inclined trench dimples

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Abstract. Experimental measurements and numerical predictions of the longitudinal component of the air velocity in a narrow channel with two rows of 26 densely packed oval trenches at angles of ±45° and ±135° in laminar (Re=10³) and turbulent (Re=4×10³) regimes have been compared. The acceptability of the RANS approach using the modified SST turbulence model within the Rodi–Leschziner–Isaev approach has been substantiated. The flow acceleration in the dimpled channel up to the longitudinal velocity maxima of 1.85 and 1.55 of the average bulk velocity for laminar and turbulent air flows has been experimentally confirmed.

1. Introduction

Interest in surface vortex generators, dimples, is largely defined by their ability to create energy-efficient surfaces with an increase of heat transfer outstripping an increase in hydraulic losses [1, 2]. Spherical dimples are the simplest technological vortex generators [3, 4]. However, the separated flow around surfaces with ordered spherical dimples is characterized by zones of rather weak recirculation and secondary flows inside the dimples, as well as extremely low heat transfer much inferior to heat transfer on a flat wall [5-9].

A new type of surface generator of spiral vortices is proposed in the form of an inclined oval trench (OT) with a significant elongation of the cylindrical part (about 3-6 widths). In accordance with [10], when a turbulent flow of water streamlines a single OT with 0.39 depth inclined at an angle of 45° in a narrow channel with a height of 1 and a width of 7.5, the maximum velocity of the secondary flow in the dimple reaches 80% of the bulk velocity, and the minimum of the relative negative friction and the maximum of the relative heat transfer in the zone of the recirculation flow in the dimple are 1.5 and 2, respectively.

The phenomenon of abnormal enhancement of the separated flow and heat transfer at the inlet of the inclined OT, as well as the acceleration in the core of the channel flow is revealed numerically for laminar and turbulent air flow in narrow channels with single-row packets of inclined OT in [11-15]. Periodic sections of a stabilized flow in narrow channels and 1-height microchannels are considered. The Reynolds numbers determined by the bulk velocity are set equal to 103 and 104. Typically, the angle of inclination of the OT is chosen equal to 45°. In the case of a turbulent air flow for a rare-
arranged OT package with one 7.05-long, 1.05-wide, and 0.3-deep dimple in the center of a periodic channel section with a length of 6 and a width of 7 on the heated inner surface, a 4-fold increase in the absolute value of the minimum relative friction and a 5-fold increase in relative heat transfer (with respect to the parameters in plane-parallel channel) are observed. The maximum absolute value of the secondary (transverse) flow velocity turns out to be of the same order with the maximum flow velocity in the plane-parallel channel.

For one-row 1-wide, 4.5-long, and more than 0.25-deep OTs in a periodic module of a narrow microchannel with a width of 6 and length of 4 with one OT inclined at an angle of 45°, the phenomenon of laminar flow acceleration with a 1.5-fold increase in the maximum core velocity is found. Clustering the dimples on a one-row surface of a periodic section on a heated wall with an elongation of 8 in the narrow (9 to 1) plane-parallel channel is considered using the example of inclined OTs with the length of 7.05, width of 1.05, and depth of 0.25 with rounding radius of edges of 0.21. The distance between the centers of the dimples varies from 2 to 8. The effect of the turbulent flow acceleration with a 1.39-fold increase in the maximum core velocity is obtained for a dense packing of OTs inclined at an angle of 65° with a step between the dimples equal to 2. In this case, the maximum absolute value of the relative projection of friction on the direction of the midsection of the OT increases 4-fold, and the relative heat transfer increases 6.5-fold (with respect to the parameters in the plane-parallel channel). The maximum absolute value of the secondary (transverse) flow velocity by approximately 10% exceeds a maximum value of flow velocity in the plane-parallel channel; and the above value of the recirculation flow velocity is almost three times higher than the same velocity of the recirculation flow in the spherical dimple, reaching 0.89 of the bulk velocity in the channel. The inclination of the OT from 0 to 60° in a rare-arranged in-line package on the hydrodynamic stabilized section of a narrow channel has a dramatic effect on the abnormal enhancement of separated and swirling flows in the dimple, leading to a 3-4-fold decrease in relative negative friction in the range of angles from 40° to 60°, to an increase in the maximum velocity of the recirculation (0.8) and secondary (1.18) flow in relation to the bulk velocity in the channel.

Distributions of pressure, relative friction, and heat transfer in the midsection of a 0.3-deep OT inclined at an angle of 45 degrees in the one-row dimples with a step of 6 on the wall of a narrow channel (with a width of 7 and a height of 1) on a stabilized hydrodynamic section of air flow at Re=104 using quite detailed (from 2 to 4 million cells) grids of different topology (monoblock, structured and unstructured with hexagonal cells, multiblock different-scale overlapping), turbulence models (k-ε Realizable, SA, SST within the Durbin and Rodi–Leschziner–Iasav approaches) and application packages (StarCCM+ and VP2/3) were refined in [15]. The reason for the hydrodynamic and thermophysical effect of the abnormal enhancement of separated flow and heat transfer has been established; it consists in the creation of a large pressure difference between the zone of flow deceleration on the windward side of the inclined OT (about 0.5-0.6) and the closely located area of rarefaction (-0.3--(-0.6)) in the place of a tornado-like vortex structure generation at the inlet spherical segment of the OT.

The computational and experimental study is aimed at experimental substantiation of the effects of acceleration of laminar (Re=103) and turbulent (Re= 4×103) air flows in narrow dimpled channels with two rows by 26 OTs located at inclination angles of ±45°. The phenomenon of abnormal enhancement of separated flow and heat transfer in narrow channels with inclined OT is analyzed numerically.
2. Results and Discussion

Vector fields of flow velocity at two values of the Reynolds number $10^3$ and $4.3\times10^3$ are measured in an optically transparent narrow channel of the Kazan Scientific Center of RAS (10 mm height, 100 mm width, 800 mm length) with two-row 26 OTs on the wall, and the experimental data are generalized on flow structure and turbulence in comparison with the characteristics for a smooth plane-parallel channel. Flow is uniform at the channel inlet. The trench width of 10mm is chosen as the characteristic dimen- 
sion (Figure 1). The length of the oval dimples with sharp edges is 4.5, the depth is 0.25, the step between the centers of the dimples is 2.53 (a dense packing of the dimples is set). Two OT arrangements are considered: when the dimples are turned to the side walls (in this case, the inlet parts of the dimples are near the plane of symmetry) at an angle of $\pm 45^\circ$ to the plane of symmetry of the channel and at an angle of $\pm 135^\circ$ to the plane of symmetry and the turn of the dimples from the side walls (in this case, the inlet parts of the dimples are located near the walls). An electronic database of measurements of the longitudinal velocity component is compiled using the SIV method [16].

The measured transverse velocity profiles in Figure 2 show a zone of increased velocity, which is observed at the height of about 25-40% of the channel size in the flow, formed at the end of the dimpled channel above the inlet to the dimples. The velocity profile of the longitudinal velocity component in the channel symmetry plane strongly depends on the orientation of the dimples relative to the flow. When the OT is located at an angle of $\pm 45^\circ$ to the symmetry plane, the longitudinal velocity component $u$ near the channel axis is maximum and exceeds the average velocity over the channel cross-section about 1.55 times in turbulent and 1.85 in laminar regime. When the OT is
located at an angle of ±135° to the plane of symmetry, the opposite picture is obtained. The velocity on the axis is about 50%-85% of the average flow rate. Thus, the profile $u(z)$ in cross-section in the region of the 22nd dimple is bell-shaped with a maximum in the vicinity of the plane of symmetry for the OT at an angle of ±45°. The velocity profile changes dramatically in OT inclined at an angle ±135°. In this case, a velocity profile with two peripheral maxima of the longitudinal velocity component located near the side walls appears in the channel.

Figure 3. Calculated fields of static pressure ($a$), relative friction with the spreading pattern ($b$) and in the 3D version ($c$) in the vicinity of the 22nd oval trench at an angle of 45°. Re=10³.

Figure 4. Calculated fields of the relative Nusselt numbers ($a$) including the spreading pattern ($b$) of the vicinity of the 22nd oval trench at an angle of 45° and in the entire dimpled channel in the 3D version ($c$). Re=10³.

To compare the experimental data on the longitudinal velocity with the results of numerical simulation, the calculations of laminar (Re=1000) and turbulent (Re=4000) flows in a narrow channel with two-row 26 OTs (Figure 2, c) were carried out. The sharp edges of the dimples are rounded along a radius of 0.1 in the calculations. The calculated profiles for laminar and turbulent air flows in the channel at the considered inclination angles of the dimples are in satisfactory agreement with the experimental ones. The distance from the wall is chosen to reach the maximum velocity in the considered cross-section. Thus, a shear flow with a maximum velocity above the inlet to the dimples is formed above the channel wall with a two-row ensemble of dimples. This maximum noticeably exceeds the maximum velocity in the plane-parallel channel and thus confirms the previously numerically detected phenomenon of flow acceleration in the dimpled channel [11]. The reason for this behavior of the velocity profile is undoubtedly associated with the abnormal enhancement of the separated flow and heat transfer in inclined OT.
Figures 3-6 show the results of calculations of laminar and turbulent flow and heat transfer in a simplified analogue of the experimental setup, in a channel with single-row 26 OTs located at an angle of 45° on the heated wall, with setting symmetry conditions on the lateral faces. The lower wall with $T=1.034$ and upper one with $T=1$ are isothermal. The emphasis is on the analysis of the relative heat transfer on the entire dimpled heated channel wall and the region of the 22nd dimple as well as the pressure field in the vicinity of the 22nd dimple. When flowing around dimples far from the channel inlet, an abnormal enhancement of the separated flow and heat transfer in the inlet of the inclined OT described in [11–15] is observed. The minima of the relative negative friction reach values of the order of -2.5 - (-4.5) for the laminar and turbulent regimes, respectively. The swirling flow is generated along the entire length of the inclined OT. Static pressure drops between the air deceleration zone on the windward side of the 22nd dimple and the rarefaction region in the area of tornado-like vortex generation on the spherical entrance segment of the dimple are 0.5 and 0.8 for the laminar and turbulent regimes, respectively. As noted earlier, these are the pressure drops that cause high velocity gradients and heat fluxes within the inclined OT. The relative friction at the edge of the 22nd OT reaches 8-11. The distributions of the relative Nusselt numbers on the heated wall demonstrate a gradual increase in heat transfer with distance from the channel inlet. The maximum of $\text{Nu}/\text{Nu}_{pl}$ reaches 17 in laminar regime and 31 in turbulent one. The maximum relative heat transfer in the area of the 22nd dimple is 15 and 24 in the laminar and turbulent regimes, respectively.
3. Conclusion
The numerically obtained abnormal enhancement of the separated flow and heat transfer in inclined oval trenches (OT) and the flow acceleration in the dimpled narrow channel have been experimentally substantiated. SIV-measurements (in Kazan Scientific Center of RAS) of the velocity field in a narrow transparent channel with a dense two-row packet of 26 OTs with inclination angles of ±45° and ±135° have revealed the formation of a shear flow in the flow core with a maximum velocity above the inlet to the dimples, significantly exceeding the maximum velocity in a plane-parallel channel at laminar (Re=103) and turbulent (Re=4300) regimes. The numerical predictions have been found to quite well correlate with the experimental data obtained by qualitative and quantitative indicators.

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