Abnormal separated flow intensification and heat transfer enhancement in single-row inclined oval-trench dimples on the narrow channel wall

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Abstract. Intensification of turbulent separated air flow and heat transfer enhancement at the hydrodynamic stabilization length on the periodic section of the narrow channel with inclined one-row oval-trench dimples (OTDs) is analyzed. The periodic section of the channel of height equal to 1, length – 8, and width – 9 is considered at Re=10⁴. The inclined OTD 0.5 in width, 7.05 in length, and 0.25 in depth is located in the center of the heated isothermal wall. The rounding radius of the dimple edge is 0.21. The OTD inclination angle varies from 0° to 52.5°.

It is found that the optimal inclination angles in terms of thermal and hydraulic performance (THP) are equal to 45° and 30°. It is observed that at large inclination angles the minimum value of relative friction decreases many times (up to -3.5).

1. Introduction

Vortex technologies [1], including dimpled surface technologies [2], are used in power engineering, electronics, and in transport. Unlike ordered protrusions, surface vortex generators – dimples – provide high THP at moderate hydraulic losses. Using new energy-effective surfaces [3-14] structured by inclined OTDs instead of the traditional spherical dimples for laminar and turbulent flows in narrow channels is proposed. The effect of laminar flow acceleration in the dimpled narrow channel, which yields a 1.5-fold increase in the core velocity [8-10], is established numerically. Abnormal turbulent flow intensification and heat transfer enhancement in inclined OTDs on the narrow channel wall [11-14] are revealed. In the dimples, the zones of high-intense backflow and secondary flow are formed. Their velocities are compared and exceed the bulk velocity in the channel. The minimum values of friction in the separated flow zones exceed many times the similar values of friction on the plate-parallel channel wall. The cause of this phenomenon is discovered: at the OTD windward edge, the flow slows down, and the high-pressure zone is formed. On the surface of the inlet spherical segment, the spiral vortex with an intense swirled flow is generated and the low-pressure zone is formed. As a result, in the adjacent zones a static pressure drop appears at the inclined OTD entrance and is compared with a pressure drop between the forward and backward critical points in flow around bluff bodies such as a circular cylinder or a sphere. This unique phenomenon grows with increasing the depth and the density of inclined one-row dimples in the package.
2. Task statement, solution method, and grids
Separated air flow intensification and heat transfer enhancement in the narrow channel with inclined one-row OTDs at the hydrodynamic stabilization length is calculated. The periodic section of the channel with one dimple on the wall of a length equal to 8, width – 9, and height – 1 (Fig. 1) is considered. The top wall and side walls of the channel are flat. The selected dimple is similar to that considered in [11]. It is 1.05 in width and 7.05 in length. Its depth is 0.25 and its edge rounding radius is 0.21. The dimple inclination angle varies from 0° to 52.5°. The Reynolds number based on bulk characteristic velocity is selected equal to $10^4$. The Cartesian $x,y,z$-coordinate system is centered in the middle of the bottom part of the inlet section of the channel (Fig. 1). The top isothermal wall is “cold” and is kept at a room temperature of 293 K taken as the characteristic temperature $T=1$. The bottom wall is slightly heated to the temperature $T=1.034$. The side walls are thermally insulated.

![Diagram of the periodic section of the narrow channel with the inclined OTD (with the removed top wall) and with the digitized fragment grids](image)

**FIGURE 1.** Configuration of the periodic section of the narrow channel with the inclined OTD (with the removed top wall) and with the digitized fragment grids: channel, rectangular (1), near-wall, rectangular (2), curvilinear matched to bottom wall surface (3) and “patches” (4)

Developed turbulent flow and heat transfer in the dimpled channel are described by the Reynolds averaged Navier–Stokes equations and the energy equation. The shear stress transport model (2003) considering the streamline curvature modified within the framework of the Rodi–Leschtsiner–Isaev approach has been used to close the system of the motion equations. When solving the finite-volume equations written in the increments of the governing equations, one uses the multiblock technique based on different-scale overlapping grids and hybrid grids with unstructured inserts at the places where the structured fragments are overlaid. The methods for pressure gradient and bulk temperature correction are applied. The VP2/3 code is used and the predicted results are validated on the grids of different density and topology. The modified SST (shear stress transport) model is verified against a task with a physical equivalent: vortex dynamics and turbulent convective heat transfer in the vicinity of single spherical dimples on the narrow channel wall [5]. In [7], the acceptability of the periodic boundary conditions, first developed to solve tasks of convective heat transfer in bundles of round tubes, is justified.
The computational multiblock structured overlapping grids used in numerical simulation consist of four digitized different-scale fragments (Fig. 1). Number 1 indicates the rectangular grid in the section of the channel with the longitudinal and transverse steps in the central part of the bottom and top walls. They are equal to 0.1. The grid is nonuniform and is condensed to the walls. The near-wall step is considered equal to 10^{-4}. The channel grid contains about 1.1 mln computational cells. The top heated wall with an inclined dimple in its center is covered with fine rectangular fragment grid No. 2. The top flat boundary of the grid is at a distance of 0.2 from the wall. The grid related to the longitudinal x- and transverse z-coordinates is uniform with a step of 0.05. The transverse size of grid No. 2 is equal to 8. The grid related to the vertical y-coordinate is nonuniform and is condensed to the wall. The near-wall step of the grid is equal to 10^{-4}. The total number of cells in fragment grid No. 2 is 1.08 mln. Grid No. 2 is meant for correct computation of gradient near-wall layers, in particular, those developing between the dimples. At the same time, large velocity gradients appear in flow around dimple edges. To correctly resolve these velocity gradients and to reproduce jet-vortex structures developing in the dimple, O-type elliptical curvilinear grid No. 3 is introduced. The top boundary of fragment grid No. 3 coincides with the boundary of grid No. 2 and is located at a distance of 0.2 from the plate-parallel part of the bottom wall of the channel section. The grid cells are condensed to the wall, the size of the near-wall cells being equal to 10^{-4}. Grid No. 3 contains 0.232 mln cells. Oblique fragment grid No. 4 serves as a “patch” on the central zone of grid No. 3. It rests on the rectangular base inside the OTD and its vertical grid lines are perpendicular to the top boundary of the grid coinciding with the boundaries of grids No. 2 and No. 3. Grid No. 4 has 0.103 mln cells. The near-wall step is equal to 10^{-4}. The total number of computational cells of the multiblock fragment grid with the overlapping is about 2.5 mln.

**FIGURE 2.** Profiles of static pressure $p$ (a) and relative friction $f/f_0$ (b) in the middle section of the OTD and at its entrance (c). 1 – $\theta = 0^\circ$; 2 – $1^\circ$; 3 – $7.5^\circ$; 4 – $15^\circ$; 5 – $22.5^\circ$; 6 – $30^\circ$; 7 – $37.5^\circ$; 8 – $45^\circ$; 9 – $52.5^\circ$. The dash line indicates the plate-parallel channel

3. **Discussion of the obtained results**

Figs. 2-4 depict some of the obtained results. Most of them are dedicated to assessing the influence of the OTD inclination angle $\theta$ on the integral and local characteristics of flow and heat transfer in the periodic section of the dimpled narrow channel and the surface distributions of static pressure, relative friction, and the Nusselt number in the OTD middle section.

Fig. 2 shows the distributions of static pressure averaged over a double velocity head and friction on the dimpled wall related to friction on the plate-parallel channel wall without a dimple in the middle section of the OTD at different angles of its inclination.

Two groups of the results obtained at small (from $0^\circ$ to $22.5^\circ$) and large (from $30^\circ$ to $52.5^\circ$) inclination angles are significantly different in the nature of their dependence on the longitudinal $s$-coordinate. In the first group, (the distribution of) the pressure inside the dimple has three maximum local values (Fig. 2, a). The first small maximum pressure value is seen. As $\theta$ grows, this value decreases rapidly with increasing rarefaction on the spherical segment of the dimple. The second maximum pressure value appears in the flow attachment zone behind the separated flow zone at the entrance of the inclined OTD. As $\theta$ grows, this value decreases but rather moderately. Its location is preserved. The third maximum
local pressure value appears at the OTD trailing edge (at the OTD exit) during the freezing of the flow issuing from the dimple in the spherical segment. First (to $7.5^\circ$), this maximum local value increases noticeably (twice) and then decreases 1.5 times from the initial level. Progressive pressure drop in the rarefaction zone at the beginning of the spherical segment of the dimple draws attention. It should also be mentioned that, as $\theta$ increases, the deflection of the curve of the pressure distribution grows in the OTD middle section. At $\theta$ more than $22.5^\circ$, as the swirled flow is intensified in the dimple, the increased pressure zone is transformed into the decreased pressure one.

The evolution of the friction distributions in the OTD middle section characterizes the changes in the flow structure due to the reorganization of separated flow zones at swirled flow intensification. The first group of the relative friction distributions is characterized by a cardinal difference in the results at $\theta=0^\circ$-1° and more than $7.5^\circ$ (Fig. 2, b). Dimple flow sharply grows with increasing relative friction to values more than 1. When $x$ ranges from 1.5 to 3, the distributions $f/f_{pl}(x)$ remain unchanged at $\theta$ from $7.5^\circ$ to $22.5^\circ$. In the separated flow zone at the dimple entrance, the absolute value of relative friction increases, at $\theta=22.5^\circ$ it reaches a value of 1. A peak increase in relative friction is seen at the OTD trailing edge (at the OTD exit). As $\theta$ grows, the flow developing in the dimple slows down. In the second half of the dimple, relative friction monotonically decreases.

The second group of numerical predictions significantly differs from the first. The first maximum pressure value in the separated flow zone achieves a value of -0.15 and does not depend on $\theta$ more than $45^\circ$ (Fig. 2, a). The second maximum pressure value at $\theta=45^\circ$-$52.5^\circ$ appears to be shifted to the dimple entrance and its value is close to zero. Generally, a wave-like distribution of static pressure arises in the dimple. As $\theta$ grows, the second maximum pressure value is followed by the minimum pressure value of about -0.1 that is shifted to the dimple entrance. It should be noted that the pressure sharply decreases at the beginning of the spherical segment, achieving a value of -0.2. The increased pressure zone develops behind the middle section of the dimple. The maximum local value is a little more than 0 and is shifted to the dimple entrance as $\theta$ ranges from $45^\circ$ to $52.5^\circ$.

The relative friction distributions demonstrate the flow intensification in the separated flow zone at the inclined OTD entrance and in the swirled flow in the middle section of the dimple (Fig. 2, c). The minimum value of relative friction $f/f_{pl}(x)$ decreases from -3 to about -3.5 when $\theta$ grows from $45^\circ$ to $52.5^\circ$. The maximum value of relative friction in the middle section of the dimple achieves a value of about 1.2 at $\theta=45^\circ$ and then decreases up to 0.8 at $\theta=52.5^\circ$. At the trailing edge of the dimple (at the dimple exit), a peak value of relative friction appears to be equal to 2.

Generally, the effect of abnormal separated flow intensification in the inclined one-row OTDs on the wall of the narrow channel is achieved at dimple inclination angles ranging from $37.5^\circ$ to $52.5^\circ$.

The distribution of local $Nu/Nu_{pl}$ in the middle section of the inclined OTD and of $Nu_{pl}/Nu_{mpl}$ integrated over the transverse strips of the control section with an $8\times8$ dimple in the longitudinal and transverse...
directions (Fig. 3) demonstrates the previous division of the obtained results into two groups for small and large inclination angles $\theta$ up to and over 30°. The first group illustrates the numerical predictions of the inclination angles close to $0°$-$1°$. At $\theta=7.5°$ at the OTD entrance the maximum local value of the relative Nusselt number exceeds 1. As $\theta$ grows, it attains a value of 3.3 at $\theta=52.5°$ (Fig. 3,a). Thus, abnormal heat transfer enhancement is seen in the separated flow zone of the OTD. As $\theta$ grows to more than 30°, the second maximum local value of $\text{Nu}/\text{Nu}_{\text{pl}}$ in the second half of the dimple exceeds 1 and at $\theta=45°$ it is equal to 2.

The evolution of the distributions $\text{Nu}/\text{Nu}_{\text{mpl}}(x)$ demonstrates that the maximum values of $\text{Nu}/\text{Nu}_{\text{mpl}}$ grow with increasing the OTD inclination angle corresponding to the strips passing through the dimple entrance (Fig. 3,b). The relative heat transfer at the beginning of the periodic section of the channel is stabilized at a value of about 1.16, starting at $\theta=15°$. The second maximum local value of relative heat transfer appears near the trailing edge of the dimple (the dimple exit). As $\theta$ grows, it increases and is shifted to the middle of the periodic section.

The distributions $\text{Nu}/\text{Nu}_{\text{mpl}}(z)$ integrated over the longitudinal strips illustrate the energy-effective heat transfer zones on the control section of the heated dimpled wall of the channel (Fig. 3, c). As $\theta$ grows on the right side of the control section, heat transfer enhancement increases. As the dimple entrance is displaced, a growing maximum value of $\text{Nu}/\text{Nu}_{\text{mpl}}$ is shifted to the right wall and achieves a value of 2.35 at $\theta=52.5°$. On the left side of the control section, relative heat transfer decreases, reaching a value of 0.35.

Fig. 4 compares the $\theta$ dependences of the THP integral characteristics for the control section of the heated wall with an 8×8 OTD and for the rectangular 7.05×1.05 section, incorporating the OTD contour. The density of the dimples on the channel wall is quite low and equal to 0.134. As a result, when relative heat transfer of the control section grows with increasing the OTD inclination, the numerical predictions...
are very modest. At the optimal angles $\theta$ ranging from 45$^\circ$ to 52.5$^\circ$, the thermal performance is maximum and reaches a value of 1.25. Hydraulic losses $\zeta/\zeta_{pl}$ grow linearly with increasing $\theta$. But relative heat transfer increases more quickly than hydraulic losses grow. The thermal and hydraulic performance appears to hit a maximum at $\theta=30^\circ$ and attains a value of 1.12.

The dimple areal results are very interesting. First, the thermal performance $\text{Nu}_{\text{mm}}/\text{Nu}_{\text{mmpl}}=1.64$ at $\theta=45^\circ$ is very impressive. It exceeds many times the prediction of the control section of the dimpled wall. Hydraulic losses for the dimple increase slightly faster than for the entire section but the rate of their growth is much lower than that of relative heat transfer. The OTD thermal and hydraulic performance $(\text{Nu}_{\text{mm}}/\text{Nu}_{\text{mmpl}})/(\zeta/\zeta_{pl})$ unexpectedly turned out to be optimal and equal to 1.44.

Generally, the obtained results illustrate the great potential of inclined OTDs and point to the possibility of increasing the performance of the OTDs condensed in the package.

4. Conclusion

A range of the inclination angles of loosely spaced one-row moderate-depth OTDs on the wall of the narrow channel is established, within which the effect of abnormal separated turbulent flow intensification at the dimple entrance is observed. At the hydrodynamic stabilization length, $Re=104$ and inclination angles ranging from 37.5$^\circ$ to 52.5$^\circ$, a minimum value of relative friction in the separated flow zone is much less than -2 and relative local heat transfer achieves a value of about 3.7. The intensification phenomenon occurs due to a pressure drop between the stagnation zones at the rounded edge and the rarefaction zones at a place where a spiral vortex is generated. The thermal performance of the area surrounding the OTD achieves a value of 1.64. At an optimal inclination angle of 45$^\circ$, this performance is many times higher than that of the wall of the periodic section of the channel at a low density of dimples (about 13%). The thermal and hydraulic performance of the control section of the dimpled wall of the channel is optimal at an inclination angle of 30$^\circ$ and is equal to 1.12.

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References

[1] Dzyubenko B V et al 2016 Intensification of heat and mass transfer on macro-, micro-, and nanoscales (New York, Begell House)
[2] Rashidi S Hormozi F Sunden B and Mahian O 2019 Applied Energy 250 1491
[3] Isaev S A et al 2017 Int. J. Heat and Mass Trans. 109 40
[4] Isaev S Leontiev A Chudnovsky Y and Popov I 2018 J. Enhanced Heat Trans. 25 (6) 579
[5] Isaev S et al 2019 Energies 12 (7) 1296
[6] Isaev S A Leontiev A I Gultsova M E and Popov I A 2015 Tech. Phys. Letters 41 (6) 606
[7] Isaev S A et al 2015 High Temp. 53 (3) 375
[8] Isaev S A Baranov P A Leontiev A I and Popov I A 2018 Tech. Phys. Letters 44 (5) 398
[9] Isaev S A et al 2018 J. Eng. Physics and Thermophysics 91 (4) 963
[10] Isaev S A et al 2019 Int. J. Heat and Mass Transfer 134 338
[11] Isaev S Gritchevich M Leontiev A and Popov I 2019 Acta Astronautica 163 202
[12] Isaev S A et al 2019 High Temp. 57 (5) 771
[13] Isaev S A et al 2019 Thermophysics and aeromechanics 26 (5) 697
[14] Isaev S A et al 2019 Int. J. Heat and Mass Transfer 145 118737