Effective heat transfer surfaces of tubes and plates with spiral vortex generators – inclined oval-trench dimples

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Abstract. Numerical simulation of laminar heat transfer enhancement at the hydrodynamic stabilization length of the tube with 8 inclined longitudinal oval-trench dimples (OTDs) in the transformer oil flow has revealed an optimal inclination angle of dimples, at which a value of thermal and hydraulic performance (THP) is achieved. Heat transfer of a dimpled tube increases by a factor of 28 in comparison with a smooth tube at practically invariable hydraulic losses. Heat transfer enhancement is calculated in turbulent air flow around a flat plate with a package of 16 one-row dimples inclined at an angle of 60° on the longitudinal section of 40 in length and 4 in width under the symmetry conditions at the side boundaries of the plate section and at a dimple step of 2.4. The dimple is 1 in width, 4.5 in length, and 0.2 in depth. Its rounding radius is 0.3. The boundary layer thickness at the section inlet is 0.175. The effect of abnormal separated flow intensification and heat transfer enhancement in dimples has been confirmed. \( \frac{(f/f_{pl})_{\text{min}}}{(f/f_{pl})_{\text{min}}}=3, \frac{(\text{Nu}/\text{Nu}_{pl})_{\text{max}}}{(\text{Nu}/\text{Nu}_{pl})_{\text{max}}}=4 \). Relative heat transfer grows by a factor of 1.43 in comparison with the smooth plate and the drag coefficient increases by a factor of 2.08. However the thermal and hydraulic performance defined in terms of heat load growth is 1.12.

1. Introduction

Effective heat transfer surfaces with spiral vortex generators, dimples, are relevant in power engineering, transport, and microelectronics [1-3]. When analyzing convective heat transfer enhancement near flat surfaces [4,5] and in round tubes [6] some practical experience of using spherical and asymmetric, in particular elliptical dimples has been gained. However a real breakthrough in developing dimpled surface technologies occurred when abnormal separated flow intensification and heat transfer enhancement in narrow channels with inclined one- and multi-row oval-trench dimples (OTDs) [8,9] proposed in [7] was revealed. In [10], it is shown that, when transformer oil is pumped in tubes with a package of in-line OTDs inclined at an angle of 45°, heat transfer grows 20 times in comparison with the smooth tube. The present study considers heat transfer enhancement in laminar transformer oil flow in round tubes and in turbulent air flow around a flat plate with inclined one-row OTDs. In particular, the influence of the inclination angle of OTDs on the tube surface is investigated.

2. Calculation of laminar heat transfer in the dimpled mictotube at transformer oil pumping

Heat transfer enhancement at the hydrodynamic stabilization length of the dimpled microtube at transformer oil pumping is analyzed at \( \text{Re}=667 \). Here, the tube diameter is selected as the
characteristic size. The in-line arrangement of dimples in the tube is considered. The dimples with the same spot area are uniformly arranged in a circle in the central part of the periodic section of the tube. The spherical dimple area-equivalent diameter is 0.25. The length of the periodic section of the tube is 0.5, the depth of the dimple is 0.065, and the rounding radius of the dimple edges is 0.06. The oval-trench dimples with the length-to-width ratio of 2.82 and with width of 0.137 are inclined at 30°, 45°, 55° and 60° to the flow in the tube. At an inclination angle of 60°, the cylindrical insert length of the dimples with the same spot area is varied from 0.25 to 0.2. For comparison, the periodic section with spherical dimples having a depth of 0.119 is examined. Figure 1 illustrates all the considered configurations. The bulk temperature of oil is selected equal to 293 K, the wall heating is small, and the wall-to-characteristic temperature ratio is 1.034.

![Figure 1](image)

Figure 1. Considered arrangements of smooth (a) and dimpled (b-f) tubes with spherical (b) and oval-trench dimples at the inclination angles θ = 30°(c), 45°(d), 55°(e) and 60°(f).

The Navier–Stokes equations for a medium with variable physical properties are solved using the multiblock computational technique (MCT) [10]. Calculations show that the inclination angle of an oval-trench dimple significantly affects the thermal and hydraulic performance of the dimpled tube at its hydrodynamic stabilization length. Figure 2 shows that, when the Nusselt numbers are averaged over the strips in the longitudinal and transverse directions from an inclination angle of 30° to a group of the predicted angles θ=45°-60°, thermal performance grows more than by a factor of 1.5 at a very inconsiderable increase in hydraulic losses. The highest thermal performance achieves a value of about 30 and the thermal and hydraulic performance of 20 at an inclination angle of 55° (Figure 3).

Strip-averaged relative local heat transfer achieves a maximum value of 45 at a minimum value of 5. Spherical dimples are substantially (by a factor of about two) inferior to oval-trench dimples (OTDs) at the optimal inclination angle but they are close in heat transfer characteristics to OTDs at an inclination angle of 30°.
3. Numerical simulation of heat transfer enhancement in turbulent air flow around a plate with one-row OTDs

Turbulent heat transfer in air flow around a flat plate with inclined multi-row dimples at Re=6000 is studied. The width of an oval-trench dimple (OTD) with a length of 4.5, depth of 0.2, and a rounding radius of 0.3 is selected as the characteristic size. The step between the dimple centers is 2.4. The thickness of the boundary layer in the vicinity of the first dimple is 0.175. The length of the dimpled section is 40 and the width of the section with a package of 16 one-row dimples is 4.

We solved the task of turbulent viscous incompressible liquid flow and convective heat transfer on the plate with a package of one-row dimples inclined at an angle 60°. In front of and behind the package, the upstream and wake flat stabilization sections are located (Figure 4, a). The computational domain in the form of a parallelepiped of with a length of 44, a width of 4 and a height of 20 is located
upstream. The Cartesian coordinate system is in the middle of the “inlet” to the dimpled section. The Cartesian velocity and pressure components are defined in terms of the characteristic velocity. The uniform flow velocity at the inlet to the computational domain is assigned as the characteristic velocity. The velocity profile near the plate is calculated in terms of the boundary layer thickness equal to 0.175. At the side boundaries of the computational domain, the symmetry conditions are set, i.e. it is assumed that dimples arranged in one row form a zigzag in the transverse direction. At the outlet of the computational domain, the solution continuation conditions are set. The turbulence characteristics are defined, as in [11], within the framework of the modified Rodi–Leszhiner–Isaev SSST turbulence model.

**Figure 4.** Plate section with one-row OTDs inclined at an angle of 60° (a), static pressure (b) and temperature (c) fields on the dimpled plate.

The Reynolds averaged Navier–Stokes equations, which are closed by the equations of the two-parameter turbulence model, and the energy equation are solved by using the multiblock computational technique [8-10]. Overlapped multiblock grids consisting of two fragments are used. In the first fragment, a rough rectangular grid is constructed. Its longitudinal and transverse steps are
equal to 0.07. The grid is condensed to the flat wall with a near-wall step of 0.001 and is overlapped with a finer Cartesian grid with longitudinal and transverse steps equal to 0.05 and with a near-wall step of 0.001. This grid contains 16 0-type curvilinear grids matched to the oval-trench dimple. Inside the dimples, the “patches” are constructed and cover their central part. The total number of computational cells is approx. 6.75 mln.

The calculations were made for the dimpled surface and the equivalent flat plate. The convergence of the iteration process was controlled when the smallness condition of the increments of dependent variables (less than $10^{-5}$) and total heat transfer from the dimpled section were achieved.

**Figure 5.** Longitudinal distributions of the pressure $p$ (a), relative friction $f/f_{pl}$ (b) and $Nu/Nu_{pl}$ (c) at the wall in the section $z=1.3$

**Figure 6.** Distributions of local $Tw/Tw_{pl}$ (a) (in the section $z=1.3$) and $Nu_{m}/Nu_{mpl}$ integrated over transverse (b) and longitudinal (c) strips along longitudinal and transverse coordinates

Figures 5 and 6 depict some of the obtained results. The local and integral characteristics of the flow and heat transfer on the segment of the plate with 16 inclined OTDs and the plate without dimples.

It should be noted that the longitudinal and transverse distributions of heat transfer (coordinate convolution) integrated over the transverse and longitudinal strips were compared. The longitudinal section through the centers of the inlet segments of the inclined OTDs (in the section $z=1.3$) was also selected. The relative friction change was registered in this section and served to illustrate abnormal separated flow intensification and heat transfer enhancement [9].

The performed calculations have yielded some interesting results. The distribution of relative friction in the selected longitudinal section of the fragments with one-row dimples has shown a significant increase in negative $f/f_{pl}$ (more than three times). The abnormal intensification of separated flow is found to occur on the plate within the turbulent regime ($Nu/Nu_{pl}$ grows by a factor of 4), as in
the narrow channel [8]. Pressure drops are significant. Increasing relative heat transfer is mainly associated with decreasing relative wall temperature (Figure 6,a).

The distributions of the Nusselt numbers are cyclic in nature (Figure 5, c). These numbers sharply decrease in the separated flow zones and increase at the dimple edges and in the spaces between the dimples. In the case of a package of one-row dimples, maximum and minimum values of heat transfer monotonically grow. It is seen that heat transfer increases (its maximum value is about 4.4). The minimum value of relative heat transfer in the separated flow zones of OTDs appears to be more than 1.

The arrangement of inclined OTDs on the heated wall of the plate substantially increases its integral heat transfer characteristics. Transverse coordinate-averaged relative heat transfer grows with a high rate, achieving a maximum local value of 1.9. (Figure 6, b). The analysis of the distributions of the relative Nusselt numbers averaged over the longitudinal coordinate (Figure 6, c) shows that the left side of the section has a section of decreased relative heat load (less than 1). The right side of the section illustrates about 2-fold heat transfer enhancement at relative integral heat load in the package of OTDs.

As a whole, significant separated flow intensification and heat transfer enhancement are seen on the plate with inclined OTDs. Maximum velocities of backflow and secondary flow achieve the values of 0.4 and 0.56, respectively. The flow noticeably accelerates immediately above the dimpled plate: the maximum velocity value is 1.083 in comparison with a value of 1.014 for the smooth plate. As a result, the thermal performance of a relatively small package of dimples is 43%. In this case, the drag of the dimpled plate increases 2.08 times in comparison with the flat plate. However when assessing the thermal and hydraulic performance as \( \left( \frac{\text{Nu}_{\text{dimp}}}{\text{Nu}_{\text{smooth}}} \right) \left( \frac{C_{\text{y}}}{C_{\text{inlet}}} \right)^{1/3} = \text{THP} = 1.12 \), it is significantly more than 1.

**Conclusion**
Numerical simulation of enhancement of laminar heat transfer in the dimpled tube at transformer oil (TO) pumping and of turbulent heat transfer in the flow around the dimpled plate has been performed. Inclined oval-trench dimples (OTDs) have been studied. Significant THP values have been obtained. In the case of TO flow in the dimpled tube, the effect of heat transfer enhancement is associated with decreasing the thickness of temperature layers in comparison with the smooth tube. It is found that the optimal inclination angle of dimples is equal to 55°. Abnormal separated air flow intensification on the dimpled plate and heat transfer enhancement in inclined OTDs have been confirmed. They are caused by a significant static pressure drop between the closely spaced zones of flow stagnation at the smoothed edge of the dimple “inlet” and the loosely spaced zones at a place where a spiral vortex is generated on the spherical OTD segment.

**Acknowledgments**
The research is sponsored by the Russian Science Foundation (grant 19-19-00259).

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