Anomalous intensification of separated flow and heat transfer in one and multiple row deep inclined oval trench dimples on the wall of a narrow channel and on the plate

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Abstract. At the stands of Research Institute of Mechanics at the Moscow State University, we experimentally confirmed the mechanism of anomalous intensification of the separation flow and heat exchange in inclined oval-trench dimples (OTD) on the plate, which was discovered during numerical studies. The measured static pressure differences in single OTD at Re=6.7×10⁴ are in good agreement with the numerical forecasts within the framework of the RANS approach at Re=10⁴.

1. Introduction

It is known [1-4] that surface vortex generators in the form of dimples are applied to heat exchange surfaces and can provide a faster increase in thermal efficiency compared to hydraulic losses. Spherical dimples have long been the most technologically advanced. Currently, additive technologies allow you to create reliefs from dimples of a more complex shape. It should be noted that in order to achieve high thermal efficiency, spherical dimples with a high placement density (about 70%) are applied to the walls of a narrow channel. It is shown [5-9] that the heat transfer inside the wells in the separation flow zone is reduced compared to the heat transfer on a flat wall. The intensity of the return flow in spherical dimples is low and does not exceed 30% of the characteristic velocity.

As an alternative to spherical dimples, inclined oval-trench dimples (OTD) are proposed. They are promising generators of spiral vortices [10]. The 45-degree turn of the OTD was determined by the
orientation of the tornado vortex structure in deep spherical dimples. It is established that the elongation of the OTD with respect to should be at least 4-5. In this case, for a single well, the separation zone is localized in the entrance spherical segment of the OTD, and the flow around the trench part of the well as a whole turns out to be continuous. The velocities of the return and secondary turbulent flow in an inclined OTD are much higher than similar velocities in a spherical dimple with the same spot area. In contrast to a spherical dimple, where there is virtually no heat transfer from the wall in the separation zone with a close to stagnant flow, in an inclined OTD in the separation zone, the minimum of relative friction is about 1.5, i.e. the velocity gradients are very large and exceed the gradients on the wall of a plane-parallel channel, and the maximum heat transfer exceeds more than twice the heat transfer on a flat wall with a continuous flow.

When the air coolant moves in narrow channels from single-row inclined OTDs, the phenomenon of anomalous intensification of the separation flow and heat transfer, as well as the acceleration of the flow in the channel core, is numerically achieved [11-16]. For dense ensembles of OTDs in the zones of return turbulent flow, the minima of negative relative friction and the maxima of relative heat transfer reach -5 and 7, respectively. The maximum velocity in the core of the flow in the stabilized section of the channel with OTDs in the zone above the entrance part of the inclined OTD increases by 1.5 times in laminar and 1.4 times in turbulent flow modes compared to the maximum velocity in a plane-parallel smooth channel.

The reason for the open phenomena of intensification of thermal and hydrodynamic processes in inclined OTD is the formation of high static pressure differences between closely located zones of

![Figure 1](image-url)
braking of the flow entering the dimple on the windward slope and rarefaction in the area of generation of a tornado-like vortex in the spherical segment of the OTD. The maximum velocity of the return flow reaches 0.9 of the average mass velocity, and the maximum velocity of the secondary (swirled) flow exceeds the maximum velocity in a plane-parallel channel by 10%.

Scientific achievements were made using numerical modeling based on the solution of the Navier-Stokes equations and energy in the laminar case by factorized finite-volume methods and the Reynolds-averaged Navier-Stokes equations (RANS) and energy in the turbulent case. In the latter case, the equations are closed using the equations of the SST 2003 Menter shear stress transfer model modified taking into account the correction for the curvature of the current lines within the framework of the Rodi-Lesziner-Isaev approach. To solve linearized equations, multi-block computing technologies based on multi-scale structured grids with intersections are used, implemented in a specialized VP2/3 package (Velocity-Pressure, 2D/3D).

Figure 2. Calculated domain of the plate with OTL (a), the multi-block calculation grid (b), the field of the longitudinal component of the velocity in the median longitudinal section of the plate with OTD at an angle of inclination of 45° (c), comparison of the experimental (1) and calculated (2) dependences of $p_{\text{max}}$ on the angle $\theta$ of inclination of OTD (d)

The aim of the study is to substantiate the acceptability of numerical modeling based on the RANS method and experimentally confirm the discoveries of anomalous intensification of hydrodynamic and heat exchange processes in inclined OTD and acceleration of the flow above the entrance in OTD. in the experiments is made on the turbulent flow of a single OTD on the plate when The emphasis measuring static pressure fields in the dimple in a wide range of tilt angles of the OTD from 0 to 90°.

2. Results and Discussion
In two series of experiments in Research Institute of Mechanics of the Moscow State University, static pressure distributions were measured in characteristic sections of an inclined OTD. In the first series (Figure 1,a), sharp-edged OTD with a width of 0.6, a length of 3, and depths of 0.15 and 0.3 are considered in the channel 12×1×4 by $Re=1.67\times10^5$. The second series of experiments (Figure 1,b,c) was carried out on an wind tunnel A4, in the working part underpressure of which a plate with a length of 6, a width of 1 and a depth of 0.25 is placed. The Reynolds number of the external flow is $6.7\times10^4$, and the thickness of the boundary layer in the area of the OTD is 0.16. The angle of inclination of OTD is changed from 0 to 90°. Experimental distributions $C_p$ give a clear idea of the influence of the angle of inclination on the structure of the internal flow in the OTD, in particular, they indicate a range of $25°<\theta<85°$, in which the head rounding of the OTD contains a characteristic double configuration of localized zones of pressure extremes of the opposite sign. The dependences of the absolute maxima and
minima of the pressure coefficient on the entire inner surface of the OTD with varying the angle of inclination show that the maximum underpressure at the level of $C_p = -0.22$ is observed in the range $40^\circ < \theta < 45^\circ$, and the maximum positive value of $C_p = 0.41$ is marked in the range $55^\circ < \theta < 60^\circ$.

Figure 3. Predicted (lines) and measured (points) static pressure distributions on the middle portion of the dimple at the inclination angles $0^\circ(a)$, $5^\circ(b)$, $10^\circ(c)$, $15^\circ(d)$, $20^\circ(e)$, $25^\circ(f)$

Figure 4. Predicted (lines) and measured (points) static pressure distributions on the transverse entrance portion of the dimple at the inclination angles $0^\circ(a)$, $5^\circ(b)$, $10^\circ(c)$, $15^\circ(d)$, $20^\circ(e)$, $25^\circ(f)$
Figure 5. Predicted (lines) and measured (points) static pressure distributions on the middle portion of the dimple at the inclination angles 30°(a), 35°(b), 40°(c), 45°(d), 50°(e), 55°(f)

Figure 6. Predicted (lines) and measured (points) static pressure distributions on the transverse entrance portion of the dimple at the inclination angles 30°(a), 35°(b), 40°(c), 45°(d), 50°(e), 55°(f)

The experimental data are compared with results of numerical simulations of turbulent flow (at Re=10^4) of a plate with a longituted OTD with a rounding radius of 0.2 with a variation θ from 0 to 90°, obtained using multi-block grids in the VP2/3 package (Figures 2-6).
It is established that the results of numerical simulations correlate quite satisfactorily qualitatively and quantitatively with the experimental data. The pressure maxima in the braking zone of the external flow on the windward slope in the inlet part of the OTD and in the outlet region of the OTD in the longitudinal median section are well consistent. The minima of negative pressure in the rarefaction zone, where a tornado-like vortex begins to form (turning into a swirling stream), are also well captured. Thus, the numerical and experimental confirmation of the control mechanism of the anomalous intensification of the separation flow and heat exchange in the inclined OTD is obtained, the angles of inclination at which it successfully functions are revealed.

3. Conclusions
The static pressure fields were measured during the flow around a plate with a sharp-edged OTD with an elongation of 6, a width of 1 and a depth of 0.25 at Re=6.7×10⁴ and a thickness of the boundary layer of 0.16 when the angle of inclination varies from 0 to 90° with a step of 5°. The measurement data are in good agreement with the pressure forecasts for the flow around a plate with the same OTD with a rounded edge of 0.2 at Re=10⁴, obtained using the RANS approach and a modified SST model. It is established that the angle of inclination of the OTL cardinally affects the pressure field and two regimes of flow around the OTD can be distinguished: up to 25° and from 25° to 85°. The physical mechanism of the intensification of the separation flow in the OTD, due to the difference in static pressure across the dimple between the close braking zones on the windward edge and the rarefaction in the swirling flow, is confirmed.

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