Numerical and experimental study of abnormal enhancement of separated turbulent flow and heat transfer in inclined oval-trench dimples on the plate and on the narrow channel wall

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Abstract. The numerically found abnormal enhancement of separated flow and heat transfer in inclined oval-trench dimples (OTDs) on the plate and on the wall of the narrow channel was experimentally confirmed at the stands of the Research Institute of Mechanics (Lomonosov Moscow State University), the Kazan Scientific Center RAS, and the Kazan State Research Technical University – the Kazan Aviation Institute. The measured static pressure drops in a single OTD at Re = 6.7 \times 10^4 and 16.7 \times 10^4, the velocity profiles of accelerating laminar (Re = 1000) and turbulent (Re = 4300) flows in the narrow channel with two rows of 26 OTDs, the estimate of Nusselt numbers on the channel wall with single-row OTDs are in good agreement with the numerical predictions within the RANS approach.

1. Introduction
The researchers paid attention to surface vortex generators as tools for heat transfer enhancement, allowing them to provide that heat transfer increases more quickly than hydraulic losses grow [1,2]. Spherical dimples are the simplest in the technology of applying dimples [3,4]. However, the separated flow around the dimples is accompanied by weak return and secondary currents, and a significant decrease in heat transfer occurs inside the dimples [5-9]. New-type surface vortex generators are suggested – inclined oval trench dimples (OTDs) with a significant lengthening of the cylindrical part (of the order of 3-6 of width size). As shown in [10], when a single OTD of depth 0.39 is arranged on the narrow channel wall (of height 1 and width 7.5) at an inclination angle of 45°, swirling turbulent flows are created. The maximum secondary flow velocity is of the order of 0.8 of the bulk velocity of the flow.

The phenomena of abnormal enhancement of separated flow and heat transfer on the OTD entrance portion, as well as of the core flow acceleration in the channel [11] are discovered for laminar and
turbulent flows of air in narrow channels with packages of inclined single-row OTDs. The periodic areas of stabilized flow in narrow channels and in micro channels of height 1 are considered. The Reynolds numbers are assigned as equal to $10^3$ and $10^4$. As a rule, the OTD inclination angle is selected as equal to $45^\circ$. For the package of sparsely arranged OTDs, where a single dimple has a length of 7.05, a width of 1.05, and a depth of 0.3, and it is located in the center of the periodic computational domain (of length 6) of the channel of width 7 on the heated inner surface, the absolute minimum relative friction value increases four times and relative heat transfer (in relation to the parameters in the plane-parallel channel) increases 5 times. The maximum absolute value of the secondary (cross) flow velocity appears to be of the same order as the maximum flow velocity in the plane-parallel channel. For inclined single-row OTDs of width 1, length 4.5, and of depth over 0.25, the phenomenon of the laminar flow acceleration with a 1.5-fold growth of the maximum velocity in the flow core is found in the periodic computational domain of the narrow micro channel of width 6 and length 4 with a single dimple inclined at $45^\circ$. The influence of the packing of dimples in one row is studied in the periodic computational domain (of lengthening 8) of the narrow (9 to 1) plane-parallel channel. Its heated wall is provided with the inclined OTD of length 7.05, width 1.05, and depth of 0.25 at the rounding radius of edges equal to 0.21. The distance H between the centers of the dimples is varied from 2 to 8. Like the laminar flow acceleration in a narrow channel with inclined OTD, when compaction of a packet of inclined OTD at an angle of $65^\circ$, the turbulent flow acceleration effect is obtained, showing that the maximum velocity in the flow core increases by a factor of 1.39 at the step H equal to 2 between the dimples. The packing of single-row dimples significantly augmented abnormal enhancement of separated turbulent flow and heat transfer on the entrance portion of the OTD inclined at an angle of $65^\circ$ in the periodic computational domain of the narrow channel on its heated wall. At $H=2$, it is characterized by a 4-fold increase in the maximum absolute value of the relative friction projection onto the direction of the middle portion of the OTD and an almost 6.5-fold increase in relative heat transfer (in relation to the parameters in the plane-parallel channel). The maximum absolute value of the secondary (cross) flow is about 10% higher than the value of the maximum flow velocity in the plane-parallel channel. The maximum absolute value of the recirculating flow velocity almost three times exceeds the same velocity of the backflow in the spherical dimple, reaching a value of 0.89 of the bulk velocity in the channel. The inclination of OTDs within the range of 0-60$^\circ$ in the package of sparsely arranged in-line dimples on the stabilized section of the narrow channel has a drastic impact on abnormal enhancement of separated and swirling flows in the dimple. This results in the 3-4-fold decrease in relative negative friction at the angles from 40$^\circ$ to 60$^\circ$, in the increase in the highest velocity of the backflow and the secondary flow from 0.8 to 1.18 with respect to the flow bulk velocity in the channel.

Work [12] consider the numerical simulation of laminar and turbulent heat transfer enhancement in the space between the ribs of the air condenser – the finite-size narrow channel with a package of inclined single-row OTDs at $Re=1000$ and 6000 (the symmetry conditions on the lateral sides). 31 dimples are applied on the channel wall section of length 80. Each dimple has a length of 4.5, a width of 1, an edge rounding radius of 0.2, and an inclination angle of $45^\circ$. The OTD depth is varied from 0 to 0.35. The channels with the sparsely (21) and densely (31) arranged OTDs placed on the heated wall are compared. The influence of the dimple depth on the thermal and thermal–hydraulic performance is assessed. In the laminar regime, the variant with the 31$^{th}$ OTD of depth 0.25 (the growth of hydraulic losses does not exceed 46% at an almost 2-fold increase in heat transfer in comparison to the plane-parallel channel) is preferred. A decision was suggested for packages of air condensers composed of dimpled ribs and intermediate plates with variable gaps between them and the plates. In the turbulent regime, the effect of abnormal enhancement of separated flow and heat transfer, earlier observed in the area of stabilized heat transfer in the inclined OTDs, which increases with the growth of their depth, has been confirmed. The relative negative friction reaches a value of -3.5 and the maximum relative values of the local Nusselt numbers appear to be of the order of 14. The highest total relative heat transfer reaches a value of 2.4 at a 70% growth of relative hydraulic losses. The earlier discovered effect of turbulent flow acceleration in the narrow channel with the inclined OTDs placed on the wall has also been confirmed. In the dimpled channel, the local longitudinal velocity increases more than one and a
half. The secondary flow velocity in the separation zones achieves a characteristic flow velocity at the channel inlet.

Figure 1. Projections of the working section of the wind tunnel with the inclined OTD model (a), the layout of drain holes meant for static pressure measurement and the dimple contours (b), the layout of points for static pressure measurement (c).

Figure 2. Fields of the static pressure coefficient at the inclination angles 0°(a), 45°(b), 90°(c) and the predicted and measured maximum static pressure distributions (d).
The cause of the hydrodynamic and thermophysical effect of abnormal enhancement of separated flow and heat transfer has been established and consists in creating a large pressure drop between the flow stagnation zone on the windward slope of the inclined OTD (of the 0.5-0.6) and the closely spaced rarefaction region ((-0.3 –(-0.6)) at the place where a tornado-like vortex is generated on the OTD entrance spherical portion.

2. Results and Discussion

The main objective of the experiments at the Research Institute of Mechanics (Moscow State University) was to measure static pressure distributions on the characteristic portions of an inclined OTD. A series of experiments was carried out in the wind tunnel A4, in the working section of which the plate with the OTD of length 6, width 1, and depth 0.25 (Figure 1) was positioned (Figure 1). The external flow Reynolds number was equal to 67000 and the boundary layer thickness in the vicinity of the OTD was 0.16. The OTD inclination angle was varied from 0 to 90°. The experimental distributions of $C_p$ as shown in figure 2 clearly illustrate the influence of the inclination angle on the internal flow structure in the OTD; in particular, they indicate the range $25^o < \theta < 85^o$, within which the main rounding of the OTD has a double configuration consisting of the localized zones of the extreme values of the opposite-sign pressure (in the terminology [11], this corresponds to the OTD ‘operating’ regimes).

The dependences of the absolute maximum values and absolute minimum values of the pressure coefficient over the OTD entire surface, when the inclination angle $\varphi$ is varied, show that the maximum rarefaction at $C_p = -0.22$ is seen within the range $40^o < \theta < 45^o$ and the maximum positive value of
$C_p = 0.41$ is observed within the range $55^\circ < \theta < 60^\circ$. The numerical predictions of the turbulent flow of air (at $Re=10000$) around a plate with a single OTD at the inclination angle from 0 to 90$^\circ$ are obtained with the use of the VP2/3 code. The simplified model of the OTD with a radius of 0.2 (of the dimple width) is considered. It is found that the numerical predictions quite qualitatively and quantitatively correlate with the experimental data obtained at the Research Institute of Mechanics (Moscow State University). Figure 3 shows that the maximum pressure values in the external flow stagnation zone on the windward slope on the OTD entrance portion and on the OTD exit portion in the longitudinal middle section of the channel agree well (figure 3). Figure 4 illustrates that the minimum negative pressure values are also clearly seen in the rarefaction region where a tornado-like vortex (transforming into the swirling flow) starts forming. Thus, the numerical and experimental confirmation of the controlling mechanism of abnormal enhancement of separated flow and heat transfer in the inclined OTD is obtained, the inclinations angles are found, at which this mechanism is successful. It is important to emphasize that the external Reynolds number range is significantly expanded, within which this interesting phenomenon is observed. The dimpled channel experiment carried out on the setup of the KazSC RAS is aimed at confirming the acceleration phenomenon in the flow core with a noticeable excess of the maximum velocity in comparison to the maximum velocity in the plane-parallel smooth-wall channel.

![Figure 3](image3.png)

**Figure 3.** Setup for measuring the velocity profiles in the channel with two-row OTDs (a), the dimpled wall fragment at the inclination angle of 45$^\circ$ (b), and the $U/U_{bl}$ profiles on the middle portion of the 22$^{nd}$ dimple in the laminar (c) and turbulent (d) regimes. 1 – $\theta = 135^\circ$; 2 – $45^\circ$.

In the case of the optically transparent channel (of height 10 mm, width 10 mm, length 800 mm) with 26 two-row oval trench dimples placed on the wall at two Reynolds numbers 1000 and 4300, the vector fields of the flow velocity were measured. The experimental data on the flow structure and turbulence

![Figure 4](image4.png)
were generalized and the smooth-wall channel characteristics were compared (Figure 5). The dimple width of 10 mm is chosen as the characteristic size. The length of dimples is equal to 4.5. The depth of dimples is 0.25, and the step between the dimple centers is 2.53 (the dense packing of dimples). Two locations of OTDs are considered: at the angle of 45° to the channel symmetry plane, the dimples are turned to the side walls (in this case, the entrance portions of dimples are near the symmetry plane) and at the angle of 135° to the channel symmetry plane, the dimples are turned from the side walls (in this case, the entrance portions of the dimples are near the walls). The velocity profile of the longitudinal velocity component in the channel symmetry plane strongly depends on the orientation of dimples relative to the flow: when orienting the wedge towards the flow, the velocity near the channel axis is maximum and exceeds approx. 1.5 times the average velocity in the channel cross-section; when orienting the wedge along the flow the axial velocity is from 50 to 75% of the bulk velocity.

Figure 6. Predicted (1, 2, c, d) and measured (red lines) velocity profiles on the middle portion of the 22nd OTD in laminar (a, c) and turbulent (b, d) regimes. 1 – \( \theta = 45^\circ \); 2, c, d – \( \theta = 135^\circ \). zo - transverse coordinate along the channel half-width (calculation with lateral symmetry conditions).

Thus, the profile of the longitudinal velocity component in the channel cross-section in the vicinity of the 22nd dimple has a maximum value in the vicinity of the symmetry plane for the OTD oriented at the angle of 45°. The velocity profile changes radically at the OTD inclination angle of 135°. In this case, the velocity profile with two peripheral maximum longitudinal velocity values located near the side walls appears in the channel. The maximum velocity exceeds approx. 1.3 times the bulk velocity in the channel (Figure 5). To compare the experimental longitudinal velocity data with the numerical
simulation results, the laminar (Re=1000) and turbulent (Re=4000) flows in the narrow channel with 26 single-row dimples, close in geometry to the experimental analogs, have been computed. In the computations, the sharp edges are rounded along the radius equal to 0.2. On the side boundaries of the computer analog, the symmetry conditions are assigned. The predicted profiles for laminar and turbulent flows in the channel agree fairly well with the experimental ones at the considered inclinations angles of dimples (Figure 6). The distance from the wall is chosen such as to capture a maximum velocity in the considered cross-section. Thus, shear flow with a maximum velocity above the dimple entrance develops on the longitudinal strip of the channel above the package of single-row dimples. The maximum shear flow velocity exceeds the maximum velocity in the plane-parallel channel and thus confirms the numerically discovered phenomenon of the flow acceleration in the dimpled channel.

3. Conclusion
The phenomenon of abnormal enhancement of separated flow and heat transfer in inclined OTDs is confirmed experimentally. The computational models are verified. It was established that the interference of the incident flow with the profiled wall and the emerging powerful tornado-like vortex structure hidden in the depression causes a large pressure drop and high velocity gradients in the OTD.

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References
[1] Dzyubenko B V, Kuzma-Kichta Y A, Leontiev A I, Fedik I I and Kholpanov LP 2016 *Intensification of heat and mass transfer on macro-, micro-, and nanoscales* (New York: Begell House)
[2] Leontiev A et al. 2017 *Vortex technologies for energy* (Moscow: MEI)
[3] Ligrani P, Oliveira M and Blaskovich T 2003 *AIAA J.* **41** (3) 337
[4] Rashidi S, Hormozi F, Sunden B and Mahian O 2019 *Applied Energy* **250** 1491
[5] Hwang S D, Kwon H G and Cho H H 2008 *Int. J. Heat and Fluid Flow* **29** (4) 916
[6] Hwang S D, H G Kwon and Cho H H 2010 *Energy* **35** 5357
[7] Kwon H G, Hwang S D and Cho H H 2011 *Int. J. Heat and Mass Transfer* **54** 1071
[8] Xiao N, Zhang Q, Ligrani P and Mongia R. 2009 *Int. J. Heat and Mass Transfer* **52** (7-8)
[9] Tay C M, Chew Y T, Khoo B C and Zhao J B 2014 *Exp. Thermal and Fluid Science* **52** 278
[10] Isaev S A, Schelchkov A V, Leontiev A I, Gortyshov Yu F, Baranov P A and Popov I A 2017 *Int. J. Heat and Mass Transfer* **109** 40
[11] Isaev S, Grütkevich M, Leontiev A and Popov I 2019 *Acta Astronautica* **163** (Part.A) 202
[12] Isaev S A, Leontiev A I, Milman O O, Nikushchenko D V and Sudakov A G 2020 *AIP Conf. Proc.* 2211 020003