Experimental investigation of pressure fields in a single trench dimple

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Abstract. The paper describes the technique and results of an experimental investigation of the pressure distribution over the surface of an oval trench dimple (OTD). The trench dimple in cross-section is a cylindrical segment on one of the flat channel walls. The experiments were carried out at a constant Reynolds number $Re_D = 3.2 \cdot 10^4$ and variation of the inclination angle relative to the longitudinal axis of the channel in the range $\phi = 0 - 90^\circ$.

1. Introduction
When developing modern heat exchangers, one of the most important parameters, along with their compactness, simplicity, and reliability in operation, is thermohydraulic efficiency. This parameter is determined by the ratio of the level of heat transfer enhancement to the increase in hydraulic losses. There are many ways to increase heat removal from a unit of heat transfer surface due to its modification using various obstacles and cavities; however, in this case, hydraulic losses grow much faster than heat transfer [1, 2]. Numerous experimental and numerical studies have shown that surfaces with hemispherical depressions (dimples), whose hydraulic resistance does not increase significantly and the coefficient of thermohydraulic efficiency may exceed unity, are devoid of this drawback [2-4]. The so-called oval trench dimples (OTD), represented by elongated cylindrical trenches with hemispherical curvatures at their edges, ensure even stronger effects of heat transfer enhancement. As it is shown by numerical studies [5, 6], OTDs give an outstripping increase in heat transfer in comparison with hydraulic losses, and the authors called this effect anomalous enhancement of heat transfer.

Not many experimental studies of aerodynamics and heat transfer of OTD have been carried out to date. The only exceptions are [7, 8], where the pressure fields were measured in the OTD located on the channel wall with a cross-section of $0.3 \times 0.5$ m$^2$ and dimples of $10.2 \times 40.6 \times 244$ mm$^3$ in depth, width, and length, respectively. The authors of [7] showed that in addition to the known complex features of formation of the separated flow structure in axisymmetric dimples [9] when flowing around the OTD, another parameter appears, namely, the angle of trench inclination relative to the airflow direction. In [7], the inclination angle varied over the entire range from a trench located normally to the flow to the case of the longitudinal flow around it $\phi = 0 - 90^\circ$.

The topology of the flow in the OTD and hemispherical dimples was experimentally studied in [8]. A wide range of possible scenarios for the development of separated flows, whose existence depends on the dimple geometry, was distinguished. For short cavities, including in a hemispherical dimple, three equilibrium states are observed: one symmetric and two mirror-asymmetric “mono-vortex” ones. At that, asymmetric states are metastable, and symmetric states are unstable. For this reason, the flow around such cavities has the character of spontaneous aperiodic switching between two asymmetric
metastable states. As the length of the cavity increases, the stabilization of the symmetric state of the flow is observed.

The switching flow regime was first discovered in [10] when studying the flow around a cylindrical cavity located on the channel surface. For a hemispherical cavity, this regime was described in [9], and a strong contribution of the quasiperiodic nature of the flow to heat transfer enhancement in the region behind the spherical dimple was shown in [11].

In addition to these factors, the relative height of the channel can have a strong effect on the structure of the separated flow. It is known [1-3] that the strongest heat transfer enhancement when using dimples takes place in narrow channels. This conclusion, important in the applied aspect, served as a foundation for carrying out a cycle of studies of aerodynamics and heat transfer when flowing around an OTD in a narrow channel. At the first stage of studying the flow structure and heat transfer, as a rule, the pressure fields are investigated, both on the dimpled surface and in its vicinity. Such data allow a deeper understanding of the flow features in the presence of complex separated flows, as, for example, in the study of pressure fields in an axisymmetric single dimple [9], and they can also serve as a basis for verification of numerical calculation models.

2. Experimental setup
A diagram of the experimental setup is shown in Fig. 1. A fan (1) supplied air to the rotary channel (2). The rotation speed was controlled by a frequency converter (3) governed by special programs at a PC (4) with an accuracy of 0.01 Hz. Feedback from the fan was carried out using a DM2 manometer (5). A Vitoshinsky nozzle (9) and flow-leveling meshes (8) were located in front of the test section.

The working channel had a rectangular shape with a cross-section of 20 x 150 mm and a length of 410 mm. The studied trench was mounted on a turn-table (6), whose center was 205 mm from the beginning of the channel. Turning the trench by 180° allowed doubling the number of measuring points since the pressure taps were located asymmetrically relative to the trench axes. The developed boundary layer was formed in the channel by this cross-section; the relative displacement thickness of this layer was 2δ*/H = 0.137, where H is the channel height. The airflow rate through the channel was measured with uncertainty not exceeding 0.2%. This value was used to determine the mean mass velocity $U_m$, which was used to calculate the pressure coefficient.

A semi-cylindrical trench with width D = 16 mm and length L = 105 mm (Fig. 1) was located on one of the channel walls. The radius of the cylindrical surface of the trench was R = 19 mm, and the depth was h = 3.3 mm so that the relative depth was h/D = 0.21 in relation to its width and h/H = 0.165 in relation to the channel height. A significant effect of heat transfer enhancement was observed in numerical studies for such geometrical parameters of the trench [6]. The edges of the trench were slightly blunted with a rounding radius of about 1-2 mm.

The dimple has 32 pressure taps with a diameter of 0.5 mm, located normal to the surface. There were 5 dimples directed normal to the trench, and 21 dimples were directed longitudinally. Taking into account the doubling of the measuring points, their number was 9 and 41 for the indicated directions. The pressure was measured using a differential method between the measured and control points $\Delta p = p_i - p_0$. The control point was located on the same wall as the trench, at a distance of 85 mm from the turn-table axis. Subsequently, when processing the data, the pressure drop values were brought to a control point located directly in front of the leading edge of the trench. The pressure drops $\Delta p$ on the dimple were measured using a DM2 manometer (5) with an accuracy of 0.1 Pa. The pressure coefficient was determined by the following formula:

$$C_p = \frac{2\Delta p}{(\rho u_m^2)}$$

where $u_m$ is the mean mass velocity in the channel.

The air density was calculated from the air temperature in the channel, measured with a platinum resistance thermometer with an accuracy of $\Delta T = 0.1^\circ C$. The relative uncertainty in measuring the pressure coefficient in the experiments did not exceed 2.6%.
All the experiments were carried out at a fixed bulk velocity in the channel $u_m = 30 \text{ m/s}$, and the Reynolds number calculated by the trench width $Re_D = 3.2 \cdot 10^4$ or channel hydraulic diameter $Re_{ch} = 7 \cdot 10^5$ corresponded to this velocity.

3. Results and discussion
The measurements were carried out over the entire range of trench inclination angles relative to the flow direction $\phi = 0 - 90^\circ$ with a step of $5^\circ$. The results of measuring the pressure distribution in the direction transverse to the trench along the Y-axis, both inside the trench, and in the areas before and after it, are shown in Fig. 2. It can be seen that the main pressure changes are observed in the area where the trench is located, and in the areas before and after the trench, these changes are not significant. At the same time, in these areas, a decrease in pressure directly in front of the leading and trailing edges of the trench is clearly observed, and this speaks in favor of the formation of separated flows there. Moreover, their intensity is maximum when the trench is oriented normally to the channel axis ($\phi = 0^\circ$) and they almost disappear while approaching the case of a longitudinal flow around the trench ($\phi = 90^\circ$).
Let us consider in more detail the evolution of pressure fields in the transverse direction directly inside the trench. These data are presented in Fig. 3, the data of the current study are shown in Fig. 3a, and the data of [7] are shown in Fig. 3b, respectively. The zero value of pressure coefficient \( C_p = 0 \) in Fig. 3a was taken at the leading edge of the trench. As it can be seen, almost the entire area of the trench in the transverse direction is under increased pressure, which indirectly indicates the absence of return flows in the median plane normal to the major axis of OTD. A similar tendency is observed when flowing around axisymmetric dimples [9], when, with a decrease in their depth, the flow tends to be continuous and the pressure does not decrease. At that, this regime for axisymmetric dimples is achieved at significantly shallower depths than in cylindrical trenches.

The front half of the trench with respect to the incident flow, as it follows from Fig. 3a and 3b, is occupied by the area of zero overpressure. Further, in the second half of the trench, the pressure coefficient increases sharply due to deceleration and subsequent collision of the flow with the rear wall; it reaches a maximum, and then changes its sign to the opposite in the area of the trench edge, which indicates flow separation. The largest value of the pressure coefficient occurs when the trench orientation is normal to the flow. As the inclination angle increases, its value decreases gradually, and with the longitudinal flow around the trench along the entire generatrix of the cylinder, the \( C_p \) value is close to zero \( C_p \rightarrow 0 \).

**Figure 3.** Distribution of the pressure coefficient across the trench: a) current study, b) experiments of [7].
Despite the strong differences in sizes of the channel and the trench in [7] and in this work, the results of these studies are similar. The only exception is represented by the results of measurements at y/D = - 0.2 and 0.2, where an abrupt change in pressure is observed (Fig. 3b). It does not seem possible to explain the reasons for such an unusual behavior of pressure at these points; this requires a detailed study of the flow hydrodynamics.

The noted qualitative similarity of the results obtained in the slotted and high channels is clearly confirmed by the results of measurements of pressure fields along the trench span. These data are presented in Fig. 4. Negative values on the X/D axis in these figures correspond, according to Fig. 1, to the left half of the trench, and the positive values correspond to the right half. As it can be seen, the pressure distribution has a saddle-like character with maxima at the trench edges. Between these maxima, there is an area of pressure decrease along the trench. Moreover, the pressure gradient increases there as the trench inclination angle increases. Apparently, this is a consequence of flow acceleration along the trench when it is oriented at an angle to the flow. If the trench is located along the normal to the longitudinal axis of the channel, the pressure coefficient is everywhere close to zero \( C_p \rightarrow 0 \), except for the small areas at the hemispherical ends.

![Figure 4](image1.png)

**Figure 4.** Pressure fields along the longitudinal axis of the trench with the variation of its inclination angle.

In the right half of the trench (X/D > 0), in front of the zone of flow deceleration, a periodic pressure change, similar to the distribution in the presence of Taylor-Gertler vortices, is observed. The presence of unstable vortex formations in this zone is also noted in [8], however, in experiments of [7], as it can be seen in Fig. 4b, no such effects were found. It is obvious that this flow region plays an important role in the flow and heat transfer scenario, which makes it necessary to study the problem in more detail.

The influence of the trench inclination angle on the maximum values of the pressure coefficients in the transverse and longitudinal directions is shown in Fig. 5. In these figures, the data of this study are compared with the results of measurements presented in [7]. As it is seen in Fig. 5a, the results of our experiments give a monotonic decrease in the pressure maximum in the transverse direction with an increase in the trench inclination angle so that when it is directed along the flow (\( \phi \rightarrow 90^\circ \)), this value vanishes (\( C_{p_{\text{max}_y}} \rightarrow 0 \)). The data of [7] give close results, but only up to the values of inclination angle, less than 45°. For the larger angles, the maximum pressure in [7] increases significantly, which is not of a physical nature and requires additional confirmation.
Figure 5. The effect of the trench inclination angle on the maximum values of pressure coefficients in the transverse (Cpmax_y) - a) and longitudinal directions (Cpmax_x) - b).

The maximum pressure coefficient in the longitudinal direction of the trench (Fig. 5b) in comparison with the transverse direction, on the contrary, increases with increasing angle $\phi$. As in Fig. 5a, the experimental data are close to those of [7] in the range of variation of angle $\phi = 0 - 45^\circ$, and at large values of $\phi$ such a correspondence is not observed.

One of the parameters characterizing the pressure field inside the trench is its average value and, in particular, its value in the transverse direction. Its value was determined by integrating the pressure profile on the wall along the y axis:

$$\overline{C_p} = \frac{1}{L'} \int_0^{L'} C_p dy'$$

Here $\overline{C_p}$ is the average pressure coefficient, $L'$ is the length of the forming dimple, and $y'$ is the curvilinear coordinate.

Figure 6. The average pressure coefficient in the transverse direction depending on the variation of the trench inclination angle.

The dependence of $\overline{C_p}$ in the cross-section (along the Y-axis) on the inclination angle $\phi$ is shown in Fig. 6. In this figure, the results of [7] are compared with the present work. As in Fig. 5, we can see the similarity between these data in the range of angles from 0 to 45 degrees. The results then diverge
significantly. It can be seen that the average pressure coefficient \( \overline{C_P} \) decreases with an increase in the angle of dimple rotation in about the same way as its maximum in Fig. 5. This can be explained by the fact that as the trench approaches the channel axis, the resistance across the dimple decreases since most of the air moves along the OTD.

4. Conclusion

The results of an experimental study of the pressure fields in the OTD and its vicinity in the slotted channel with a change in the angle of its inclination to the flow direction are presented. The complicated character of a change in the pressure coefficients in the longitudinal and transverse cross-sections of the trench is shown. The pressure coefficient in the cross-section behind the leading edge up to the trench axis is close to zero, and then it increases towards the trailing edge due to flow deceleration. In the longitudinal direction along the major axis of OTD, the pressure distribution is saddle-shaped with two maxima in the region of the hemispherical curvature of the trench. In the region of the OTD outlet, periodic pressure changes are observed, which are characteristic of the flows with Taylor-Gertler vortices.

The pressure coefficient maximum decreases monotonically with an increase in the angle of OTD inclination. Its average behaves similarly. In the longitudinal direction, on the contrary, the value of \( C_P \) decreases and tends to zero at \( \phi \to 90^\circ \). Comparison with the experimental data [7] obtained in the high channel showed good agreement with the results of the present work only within the variation range of inclination angle \( \phi = 0-45^\circ \). The reasons for data discrepancy at large angles require a more detailed study.

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