Experimental study of the three-dimensional flow structure in matrix channels

M V Philippov, I A Chokhar, A V Zolotukhin, A V Barsukov, V V Terekhov, V I Terekhov, and I N Baranov
Kutateladze Institute of Thermophysics SB RAS, 1, Ac. Lavrentyev av., Novosibirsk, Russia, 630090
E-mail: mfilippov181096@gmail.com

Abstract. The article presents an experimental study of the turbulent flow in matrix channels. Using the modern optical contactless laser Doppler anemometer (LDA) method, an idea of the turbulent three-dimensional flow inside the cells of matrix channels is developed. The results of the study of the matrix channel show that the so-called vortex matrix effect is not formed. The most important factor that causes a high degree of heat transfer from the walls is the intense spiral motion between the matrix cells. The measurements also show that the effects associated with the lateral boundaries of the channel play a significant role. Based on the assumption of the decisive role of the spiral flow between the cells of the matrix channel, a formula for the integral pressure loss is proposed.

1. Introduction
To protect the blades in gas turbines, many internal cooling structures, such as fins, tabs, wells, etc. are used. However, for high-enthalpy structures, methods with high hydraulic losses may be used to increase heat removal. One of such methods is matrix channels, the distinctive feature of which is the finning of opposite walls contacting each other. Today one of the most important and urgent tasks in the study of matrix channels is the optimization of thermal and hydraulic efficiency. To increase the efficiency of heat exchange with the lowest losses, it is necessary to have a detailed idea of the flow structure in the channel cell. Therefore, the purpose of this work is an experimental study of the turbulent flow structure in matrix channels.

To date, significant amount of data has been accumulated from the numerical and experimental study of aerodynamics and heat transfer inside the matrix channel [1-3]. It is shown that the matrix channel is an effective method for improving heat removal, for example, in the work of Carcasci et al. [4] the level of improvement in Nu/Nu0 heat transfer decreases with increasing Reynolds, but always remaining above 2. However, it should be emphasized that experimental works often study only integral parameters [5,6] and heat transfer distributions on the walls [7-9], however data on the flow structure are practically absent.

2. Experimental setup
The experimental setup (Fig. 1a) consisted of a two-component laser-Doppler anemometer with adaptive time selection of channels, a speed measurement range V = 0-120 m / s and a three-component coordinate positioning device. An aerosol, formed during the recondensation of glycerol vapors using an aerosol generator created by the authors, was used as a source of light-scattering...
particles. The fan pumped the air flow through the diffuser, the corner (turning elbow) and the confuser (Vitoshinsky profile) into the channel (Figure 1c). The test area (fig. 1b) was a matrix channel formed by edges intersected at an angle of $2\alpha$ equal to $90^\circ$. The distance between the stiffeners was 15 mm, and the section dimensions were $400\times150\times20$ mm$^3$. The average speed at the entrance to the channel was $8$ m / s. The numbers 1-3 indicate the cells in which the experiment was conducted (Figure 1bc).

The accuracy of measuring the velocity $V_x$ and $V_z$ was about 2 percent, and the accuracy of the velocity $V_y$ was about 11 percent, which helped us to qualitatively understand the physics of the flow in the volume under consideration (Figure 2ab). The measurement time was approximately 30 seconds per measurement of the full velocity vector at each point. The number of particles at each point was over 4000. To measure the three velocity components, the velocity was measured at 2 angles at each point. The laser-Doppler anemometer was rotated around the $Y$-axis by 45 degrees (figure 1 (a)). Then, to measure the third velocity component, plane $XY$ (figure 2 (a)) was turned by $\alpha_1 = 10^\circ$ and $\alpha_2 = -190^\circ$ by rotating LDA by $\pm10^\circ$ and channel by $0^\circ$ and $180^\circ$ relative to the $Z$ - axis. Let us denote two velocity components measured by LDA after the turn by $\alpha_1 = 10^\circ$ and $\alpha_2 = -190^\circ$ as $U_{1,2}$ and $V_{1,2}$, respectively. Finally, we obtain three velocity components:

$$
\begin{align*}
V_x &= \frac{1}{2\sqrt{2}\cos 10}(U_1 + V_1 - U_2 + V_2) \\
V_y &= \frac{1}{2\sqrt{2}\sin 10}(U_1 + V_1 + U_2 + V_2) \\
V_z &= \frac{\sqrt{2}}{2} U_1 - \frac{\sqrt{2}}{2} V_1 = \frac{\sqrt{2}}{2} U_2 - \frac{\sqrt{2}}{2} V_2
\end{align*}
$$
Figure 1. (a) measurement system, (b) test section (the investigated cells are indicated by numbers), (c) experimental setup (1 – blower, 2 – inlet diffuser, 3 – working channel, 4 – aerosol generator, 5 – compressor, 6 – LDA).

Figure 2. (a) measured cells in the matrix channel, (b) studied region in each cell.
3. Experimental results

3.1. Boundary cell 1

Figure 3. The flow velocity in the center of the first cell at $X = 0$, $Z = 0$ (a) $V_x$ (b) $V_y$ (c) $V_z$ (d) $V = \sqrt{V_x^2 + V_y^2 + V_z^2}$.

Let us consider cell 1 (figure 2a, 3). As it was shown in [1], a reversal of the flow occurs in the extreme cell, since the wall hinders the further movement of the liquid. In accordance with Figure 3b, a flow reversal does occur in the extreme cell, since the velocity $V_y$ is negative almost along the entire length. The velocity $V_x$ has an antisymmetric form, since the flow inside the cell has 2 directions corresponding to the direction of the edges. The velocity $V_z$ always has a positive direction, which makes sense, since the air flow as a whole is directed upwards. The velocity $V_y$ has a section of positive velocity, since part of the air flows into the cell located at the top left of cell 1. One cannot fail to notice that the total velocity $V$ is only 50 percent of the average flow velocity blown into the matrix channel. This is due to the fact that the main flow occurs in the central cells.

3.2. Cell 2

Let us consider cell 2 (figure 2a, 4). In [2], for channels with crossed and parallel edges, vorticity was shown inside each channel cell. It was assumed that the cells were a kind of vortex generators, and also that the size of the averaged vortex was comparable to the cell size. In [3], it was clearly demonstrated using numerical modeling that the overflow occurred not only in the end cell. Let us analyze the results obtained by the authors of this work (figure 4). As can be seen from figure 4b, the velocity $V_y$ has positive values that are significantly higher in magnitude than the values in the end cell. This means that the main flows occur between the central cells. The maximum velocity modulus
\( V_x \) and \( V_z \) is almost 3 times higher than the similar velocity components in the end cell (figure 3ac, 4ac). This is the reason to believe that only a small part of the flow reaches the extreme cell. The graph of the full velocity corresponds well to the velocity profile in a flat channel. This is quite interesting, since the edges are a significant obstacle. From all the above, we may assume that inside the 2 cells, the main flow flows upwards along a complex trajectory, circumventing the edges.

![Graphs](image)

**Figure 4.** Flow velocity in the center of the second cell at \( X = 0, Z = 0 \) (a) \( V_x \) (b) \( V_y \) (c) \( V_z \) (d) \( V = \sqrt{V_x^2 + V_y^2 + V_z^2} \).

3.3. Cell 3

Let us consider cell 3 (figure 2a, 5). Apparently, the flow has a similar structure to cell 2. So, in more detail, the velocity \( V_y, V, V_{xz} \) was considered for the case when \( X \) varied from -4 to 4 and \( Y \) from 0 to 20. It may be seen that the velocity \( V_y \) has positive values on almost the entire XZ plane. At the same time, due to the variable sign of the velocity profile \( V_x \), the air flow passes through an arc. And since \( V_z \) is always positive, the flow goes spirally up, circumventing the edges. Thus, based on the assumption of the decisive role of the spiral flow between the cells of the matrix channel, we can assume the formula for the integral pressure loss as follows:

\[
\Delta p = K \frac{V^4}{d} \rho \sin(\alpha)^{4.76}
\]

where \( K \) is the constant, \( l \) is the length of the channel, \( d \) is the hydraulic diameter, \( \rho \) is the density, \( 2\alpha \) is the tilt of the edges, and \( V \) is the velocity. In this formula, the coefficient of resistance does not depend on \( Re \) and is proportional only to the angle of inclination of the edges. This formula converges well with the experimental results for different angles of inclination of the edges with a different number of \( Re \) (figure 6).
It is also possible to note the significant influence of the third component of the velocity $V_y$ on the magnitude of the vector of the total $V$. In [4-9], model representations were formed mainly under the assumption that this component was close to zero. At that, the results of this work show that it is ~25 percent of the full velocity (Fig. 3b, 4b, 5b) and it is important to take this velocity component into account in order to build a correct picture of the flow.

$$V = \sqrt{V_x^2 + V_y^2 + V_z^2}$$

**Figure 5.** The flow velocity in the center of the second cell at $X = 0, Z = 0$, $Y$ from $-10$ to 10 (a) $V_x$ (c) $V_z$; $X$ from $-4$ to 4, $Z = 0$, $Y$ from $-10$ to 10 (b) $V_y$ (d) $V = \sqrt{V_x^2 + V_y^2 + V_z^2}$ (e) $V_{xz} = \sqrt{V_x^2 + V_z^2}$. 
Figure 6. The pressure drop in the matrix channel as a function of Re at different angles of inclination of the ribs. The dots indicate the experiment, and the lines indicate the data calculated according to formula (1).

Conclusions
The paper presents the results of an experimental study of the turbulent flow in channels formed by a system of crossing edges. The LDA method was used to measure all 3 components of the velocity vector in several cells that differ in position relative to the channel boundary. The importance of vertical component of the velocity $V_y$ for describing the flow structure inside the cells has been shown. The behavior of the flow inside the cell has been analyzed. It is shown that there is an intense spiral motion, which could cause a high degree of heat transfer from the walls. Based on the assumption of the decisive role of the spiral flow between the cells of the matrix channel, a formula for the integral pressure loss has been proposed.

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