Experimental study of a turbulent structure in coplanar channels

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Abstract. The experimental results of a three-dimensional turbulent flow structure inside the cells of flat coplanar channels with mutually intersecting edges on opposite walls are presented. In the experiments, a two-component laser Doppler speed meter is used, which allows measuring the averaged and pulsating velocity components. It is shown that a flow structure varies depending on a place of measurements inside a coplanar channels cell.

1. Introduction
Coplanar channels are an original design with cross-mounted ribs on opposite channel walls providing cross coolant flow [1]. First coplanar channels were obtained by fastening two corrugated walls so that they were in contact with each other, but their grooves were located at different angles and a coolant flowed between them [2, 3].

The work of most authors on this topic suggests that the use of coplanar channels instead of smooth ones contributes to a significant intensification of heat transfer (3–6 times), but the hydraulic resistance also increases significantly. Such a significant increase in heat transfer draws attention to such devices; therefore, coplanar channels are actively used in cooled blades of gas turbine engines [4,5], combustion chambers of liquid rocket engines, recuperative heat exchangers, laser mirrors [6] and many other devices with intense heat transfer [7–10].

However, most of the works are devoted to a determination of integral heat transfer and resistance of coplanar channels. Therefore, data on flow structure and turbulent characteristics, as well as on local heat transfer in such channels, are practically absent in the literature, which is a constraining factor in the creation of reliable engineering calculation methods, complicating the development of adequate physical and mathematical models. Therefore, the main goal of this research work is to study a turbulent flow structure in coplanar channel cells and to elucidate the main features of the formation of a vortex structure of flows inside a matrix.

2. Experimental setup
The experiments were carried out on a small aerodynamic setup equipped with a two-component laser Doppler anemometer (LDA) with adaptive temporal selection and velocity vector visualization for precision non-contact flow velocity vector measurement. The system consists of the following functional logic units: a signal preprocessor, an optoelectronic LDA unit, a user interface (software shell), and a Doppler signal processor. Using the communication module, preprocessor packs data into
packets and transmits them to a computer via Ethernet cable. The LDA unit is mounted on a three-component coordinate-positioning device, which is controlled by a computer.

The experimental setup consists of a high-pressure fan with an airflow rate of up to 0.9 kg/s (differential 9000 Pa), controlled by a frequency regulator, and a mini wind tunnel. The inlet area in the working channel front is made of steel and coated with black polymer paint. The inlet section consists of an adapter, a diffuser, a rotary elbow, a pressure selection section and a confuser, the geometry of which corresponds to Vitoshinsky profile.

The fan has a feedback system through an electronic differential pressure gauge, ensuring specified steam flow characteristics.

Work areas are 406 mm long, 150 mm wide and 20 mm high. The material of walls of the main channel and sections is textolite. Ribs that form the coplanar channels are made of steel with a thickness of 1 mm, width of 10 mm and various lengths. All fins are coated with black plastic, thereby preventing glare from studying aerodynamics using optical methods.

Figure 1. Photos of work sites. The angle between crossed edges of $2\beta$ is 60°, 90° and 120° (from left to right).

Photos of work sectors are shown in Fig. 1. The distance between adjacent ribs, both on the upper and lower walls, in all models remains unchanged and equal to 15 mm. In total, three working models are used in the experiments with different values of the angle between intersecting edges on opposite walls of the channel $2\beta = 60^\circ, 90^\circ, \text{and} 120^\circ$.

In aerodynamic studies, the walls of the experimental channel were made of optically transparent material. The coordinate system allowed positioning the LDA with an accuracy not exceeding 0.1 mm. The flow was seeded with a glycerol aerosol with a particle size of the order of 0.3 μm, which under the experimental conditions monitored the flow well. The hydraulic losses in the coplanar channel section were determined by the difference in static pressure before and after it. The pressure was taken through special holes with a diameter of 0.8 mm, located at a distance of 200 mm to the site and 200 mm after it. This eliminated the influence of possible turbulent flow disturbances on a static pressure. The Reynolds number in experiments was calculated by the formula

$$\text{Re} = \frac{U_m D_h}{v},$$

where $U_m$ is the average velocity in the channel, and $D_h = 2LH / (L + H) = 35.3 \text{ mm}$ is the channel hydraulic diameter, and $L$ and $H$ are the channel width and height, respectively.
3. Results and discussion
A series of experiments is carried out in coplanar channels with an angle of ribs intersection equal to \(2\beta = 90^\circ\) and with a Reynolds number \(Re = 1.7 \times 10^4\). The measuring points layout and directions of coordinate axes are shown in Fig. 2. The Z axis is directed along the longitudinal axis of the channel, the X axis is transverse, and Y is along a channel height (H), respectively. Two velocity components and their fluctuations are measured in the direction of Z and X axes at 12 points in the X-direction with an interval of 1 mm. This allows reconstructing a flow pattern in the Z-X plane and determining the velocity vector magnitude and its direction. The obtained data could be transformed in any coordinate system, including that related to the ribs direction along which a flow is formed in the channel.

![Figure 2. Measuring cell scheme.](image)

The distribution of longitudinal and transverse velocity components along the channel height and in the cell center is shown in isometry in Fig. 3. As can be seen, the longitudinal velocity component \(V_Z\) has a form similar to the velocity profile in a flat channel. However, in the center of the channel, where ribs join each other on the lower and upper walls, the flow instability is observed and the velocity profile \(V_Z\) is not smooth.

The flow in the measuring cell is three-dimensional. The transverse velocity component \(V_X\) in the lower and upper channel parts reverses sign because ribs mounted on them are oriented orthogonally. In this case, the value of transverse velocity \(V_Z\) is of the same order of magnitude with a longitudinal component \(V_X\), which indicates a powerful rotational gas motion in a vortex cell.
Figure 3. The distribution of velocity components along the channel height (a) at a center cell point, (b) – 2 mm to the right of a center point, (c) – 2 mm to the left of a center point, (d) – a leftmost measuring point in the cell (9 mm to the left of the center point).

The distribution of velocity components changes in the X coordinate direction. This conclusion can be drawn by analyzing the measurement results presented in Fig. 3, where longitudinal ($V_Z$) and transverse velocity ($V_X$) profiles are shown in the central coplanar channel cell (Fig. 2). Both profiles are symmetrical about the channel height middle ($Y = 10$ mm) only in the central cell (Fig. 3a), while at other measuring points profiles are severely deformed (Fig. 3b, c, d). At an extreme measuring point of the coplanar channels cell ($X = 9$ mm), the longitudinal velocity profile $V_Z$ is severely deformed: it has three peaks and is absolutely asymmetric relative to the channel height middle (Fig. 3d).

In addition, measurements have shown that a flow structure in each cell is affected by the flow history, caused, inter alia, by a flow “re-reflection” from the side channel walls. This effect can be quite strong, which greatly complicates the measurement program and requires a detailed study of flow characteristics after each reflection from side channel surfaces.

**Conclusion**

Experiments have been carried out to study a turbulent flow in individual coplanar channels cells. Averaged flow parameters and their fluctuations have been determined using the two-component LDA system. The results of investigations are presented for a value of an angle between ribs equal to $2\beta = 90^\circ$. Measurements have shown that the symmetry of profiles of longitudinal and transverse velocity components relative to a channel height middle is observed only near the cell center. As the distance from it increases, the asymmetry of the profiles increases. The components of longitudinal and transverse velocities are found to be comparable with each other, and a flow inside coplanar channels cells is three-dimensional, vortex, and extremely complex.
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