Experimental study of a flow structure in coplanar channels

V I Terekhov 1,2, A V Zolotukhin 1,2 and I A Chohar 1
1 Institute of Thermophysics SS Kutateladze SB RAS, Russia, 630090, Novosibirsk, Academician Lavrentyev Avenue, 1
2 Novosibirsk State Technical University, Russia, 630073, Novosibirsk, Karl Marks Avenue, 20
terekhov@itp.nsc.ru, zoloav.hm@gmail.com, dstarter@ngs.ru

Abstract. The results of an experimental three-dimensional flow structure study in flat coplanar channels with mutually intersecting ribs on opposite walls are presented. The measurements were carried out for different angle values between ribs (2\(\beta\) = 60°, 90° and 120°) and Reynolds number variations. In the experiments, a two-component laser Doppler speed meter was used, which makes it possible to measure both averaged and pulsating velocity components. It is shown that a flow structure in vortex cells between ribs varies greatly from a cell location and an angle between ribs. The magnitude of hydraulic losses in coplanar channels significantly exceeds losses in smooth channels, and they increase with increasing angle between ribs.

1. Introduction
Coplanar channels are an original design with cross-mounted ribs mounted on opposite channel walls and providing cross coolant flow [1]. One of special cases of such channels is a fastening of two corrugated surfaces so that they are in contact with each other, but their grooves are located at different angles [2, 3]. A coolant flowed between these mating surfaces.
The work of most authors on this topic suggests that the use of coplanar paths instead of smooth channels contributes to a significant intensification of heat transfer (by 3–6 times), but a hydraulic resistance also significantly increases. 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, combustion chambers of liquid rocket engines, regenerative heat exchangers, laser mirrors, and many other devices with intense heat transfer [4, 5].
A large number of experimental and computational works are devoted to the study of aerodynamics and heat transfer in channels with intersecting fins. In this case, both stationary matrices [4–7] and rotating matrices [8, 9], which simulate heat transfer and flow inside the working blades of gas turbines, were studied.
However, the vast majority of works are devoted to the determination of integral heat transfer and resistance of coplanar channels. Therefore, data on the complex 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 development of adequate physical and mathematical models and makes it difficult to create reliable engineering calculation methods. Therefore, the purpose of this experimental work is to study the three-dimensional structure of turbulent flow in cells of coplanar channels and to elucidate the main features of a vortex structure formation of flows inside the matrix.
2. Experimental setup

The experiments were carried out on an aerodynamic bench equipped with a two-component laser Doppler anemometer (LDA) with adaptive temporal selection and visualization of the velocity vector for precision non-contact measurement of the flow velocity vector. The system consists of the following functional logic blocks: the LDA optoelectronic block, the signal preprocessor, the Doppler signal processor, the user interface (software shell). 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 bench consists of a high-pressure fan with an air flow rate of up to 0.9 kg/s (differential 9000 Pa), controlled by a frequency regulator, and a mini wind tunnel. The fan has a feedback system through an electronic differential pressure gauge, ensuring a maintenance of specified flow characteristics.

Work areas are 406 mm long, 150 mm wide and 20 mm high. The material from which main channel walls and sections are made is textolite. Ribs that form coplanar channels are made of steel 1 mm thick and 10 mm wide and of various lengths. All fins are coated with black plastic, thereby preventing glare when studying aerodynamics using optical methods, as well as to avoid short circuits between fins when studying heat transfer in coplanar channels by ohmic heating.

![Figure 1. Photos of working channels.](image_url)

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

An inlet area in working channel front was made of steel and coated with black polymer paint. An inlet section consists of an adapter, a diffuser, a rotary elbow, a pressure selection section and a confuser, the geometry of which corresponded to the Vitoshinsky profile.

In aerodynamic studies, channel walls were made of optically transparent material. The coordinate system made it possible to position the LDA with an accuracy not exceeding 0.1 mm, and it was not possible to make measurements directly in a wall vicinity at a distance of approximately 1 mm due to optical effects. The flow was seeded with a glycerol aerosol with a particle size of the order of 0.3 mm, which under the experimental conditions monitored the flow well.
A determination of hydraulic losses in a coplanar channel section was carried out by a difference in static pressure before and after it. Pressure was taken through 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 value.

The Reynolds number in experiments was calculated by the formula
\[ Re = \frac{U_m D_h}{v} , \]
where \( U_m \) is an average velocity in a channel, and \( D_h = \frac{2LH}{L + H} = 35.3 \text{ mm} \) is a channel hydraulic diameter, and \( L \) and \( H \) are channel width and height, respectively.

3. Results and discussion

3.1 The distribution of velocity components

The main series of experiments was carried out with channels with the angle of ribs intersection equal to \( 2\beta = 90^\circ \) and with the Reynolds number \( Re = 1.7 \times 10^4 \). The measuring arrangement points and coordinate axes directions are shown in Fig. 2a. The Z axis is directed along the longitudinal axis of the channel, the X axis is transverse, and Y is along the height of channel H, respectively. Two velocity components and their fluctuations were measured in the direction of Z and X axes at 12 points in the X-direction with an interval of 1 mm. This made it possible to reconstruct the flow pattern in the Z-X plane, to determine the velocity vector magnitude and its direction. The obtained data could be transformed in any coordinate system, including that related to ribs direction along which a flow is formed in a channel.

The distribution of longitudinal and transverse velocity components along channel height and in a cell center is shown in isometry in Fig. 2b. As can be seen, the longitudinal component of a velocity \( V_Z \) has a form similar to the velocity profile in a flat channel. However, in a channel center, where ribs are joined on the lower and upper walls, flow instability is observed and the velocity profile is not smooth. A flow in the measuring cell is three-dimensional. The transverse component of the velocity \( V_X \) in the lower and upper channel parts reverses sign because ribs mounted on them are oriented orthogonally. In this case, a transverse velocity is approximately equal to half the longitudinal, which indicates a powerful rotational gas motion in a vortex cell.
The velocity components distribution changes in the X-coordinate direction. This conclusion can be drawn by analyzing the measurement results presented in Fig. 3., where longitudinal (Vz) and transverse velocity (Vx) profiles are shown along a center coplanar channels cell line (Fig. 2a). Both profiles are symmetrical about the middle of a channel height (Y = 10 mm) only in a central cell, while the other profiles are strongly deformed.

When processing the experimental results, the authors encountered the fact that the profiles symmetry of both Vz and Vx velocity components is observed only on a cell axis. As you move away from a axis, symmetry breaks and a closer the cell to the wall, the more asymmetric velocity profiles in upper and lower channel parts become. Measurements showed that a flow history in each cell is affected by a flow history, caused, among other things, by a flow “re-reflection” from side channel walls. This effect can be quite strong, which greatly complicates a measurement program and requires a detailed flow characteristics study after each of it from side channel surfaces.

3.2 Measurement of hydraulic losses

The coefficient of hydraulic resistance was calculated by the formula

$$\xi = \frac{2\Delta P}{\rho U^2},$$

where $\Delta P$ is a static pressure drop between ampling points before and after a working channel, and $U_m$ is an average flow rate in a channel.

All experimental data on hydraulic losses were presented in a relative form $\xi / \xi_0$, where $\xi_0$ is the coefficient of hydraulic resistance in a flat channel without a section with coplanar channels.

![Figure 4. The relative coefficient of hydraulic resistance dependence from Re](image-url)
The relative coefficient dependence of hydraulic resistance on a Reynolds number is shown in Fig. 4. It is seen that an increase in a angle between the ribs leads to an increase in hydraulic resistance. Moreover, an increase in hydraulic losses in the coplanar channels is very large and at an angle of $2\beta = 120^\circ$, the maximum increase in resistance reaches 20 times. A figure also shows that an increase in the Reynolds number leads to an increase in a relative coefficient of hydraulic resistance, which is probably due to more turbulent flow at high Reynolds numbers.

4. Conclusion
A set of experimental studies was carried out to study the three-dimensional flow in coplanar channels. Averaged flow parameters and their flow fluctuations were determined using the LDA system. Measurements showed that the profiles symmetry of longitudinal and transverse velocity components is symmetric with respect to a channel height midpoint only near a cell center. As you move away from it, a asymmetry of profiles increases. It has been established that a flow inside coplanar channels cells is three-dimensional and vortex. The coefficient of hydraulic resistance in coplanar channels is significantly (up to 20 times) higher than in a smooth channel, and it increases both with an increase in an angle between ribs and in a Reynolds number.

5. References

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