Investigation of the influence of Taylor-Görtler vortexes on heat transfer of annular channel

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Abstract. This article is about the influence of Taylor-Görtler vortices on heat transfer in concentric annular channels with turbulent decaying swirling flows. The study shows that the occurrence and transformation of secondary vortex structures has a significant effect on the distribution of heat flux over the annular channel surface. An explicit is relationship between the radial velocity fluctuations and the heat flux density distribution. The highest intensity of heat transfer on the outer surface is observed in the areas of positive radial velocity values, while on the inner surface it is observed in the areas of negative radial velocity values.

1. Introduction
Secondary flows often arise in annular channels under different conditions. The presence of additional vortex structures allows for more efficient dissipation of thermal energy. Secondary flows are divided into several types. The circulating motion in the shape of paired vortices is indicated by a secondary flow of the first kind. [1,2]. This type of flow is formed when the centrifugal force F at any point satisfies the condition rotF ≠ 0. Vortex structures with alternation of right and left rotation along the swirling flow at rotF = 0 are indicated by a secondary flows of the second kind [1,2].

M. Couette was one of the first to experimentally study unstable flows limited by two dimensions in 1890 [3]. He studied the flow in an annular channel formed by two concentric cylinders, while the inner cylinder was fixed, and the outer one was rotating. As a result, when the velocity was less than a certain value it was found that the friction loss exerted by the fluid on the inner cylinder was proportional to the velocity of the outer cylinder. When this velocity was exceeded, the friction loss increased. The author explains this change by the transition of the flow from laminar to turbulent motion.

A. Mallock obtained in his study results similar to those of Couette in 1896 [4]. In addition, he conducted a series of experiments covering cases where the inner cylinder was rotating and the outer one was at rest. In this configuration, flow instability was found for all rotation velocity values of the inner cylinder. Also, a large difference was noted in terms of stability between the cases where the inner and outer cylinders were fixed. It shows that in the case when the inner cylinder rotates while the outer cylinder is stationary, the secondary flows have a complex three-dimensional character.

One of the most important studies related to secondary vortices was carried out by D. Taylor in 1923 [5]. In this research he studied the stability of a viscous fluid located between two rotating cylinders. He showed that fluid flow becomes unstable when the angular velocity of the inner cylinder exceeds a certain value. This instability is represented by axisymmetric toroidal vortices, which have...
alternating left and right rotation.

G. Görtler investigated a similar problem on the rotation of two coaxial cylinders in 1955 [6]. He was the first who showed that the action of centrifugal forces in the boundary layer on concave surfaces leads to flow instability. D. Taylor observed similar secondary vortices in his work. In all previous works, cases were investigated when secondary flows are formed during the motion of an annular channel surfaces.

However, secondary flows can form in a swirling flow when the surfaces of the annular channel are stationary [1,7]. In the author's previous work [8], it was shown that secondary flows of the Taylor-Görtler type can be formed when the flow swirls with fixed surfaces of the annular channel. However, the effect of Taylor-Görtler vortices on the intensification of heat transfer in an annular channel during flow swirling has not been studied enough.

2. Methods

The considered in this work geometry is shown in figure 1. The annular channel (2) is defined by two coaxial cylinders. The inner surface (1) with a diameter of \( d_1 = 152 \) mm, and the outer (3) with a diameter of \( d_2 = 184 \) mm. Channel length \( l \) is 840 mm. Air is supplied through a tangential channel (3) with dimensions of \( 35 \times 70 \) mm to the swirl generator (4) with a diameter of \( D = 259 \) mm and a length of \( L = 126.5 \) mm. The flow movement is measured by the angle \( \varphi \). This angle is measured from the mating point of the tangential channel from the inner surface.

![Figure 1. The geometry of the investigated annular channel.](image)

Aerodynamics was investigated using a Laser Doppler Anemometer (LDA). For this, an optically transparent experimental model of the annular channel in full-size was made. The velocity measuring section is equipped with a corrective lens. The lens eliminates unwanted aberrations of the laser beams. This improves the measurement accuracy [9]. The error in measuring the LDA velocity is less than 0.1 %. by the method.

In the experimental bench for measuring aerodynamics, air inoculated with propylene glycol tracer particles with a size of 1 to 1.5 μm was used. The volumetric flow is controlled via a fans with frequency converter. Air flow is measured using the differential pressure method. A flow preparation device is installed on the sensing line, which allows to reduce turbulence in front of the diaphragm. To determine the physical quantities in the experimental bench, the following are used: a thermal resistance sensor, gauge pressure sensors, and a differential pressure sensor. All signals from the sensors are fed into the data collection system, which allows you to process and analyze the signals received from the sensors in real time. The flow measurement error is 2.7%.

Heat transfer was investigated using gradient heat flux sensors. A calorimeter was made to install the sensors. It is a hollow tube to which superheated steam is supplied. The heat flux profiles in the cross section were measured by rotating the calorimeter every 10° around its axis. The length measurement was carried out by moving the calorimeter in the horizontal plane. On the surface of the calorimeter there are four heat flow sensors with a step of 90°. The error of the heat flux gradient sensor is no more than 1%.

ANSYS Fluent was selected as the CFD simulation software. This program is based on the finite volume method. The system of Navier-Stokes’s equations is considered to solve the problem. It consists of the equations of continuity, motion and energy. The SST \( k - \omega \) model with a curvature
correction was chosen as a turbulence model [10].

For numerical simulation, the following boundary conditions are set. A velocity profile is set at the entrance to the swirl generator. The velocity profile was obtained as a result of additional numerical modeling of the entrance section. For this, a straight entrance section with a length of 2 meters and an overall dimension of $35 \times 70$ mm was built. At the entrance to it, the air flow rate is set, similar to the physical experiment, and at the exit, the barometric pressure. The resulting velocity profile at the exit from the stabilization inlet section is exported to the inlet to the swirl generator. The boundary conditions on the heated wall were set equal to 100 °C, which corresponded to the wall temperature in the physical experiment. The unheated wall was considered adiabatic. The boundary conditions at the outlet of the annular channel are specified as atmospheric pressure.

The hexahedral mesh model was implemented in ICEM CFD. To model the boundary layer, special attention should be paid to the mesh model near the walls. To carry out a numerical calculation near the wall, near-wall functions are used, which describe the inner region (viscous and transitional sublayer). Semi-empirical turbulence models resolve the entire internal flow region, including the viscous sublayer. At the same time, the quality of the obtained result increases in the entire computational domain. To implement this approach, it is necessary to provide a mesh resolution of the boundary layer $y^+ \leq 1$. Based on this, a mesh-independent solution was obtained. For each mesh model, a test problem was solved in order to determine the optimal dimension in terms of computational costs and the accuracy of the data obtained. The characteristics of all investigated mesh models are shown in Table 1.

| Dimension, count cells, pcs | Average mesh size, mm | $y^+$ |
|-----------------------------|-----------------------|-------|
| 1 1 819 264                 | 7.5x7.5               | 1.1   |
| 2 6 071 917                 | 5x5                   | 1     |
| 3 14 184 394               | 2.5x2.5               | 0.9   |
| 4 24 841 784               | 1x1                   | 0.85  |
| 5 38 184 612               | 0.5x0.5               | 0.85  |

The verification of the results of numerical simulation was carried out on the basis of experimental data at the input Reynolds number $Re_{in} = 21 \cdot 10^3$. This data was obtained by a physical model of a straight annular channel with close geometric dimensions. Figure 2 (a) shows the distribution of the dimensionless tangential velocity profile $w_p = w_q / V_{in}$ (where $w_q$ is the current tangential velocity and $V_{in}$ is the average input velocity) in the swirl generator for various sizes of the mesh model.

![Figure 2](image_url)

**Figure 2.** Profiles of tangential velocity (a) and heat flux density (b) for different dimensions of the mesh model.
Figure 2 (b) shows the distribution of the average heat flux profile along the length of the annular channel for different sizes of the mesh model. The tangential velocity and heat flux density practically don’t change when the dimension of the mesh model is more than 14 184 394 cells. Therefore, a grid model was used with a cell size of 2.5 x 2.5 and a y + value of 0.9 and an increase in the wall layer by 20 percent.

3. Results
The study was carried out for dry air at an inlet temperature of 20 ℃, when entering the Reynolds number $Re_{in} = 21 \cdot 10^3$ and Prandtl number $Pr_{in} = 0.7$. Aerodynamics in the annular channel depends on the geometry of swirling flow generator. The analysis of velocity for the considered swirl generator geometry shows that the one-way air supply has a significant non-uniformity of the flow throughout the volume. This is due to fact that the air stream enters the swirl generator through the tangential channel and expands in the radial and axial directions. Vortex structures are formed at the lateral boundaries of the jet. The interaction of these vortex structures with the existing air flow at the walls leads to the formation of secondary paired vortices, as it is shown in figure 3 (a).

![Figure 3. Radial velocity distribution in the flow swirl generator at $\phi = 0^\circ$ and $\phi = 90^\circ$.](image)

Further, the flow propagates along the concave surface of the swirl generator. Part of air from the jet center enters to annular channel. It leads to the loss of flow stability and the appearance of one more pair vortex, as shown in figure 3 (b). The formed vortices with opposite directions of rotation are separated from the surface and enter the annular channel. At the same time, it breaks down into smaller structures.

The swirling turbulent flow is fed into the annular channel asymmetrically and unevenly. This process is periodic and characterized by Strouhal numbers of the order of 0.22. At the entrance to the annular channel, flow separations are observed, generating large-scale unsteady turbulent vortex structures. These vortex structures drift downstream as it is shown in figure 4.

![Figure 4. Distribution of radial velocity in a longitudinal section in an annular channel.](image)
the annular channel. The propagation of secondary vortices coincides with the swirl angle of the main flow. In this case, the number of vortices increases in the direction of the outlet section. Thus, for a straight annular channel, with increasing z, the number of well-formed vortices increases from 2 to 14, and the process of forming new ones continues.

Changes of the dimensionless radial velocity $w_r/w_V$ (where $w_r$ is the current radial velocity) in the middle section along the length of the annular channel $z/d_h$ (where $d_h = d_2 - d_1$ is hydraulic diameter) are shown in figure 5. Along the entire length of the channel there is an alternation of maximum and minimum velocity values. This is due to the transfer of vortex flows from the core of the flow to the wall and vice versa. The limiting angles of swirling of the flow on the outer and inner surfaces are different. Therefore, the vortex structures are stretched in the azimuthal direction, and then the large ones are divided into smaller ones.

![Figure 5. Change of the dimensionless radial velocity in the middle section along the length of the annular channel.](image)

As in channels with non-swirling axial air flow, the heat transfer coefficient decreases as the flow moves towards the outlet section. Moreover, its largest values in the cross section are observed on the trajectory of the swirling jet moving from the swirl generator. Performed using numerical methods calculations make it possible to obtain a qualitatively similar averaged pattern of heat flux density distributions as it is shown in figure 6.

![Figure 6. Distribution of heat flux density on the outer and inner surfaces of the annular channel.](image)
The emergence and transformation of vortex structures have a significant impact on the distribution of heat flux over surfaces. Spiral lines of distributions along the length of the heat flux densities coincide with the limiting angles of flow swirling on them. There is a clear relationship between the total velocity fluctuations and the heat flux density distribution, as it is shown in figure 7. It should be noted that the highest intensity of heat transfer on the outer surface is observed in the regions of positive values of the radial velocity, and on the inner surface – in negative ones.

Figure 7. Change in the heat flux density along the length of the annular channel.

Due to the swirling flow decay, there is a significant decrease in the average heat transfer coefficient along the length of the outer surface. On the inner wall the drop in heat transfer is less intense. It is explained by the fact that the transfer of a more tribalized flow from the outer surface to the inner surface by secondary vortices reduces the conservative effect of centrifugal forces on heat transfer.

4. Conclusion
It was found that nonstationary Taylor - Görtler vortices gradually occupy the entire space of the annular gap. The emergence and transformation of these secondary flows affect the distribution of the heat flow over the working surfaces. A clear connection is observed between the fluctuations of the total velocity and the heat flux density on them. The highest intensity of heat transfer on the outer surface is observed in the regions of positive values of the radial velocity, and on the inner surface - in negative ones.

Acknowledgments
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5. References
[1] Mitrofanova O V 2010 Hydrodynamics and heat transfer of swirling flows in channels of nuclear power plants [in Russian] (Moscow: FIZMATLIT)
[2] Shechukin V K 1980 Heat Exchange and Hydrodynamics of Internal Flows in Fields of Body Forces [in Russian] (Moscow)
[3] Couette M M 1890 Études sur le frottement des liquides Ann. Chim. Phys. 21 433–510
[4] Mallock A 1896 Experiments on Fluid Viscosity Phil. Trans. R. Soc. Lond. A 187 41–56
[5] Taylor G I 1923 Stability of a viscous liquid contained between two rotating cylinders Phil. Trans. R. Soc. Lond. A 223 289–343
[6] Görtler H 1955 Dreidimensionales zur Stabilitätstheorie laminarer Grenzschichten Z. Angew. Math. Mech.

[7] Shchukin V K and Khalatov A A 1982 Heat Exchange, Mass Exchange, and Hydrodynamics of Internal Flows in Fields of Body Forces [in Russian] (Moscow)

[8] Leukhin Y L, Pankratov E V and Karpov S V 2017 Investigation into aerodynamic and heat transfer of annular channel with inner and outer surface of the shape truncated cone and swirling fluid flow J. Phys.: Conf. Ser. 891

[9] Zhang Z 2010 LDA Application Methods (Berlin, Heidelberg: Springer Berlin Heidelberg)