Flow structure and heat transfer around the cube

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Abstract. In this paper we present the results of a numerical study of convective heat transfer from a single cube, located on a plane surface perpendicular to the incoming flow. The Reynolds numbers, calculated from the height of the cube and the average velocity, are Re = 4200 and 46400. Numerical simulation is performed using the RANS and LES methods. The working fluid is air. Thermal condition on a flat surface and on the cube faces is a constant heat flux. A three-dimensional picture of the structure of the horseshoe-shaped vortex around the cube is clearly shown. Areas with maximum pressure loads on the surface of the cube are identified. The main attention is paid to the peculiarities of heat transfer in the flow around a cube with a turbulent flow. Areas on the cube surface where the most effective heat transfer occurs, as well as low-efficiency stagnant zones with low fluid velocity and high temperatures are shown. The obtained data on aerodynamics and heat transfer are compared with the experimental data of other authors.

1. Introduction

Interest in the problem of heat and mass transfer of poorly streamlined bodies arose long ago due to extensive practical applications [1-12]. The most important of them are the aerodynamics of buildings and architectural objects, as well as a large number of structural elements [4,13]. Recently, research in this field has received a new impetus with regard to solving the problems of microelectronics cooling [12,14,15]. As a rule, the design of such devices is a matrix system of parallelepipeds (chips) arranged in a certain order on a flat surface (board). These objects are quite large and cannot be considered as elements of a rough surface. So, for the analysis of aerodynamics and heat transfer of such complex systems, data on the flow around single three-dimensional obstacles will be very useful.

Among numerous poorly streamlined obstacles, the cube has a fairly simple shape, and the study of its aerodynamics can become the first stage of research of more complex bodies, which has been demonstrated in [2].

The cube streamlining with airflow has a number of features. The presence of spatial separation zones and horseshoe-shaped vortices, formed in the area of cube and plane conjugation, create strong unevenness in the distribution of heat transfer coefficients both along the cube perimeter and along its height. The identification and description of zones with increased heat transfer is an important element for predicting the thermal state of various structures, so the study of local heat transfer is an essential stage in simulating heat losses from complex shaped products.

In this paper we consider two cases of cube streamlining. In the first case, the flow pattern, the field of shear stress and static pressure on the surface of the plate, in the area of cube streamlining, as well as on the faces of the cube are studied in detail. Flow characteristics, obstacle sizes and other conditions of numerical simulation are the same as in the experiment conducted by the authors of [4]. A detailed comparison of the numerical simulation results with the experimental data presented in [4] is given. The
size of the cube is 50x50x50 mm. The incoming flow velocity is 14 m/s and the Reynolds number Re = 4.64*10^4.

In the second case, the thermal picture is considered in more detail. Particular attention is paid to the processes of heat exchange occurring in the flow area of the cube and on its surface. All parameters of numerical simulation are the same as in [1]. The experimental data [1] are compared with the results of numerical simulation performed in the framework of this study. The cube dimensions are 30x30x30 mm. The Reynolds Number in this series of calculations is Re = 4200. Thermal condition on the walls is constant heat flux.

For each of the described cases, the calculation is performed in a three-dimensional formulation on inhomogeneous grids without near-wall functions. Two calculation methods are used: RANS and LES. The results obtained by different calculation methods are compared with experimental data of [1] and [4], respectively. The calculation methodology used in this study is presented below.

2. Calculation method

In the numerical investigation the CFD code FLUENT was used. The basic equations were solved numerically by pressure based NITA-FS solver with CFL<0.5. Second order central scheme was used to discretize convective terms. The SST k-omega model was chosen to perform RANS modeling. LES calculation was carried out only for a smaller Reynolds number. WALE was chosen as the subgrid turbulence model.

The grid convergence study was carried out to find the optimal grid, which turned out 3 575 000 cells. Note that in this case y+ <1 for the first cell from any wall. At the channel entrance, an average velocity profile was set corresponding to experimental data. Synthetic turbulence corresponding to a ripple level of 5% was superimposed on this profile. On the surface of the cube, the condition of constancy of the heat flux was set, while the remaining walls were assumed to be adiabatic. Each calculation consisted of an initial stage of duration 2H/U (H- channel length, U- average speed) and averaging stage of 7.5 H/U duration.

3. Results

Fig.1 shows the flow pattern in the area of streamlining of the cube with the size of 50x50x50 cm. The incoming air flow velocity is 14 m/s. The Reynolds number Re = 4.64*10^4. Fig. 1a is the visualization performed in the framework of experimental work [4]. 1b is the flow pattern obtained by this numerical study. As you can see from comparison, the results are quite similar.

The boundary layer formed on the plate is subjected to three-dimensional separation when approaching the front face of the cube. An area of high pressure is formed in front of the cube, which has a clear visual proof. The flow region in the immediate vicinity of the cube is characterized by the presence of a horseshoe-shaped vortex that occurs on the front face and extends along the lateral faces of the cube in the downstream direction. Near the horseshoe vortex, the flow is unstable. The scale of the horseshoe vortex is approximately the same as the thickness of the boundary layer of the free flow. Recirculation of the flow is observed on the lateral faces. These vortices cover a significant part of the lateral surfaces.

Flow patterns indicate an unstable pulsation flow occurring downstream from the corners of the lateral faces, where the horseshoe vortex turns. The recirculation zone on the side faces occurs due to the flow breakdown on the front face and its re-attachment with the forming of a separation bubble. In the area behind the cube, a dome-like vortex is formed. Its prints on the substrate as a result of visualization are found in the form of two opposite rotating vortices. A region of reduced pressure is formed behind the prism, which is followed by formation of a vortex wake. It is obvious that the qualitative structure of complex separation flows described above will directly affect the nature of changes in local heat transfer.

Let us note the characteristic features of the behavior of the pressure coefficient \( C_p \). Fig. 2 shows the field of the static pressure distribution over the faces of the model cube of 50 × 50 × 50 mm. The top face of the cube is covered by the separation zone, which starts near the front edge of the upper face.
the front face in the central region, there is a stagnant zone of high pressure and, according to thermal studies, the heat exchange here is minimal. The stagnant flow is accelerated radially from the center to the outer corners, which leads to an increase in heat transfer from the center to the periphery. This fact is confirmed in Fig.3, which shows horizontal distribution of the static pressure in the middle section.

On the frontal face, the pressure coefficient does not exceed $C_p < 0.9$, which indicates the absence of complete braking of the incoming flow. This can be caused by the spreading of decelerated jets from the center to the ribs. Indeed, if you look at the distribution of the pressure coefficient $C_p$ across the cube, you can clearly see that the pressure in the central part of the frontal face is higher than at the edges. This pressure difference causes the flow spread from the center to the edges of the cube. This corresponds to data of [5] and [9], which indicates a significant influence of air spreading over the cube surface on the nature of the pressure distribution. There is a fairly good agreement of the calculation results with experimental data [4], presented in Fig.3.
The field of the local heat transfer coefficient distribution on the faces of the cube is shown in Fig.4. The distribution of the local Nusselt number on the central line of the front, back and side faces of the cube is shown in Fig.5. There is a fairly good agreement between the calculation results and experimental data [1]. As mentioned above, in the central region of the front face of the cube there is a stagnant zone of high pressure, where there is minimal heat transfer. Below the central zone there is a vortex flow with a high heat exchange, which is due to the formation of a horseshoe-shaped vortex in the lower part of the front face.

The side faces are in the recirculation region, where heat transfer increases to the back edges of the faces downstream. Very high heat transfer is observed in the lower part of the lateral faces, where the flow is unstable. Behind the cube in the area of the back face, there is a strong influence of the dome-like vortex. In this area, the turbulent flow prevails, resulting in a fairly uniform heat exchange. Here,
the central area of the face is also in the stagnant zone with minimal heat exchange increasing to the outer corners.

**Conclusion**

The paper presented the results of a numerical study of convective heat transfer from a single cube, located on a flat surface perpendicular to the incoming flow. Numerical simulation was performed by RANS and LES methods. The distributions of coefficients of pressure $C_p$ and heat transfer $Nu$ obtained as a result of the calculation, have shown a rather good agreement with the experimental data of other authors. The three-dimensional structure of the horseshoe vortex around the cube has been clearly shown. Areas with maximum pressure loads on the cube surface have been revealed. The main attention has been paid to the features of heat transfer at cube streamlining by a turbulent flow. The areas on the cube surface where the most efficient heat transfer occurs, as well as low-efficiency stagnant zones with low fluid velocity and high temperatures have been shown.

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