NUMERICAL SIMULATION OF SEPARATE FLOW AROUND A HEATED SQUARE CYLINDER

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ABSTRACT

The paper presents a new approach to modeling the turbulent external flow around square cylinders and heat transfer based on the thermodynamics of two fluids. This work is a development of Malikov's two-fluid turbulence model. It is shown that the temperature fluctuation in a turbulent flow is due to the temperature difference between these liquids. The resulting mathematical model of turbulence is used to study the turbulent heat propagation in a square in a flat channel.

CCS CONCEPTS

• **Navier–Stokes equations, separated flow, QUICK scheme, control volume method, two-fluid Malikov model. SIMPLE algorithm.**;

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1 INTRODUCTION

The modes of separated flows of a viscous fluid near bluff bodies or engineering structures are often encountered in nature and technology. The complexity of the study of such flows is due to the fact that at certain Reynolds numbers, the flow separates from a solid streamlined surface, which causes the flow to be unsteady and the formation of various vortex structures [1–4]. Understanding the mechanism of their occurrence is of great practical importance for the design of various aircraft, their elements and other technical devices.

Due to the complexity of separated flows, they are very often studied using examples of two-dimensional problems of external flow around cylinders with various cross-sectional shapes (circular, elliptical, square, rectangular). A large number of theoretical and experimental works [4–7] are devoted to the study of this class of flows, especially the flow around a circular cylinder [8–11].

In this work, two problems are considered. The first temperature distribution from the square at the Reynolds number Re=20000. The second flow around cylindrical bodies with a square shape of their cross section. Experiments show that in problems of this class, depending on the Reynolds number, a stationary continuous flow and a nonstationary periodic separated flow can be realized. In the latter case, a system of free vortex formations appears in the wake of the cylinder, which appear when they are separated from the corner edges of the streamlined cylinder; these vortex streets also affect the temperature distributions.

Many papers have been devoted to the study of resistance and the processes of vortex shedding from bluff bodies in a steady flow of an incompressible fluid. The nature of the flow around cylinders with a square and rectangular cross-sectional shape differs from the flow around a circular cylinder. Many of the works in this direction combine both experimental [12] and theoretical approaches.

Many numerical models of the flow around a square cylinder, based on the solution of the Navier-Stokes equations, were performed using variables of the stream-vortex function and the discrete-vortex method. Direct numerical simulation of the flow near a rectangular cylinder at low Reynolds numbers was undertaken in the pioneering work [13], but the use of a scheme with central differences in it led to the appearance of oscillations in the solution. The paper [14] presents the results of a numerical solution of the problem of flow around a rectangular cylinder in an unbounded flow using special difference schemes for the time derivatives of the convective terms. Simulation results were successful up to Reynolds numbers Re<1000. For the case of a square cylinder, the time dependences of the drag coefficients are obtained in the form of a sinusoid. In [12], to solve this problem, the authors use the system of Navier-Stokes equations in the variables "velocity-vorticity" and combine the use of Euler grids, Lagrangian vortex particles and the method of discrete vortices. Other methods for solving this problem are also known in the literature [15, 16].

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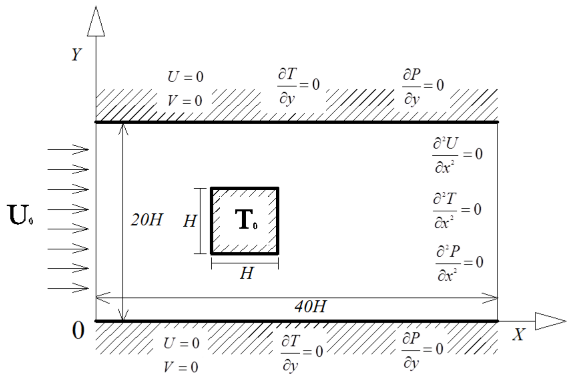

Figure 1: Schematic diagram of the transverse flow around a square cylinder

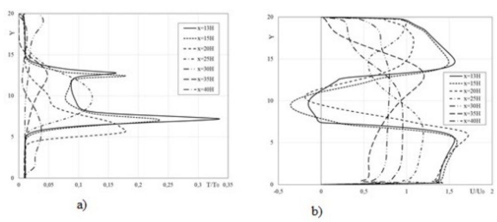

Figure 2: Distribution results, a) temperature and b) flow velocity for different channel sections

Modern approaches to numerical simulation of a viscous incompressible fluid around bodies at moderate Reynolds numbers are often based on the direct solution of the complete system of Navier-Stokes equations. One of the first and most complete works on the flow around a square cylinder should be noted the work of Davis and Moore [16], in which the algorithm for solving the initial equations uses the grid method and the finite volume method.

The certain complexity of the physical picture of the flow around a square cylinder makes this problem suitable for testing new and modified numerical schemes for calculating separated flows with recirculations. Recently, in our paper [17], an efficient method for the numerical integration of the complete system of non-stationary Navier-Stokes equations in the physical variables velocity-pressure has been proposed.

The purpose of this work is to apply the method SIMPLE to calculate the fields of velocity, pressure, vortex structure flow in a streamlined square cylinder at the Reynolds number Re=20000 and studying the distribution of temperature entering from the square.

2 DATA AND METHODOLOGY

Let us consider the two-dimensional problem of the transverse flow around a cylindrical body with a square cross-section, in which the temperature propagates in a square T_0, turbulent flow at speed U_0 The physical scheme of the flow and the boundaries of the computational domain are shown in Fig. 1

The origin of the entered Cartesian coordinate system is in the lower left corner at point 0. The width of the channel in the inlet and outlet sections has the size $20H$ The channel length is $40H$ The size of the square is H The square cross-sectional shape begins with x=8H and end x=12H.

A new two-fluid turbulence model by Z.M. Malikov. The non-stationary system of equations of turbulent thermodynamics according to the new two-fluid model in Cartesian coordinates has the following form [18, 19]:

$$\begin{cases} \frac{\partial U}{\partial x}+\frac{\partial V}{\partial y}=0, \\ \frac{\partial U}{\partial \tau}+U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}+\frac{\partial p}{\partial x}=\frac{1}{\mathrm{Re}}\left(\frac{\partial^2 U}{\partial x^2}+\frac{\partial^2 U}{\partial y^2}\right)-\frac{\partial uu}{\partial x}-\frac{\partial uv}{\partial y}, \\ \frac{\partial V}{\partial \tau}+U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}+\frac{\partial p}{\partial y}=\frac{1}{\mathrm{Re}}\left(\frac{\partial^2 V}{\partial x^2}+\frac{\partial^2 V}{\partial y^2}\right)-\frac{\partial vu}{\partial x}-\frac{\partial vv}{\partial y}, \\ \frac{\partial u}{\partial \tau}+U\frac{\partial u}{\partial x}+V\frac{\partial u}{\partial y}=-\left(u\frac{\partial U}{\partial x}+v\frac{\partial U}{\partial y}\right)-C_s\left(\left(\frac{\partial V}{\partial x}-\frac{\partial U}{\partial y}\right)v\right)+ \\ \qquad +\frac{\partial}{\partial x}\left(2v'_{xx}\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(v'_{xy}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right)-C_r u, \\ \frac{\partial v}{\partial \tau}+U\frac{\partial v}{\partial x}+V\frac{\partial v}{\partial y}=-\left(u\frac{\partial V}{\partial x}+v\frac{\partial V}{\partial y}\right)+C_s\left(\left(\frac{\partial V}{\partial x}-\frac{\partial U}{\partial y}\right)u\right)+ \\ \qquad +\frac{\partial}{\partial x}\left(v'_{xy}\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y}\right)\right)+\frac{\partial}{\partial y}\left(2v'_{yy}\frac{\partial v}{\partial y}\right)-C_r v, \\ \frac{\partial T}{\partial \tau}+U\frac{\partial T}{\partial x}+V\frac{\partial T}{\partial y}=\frac{\partial}{\partial x}\left(\frac{1}{\mathrm{Pr\,Re}}\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{1}{\mathrm{Pr\,Re}}\frac{\partial T}{\partial y}\right)-\frac{\partial ut}{\partial x}-\frac{\partial vt}{\partial y}, \\ \frac{\partial t}{\partial \tau}+U\frac{\partial t}{\partial x}+V\frac{\partial t}{\partial y}=-\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial x}\left(\kappa_u\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\kappa_v\frac{\partial T}{\partial y}\right)-K_t t. \end{cases}$$

Here

$$\begin{aligned} &\nu_{xx}=\nu_{yy}=\frac{3}{\mathrm{Re}}+2\frac{S}{|\mathrm{def}\bar{\mathrm{U}}|},\ \nu_{xy}=\frac{3}{\mathrm{Re}}+2\left|\frac{uv}{\mathrm{def}\bar{\mathrm{U}}}\right|, \\ &S=\frac{u^2J_x+v^2J_y}{J_x+J_y},\ \ J_x=\left|\frac{\partial u}{\partial x}\right|,\ \ J_y=\left|\frac{\partial v}{\partial y}\right|, \\ &\left|\mathrm{def}\bar{\mathrm{U}}\right|=\sqrt{2\left(\left(\frac{\partial U}{\partial x}\right)^2+\left(\frac{\partial V}{\partial y}\right)^2\right)+\left(\frac{\partial V}{\partial x}+\frac{\partial U}{\partial y}\right)^2}, \\ &K_t=C_{t1}\lambda_{\max}+C_{t2}\left|\frac{C\tau_w\,\mathrm{grad}T}{q_w}\right|. \\ &C_r=C_1\lambda_{\max}+C_2\frac{|d\cdot V|}{d^2},\ \kappa_u=\frac{3}{\mathrm{Pr\,Re}}+2\frac{|tu|}{|\mathrm{grad}T|}, \\ &\kappa_v=\frac{3}{\mathrm{Pr\,Re}}+2\frac{|tv|}{|\mathrm{grad}T|},\quad \mathrm{grad}T=\frac{\partial T}{\partial x}+\frac{\partial T}{\partial y}. \end{aligned}$$

In the above equations U, V -respectively axial, radial components of the flow velocity vector, T- temperature

p– hydrostatic pressure, u, v -relative velocities of the first fluid, ν'_{xx}, ν'_{yy}, ν'_{xy}-effective molar viscosities,

t- fluctuating temperature, d-closest distance to solid wall, τ_w-friction stress, q_w-wall heat exchange flow, Pr-molecular Prandtl number. The constant coefficients are $C_1 = 0.7825$, $C_2 = 0.306$, $C_s = 0.2$, $C_{t1} = 0.939$, $C_{t2} = 0.1$. In this work, for the difference approximation of the initial equations, the control volume method is applied SIMPLE (Semi-Implicit Method for Pressure) [20]. In this case, the viscosity terms were approximated by the central difference, and for the convective terms, the scheme of the second order of accuracy was used QUICK (Quadratic Upstream Interpolation for Convective Kinematics) [21].

An turbulent flow in the entire computational domain was set as the initial condition. For numerical calculation, an experimental velocity profile was set at the input, corresponding to the location of the input of the computational domain. No-slip conditions were imposed on the walls. Extrapolation conditions were set at the output. The system of equations (1) was reduced to a dimensionless form by correlating all velocities to the average velocity at the inlet, and the spatial dimensions to the height of the square H. The number of Reynolds was Re_H =20000.

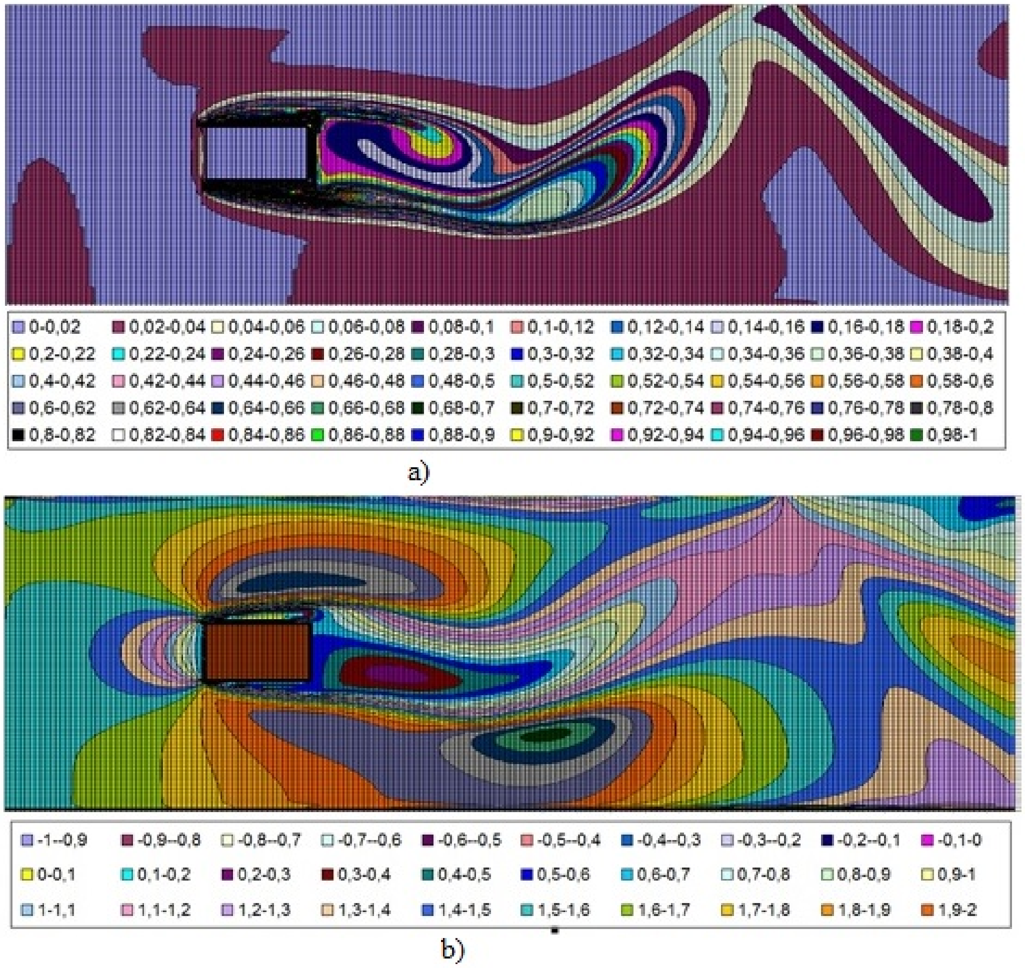

Figure 3: Results of isolines distribution, a) temperature and b) flow velocity

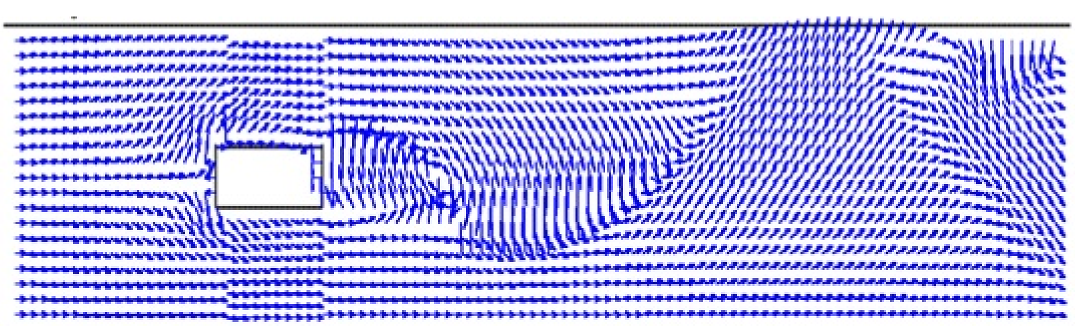

Figure 4: Vector velocity fields in a square flow

3 RESULTS AND DISCUSSION

This work pursued three main goals. The first one consisted in approbation of the numerical scheme for integrating the two-dimensional non-stationary equations of the two-fluid model of turbulence by Z.M. Malikov in velocity-pressure variables on the example of calculating a turbulent flow in a flat channel with a square obstacle.

The second - in the finite-difference approximation of the original equations, the scheme was used QUICK. Third - in the study of the detailed structure of the distribution of temperatures, speeds and pressures. The main numerical calculations were carried out on grids 200×100 with steps $\Delta x = 0.02$, $\Delta y = 0.01$ Calculations are made for the Reynolds number (Re=20000) in the channels.

On fig. Figure 2 shows the results of temperature distribution and flow velocity for various channel sections. τ-50.

On Fig. 3 shows the results of isolines for the distribution of temperature and flow velocity at τ-50.

It is easy to see in the figures that Re =20000 there is a well-defined zone with a steady reciprocating circulation flow in the form of a vortex elongated along the flow after the square.

On Fig. 4 shows the vector field of velocities at the Reynolds number Re=20000. The analysis of these fragments shows that the formation of a reverse flow is typical behind the cylinder. In this case, the circulation zone is elongated along the flow, and the symmetry is broken. Ahead of the cylinder, the flow is decelerated and flows around it without the formation of vortex zones on the leading edges of the cylinder.

This flow pattern is periodically repeated, since the vortex clusters on the upper and lower edges of the cylinder are generated and torn off in turn, and then are carried away from the bottom region. This leads to the appearance of a periodic flow behind the cylinder in the form of the so-called Karman vortex street, which is well observed in the calculations in Fig. 3 - 4 and in experiments with flow visualization [15].

It can be seen that GDP correlated negatively and slightly with EGDI (-0.198). GDP has a negative relationship also with tax revenue, inflation, and the unemployment rate. According to these results, GDP correlated positively with agriculture, industry, and population growth rate. Regarding the EGDI, it has a strong and negative relationship with agriculture, whereas the relationship with tax revenue and industry is positive but with small strength.

4 CONCLUSION

The present work is devoted to the development of a new two-fluid Malikov turbulence model and a numerical method for calculating the parameters of a separated flow around bodies by a boundless viscous incompressible fluid in velocity-pressure variables. This model allows a deeper study of the mechanism of formation and evolution of vortex structures behind bluff bodies at high Reynolds numbers. It is shown that for a cylinder with a square cross section, it is formed as an unsteady flow regime, in which the flow structure behind the cylinder is periodic and has its own spatial and temporal scales, determined by the Strouhal number. The distribution of temperature entering from the square was studied.

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