Modeling the flow in the presence of underwater vegetation

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Abstract. The paper investigates the flow of an incompressible fluid in an open stream with an unequal bottom and slope. The uneven bottom is due to vegetation. The flow is modeled on the basis of the two-velocity Rakhmatulin model, in a laminar regime from zero velocity of the discrete phase. The flow of a viscous fluid in a channel with an open stream with vegetation at the bottom of the stream is considered. The results of numerical simulation of the hydrodynamic features of a two-dimensional viscous flow are presented. The Kozeny-Karman ratio is used as the force of interaction with vegetation. The methods of computational experiment are used to study the effects of non-uniformity of the fluid velocity field, which arise due to vegetation. A qualitative comparison of velocity inhomogeneities is carried out. For the numerical implementation of the resulting equation, which is a generalization of the Navier-Stokes equation, a SIMPLE-like algorithm with appropriate generalizations was used. A single algorithm is applied for the entire area, without highlighting the free and porous zone.

1 Introduction

In many ecological and technical processes, river vegetation plays a central role in the management of river channels. In channel processes, the interaction of a fluid flow with heterogeneous media is observed. A heterogeneous environment is a combined area in which there is a free zone and a porous layer. For example, flow in rivers with sediment, flow in rivers with vegetation, flow with unequal bottoms, flow through a layer containing porous media, etc. The study of the laws of flow of continuous media through a heterogeneous layer is one of the areas of research in the field of mechanics of multiphase media [1-9].

When modeling hydrodynamic processes in such media, the layer creates significant hydrodynamic resistance. In this case, immediately behind the layer, an inhomogeneity of the flow is formed, and secondary flows arise. In [10], the velocity profile of a flow with a permeable bottom in an open flow with a slope was experimentally studied. During the experiments, a turbulent boundary layer was observed over a rough bottom. The study carried out in [11] is aimed at revealing the structure of the flow in the channel, where the width of the vegetation zone changes along a sinusoidal curve. Three-dimensional numerical simulations were carried out with a standard k-ε model to study the distribution of mean structure velocity and turbulence in the main channel and vegetation zone.
In [12], a mathematical model of the problem of the motion of a twodimensional turbulent fluid flow in a pressure channel with a wavy bottom is proposed. The mathematical model includes the Reynolds equations, the equations of kinetic energy transfer and turbulence dissipation reduced to a quasi-hydrodynamic form. An algorithm for solving the problem using the control volume method and the finite element method is proposed. The problem of the motion of a turbulent flow over immobile gently sloping sand dunes is solved numerically. The obtained calculations are compared with experimental data.

In works [13-15], while studying currents with underwater plants, S-shaped velocity profiles were obtained. This work is devoted to the study of the redistribution of fluid flow in an open stream with a channel slope in the presence of vegetation based on a two-velocity model.

2 Mathematical model and numerical method

Let us consider an interpenetrating model describing the flows of two-phase media [8-9], where the velocity of the discrete phase is neglected. Then the liquid phase flow is described by the system of equations (two-dimensional case):

\[ \begin{align*}
\partial (f u) / \partial x + \partial (f v) / \partial y &= \frac{\partial}{\partial x} \left( f \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left( f \frac{\partial u}{\partial y} \right) - C_u - \frac{\alpha}{Fr}, \\
\partial (f v) / \partial x + \partial (f u) / \partial y &= \frac{\partial}{\partial x} \left( f \frac{\partial v}{\partial x} \right) + \frac{\partial}{\partial y} \left( f \frac{\partial v}{\partial y} \right) - C_v - \frac{\alpha}{Fr}, \\
\partial (f u) / \partial x + \partial (f v) / \partial y &= \frac{\partial}{\partial x} \left( f \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left( f \frac{\partial u}{\partial y} \right) - C_u - \frac{\alpha}{Fr},
\end{align*} \]

Here, \(u, v\) - longitudinal and longitudinal flow velocities, pressure, volumetric concentration, \(Re\) is Reynolds number, \(C\) is interaction coefficient. In equations (1-3) the parameters are dimensionless (\(Re=UH/\mu\)), \(U\) is the average volume velocity, \(L\) is the characteristic scale, \(\rho\) is the liquid density, \(\mu\) is the viscosity). For the interaction coefficient, the Kozeny-Karman ratio was used:

\[ C = \frac{D}{f} \frac{f^2}{D} = \frac{\beta}{H} \frac{\alpha}{d} \]

\[ \frac{\partial u}{\partial y} = \frac{\partial v}{\partial x} = \]
3 Results and discussion

3.1 Influence of porosity

Let part of the open channel be filled with vegetation. Equation (1)–(3) is considered in the area: $0 \leq x \leq L$, $0 \leq y \leq 1$. The $x$-axis is directed along the lower wall of the channel, and the $y$-axis is perpendicular to it. When entering the channel, a parabolic velocity profile is given. Part of the channel $0, 5 \leq x \leq 1, 5, 0 \leq y \leq 0, 2$ is filled with vegetation. a) The porosity is 0, 2

![Graph showing influence of porosity](image)

Fig.1. Longitudinal velocity profiles for different channel sections: $x = 0, 05; 1, 025; 1, 933; 3, 216; 4, 072$ and with parameters: $D=100; Re=500$.

Figure 1 shows the strong effect of vegetation porosity on the velocity profile, not only inside but outside of it. With moderate porosity, the velocity profile within the vegetation is uniform, and with an increase in porosity, an uneven distribution of the velocity profile is observed. Behind the vegetation, the pattern of the velocity profile changes: with moderate porosity behind the layer, the profile is observed more unevenly than with a high porous layer.

3.2 Influence of the Reynolds number

![Graph showing influence of Reynolds number](image)

Figure 2 shows the distribution profiles for $Re=1000$. An increase in the Reynolds number will lead to an increase in the secondary flow zone (comparison of Fig. 1 and Fig. 2).
3.3 The nature of the change in transverse velocity and pressure

Fig. 2. Longitudinal velocity profiles for different channel sections: $x = 0, 0.05; 1, 0.25; 1.933; 3.216; 4, 0.072$ and with parameters: $D = 100; f = 0.2$

Fig. 3. Profiles of transverse velocity for different sections of the channel: $x = 0, 0.05; 1, 0.25; 1.933; 3.216; 4, 0.072$ and with parameters: $D = 100; f = 0.2$
Fig.4. Pressure change along the longitudinal sections of the channel. The upper line corresponds to the longitudinal section close to the channel bottom, the middle line corresponds to the middle longitudinal section, and the lower line corresponds to the section near the water surface (Re=500, f=0.2).

In Fig.4, along the y-axis, the difference in the dimensionless pressure is plotted: . Here is the pressure at the entrance to the channel on the free surface. A significant change in pressure endures near vegetation.

3.4 The nature of the change in the drag coefficient on the bottom surface

To analyze the obtained solutions of the problem, it is useful to consider the coefficient of friction [22]:

\[
\tau_w = \frac{\rho U}{\mu} \left( \frac{\partial u}{\partial n} \right)
\]

where \( \tau_w \) is the friction stress on the bottom surface. Using the nondimensionalization parameters, we can write an expression for the friction stress

\[
\frac{\tau_w}{\mu U} = \frac{\partial u}{\partial n}
\]

Substitution (5 in (4) leads to the expression for the friction coefficient:

\[
C_f = \frac{\tau_w}{\rho U^2} = \frac{\mu U}{H \left( \frac{\partial u}{\partial n} \right)}
\]

However, in the analysis, the so-called modified friction coefficient [8] is more convenient, which is defined as

\[
C_f = \frac{\left( \frac{\partial u}{\partial n} \right)}{\left( \frac{\partial u}{\partial n} \right)_w}
\]

\[
C_f^* = C_f \frac{\left( \frac{\partial u}{\partial n} \right)_w}{\left( \frac{\partial u}{\partial n} \right)}
\]
Fig. 5 shows that vegetation porosity has a significant effect on the drag coefficient: for large porosities, the distribution is more even on the vegetation surface than for small values.

4 Conclusion

Using a two-velocity model in a laminar regime, it is possible to obtain a velocity profile in qualitative agreement with the experimental data. The extended Navier-Stokes model can be used to investigate hydrodynamic structures for flow in open streams with underwater vegetation. The Koseniya-Karman ratio applied in porous media can be used as a drag force with vegetation.

References

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