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Experimental and Numerical Study of Turbulent Flow in Open Channels with Impermeable and Porous Bed

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Abstract

In order to experimentally and numerically investigate turbulent flow in an open channel with porous (vegetated) and impermeable bed 2D Particle Image Velocimetry (PIV) and a Computational Fluid Dynamical (CFD) model were used. PIV is an optical method of flow visualisation that is used to obtain instantaneous velocity measurements on a plane of a flow field. The CFD model is based on the CFX computer package, a high-performance general purpose fluid dynamics program that has been applied to solve wide-ranging fluid flow problems.

In order to validate the results of the numerical model, the CFX based results were compared with experimental data from PIV measurements. The comparison is carried out for two cases: a) impermeable bed and b) porous bed. For the simulation of the porous bed a grass-like of flexible vegetation of 2 cm thickness was used. Vertical distributions of velocities above the impermeable bed and above the vegetation for the porous bed for the same different total depths were evaluated.

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*Keywords:*Open channel flow; PIV; CFX; Turbulent flow;Velocity distribution;

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1. Introduction

Vegetation is one of the more important factors that shape the turbulence in natural open channels, influencing thus the operation of wetlands and the rivers. The existence of aquatic plants has as result the increase of resistance in the flow and the reduction of the mean velocity in comparison with beds without vegetation. The last 20 years a lot of studies (experimental and numerical) have been performed, in order to focus the effect of vegetation in open channels.

As regards the experimental procedure the authors of this study have performed a lot of experiments. In the study of [1] results (experimental and computational) for turbulent flow over and within a porous bed have been presented. The simulation has been achieved with the use of a rods bundle.

In the work of [2] the turbulent flow in open channel with permeable bed is investigated experimentally, with the use of hot film anemometry (TSI cross hot film connected with IFA 100). Measurements of discharge, mean velocity and turbulent characteristics (Reynolds stresses) reveal the effect of the material used (filters, vegetation), ε (porosity) and s’/h (relative porous thickness) on the flow characteristics and the discharge capacity of the channel.

In the study of [3] the characteristics of turbulent flow above porous beds (porous filter and rods bundle) are studied experimentally with the use of hot-film anemometry (TSI cross hot film connected with IFA 100). The experimental results show many differences in both mean and turbulence characteristics between the two bed materials used.

[4] studied experimentally the characteristics of turbulent flow in an open channel above the permeable bed (grass vegetation and gravel bed) using a part a PIV. Hydraulic characteristics such as distributions of velocities, turbulent intensities and Reynolds stress are investigated and the results show that the bed type can significantly influence the turbulent characteristics of the flow.

In the study of [5] the turbulent characteristics of the flow in an open channel with horizontal and inclined impermeable bed were studied experimentally using a PIV. The channel slope influences significantly the turbulent characteristics of the flow such as the variation of longitudinal turbulent intensity the variation of vertical turbulent intensity, the turbulent kinetic energy and Reynolds stresses.

The influence of transition from vegetation to gravel bed and vice versa [6] and the effects on the velocity distribution of turbulent flow in a half-separated (impermeable and permeable) bed [7] in open channel is investigated experimentally. In the first case results show that the influence on the turbulent characteristics of transition from vegetation to gravel bed is different in comparison with those of transition from gravel to vegetated bed. This is due to the fact that the presence of gravel bed increases the turbulent characteristics of the flow in regard to the vegetated bed due to the great roughness which is observed near the interface gravel bed-water because of the presence of the gravel bed and this increase the turbulence. In the second case results show that the presence of half-separated impermeable and permeable bed influences the values of velocity distribution in comparison with situations over permeable or impermeable bed. The comparison with the same experiments when it has transition from permeable to impermeable bed and vice versa shows that there are a lot of differences on velocity distribution.

As regards the numerical studies initially [8] and [9] developed a method for the determination of the velocity profile which separates the flow region in two layers, one inside the vegetation and the other over the vegetation. This theory was based on the two layer method. Contrary to the theory of [8], [10] developed a model for the calculation of mean velocity and turbulent characteristics of the flow in an open channel with vegetation. Their theory was based on the fact that the vegetation resistance has an impact not only in the momentum equation but and in k-ε model equations.

[11] modified these two models in order to examine the vegetation geometry and the drag resistance as a function of the flow depth. In this theory they added the turbulent kinetic energy equation for two layers model. [12] used 3D finite element program (SSIM) for the study of the vegetation influence in velocity distribution. This model solves the momentum and continuity equations for each element and uses the k-ε model for the turbulence modeling.

In this study in order to experimentally and numerically investigate the turbulent flow in an open channel with porous (vegetation) and impermeable bed, 2D PIV and a CFX model were used. For the simulation of the porous bed a grass-like vegetation was used. Vertical distributions of velocities above the impermeable bed and above the vegetation for the porous bed for the same different total heights were evaluated. Results show that there is a good agreement between experimental and numerical study.

2. Experimental Procedure

In total, twenty-four (24) experiments were carried out in the laboratory of Hydraulics in the Department of Civil Infrastructure Engineering of Alexander Technological Educational Institute of Thessaloniki, Greece. The channel has a length of 6.5 m, width of 7.5 cm and height of 25 cm. The vegetation of 2 cm thickness was attached to a 1.0 cm thick wood, so that it remains fixed to the bed during the experiments. Hydraulic characteristics were measured at four different total flow depths h = 7, 9, 11 and 13 cm both for impermeable and porous bed and for three different discharges (0.735, 0.845 and 0.970 l/s). The flow depth over the porous bed h′ was h′ 5, 7, 9, 11 cm. With these conditions the total flow depth was kept constant equal to h 7, 9, 11 and 13 cm for both impermeable and porous beds ($h = h'+h_v$, h_v : height of vegetation). The blades were made from plastic. The geometrical characteristics of the flow are presented in Figures 1 and 2. The morphology of the vegetation is illustrated in Photograph 1.

Measurements of velocity were taken for horizontal channel slope. PIV is an optical method of fluid visualization and is used to obtain instantaneous velocity measurements and related properties in fluids. The fluid is seeded with tracer particles which, for the purposes of PIV, are generally assumed to faithfully follow the flow dynamics. The motion of the seeding particles is used to calculate the velocity profile of the flow. The experimental uncertainty of the measured velocity with this technique is approximately ± 2%.

The measurements were conducted at a 4 m distance from the channel's entrance and above the top of the vegetation, where the flow is considered fully developed. The full development of the flow was confirmed comparing the velocity distributions above the vegetation in two vertical sections with a 60 cm separation distance. The uniformity of the flow was checked measuring the flow depth with point gauges at two cross-sections (4 m between the two sections). The desirable flow depth in the downstream section could be controlled using a weir at the channel's outlet. The error of the measured flow depth with the point gauge was ± 0.1 mm. The total discharge was measured at the channel's outlet using a triangular tank.

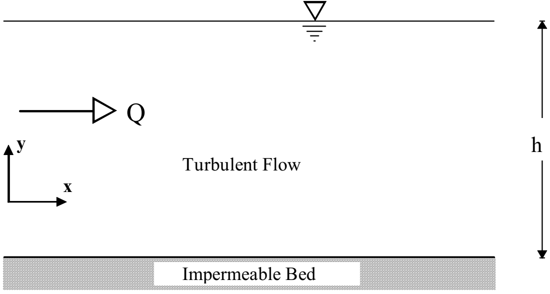


Fig. 1. Geometrical characteristics of the flow above impermeable bed

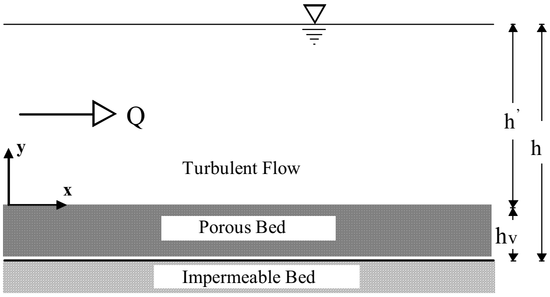
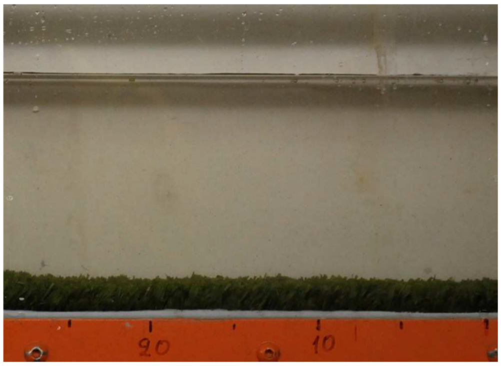


Fig. 2. Geometrical characteristics of the flow above porous bed



Phot. 1. Vegatation of 2 cm thickness

3. Mathematical Model and Numerical Solution

3.1 Mathematical Model

In developing a mathematical model for turbulent flow, one seeks to modify the full unsteady Navier-Stokes equations by introducing averaged and fluctuating quantities to produce the Reynolds-Averaged Navier-Stokes (RANS) equations. These equations represent the mean flow quantities only, while modeling turbulence effects without the need for resolution of the turbulent fluctuations. Turbulence models based on Reynolds-averaging are known as Statistical Turbulence Models due to the statistical averaging procedure employed to obtain the equations.

In this framework, each variable calculated at a point of the flow field is decomposed in an average component and a time varying component. For example, the velocity (instantaneous velocity at a point) is the sum of an average component $\overline{U}$ and a time varying component (fluctuation) u, i.e.

$$\vec{U} = \vec{\overline{U}} + \vec{u} \quad (1)$$

The time-averaged component is defined as:

$$\vec{\overline{U}} = \frac{1}{\Delta t}\int_{t}^{t+\Delta t} \vec{U} dt \quad (2)$$

where Δt is a time scale that is large relative to the turbulence fluctuations, but small relative to the time scale to which the equations are solved. In the most general form the continuity equation is written as

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \vec{U}\right) = 0 \quad (3)$$

The momentumequation is modified relative to the form for laminar flow as it comprises more terms known as Reynolds stresses (or turbulent stresses):

$$\frac{\partial \rho \vec{U}}{\partial t} + \nabla \cdot \left(\rho \vec{U} \otimes \vec{U}\right) = \nabla \cdot \left(\tau - \rho \overline{\vec{u} \otimes \vec{u}}\right) + \vec{S}_M \quad (4)$$

The stresses in the turbulent flow are composed of two parts: a) Stresses due to molecular viscosity which are similar to laminar flow stresses and b) Turbulent stresses, known also as Reynolds stresses, which are presented by the term $-\rho\overline{\vec{u}\otimes\vec{u}}$ in equation (4).

In this work we use the k-epsilon turbulence model. k is the turbulence kinetic energy. The k-epsilon model introduces two new variables into the system of equations. The form of the continuity equation is unaffected, i.e.,

$$\frac{\partial\rho}{\partial t}+\nabla\cdot\left(\rho\vec{U}\right)=0 \quad (5)$$

and the momentum equation becomes

$$\frac{\partial\rho\vec{U}}{\partial t}+\nabla\cdot\left(\rho\vec{U}\otimes\vec{U}\right)-\nabla\cdot\left(\mu_{eff}\nabla\vec{U}\right)=-\nabla p'+\nabla\cdot\left(\mu_{eff}\nabla\vec{U}\right)^{T}+\vec{\mathrm{B}} \quad (6)$$

where $\vec{\mathrm{B}}$ is the sum of body forces, μ_{eff} is the effective viscosity accounting for turbulence, and p' is the modified pressure defined as

$$p'=p+\frac{2}{3}\rho k+\nabla\cdot\vec{U}\left(\frac{2}{3}\mu_{eff}-\zeta\right) \quad (7)$$

where ζ is the bulk viscosity, ρ is the fluid density and k is the turbulence kinetic energy.

The k-epsilon model, is based on the eddy viscosity concept, i.e., it is assumed that

$$\mu_{eff}=\mu+\mu_t \quad (8)$$

where μ_t is the turbulent viscosity. The k-epsilon model further assumes that the eddy viscosity is linked to the turbulence kinetic energy and the turbulence dissipation rate ε via the relation

$$\mu_t=C_\mu\rho\frac{k^2}{\varepsilon} \quad (9)$$

where C_μ a constant [13]. In the calculation process, the values of k and ε at a point are computed directly from the differential transport equations for the turbulence kinetic energy and the turbulence dissipation rate ([14],[15]):

$$\frac{\partial(\rho k)}{\partial t}+\nabla\cdot(\rho\vec{U}k)=\nabla\cdot\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\nabla k\right]+P_k-\rho\varepsilon \quad (10)$$

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\nabla\cdot(\rho\vec{U}\varepsilon)=\nabla\cdot\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\nabla\varepsilon\right]+\frac{\varepsilon}{k}(C_{e1}P_k-C_{e2}\rho\varepsilon) \quad (11)$$

where $C_{e1}=1.45$, $C_{e2}=1.90$, $\sigma_k=1.00$ and $\sigma_\varepsilon=1.30$. Here, P_k is the turbulence production due to viscous forces, i.e.

$$P_k=\mu_t\nabla\vec{U}\cdot(\nabla\vec{U}+\nabla\vec{U}^T)-\frac{2}{3}\nabla\cdot\vec{U}(3\mu_t\nabla\cdot\vec{U}+\rho k) \quad (12)$$

In all simulations in this work, the ANSYS-CFX computer simulation program for incompressible flow $(\rho=const.)$ was used.

3.2 Numerical solution

In the present work the effect of vegetation of height of 2cm on flows in open channels of height 7, 9, 11 and 13 cm by using the CFX solver was investigated. Simulations are performed for total computational domain length equal to 1.5 m while the other parameters used are equal to those described in the experimental procedure. The equations are solved in each tetrehedron of the numerical grid produced by using minimum and maximum edge length equal to 0.0000007 m and 0.0075344 m. Periodic boundary conditions are imposed in the stream wise direction. Free slip was applied in the free surface whereas the no-slip condition was applied in the wall components. For all simulations investigated in this work the velocity is calculated as mean value at parallelepiped bins parallel to the wall for the smooth channels, whereas for the rough channels it is calculated in an area above the top of the vegetation. Figure 3 shows the isolines of velocity on the free slip wall and a) for impermeable bed and b) for porous bed.

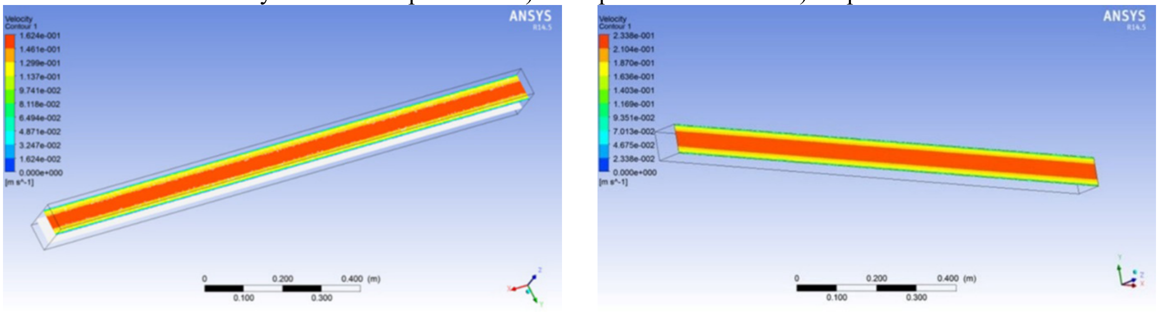


Fig. 3. Isolines of velocity on the free slip boundary a) for impermeable bed (Q=0.970 l/s and h=11 cm) and b) for porous bed (Q=0.845 l/s and h=7 cm)

4. Comparison Between Experiments and Model - Conclusions

Table 1 shows the mean velocities for both beds (impermeable and porous) and for a) experimental procedure and b) numerical simulation. There is a good agreement between experimental and numerical results (relative difference under 10 %). Small differences (11.2 %) are observed only in the case of porous bed and for the maximum discharge (Q=0.970 l/s) and for the higher total flow depths h (h=11 cm and h=13 cm). This is due to the fact that the major discharge and the high total flow depth provide much turbulence which reduces the velocities over the porous bed and the model overestimates the velocities in these cases.

Table1. Mean velocities of impermeable and porous bed

		Impermeable Bed		
Discharge Q (l/s)	Total Flow Depth h (cm)	U_{mean} (m/s) experimental	U_{mean} (m/s) numerical	Difference (%)
0.735	7	0.188	0.195	3.7
0.735	9	0.136	0.141	3.7
0.735	11	0.103	0.109	5.8
0.735	13	0.085	0.092	8.2
0.845	7	0.197	0.204	3.5
0.845	9	0.153	0.164	7.2
0.845	11	0.119	0.123	3.4
0.845	13	0.098	0.096	2.0
0.970	7	0.251	0.254	1.2
0.970	9	0.193	0.190	1.6

Impermeable Bed

Discharge Q (l/s)	Total Flow Depth h (cm)	U_{mean} (m/s) experimental	U_{mean} (m/s) numerical	Difference (%)
0.970	11	0.138	0.149	8.0
0.970	13	0.115	0.112	2.6

Porous Bed

Discharge Q (l/s)	Total Flow Depth h (cm)	U_{mean} (m/s) experimental	U_{mean} (m/s) numerical	Difference (%)
0.735	7	0.149	0.161	8.1
0.735	9	0.129	0.119	7.8
0.735	11	0.101	0.095	5.9
0.735	13	0.084	0.083	1.2
0.845	7	0.167	0.180	7.8
0.845	9	0.143	0.138	3.5
0.845	11	0.109	0.112	2.8
0.845	13	0.089	0.095	6.7
0.970	7	0.186	0.202	8.6
0.970	9	0.153	0.157	2.6
0.970	11	0.116	0.129	11.2
0.970	13	0.098	0.109	11.2

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