Jaromir Prihoda – Pavel Zubik – Jan Sulc – Milan Sedlar *

EXPERIMENTAL AND NUMERICAL MODELLING OF TURBULENT FLOW OVER AN INCLINED BACKWARD-FACING STEP IN AN OPEN CHANNEL

The contribution deals with the experimental and numerical modelling of the turbulent flow over an inclined backward-facing step in an open water channel. The modelling was carried out in the wide range of the Froude number covering the subcritical, supercritical and near critical regimes as well. The study was concentrated particularly on the development of flow separation and on changes of free surface. Numerical results obtained using the commercial software ANSYS CFX 12.0 for the two-equation SST model and the EARSM model were compared with experimental data obtained by means of PIV and LDA measuring techniques.

Keywords: *Open channel flow, inclined backward-facing step*

1. Introduction

Turbulent flow over an inclined backward-facing step in the open channel occurs very often in hydraulic applications. The character of flow over the inclined step depends on the inclination angle changing from the perpendicular backward-facing step with flow separation at the step edge up to a small inclination without flow separation. The flow pattern is relatively complicated in spite of a simple geometry because it includes an extensive separation region and secondary flows near side walls behind the inclined step. The character of flow is as well very influenced by gravitational forces and depends on flow conditions.

Turbulent flow over the inclined backward-facing step situated in the open channel was investigated experimentally and numerically for a wide range of flow parameters. Flow conditions are described notably by the Froude number Fr covering the range from $Fr = 0.42$ up to $Fr = 2 .14$. The contribution summarizes results of the investigation of turbulent flow over an inclined backward-facing step with subcritical, supercritical and near-critical regimes as well (see Prihoda et al. [1], [2], [3]). Results of experimental investigation of turbulent flow over an inclined step in the closed channel and in an open channel with sub- and supercritical flow are given by Zubik et al. [4].

While the subcritical regime is characterized by a large separation region near the channel bottom and a slightly rippled free surface, the supercritical flow is practically without separation and free surface traces the inclined step. The critical regime called the hydraulic jump comes about during the transition from the supercritical to subcritical flow. A comprehensive review of experimental results related to the hydraulic jump was given by Chanson [5]. The presented contribution includes the overview and comparison of all mentioned regimes of turbulent flow over the inclined backward-facing step in an open channel.

2. Experimental investigation

Experiments were carried out in a straight channel of constant cross-section 0.2 × 0.2 m with the length 4.475 m and with the slope of the bottom corresponding to the chosen flow conditions. The open channel was linked to the water tank with a pump driven by a motor equipped with a frequency converter. The pump with the maximum flow rate of $Q = 7.2\ \mathrm{m^3/min.}$ enabled the maximum speed in the channel of 3 m/s. To stabilize the inflow rate, a wire mesh screens and a honeycomb were installed at the entry of the straight inflow part. The channel is made of transparent plastic material allowing the use of contactless optical measuring techniques. The laser Doppler anemometry (LDA) for measurements of one and/or two velocity components in selected points of the flow field and the particle image velocimetry method (PIV) were used for measurements of the velocity field in selected channel sections. The extended uncertainty guess of flow velocity determination at reliability level of 95% was less than 5% for LDA and 15% for PIV techniques.

The sketch of the test section of the channel with an inclined backward-facing step with the inclination angle $\alpha = 20°$ is given in Fig. 1. The distance of the edge of the inclined step from the channel entry is 0.9 m. The height of the inclined step is $H = 100$ mm. The whole length of the investigated section is 2.1 m. Boundary con-

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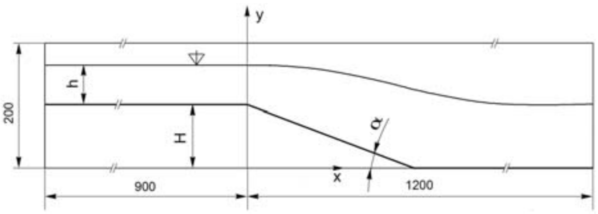

Fig.1 Sketch of the geometrical arrangement

ditions for the numerical simulation were examined in cross-sections $x = -0.9$ and -0.6 m using the PIV and LDA methods. The PIV measurements were taken at vertical and horizontal planes parallel with the channel axis with the aim to determine the general view of the flow with separation and secondary flows behind the step as well. In the mean vertical plane, profiles of mean and fluctuation longitudinal velocities were determined by the LDA method at selected sections x = const.

The free-surface flow over the inclined backward-facing step is characterized by the Reynolds number $Re = U_m H/\nu$ and the Froude number $Fr = U_m/(gh)^{1/2}$ where U_m is the mean bulk velocity and h is the initial height of the water level. The turbulence level in the stream core was about 2.4 % at the inlet of the channel.

3. Numerical simulation

The numerical simulation of the turbulent flow over the inclined step in an open channel was accomplished by means of the commercial software ANSYS CFX version 12.0 solving Reynolds-averaged Navier-Stokes equations including the gravity effect. A second-order scheme was used for calculations. The numerical solution of free-surface flow was carried out by means of the Volume-of-Fluid (VOF) method based on the monitoring of the volume fraction α_i of both fluids in the each computational cell. The "non-homogeneous" model where the governing equations for the both fluids are solved separately was chosen for the calculation. The SST $k-\varepsilon/k-\omega$ model proposed by Menter [6] and the EARSM (Explicit Algebraic Reynolds Stress Model) model were used for the sub- and supercritical flow. As the turbulent flow near the critical regime should be solved as unsteady, the only SST model was used due to the enormous time demands. The EARSM model is based on a nonlinear relation between the Reynolds stresses and the mean strain rate and vorticity tensors. The used version corresponds to the model proposed by Wallin and Johansson [7].

The distribution of mean velocity, turbulent energy, and dissipation rate was prescribed as inflow boundary conditions according to experimental data. The mean value of static pressure was prescribed as the outflow boundary condition and the open-boundary condition was applied at the upper boundary. The scalable wall functions according to Grotjans and Menter [8] were used as wall boundary conditions. The non-dimensional distance y+ of the first grid point from the wall was $y^+ = 1 \div 5$. The computational domain begins in the cross-section $x = -0.6$ mm before the edge of the inclined step and finishes at the distance $x = 1.2$ m. The domain consists of one half of the channel width with the symmetric boundary condition in the symmetry plane ($z = 0$). A structured monoblock type grid refined near walls and near the free-surface was used for calculations. The grid refinement was adapted to the shape of free surface obtained by preliminary calculations. According to the initial height of the free surface, the height of the computation domain 0.2 m was chosen. The grid consists of $367 \times 169 \times 51$ grid points, i.e. approximately 3.1×10^6 grid points. The detail of the computational grid near the inclined step is shown in Fig. 2.

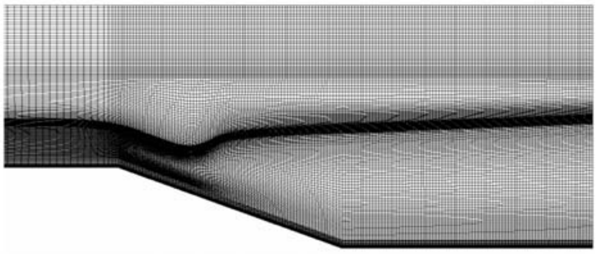

Fig. 2 Detail of the computational grid

4. Results

The analysis of experimental and numerical results was concentrated mainly on the development of flow separation behind the inclined step and on the corresponding changes of free surface. Further, the origin and development of secondary flow near side walls of the channel behind the inclined step was investigated.

4.1 Subcritical flow

The measurement of the subcritical free-surface flow was carried out with the slope of the bottom 0.23 deg for the mean bulk velocity $U_m = 0.38$ m/s and for the initial height of the water level $h = 0.082$ m, i.e. for the Reynolds number $Re = 44100$ and the Froude number $Fr = 0.42$.

Fig. 3 shows mean longitudinal velocity profiles in the symmetry plane over the step and in the outlet channel. Velocity profiles obtained by the EARSM and the SST models are compared with experimental data from PIV technique. It follows from the comparison that the turbulence model based on the assumption of the turbulent viscosity is not able to predict correctly the complicated flow pattern in the relatively narrow open channel with an inclined step. A satisfactory agreement with experimental data was obtained for the EARSM model only. Due to 3D character of flow with secondary effects near side walls, the velocity profiles obtained by the SST model in the middle plane are not believable.

The form of free surface and the extent of the separated region in the middle plane are compared in Fig. 4 with experimental data.

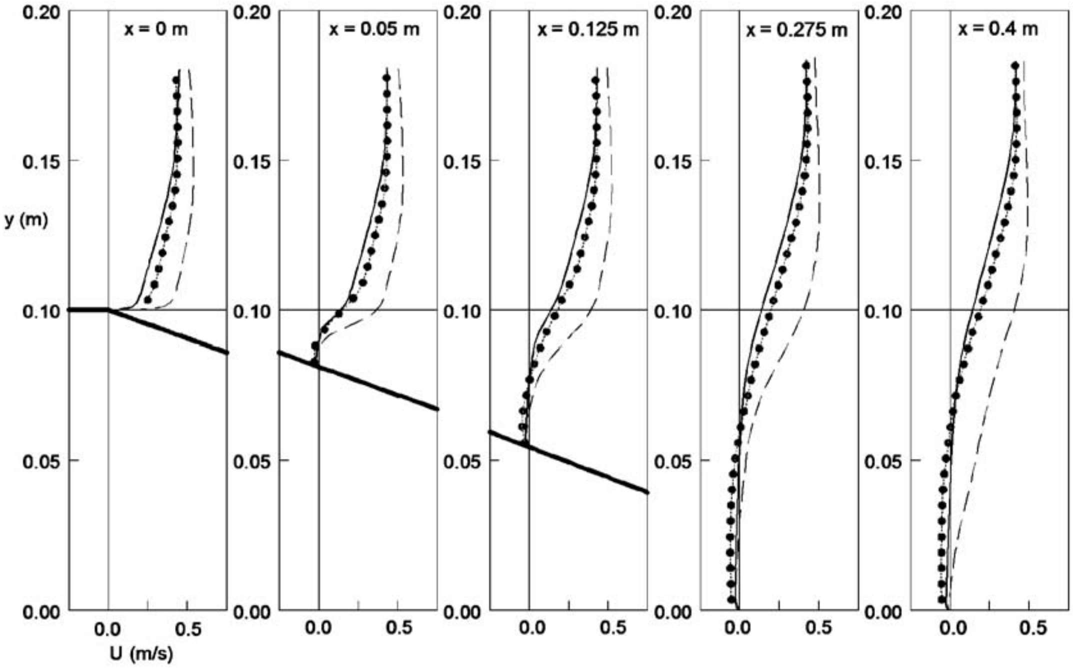

Fig. 3 Mean velocity profiles in the channel for the subcritical regime (full line - EARSM model; dashed line - SST model)

The free surface is in the whole investigated area slightly rippled only. The predicted separated region corresponds to predicted velocity profiles. The extent of the region of the separated flow obtained by the EARSM model is in a good accordance with the experiment, while the SST model gives a smaller separation region. The length of the separation region behind the inclined step is approximately $x_s/H \approx 7.2$, while the length predicted by the EARSM model is $x_s/H \approx 7.6$.

The distribution of turbulent energy in the middle plane of the channel determined by means of the SST and the EARSM model is given in Fig. 5. According the SST model the maximum of turbulent energy is more noticeable in the mixing region immediately behind the flow reattachment. The maximal values of turbulent

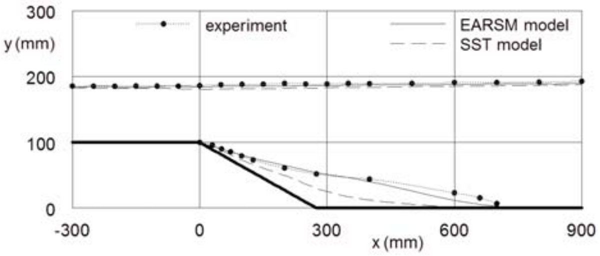

Fig. 4 The extent of the separation region and the form of the free surface for subcritical flow (full line - EARSM model; dashed line - SST model)

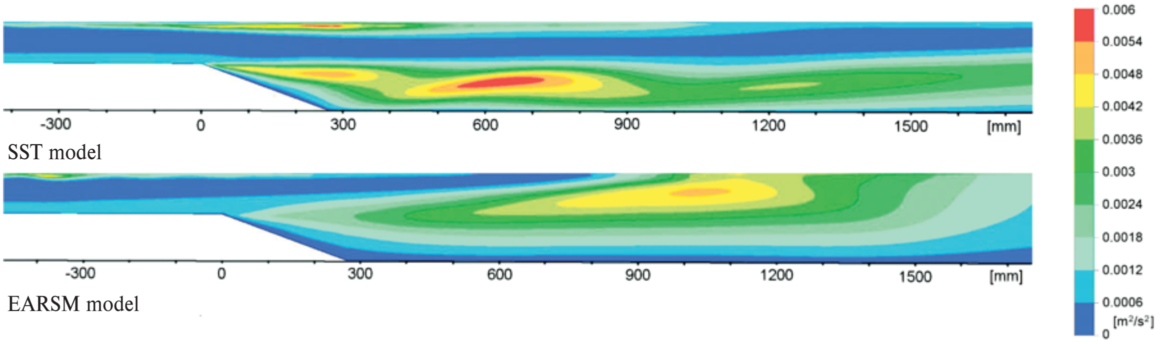

Fig. 5 Distribution of turbulent energy in the middle plane of the channel

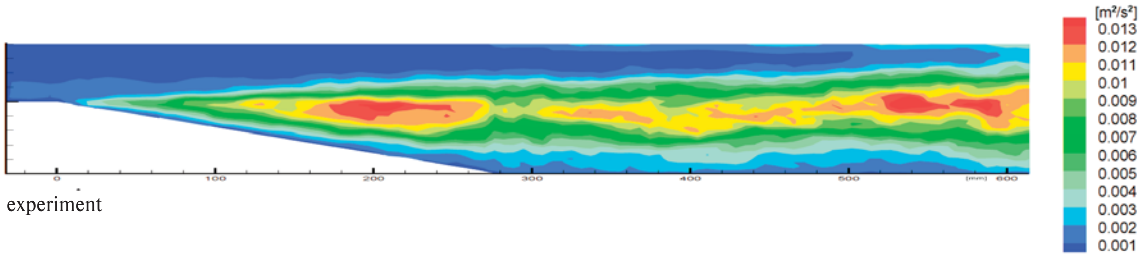

Fig. 6 Distribution of normal stress in the middle plane of the channel

energy obtained by the EARSM model are smaller and the maximum moves to the proximity of free-level. The distribution of the longitudinal component of turbulent normal stress obtained by the PIV technique behind the step is given in Fig. 6 for comparison.

4.2 Supercritical flow

The measurement of the supercritical free-surface flow was carried out with the slope of the bottom 2.025 deg for the mean bulk velocity $U_m = 1.92$ m/s and for the initial height of the water level $h = 0.086$ m, i.e. for the Reynolds number $Re = 200100$ and the Froude number $Fr = 2.14$. At the chosen mean bulk velocity, the turbulence level in the stream core was about 2 %. Fig. 7 shows mean longitudinal velocity profiles in the symmetry plane over the step and in the outlet channel. Velocity profiles obtained by the EARSM model are compared with experimental data from PIV measurement. A surprisingly satisfactory agreement with experimental data was obtained for the EARSM model. The SST model gives nearly same velocity profiles unlike the subcritical flow with a large separation region, where the differences between various turbulence models were distinct.

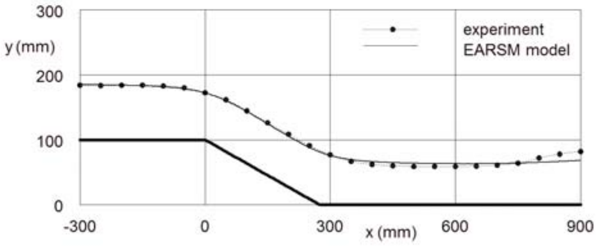

Fig. 8 The extent of the separation region and the form of the free surface for supercritical flow

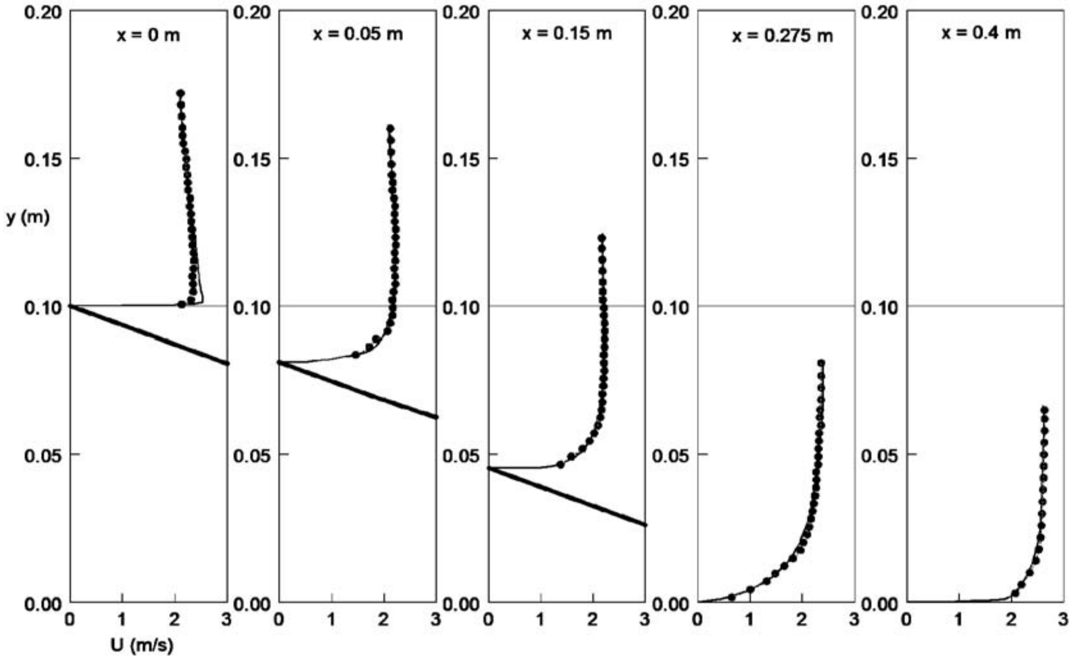

Fig. 7 Mean velocity profiles in the channel for the supercritical regime

The form of free surface in the middle plane is compared in Fig. 8 with experimental data. The supercritical flow over the inclined step is practically without any separation. The form of free surface imitates the bottom of the channel. The free surface is slightly waving behind the root of the step. Besides transversal waves, two distinct oblique waves arise at side walls. The form of free surface predicted by the EARSM model corresponds very well with experiment, even though the response of the numerical model on any change is rather slower than in reality.

4.3 Near-critical flow

The measurement of the free-surface flow near critical conditions was carried out with the slope of the bottom 0.16 deg for the mean bulk velocity $U_m = 0.97$ m/s and for the initial height of the water level $h = 0.056$ m, i.e. for the Reynolds number $Re = 101400$ and the Froude number $Fr = 1.31$. The turbulence level in the stream core was about 2.4 % at the inlet of the channel. The numerical simulation started for flow conditions corresponding to experimental results. For these conditions, the numerical simulation gives flow field corresponding to the supercritical flow. Mean longitudinal velocity profiles in the symmetry plane over the step are shown in Fig. 9. Velocity profiles obtained by the SST model are compared with experimental data from LDA measurements. It can be seen that a satisfactory agreement of predicted mean velocity profiles with experimental data was obtained for the supercritical flow except a short region behind the step edge.

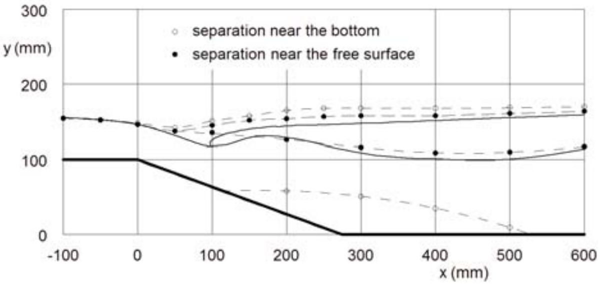

Fig. 10 Extent of the separation region and the form of the free surface for the near-critical flow (symbols as in Fig. 9)

The form of free surface and the extent of the separated region in the middle plane are compared with experimental data in Fig. 10. The free surface for both cases is very similar with a mild waving just behind the step edge only. For the flow regime with separation near the bottom, the separation region does not start at the step edge as for the subcritical flow but approximately at $x/H = 1.2$ and reaches up to $x/H = 5.2$. The extent of the back flow near the free surface in the supercritical case is much longer and separation region takes up to $x/H = 9$.

As the numerical simulation gives for these boundary conditions the supercritical regime only, the further simulation of the

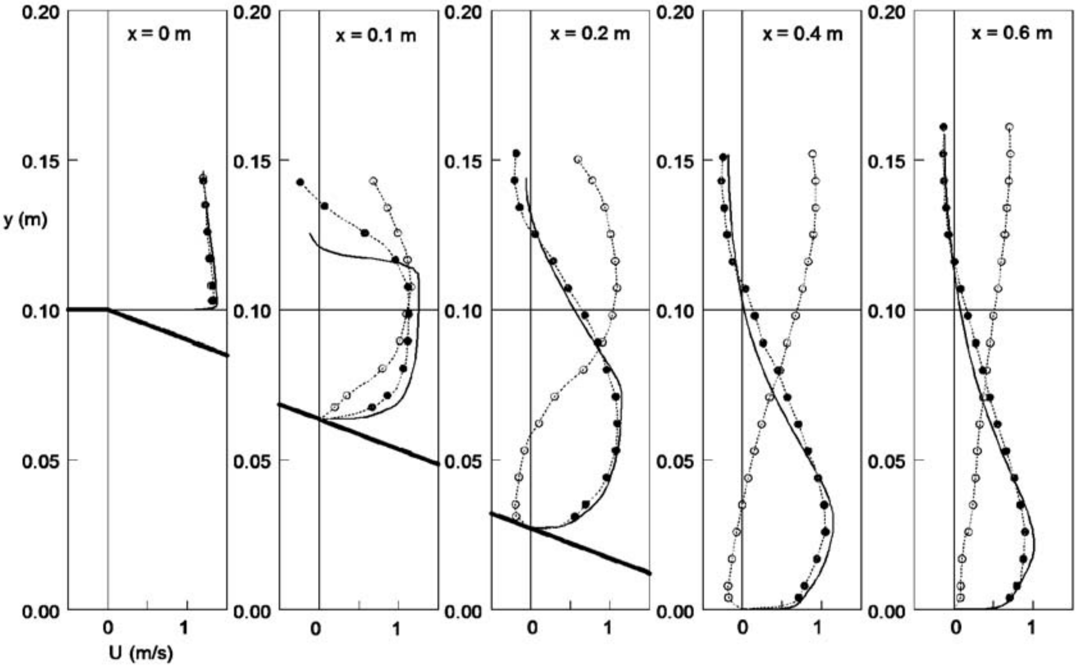

Fig. 9 Mean velocity profiles for the near-critical flow at $U_m = 0.97$ m/s (full line - SST model simulation, - supercritical regime - subcritical regime)

unsteady flow was realised for various inlet velocities. The critical regime with the transition from the supercritical to subcritical flow was achieved for the mean bulk velocity $0.78U_m$ corresponding to the Froude number $Fr = 1.02$. The simulation using the time step $\tau = 0.05$ s gives a periodic process with the period approx. 15 s. Unfortunately, the simulation of one second of the flow needs 5:45 hours of the computational time using the computational cluster with two parallel processors. Therefore the numerical simulation was limited to 55 sec, i.e. approximately 3½ periods of the process only.

Mean velocity profiles in the symmetry plane of the channel are shown for the mean bulk velocity $0.78U_m = 0.76$ m/s in Fig. 5. The flow regime is unstable starting with the supercritical character (time $t_o + 0.15$ sec) and switches to the subcritical character approximately after 39 sec (time $t_o + 39.15$ sec). Further, the process is periodic with the period about 15 sec (see full line for time $t_o + 46.15$ sec).

The character of mean velocity profiles for both regimes is very similar to experimental data obtained for the mean velocity U_m. Predicted extent of the separation region and the form of the free surface in the middle plane for the mean bulk velocity $0.78U_m$ are given in Fig. 5. The form of free surface is like the mean velocity profiles similar to the basic case with the mean velocity U_m but the extent of the separation region for both regimes is much longer. The separation near the bottom starts at approx. $x/H = 0.2$ while the separation near the free surface occurs at $x/H = 0.6$. The length of the separation region is approx. $x/H \approx 10$ for both regimes.

The character of the turbulent energy fields corresponds to mean velocity profiles. The level of turbulent energy is maximal in the mixing layer between the attached and back flow in all cases but the maximum of turbulent energy is approximately twice higher for the case with the separation near the free surface (supercritical regime) than for the case with separation near the bottom (subcritical regime).

5. Conclusions

Experimental and numerical investigation of turbulent flow over an inclined backward-facing step in an open channel was carried out for a wide range of flow conditions covering the subcritical, supercritical and near-critical regimes as well. The preliminary analysis of experimental and numerical results was concentrated mainly on the development of flow separation behind the inclined step and on the corresponding changes of free surface.

The subcritical free-surface flow over a backward-facing inclined step showed the complicated three-dimensional character of flow. The relatively long separation region occurs behind the inclined step while the free-level is slightly rippled only. Secondary flows arise behind the step edge near side walls partly close to the channel bottom and partly to the free-level. It follows from the testing of turbulence models that models based on the turbulent viscosity are not able to predict correctly the complicated flow pattern in this case. A satisfactory agreement with experimental data was obtained for the EARSM model only.

The supercritical free-surface flow is practically without any separation and free surface imitates the bottom of the channel. A very satisfactory agreement with experimental data was obtained for the EARSM model. Unlike the subcritical flow, the free surface of the supercritical flow is slightly waving behind the root of the step. Besides transversal waves, two distinct oblique waves arise at side walls. The predicted free surface corresponds very well with experiment, even though the response of the numerical model on any change is rather slower than in reality.

The critical regime with the abrupt change of the flow character from the supercritical flow to the subcritical flow was experimentally obtained for the mean bulk velocity $U_m = 0.97$ m/s corresponding to the Froude number $Fr = 1.31$. The supercritical regime with the separation near the free surface switches to the subcritical one with the separation near the bottom by a very small change of the velocity. The numerical simulation of the unsteady two-phase turbulent flow using the SST turbulence model gives for these conditions the flow field corresponding to the supercritical flow only. A satisfactory agreement of predicted mean velocity profiles with experimental data obtained by the LDA measuring technique was obtained for the supercritical regime except a short region behind the step edge. On the basis of the series of simulations of the unsteady flow for boundary conditions, the critical regime was determined for the mean velocity $0.78U_m$ i.e. for the Froude number $Fr = 1.02$. In this case the prediction gives the unstable flow regime starting the supercritical character and switches to the subcritical character approx. after 39 sec. Further, the process is periodic with the period about 15 sec. The character of the flow field for these boundary conditions is very similar to experimental data obtained for the nominal mean velocity. Nevertheless, the predicted extent of the separation region in both regimes with the separation near the free surface and near the bottom is noticeably longer than experimental results for the nominal velocity.

The presented results are the first attempt on the detailed experimental and numerical modelling of the two-phase turbulent flow over an inclined backward-facing step including the near-critical regime and be applied in the further research and in hydraulic applications.

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