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MODELLING OF SUPERCRITICAL TURBULENT FLOW OVER AN INCLINED BACKWARD-FACING STEP IN A OPEN CHANNEL

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Abstract: *The contribution deals with the experimental and numerical modelling of supercritical turbulent flow in an open channel with an inclined backward-facing step on its bottom. The step with the height h = 100 mm and the inclination angle $\alpha = 20^o$ was placed in the water channel of the cross-section 200x200 mm. Experiments were carried out by means of the PIV and LDA measuring techniques. Numerical simulations were executed by the commercial software ANSYS CFX 12.0. Numerical results obtained by the two-equation SST model and the EARSM model completed by transport equations for turbulent energy and specific dissipation rate were compared with experimental data. The modelling was concentrated particularly on the flow pattern near the step including the possible flow separation and the corresponding changes of free surface. The agreement of numerical results obtained by means of the EARSM model with experimental data is quite good.*

Keywords: *Backward-facing inclined step, free-surface supercritical flow.*

1. Introduction

An inclined backward-facing step occurs in many practical applications of aerodynamics and hydrodynamics. While the flow pattern behind the step in closed channels is given mainly by the extent of the separation, the flow over an inclined step in open channels is much more complicated. For flows in open channels with an inclined step, the flow character is quite different for sub- and supercritical flow due to the gravitational forces. The subcritical flow is characterized by a relatively massive separation but only small changes of free surface. On the contrary, the supercritical flow is practically without separation with changes of free surface corresponding to the form of the inclined step. Results of the investigation of turbulent flow over an inclined step in the closed channel and in the open channel with sub- and supercritical flow are summarized by Zubík et al. (2010). The subcritical flow over the inclined step was described by Příhoda et al. (2010). The presented contribution deals with modelling of supercritical flow characterised by the Froude number $Fr = 2.14$.

2. Experimental arrangement

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 2.025 deg corresponding to the chosen supercritical regime. 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 $Q = 7.2$ 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 particle image velocimetry method (PIV) was used for measurements of the velocity field in selected channel sections and the laser Doppler anemometry (LDA) for measurements of one and/or two velocity components in selected points of the flow field. The extended uncertainty guess of flow velocity determination at reliability level of 95% was less than 5% for LDA and 15% for PIV techniques.

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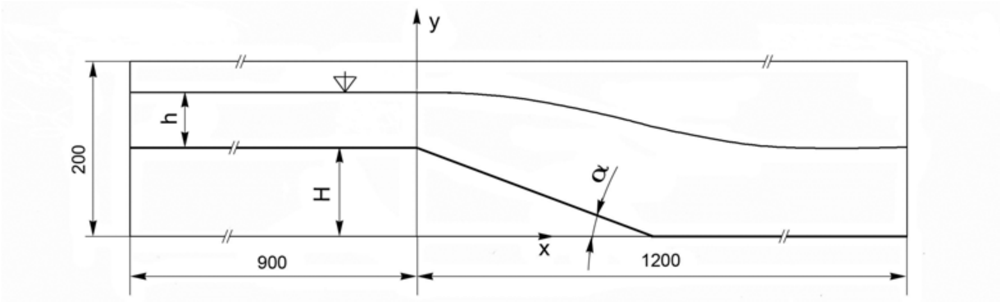

Fig. 1: Sketch of the geometrical arrangement.

The sketch of the geometrical arrangement of the channel with an inclined backward-facing step is given in Fig. 1. The height of the inclined step is H = 0.1 m. The PIV measurements were taken at vertical and horizontal planes parallel with the channel axis. For comparison, profiles of mean and fluctuation longitudinal velocities were measured by the LDA method in the mean vertical plane at selected sections x = const. The measurement of the supercritical free-surface flow was carried out 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 $Re_b = U_m H/\nu = 200100$ and the Froudé number $Fr = U_m/(gh)^{1/2} = 2.14$. At the chosen mean bulk velocity, the turbulence level in the stream core was about 2 %.

3. Mathematical model

The numerical simulation of the turbulent flow over the inclined step in an open channel was carried out 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 monitoring of the volume fraction 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 EARSM (Explicit Algebraic Reynolds Stress) model based on transport equations for turbulent energy k and specific dissipation rate ω was used for the supercritical flow. Besides, the SST k-ω model proposed by Menter (1994) was used for comparison.

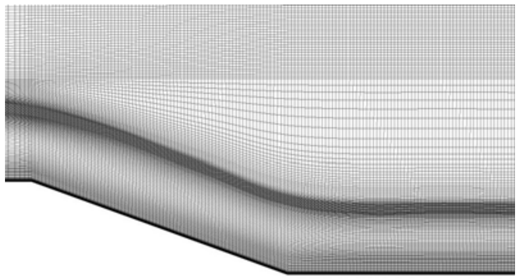

Fig. 2: Detail of the computational grid.

The computational domain corresponding to the experimental arrangement starts 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 computational domain consists of one half of the channel width with the symmetric boundary condition in the symmetry plane (z = 0). The computational grid in the channel with the inclines step is shown in Fig.2. A structured mono-block 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. The grid consists of 367×169×51 grid points, i.e. approx. 3.1×10^6 points. 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 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 models proposed by Wallin and Johansson (2000). The constitutive relation for the turbulent viscosity is replaced by the introduction of the anisotropy tensor a_{ij} by the relation

$$a_{ij} = \frac{\overline{u_i u_j}}{k} - \frac{2}{3}\delta_{ij} \tag{1}$$

The anisotropy tensor a_{ij} is given by the equation

$$\begin{aligned} a_{ij} &= \beta_1 S_{ij} + \beta_3 \left(\Omega_{ik}\Omega_{kj} - \frac{1}{3}\delta_{ij} II_{\Omega} \right) + \beta_4 \left(S_{ik}\Omega_{kj} - \Omega_{ik}S_{kj} \right) \\ &+ \beta_6 \left(S_{ik}\Omega_{kl}\Omega_{lj} + \Omega_{ik}\Omega_{kl}S_{lj} - \frac{2}{3}\delta_{ij} IV \right) + \beta_9 \left(\Omega_{ik}S_{kl}\Omega_{lm}\Omega_{mj} - \Omega_{ik}\Omega_{kl}S_{lm}\Omega_{mj} \right) \end{aligned} \tag{2}$$

where S_{ij} and Ω_{ij} are non-dimensional strain rate and vorticity tensors, and II_S, II_{Ω} and IV are their invariants. The coefficients β_i are functions of the ratio P_k/ε and invariants of the strain-rate and vorticity tensors. The model is closed by the transport equations for turbulent scales. The SST model is formed by transport equations

$$\frac{Dk}{Dt} = P_k - c_{\mu}\omega k + \frac{\partial}{\partial x_j}\left[\left(\nu + \frac{\nu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] \tag{3}$$

$$\frac{D\omega}{Dt} = \alpha \frac{\omega}{k} P_k - \beta\omega^2 + \frac{\partial}{\partial x_j}\left[\left(\nu + \frac{\nu_t}{\sigma_{\omega}} \right) \frac{\partial \omega}{\partial x_j} \right] + \left(1 - F_1 \right) \frac{2}{\sigma_{\omega 2}} \frac{1}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j} \tag{4}$$

with turbulent viscosity given by the relation

$$\nu_t = \frac{a_1 k}{min\left(a_1\omega ; F_2 S \right)} \tag{5}$$

where F_1 and F_2 are blending function for the switching from the k-ε mode to the k-ω mode and S is a scalar invariant of the strain rate tensor. The function F_2 is equal to zero everywhere for the standard k-ω model.

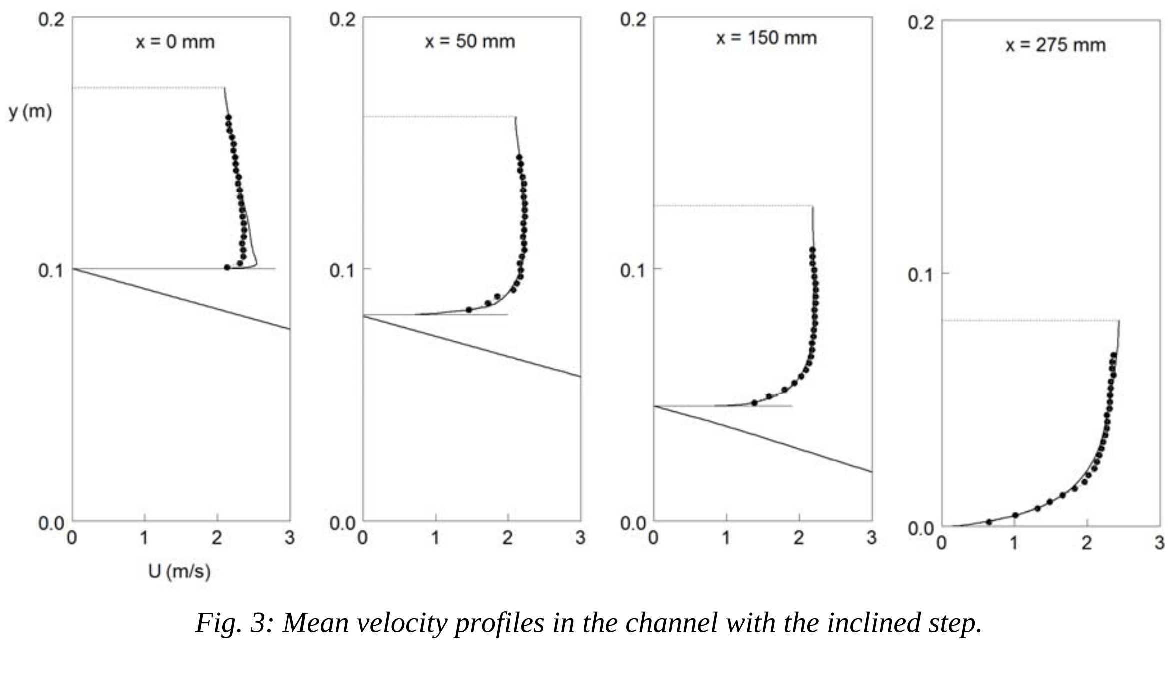

Fig. 3: Mean velocity profiles in the channel with the inclined step.

4. Results

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

The form of free surface in the middle plane z = 0 and in the plane z = -85 mm near the side wall are compared in Fig. 4 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.

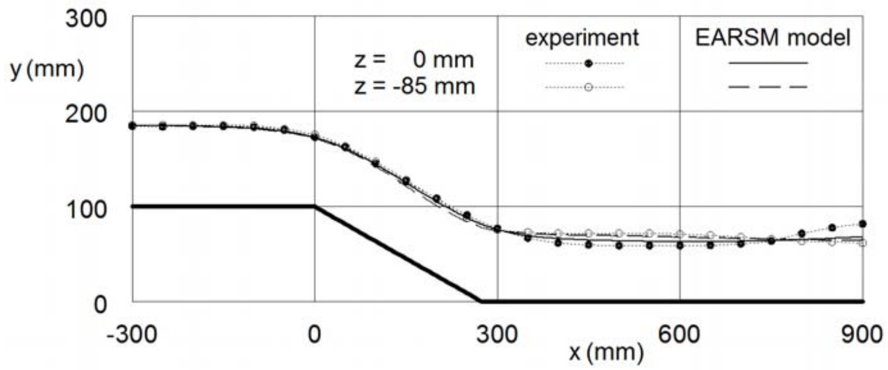

Fig. 4: The form of the free surface in planes z = 0 and -85 mm.

5. Conclusions

The supercritical free-surface flow over a backward-facing inclined step in a rather narrow channel was experimentally and numerically investigated. The flow over the inclined step 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.

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