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INFLUENCE OF THE PATTERNED SURFACES ON THE FLOW SPECTRUM AROUND THE IMMERSED BODIES

BY

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Abstract. The paper is dedicated to the experimental and numerical studies of the free surface flows around immersed bodies (a cylinder and a broad – crested weir) with smooth and patterned surface. The study analyses the qualitative differences between the smooth and patterned surfaces of the immersed bodies, as function of the immersed depths for weakly turbulent flows ($Re < 10^4$) in subcritical regimes ($Fr < 1$). The results indicate that presence of a grooved geometry with small aspect ratio on the surface of the bodies changes the flow spectrum in the vicinity and downstream the separation of the shear layers.

Keywords: immersed cylinders; broad – crested weir; visualizations flow; numerical simulations; grooved geometry.

1. Introduction

The dynamics of the flow around immersed bodies in a channel with free surface is an important topic of study in hydrology, hydraulics, in the design of water turbines plant, marine platforms and inflatable dams. The characterization of the flow over the immersed bodies becomes recently a

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subject of interest also for some other domains of fluid mechanics as microfluidics and complex flows in presence of microstructures (Sheridan *et al*., 1995; Lee and Daichin, 2004; Rahimzadeh *et al*., 2012; Chamorro *et al*., 2013).

The flow is characterized by the non-dimensional Reynolds, respectively Froude numbers:

$$Re = \frac{\rho L V_0}{\eta}, \; Fr = \frac{V_0}{\sqrt{g L}}. \tag{1}$$

where $\rho = 1000$ kg/m^3 is mass density, $\eta = 1$ mPas is the viscosity, V_0 is the average velocity upstream the broad - crested weir, g is the gravitational acceleration and L is the space scale ($L \equiv D$, D is the cylinder diameter, respectively L is the length of broad-crested weir).

The flow takes place in subcritical weakly turbulent regime, characterized by the Froude number less than one and Reynolds number less than 10^4. Numerical simulations are performed with the turbulent solvers implemented in FLUENT, using the VOF code for the calculation of the free surface geometry. The numerical results and the visualizations are corroborated to determine the influence of micro - geometries, especially in the region between the free surface and the separation point. The evolution of the wake downstream the bodies and the onset of Kelvin-Helmholtz instabilities are also investigated for the smooth and grooved geometries.

The experimental investigations were focused to the region between the free surface and the domain downstream the bodies. The positions of the upper and lower separation points of the boundary layer from the cylinder and the wake trace were the main experimental characteristics compared with the numerical results.

2. Experimental Set-up

The experiments are performed in a free surface transparent water channel, which is connected to a constant level water supply tank. The flow rate and the fluid height upstream the body are controlled by a weir. The average velocity V_0 is computed (from the measured flow rate) for the upstream area for the height H_0 which is maintained constant. The bodies are located at the distance 303 mm from the entrance section, for details see (Tănase, 2013; Tănase *et al*., 2014a; Tănase *et al*., 2014b; Tănase *et al*., 2015).

The dimensions of the broad – crested weir are: $L = 70$ mm, height 35 mm and the cylinder diameter is $D = 50$ mm. Visualizations of free surface flow and the measurements are performed at different constant entrance water levels H_0 and the constant height of the weir h_w, Fig. 1.

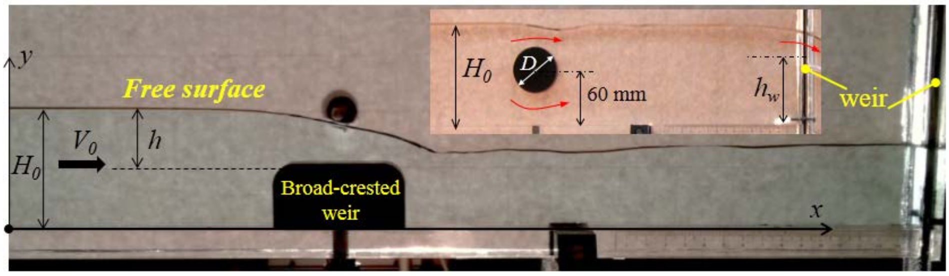

Fig. 1 – The geometry of the experimental channel of 15 mm width, cylinder diameter D = 50 mm and length broad-crested weir of L = 70 mm.

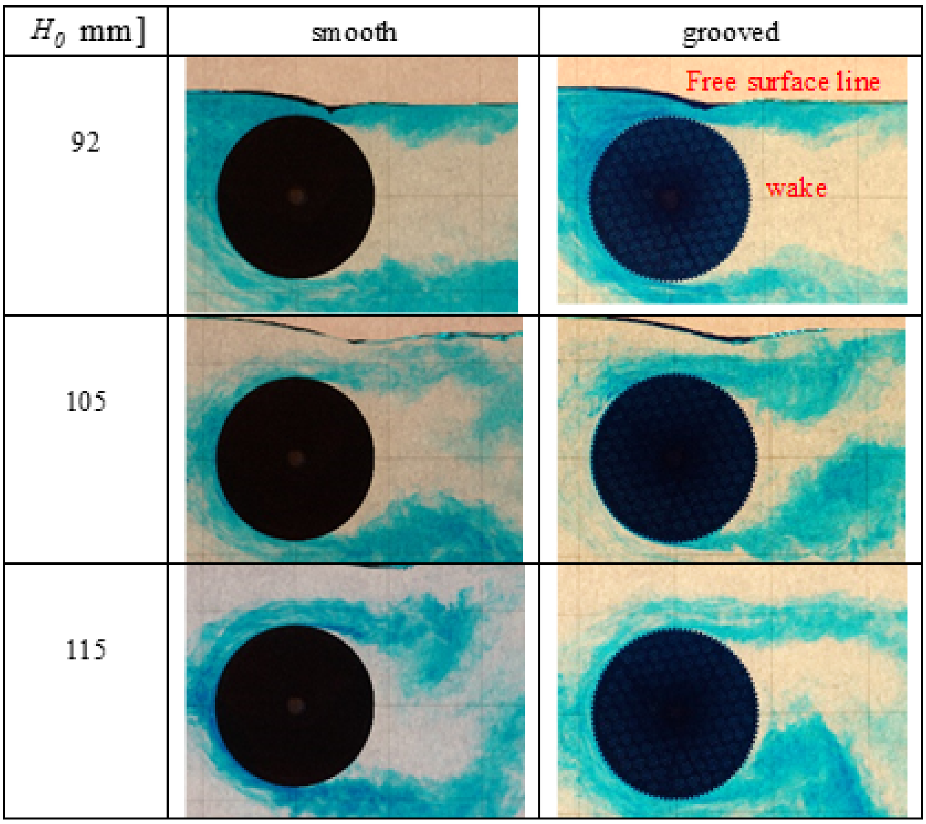

Fig. 2 – Flow visualizations around immersed smooth and grooved cylinders at different immersed depths H_0.

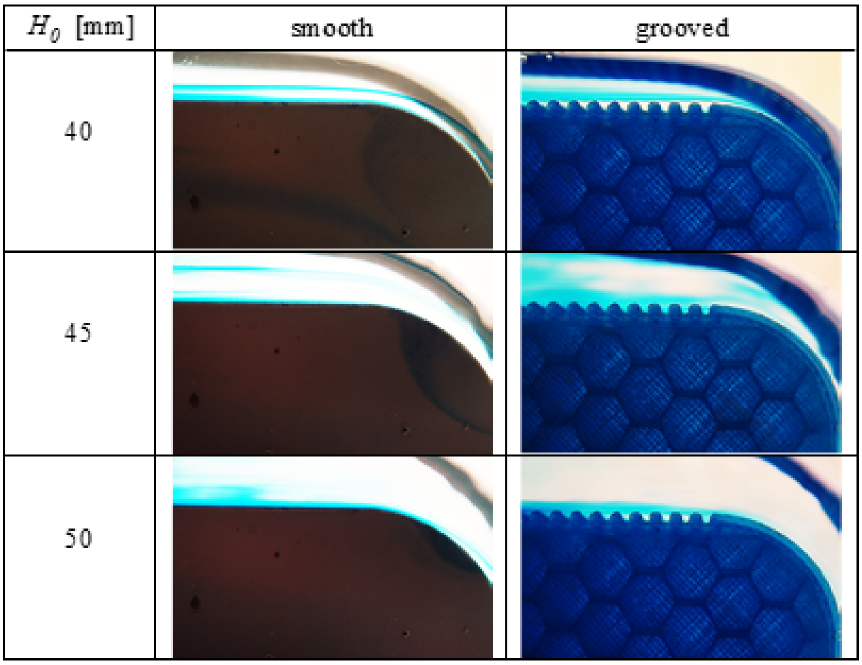

Fig. 3 – Flow visualization of the smooth and grooved surfaces of the broad - crested weir at different immersed depths H_0 .

A color dye was introduced upstream the immersed obstacle and the direct visualization of the streak lines is obtained using a performed SONY digital camera at a rate of 12 images/s, see Figs. 2 and 3. Macro lens and high resolution up to 25 MP are used to take picture of the flow in vicinity of the bodies with grooved surfaces (which were fabricated by the 3D printing technology).

3. Numerical Simulations

The free surface flow around cylinders and weirs (smooth and grooved surfaces) were investigated also numerically at constant height H_0 ($H_0 = 105$ mm for cylinders and $H_0 = 50$ mm for weirs, which corresponding to the velocity $V_0 = 0.15$ m/s, respectively $V_0 = 0.05$ m/s). Simulations are performed in a 2D and 3D geometry of the channel using structured mesh, see Table 1 and Fig. 4. All dimensions from the experiments are identical to both 2D and 3D numerical simulations ($D = 50$ mm, $L = 70$ mm). The turbulence model used for the numerical simulations of free surface flow around an immersed smooth cylinder was k - ε RNG (options Differential Viscosity

Model) with the VOF method to compute the free surface (Launder and Spalding, 1972; Broboană *et al*., 2007; Fluent Inc., 2008).

The entrance boundary condition is linear pressure distribution $p = \rho g y$, $0 \le y \le H_0$, with the exit constant atmospheric pressure imposed, $p = p_0$ and the adherence conditions on the cylinder/weir and the lower wall: $\mathbf{v} = 0$ (Tănase *et al*., 2014b). The flows are considered steady; no influence of surface tension was analyzed in these cases.

The numerical simulation are performed on a 64-bit server Dual 2.33 GHz with 16 GB RAM memory, the computation time for each 2D case being around 2 days and for 3D case around 4 days, for a precision of 10^{-5}.

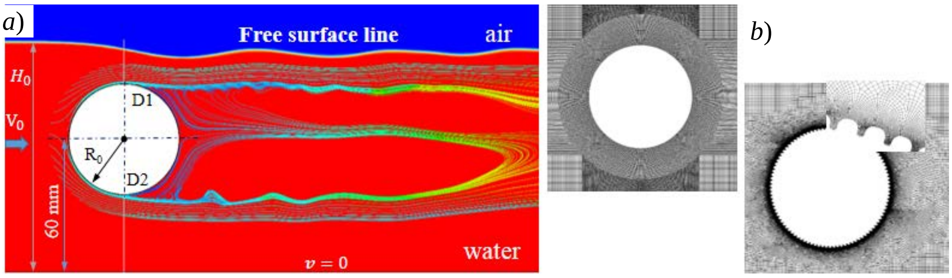

Fig. 4 – *a*) Numerical working domain, initial phases configurations, *b*) structured mesh in vicinity of the cylinder. Similar qualitatively meshes are used of the simulations around the weirs.

Table 1
The Mesh Characteristics of the 3D in Comparison with the 2D

Case	Cells	Faces	Nodes
3D cylinder	2.298.888	7.118.685	2.522.435
2D cylinder	638.436	1.270.606	632.170

The obtained 3D solutions are stable but the comparison with experiments doesn't emphasis a better fitting and representation of experiments than the 2D case, see Figs. 5 and 6. This result is consistent with the experimental conditions and observations: the width of the flow channel is relatively small in comparison to the other dimensions, so the parallel lateral walls induce a pseudo-planar motion in the region where the body is located. On the other hand, the performed 3D simulations are limited by the available computations machines on the number of nodes, so it we expect a lower precision of the computations.

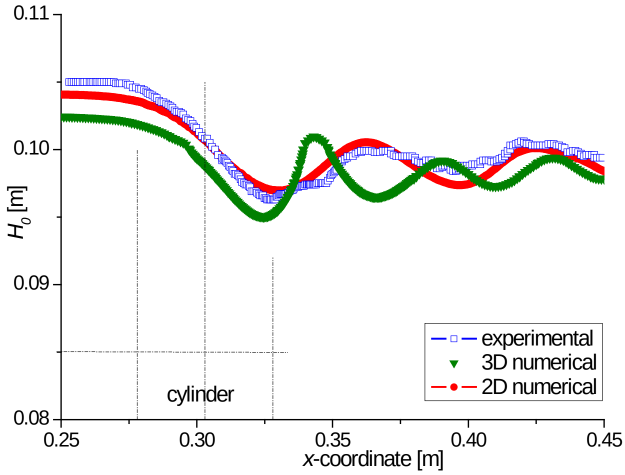

Fig. 5 – Comparison of the average measured experimental free surface with the 2D and 3D steady solutions.

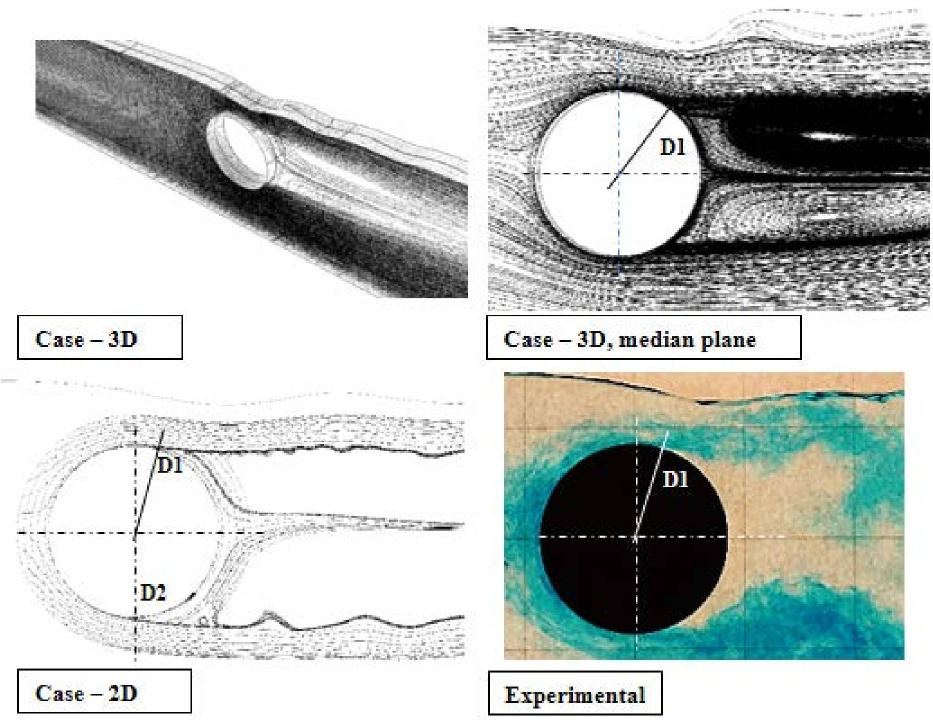

Fig. 6 – Flow spectrum in the 3D and 2D computations. It is observed that separation point D1 is located for the 3D solution at larger angle than for 2D case (which gives almost the same value as in experiments), $\theta_{2D} = 106°$, $\theta_{3D} = 110°$, $\theta_{\exp} = 107°$.

The analysis of the numerical results (free surface profile, location of separation points, wake structure) in relation to the experiments visualization concludes that 2D geometry is more indicated to simulate the flow under investigation.

The numerical spectrum is computed (for the same geometry and flow conditions) and the results are compared and calibrated with the experimental flow patterns, for both smooth and grooved geometries.

The computed free surface lines are compared with the experimental free surface line in Fig. 7. One can be noticed that experimental free surface line upstream of the cylinder is perfectly reproduced numerically, for details see (Tănase *et al*., 2014b).

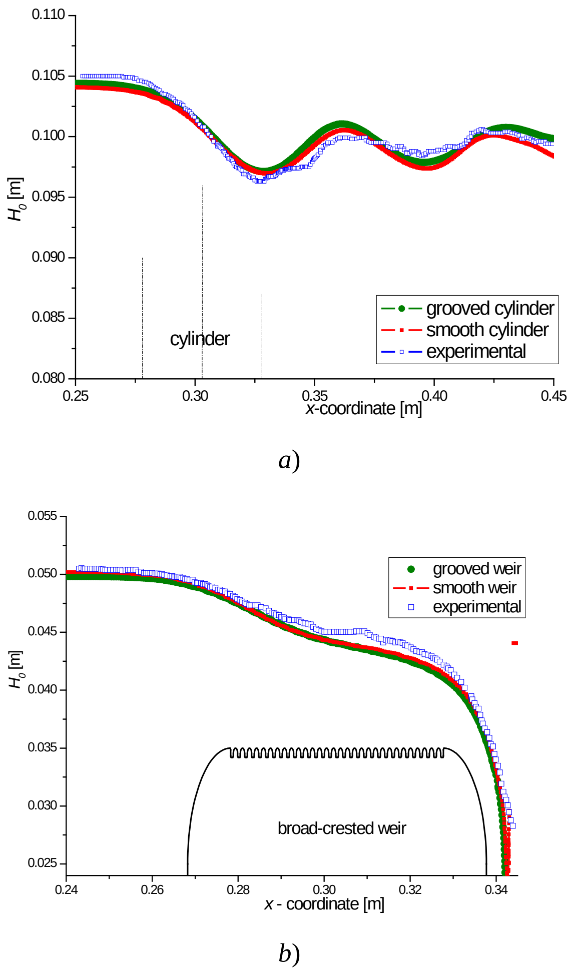

Fig. 7 – Comparison of the experimental free surface line with the numerical solutions for the both surfaces of the bodies: (*a*) cylinders and (*b*) weirs.

The free surface lines in the vicinity of the immersed bodies are almost identical for both types of surfaces, but qualitative differences in formation of Kelvin-Helmholtz instabilities are observed between smooth and grooved surfaces, Fig. 8. The patterned surface influences also the separation point position and consequently the drag force acting on the immersed bodies, (El-Makdah and Oweis, 2013).

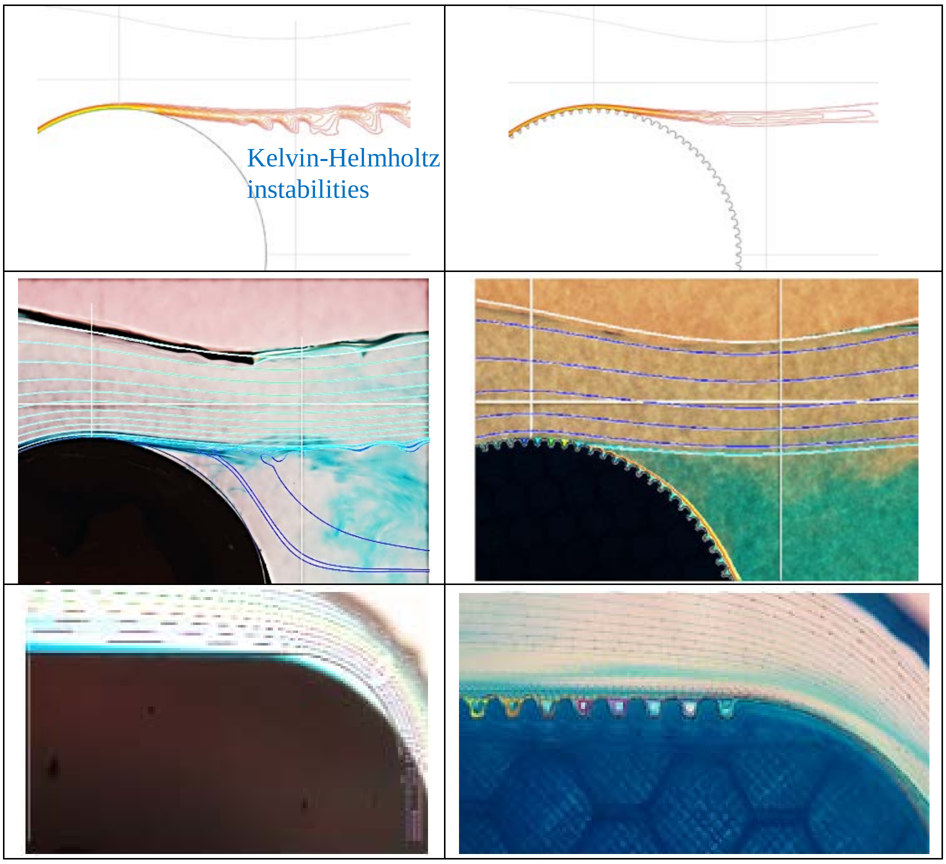

Fig. 8 – Comparison between smooth and grooved bodies: experimental and computed flow spectrum.

At the end, the numerical solutions are used to obtain value information about the flow in the vicinity of the bodies, including the influence of the wall micro-geometry on the location of the boundary layer detachment and the downstream wake formation, Fig. 9.

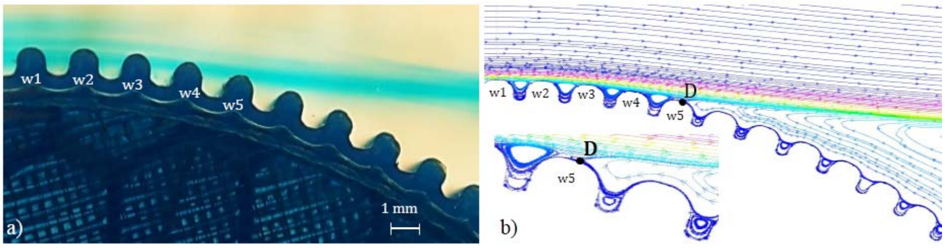

Fig. 9 – The visualisation (a) and computations (b) of the boundary layer detachment from the patterned immersed cylinder.

4. Conclusions

1. The results of the study are very promising and open the possibility to investigate in more details the influences of various forms of micro - geometries on the drag force of the immersed bodies.

2. The control of boundary layer by patterned surface is an old direction of study in fluid mechanics, but the applications of the topic in the free surface hydrodynamics are very actual.

3. Further numerical and experimental studies will be focused on two main directions: (*i*) optimize the numerical flow computation in the neighborhood of the patterned walls, (*ii*) perform experiments on immersed bodies with different micro-geometries.

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INFLUENȚA SUPRAFEȚELOR STRUCTURATE ASUPRA SPECTRULUI CURGERII DIN VECINĂTATEA CORPURILOR IMERSATE

(Rezumat)

Lucrarea prezintă studiul experimental și numeric al curgerii cu suprafață liberă în jurul corpurilor imersate (cilindru și deversor cu prag lat). Scopul principal al lucrării este studiul influenței microgeometriei suprafeței corpurilor imersate, în funcție de adâncimea la care sunt imersate acestea pentru curgerea tranzitorie – turbulentă ($Re < 10^4$) în regim subcritic ($Fr < 1$) asupra spectrului curgerii și poziției punctului de desprindere a stratului limită.