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VISUALIZATION OF FLOW PAST VERTICAL CYLINDER IN SHALLOW WATER

Katarzyna STRZELECKA[1], Henryk KUDELA[1]
[1]*Wroclaw Univeristy of Technology, Wroclaw, Poland*
E-mail: katarzyna.strzelecka@pwr.wroc.pl

Abstract

It is known from the literature (e.g. Seal and Smith, 1999) that vortex structure above the plate can lead to the eruption of boundary layer. It seems that similar phenomenon was observed behind a vertical cylinder placed in shallow water.

Vortex formation from a vertical cylinder in shallow water was investigated using visualization by dye marker. The vertical cylinder D = 14,65 mm in diameter was separated from the entrance to the test section and located at a distance of 1000 mm from it to ensure the fully formed velocity profile. Previous investigations of flow past a vertical cylinder placed in shallow water were carried out for low values of h_w/D, where h_w is the water depth in the test section, e.g. $h_w/D << 1$ (Chen and Jirka, 1995) or $h_w/D = 0,5; 1; 2$ (Akilli and Rockwell, 2002).

In the paper investigations for h_w/D changing in the range of 0,8÷4,8 for various mean velocity and various Reynolds number were carried out. Formation of three-dimensional vortex structure in the near-wake region was observed by dye visualization. It was noticed that the size, shape and evolution of this vortex structure depend on h_w/D and mean velocity.

Key words: cylinder, near-wake, shallow water

INTRODUCTION

Previous investigations of flow past a vertical cylinder placed in shallow water were carried out for low values of h_w/D (h_w is the water depth in the test section), e.g. $h_w/D << 1$ (Chen and Jirka, 1995) or $h_w/D = 0,5; 1; 2$ (Akilli and Rockwell, 2002). Chen an Jirka conducted extensive experimental researches for the case where the cylinder diameter D greatly exceeded the water depth. They described three basic categories of flow patterns of the near-wake: shedding of Karman-type vortices, an unsteady wake bubble and a steady wake bubble. Akilli and Rockwell carried out investigations using a combination of visualization marker and a technique of high-image-density particle image velocimetry. They presented visualization results of vortex formation past cylinder for relatively low velocities in test section in the range of u_{min} = 20,0 mm/s up to u_{max} = 25,0 mm/s, that was resulting in the Reynolds number (based on water depth: $Re = u \cdot h_w/\nu$) from about Re_{min} = 500 up to Re_{max} = 2500.

Both authors mentioned above and also the others referred to the problem of flow past cylinder in shallow water (e.g. Chen and Jirka, 1997; Fu nad Rockwell, 2005; Kahraman et al., 2002) didn’t investigate the vortex interaction with boundary layer and the boundary layer eruption. The phenomenon of nonstationary separation of a boundary layer leading to the eruption of fluid elements from the wall neighbourhood to the main flow was a subject matter of other researchers (e.g. Kudela and Malecha, 2006; Kudela and Malecha, 2007).

To put more light into the process of formation and development of the vortex past vertical cylinder in shallow water flow and its interaction with the boundary layer authors of this paper decided to widen experiments especially on greater values of dimensionless water depth h_w/D. Present researches were conducted for $h_w/D \in 0,8 \div 4,8$ for various mean velocity changing in the range of u = 6,00 mm/s to u = 35,0 mm/s and various Reynolds number from about Re = 370 up to Re = 2400.

EXPERIMENTAL SETUP

Experiments were conducted in water channel. Schematic of experimental setup working in closed circle was shawn in Fig. 1. In order to clean water in a system part or whole mass of the water can be exchanged. It is significant when carrying out visualization by dye marker researches as coloring water can lead to gradual loss of contrast in recorded images.

Water is pumped from bottom reservoir (BR) by one, two or three pumps (P_1, P_2, P_3) – depending on the required flow rate, than it flows through the filter (F), rotameter (system is equipped with four rotameters of measuring ranges: $R_1 \rightarrow 2 \div 19$ l/h, $R_2 \rightarrow 18 \div 180$ l/h, $R_3 \rightarrow 170 \div 1700$ l/h, $R_4 \rightarrow$ 1500-15000 l/h), pressure vessel (PR) to damp pressure fluctuation (coming from pumps) and flow regulating valve (FRV) to inlet collector (IC). End of the pipe supplying the inlet collector is perforated and placed inside the collector to avoid excessive disturbances.

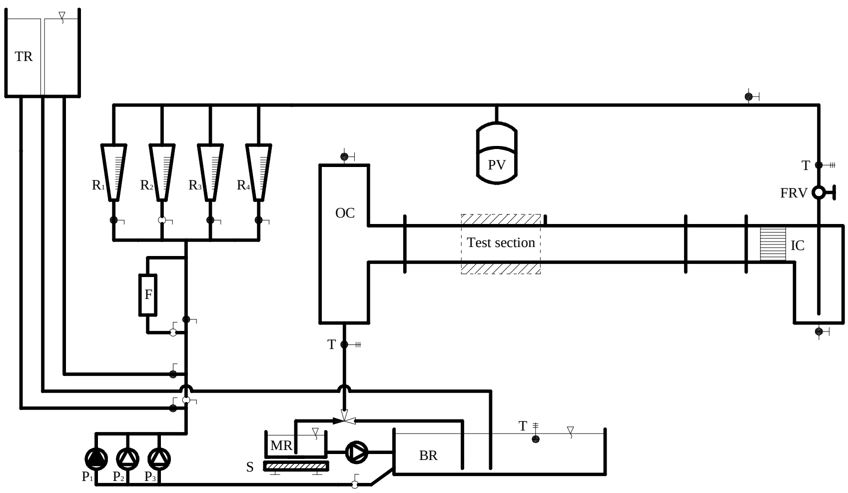

Fig. 1. Schematic of experimental setup

Rotameters fulfills the role of indicators. The accurate volumetric flow rate is done by mass measurement method. For low flow rates water is directed from the bottom reservoir (BR) to the top reservoir (TR), where the liquid level is fixed by overfall, than it flows through the rotameter (R) and flow regulating valve (FRV) to the inlet collector (IC). Next water inflows to the section consisting of two packets of drinking straws (5 mm in diameter) when disturbances are reduced. The length of each packet was determined in conformity with PN-93/M-53950. Then water flows through the Witoszynski nozzle behind which uniform velocity profile is formed. Next the liquid inflows to the test section.

The main test section built of plexi is 100 mm in depth, 100 mm in width and 2000 mm in length. Next water outflows to the outlet collector (OC), measuring reservoir (MR) placed on scales (S) to determine the flow rate by mass method and finally to bottom reservoir (BR). Temperature of the liquid is measured in three points: at inflow to the inlet collector (IC), at outflow from the outlet collector (OC) and in bottom reservoir (BR).

Vortex formation from a vertical cylinder in shallow water was investigated using visualization by dye marker. The vertical cylinder D = 14,65 mm in diameter was separated from the entrance to the test section and located at a distance of 1000 mm from it to ensure the fully formed velocity profile. Schematic of test section for shallow water (h_w – the water depth) experiments is shown in Fig. 2. The dye injection was placed in the base of cylinder and carried out by means of infusion pump. Letting in the dye marker is schematically presented in Fig. 3.

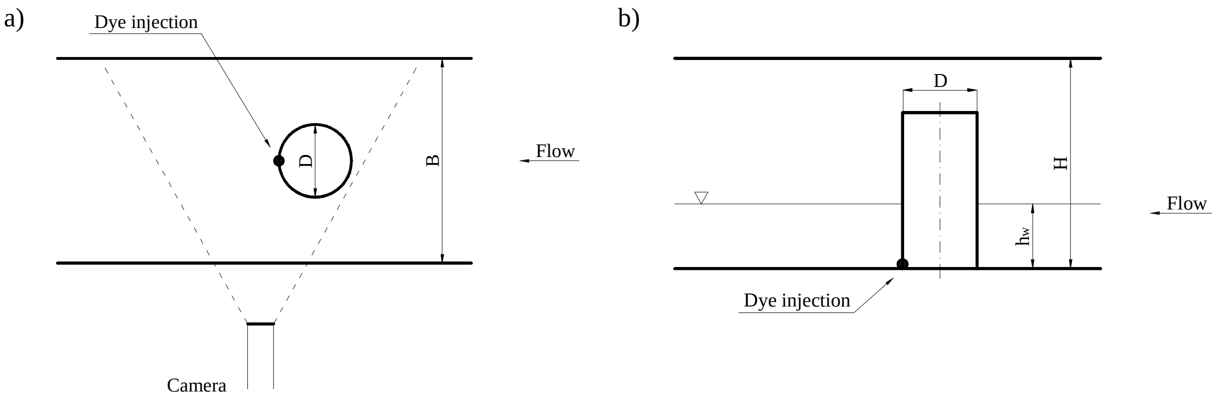

Fig. 2. Schematic of test section for shallow water experiments: a) plan view, b) side view

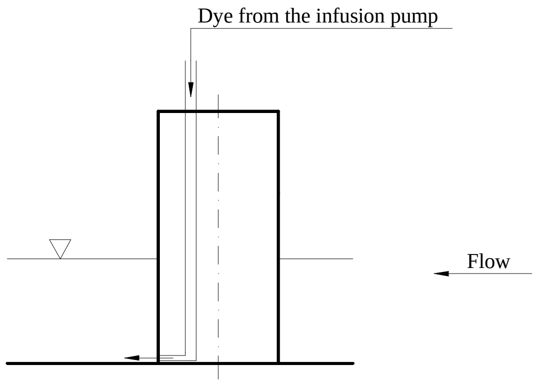

Fig. 3. Schematic of the dye marker letting in

VISUALIZED FLOW STRUCTURES

Insight into the process of vortex formation between the bottom surface and the free surface was acquired using dye visualization as described above. Experiments were carried out first for constant Reynolds number based on the water depth ($Re = u \cdot h_w/\nu$) then mean velocity in test section was kept constant. Both cases were done for various dimensionless water depth h_w/D in the range of 0,82÷4,78. Schedule of researches is presented in table 1.

Table 1. Schedule of experiments

h_w/D	u	Re
-	mm/s	-
0,82	35,4	440
1,43	20,0	
2,05	14,0	
2,80	10,2	
4,44	6,45	
4,78	6,00	
0,82	30,0	370
1,43		680
2,05		1000
2,80		1400
4,44		2200
4,78		2400

Images of visualization for constant Reynolds number

First part of investigations referred to flows with approximately constant Reynolds number Re = 440.

For all analysed images of flow for relatively low values of dimensionless water depth h_w/D = 0,8; 1,43 and 2,05 (presented in Fig. 4) the dye rapidly spread along the bottom surface of the test section and, as vortex was formed, it swept across the plane of symmetry of cylinder, over the layer of dye. Next the three-dimensional roll-up of the dye marker between the bottom and the free surface yields a vortex structure. The vortex structure is extended from the bottom to the free surface. It is evident on the left-hand side of each image.

It is apparent that the dye is rapidly displaced from the bottom area (e.g. Fig 4g) and afterwards moved inside the vortex. It seems that this vortex structure lead to the eruption of a boundary layer.

For all discussed images for $h_w/D = 0{,}8 \div 2{,}05$ the vortex structure is formed, next it loses its symmetric shape, then it promptly reconstructs itself and returns to the symmetry. Thread of dye pulls from the vortex structure and is taken away by the main stream.

It was observed, that for h_w/D = 0,8 the vortex moves continuously (waves) in direction of cylinder and then in direction of the main flow. It takes large quantity of dye marker from the bottom surface and is clearly placed behind the cylinder.

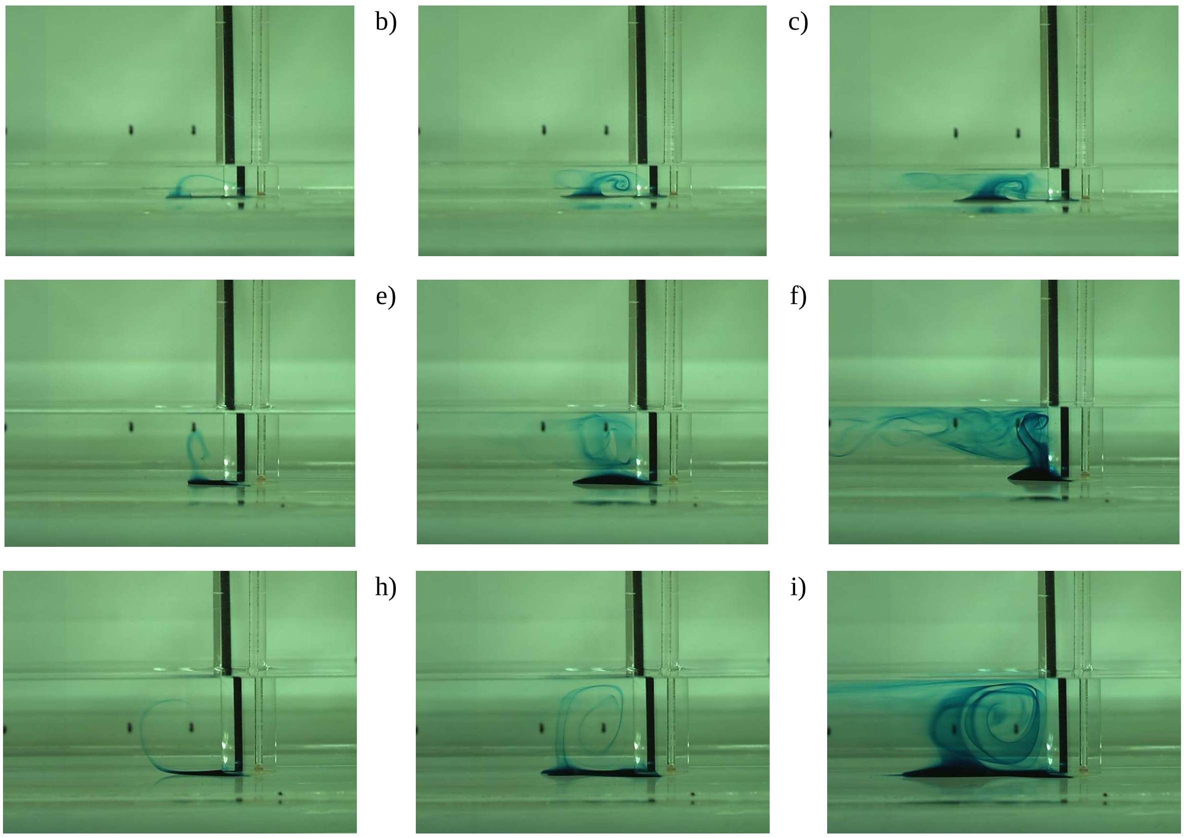

Fig. 4. Exemplary images of the near wake region, Re = 440, side view:
a) h_w/D = 0,82 – vortex formation, b), c) h_w/D = 0,82 – vortex evolution,
d) h_w/D = 1,43 – vortex formation, e), f) h_w/D = 1,43 – vortex evolution,
g) h_w/D = 2,05 – vortex formation, h), i) h_w/D = 2,05 – vortex evolution.

Increase of the dimensionless depth to h_w/D = 1,43 results in “sticking” the vortex structure to the back side of the cylinder. It hits the cylinder, loses symmetric shape and then it regenerates itself. Area where the dye marker circulates (just under the free surface) and area where the dye marker creeps in the wall of cylinder (between the bottom and approximately the half of water depth) are formed. The dye marker doesn't spread along the tunnel bottom, it is directed upwards and then ejected to the main flow.

Symmetric vortex structure of a large diameter was observed for h_w/D = 2,05. It is extended between the bottom and the free surface, oblate under the water surface.

Further increase of the dimensionless water depth (Fig. 5) results in spreading of the dye marker along the bottom surface in the direction of flow. It isn't taken from the bottom to the vortex structure and further to the main flow so intensively. Vortex structure is spread between the bottom and the free surface only for h_w/D = 2,8 (Fig. 5 a-c), it occupies significantly smaller area for higher values of h_w/D. For h_w/D = 4,44 and 4,78 the dye marker still rotates in the direction of cylinder and flows down along the back side of cylinder. The vortex structure stays closer to the bottom but constantly takes the dye marker from the bottom surface (e.g. Fig. 5 e-f).

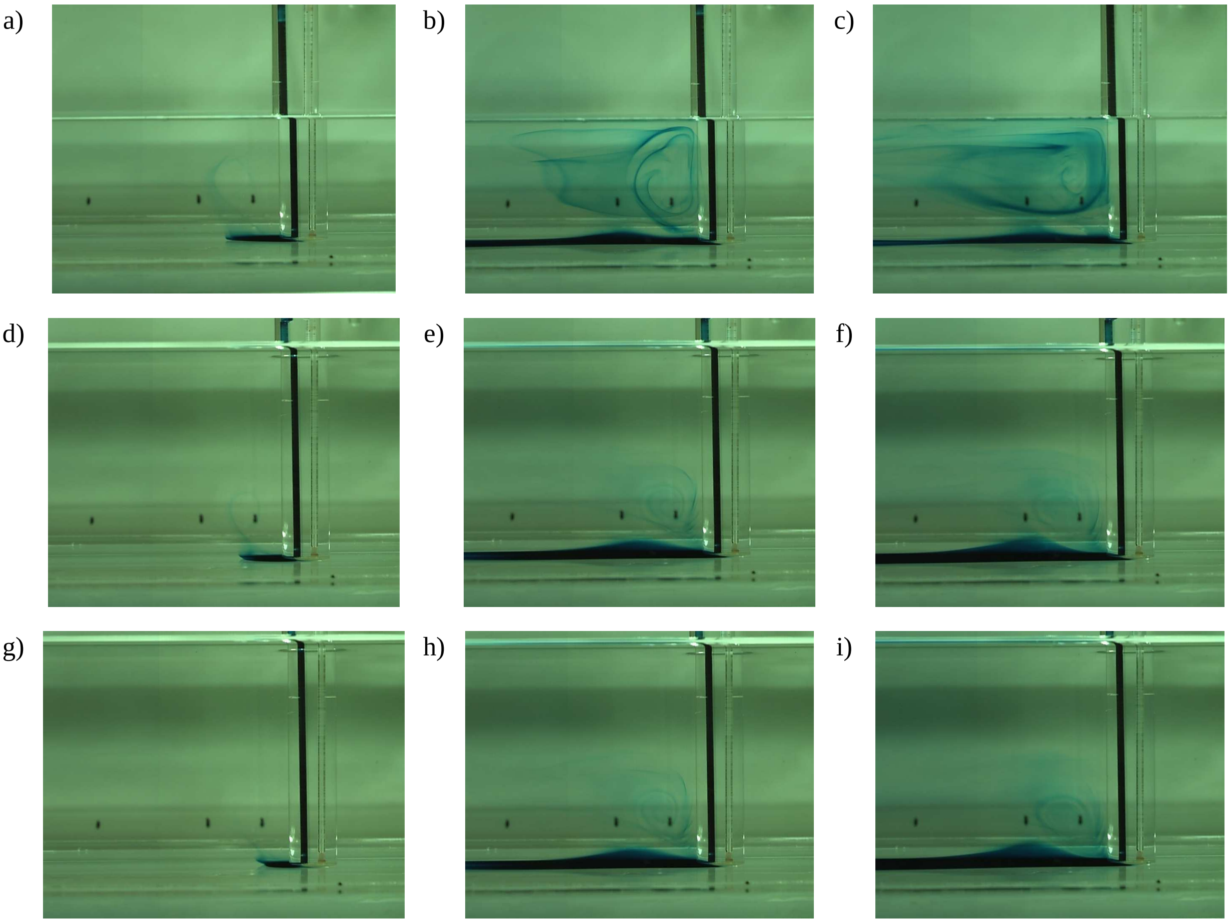

Fig. 5. Exemplary images of the near wake region Re = 440, side view:
a) h_w/D = 2,80 – vortex formation, b), c) h_w/D = 2,80 – vortex evolution,
d) h_w/D = 4,44 – vortex formation, e), f) h_w/D = 4,44 – vortex evolution,
g) h_w/D = 4,78 – vortex formation, h), i) h_w/D = 4,78 – vortex evolution.

Images of visualization for constant mean velocity

Results for experiments referred to flows with approximately constant mean velocity in test section u = 30,0m/s are presented in Fig. 6-8.

Images for h_w/D = 0,8 are similar to those observed for Re = 440 (Fig. 4a, Fig. 6a). It is connected with slight change of mean velocity in test section. The vortex structure is formed at a relatively large distance from the cylinder, turns in the direction of a body, but it doesn't creep in the wall of cylinder. Thread of dye pulls from the vortex structure and is taken away by the main stream (Fig. 8a).

For h_w/D = 1,43 and 2,05 the dye marker is taken from the bottom surface by the vortex structure and then almost immediately thrown to the main flow (Fig. 8b). The vortex structures moves continuously (waves) in direction of cylinder and then in direction of the main flow, it loses and recovers symmetry regenerating all the time. Stable clear vortex isn't possible to be observed here as it was for lower values of the mean velocity in test section.

It is difficult to observe the clear vortex behind the cylinder for h_w/D upwards of 2,05 and mean velocity u = 30,0mm/s (Fig. 7). The dye marker is rapidly displaced from the boundary layer in the direction of the free surface then it flows down along the cylinder and is dissipated by the main stream of water before reaching the bottom again.

a) b) c) d) e) f) g) h) i)

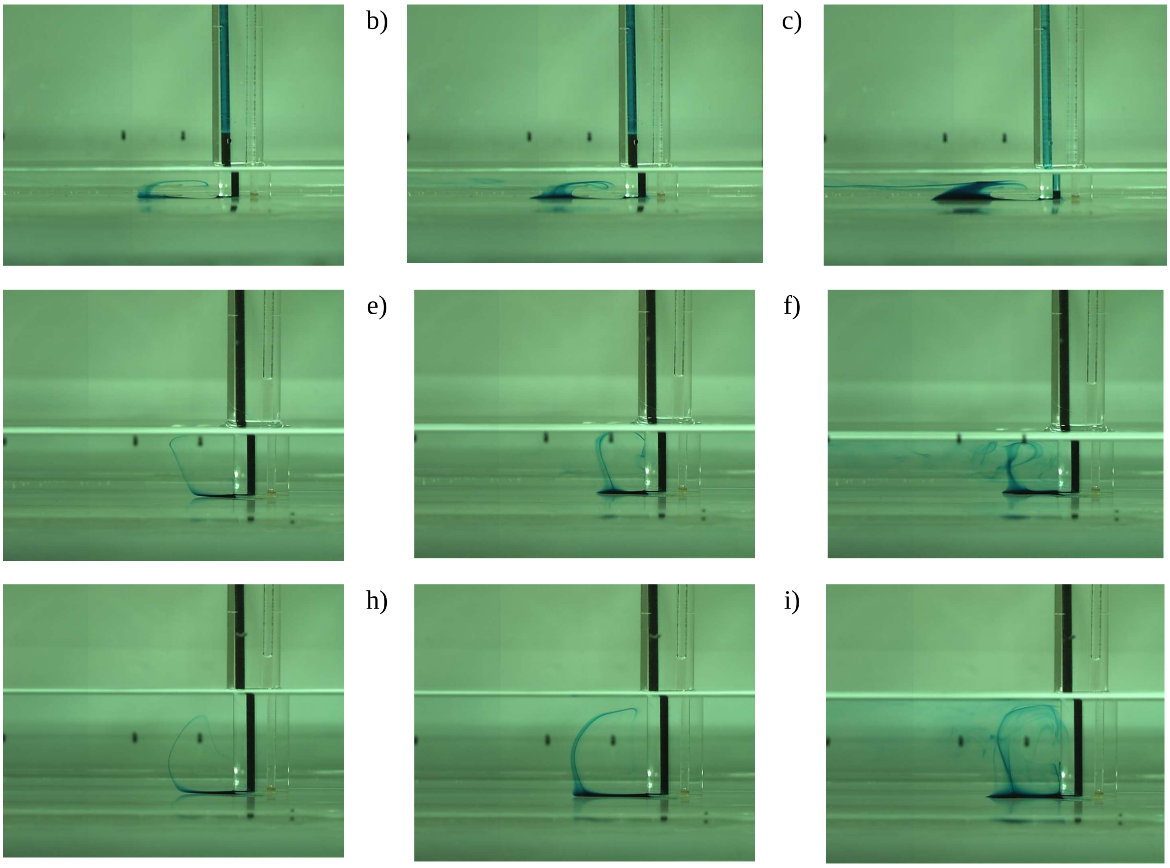

Fig. 6. Exemplary images of the near wake region, u = 30,0mm/s, side view:
a) h_w/D = 0,82 – vortex formation, b), c) h_w/D = 0,82 – vortex evolution,
d) h_w/D = 1,43 – vortex formation, e), f) h_w/D = 1,43 – vortex evolution,
g) h_w/D = 2,05 – vortex formation, h), i) h_w/D = 2,05 – vortex evolution.

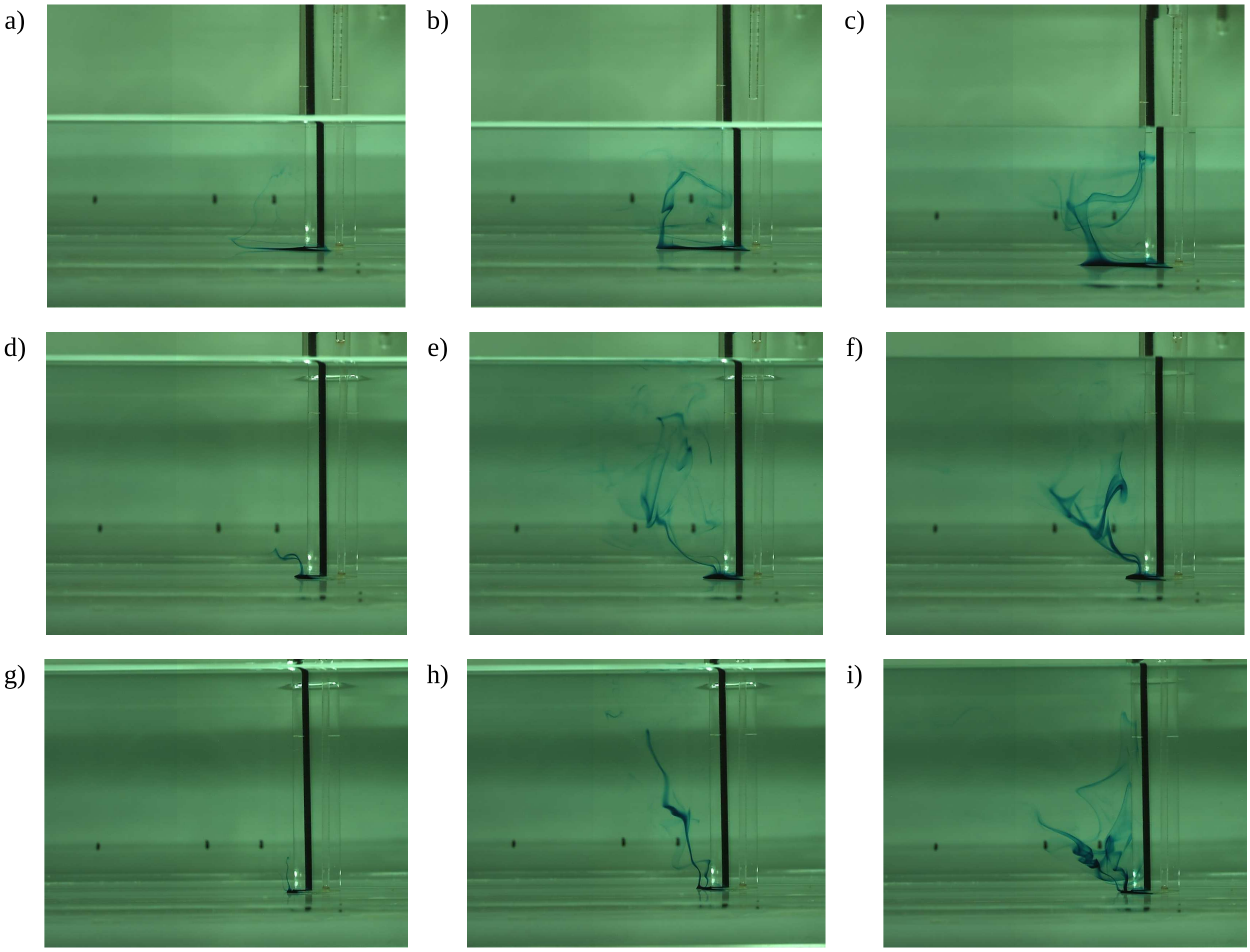

Fig. 7. Exemplary images of the near wake region, u = 30,0mm/s, side view:
a) h_w/D = 2,80 – vortex formation, b), c) h_w/D = 2,80 – vortex evolution,
d) h_w/D = 4,44 – vortex formation, e), f) h_w/D = 4,44 – vortex evolution,
g) h_w/D = 4,78 – vortex formation, h), i) h_w/D = 4,78 – vortex evolution.

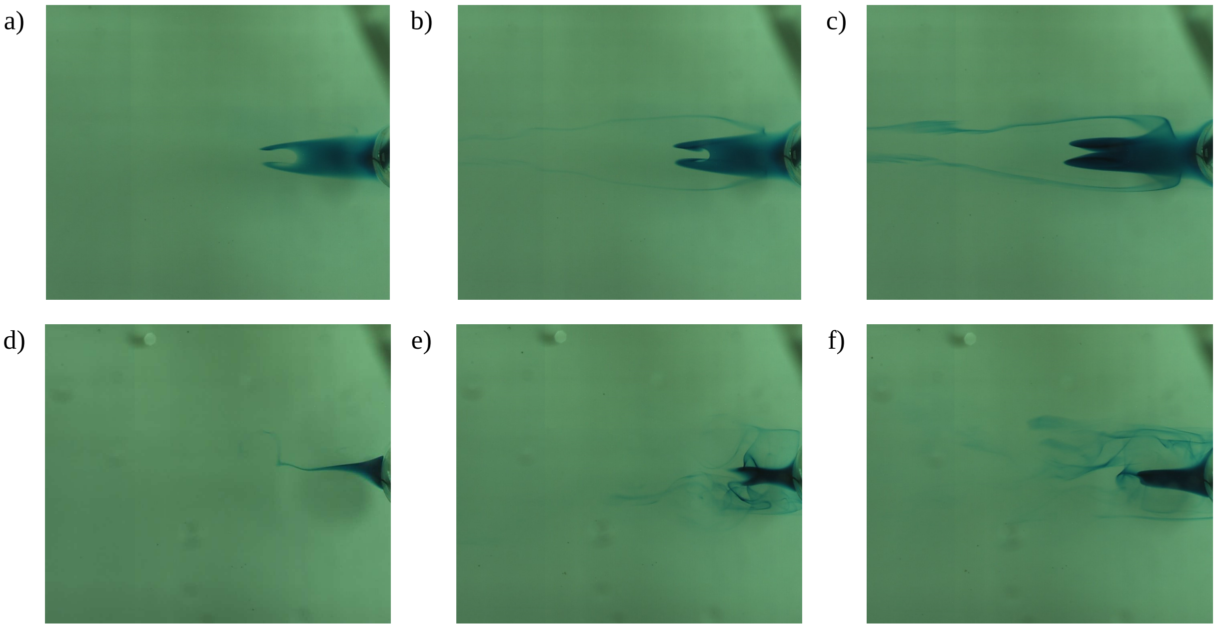

Fig. 8. Exemplary images of the near wake region, u = 30,0mm/s, plan view:
a) h_w/D = 0,82 – vortex formation, b), c) h_w/D = 0,82 – vortex evolution,
d) h_w/D = 1,43 – vortex formation, e), f) h_w/D = 1,43 – vortex evolution.

CONCLUDING REMARKS

Vortex formation from a vertical cylinder in shallow water for various values of dimensionless water depth h_w/D was investigated using visualization by dye marker. Experiments were carried out first for constant Reynolds number (based on water depth h_w, $Re = u \cdot h_w/\nu$), then mean velocity in test section was kept constant.

It was observed that the dye rapidly spread along the bottom surface of the test section and, as vortex was formed, it swept across the plane of symmetry of cylinder, over the layer of dye. It seems that the vortex structure lead to the eruption of a boundary layer.

A distinguishing feature of the shallow water wakes is the three-dimensional roll-up of the dye marker between the bottom and the free surface which yields a vortex structure. The vortex is the more stable and easy to observe the smaller the h_w/D is. For sufficiently small values of dimensionless water depth (h_w/D = 0,82÷2,80), the vortex structure is extended from the bottom to the free surface.

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