開水路急拡部における剥離流の３次元解析
A 3-D Analysis of Separating Flow in a Sudden Expanded Open Channel

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1.Introduction

Flow separation may cause a lack in functionality of engineering structures. Because of this, there has been considerable interest in developing method of predicting flow. Among them, the turbulent reattaching flow over a backward-facing step(BFS) has been studied by many researchers over the years. However there are few works on a sudden expanded open channel (SEOC).The reason why might be listed as a)simplicity in the geometry of a BFS, b)two dimensionality of flow which can be provided easily, and c)many more applications can be found in engineering both in water and air branches. One can imagine a SEOC as a BFS which is rotated 90° round both edges of the channel. The present paper will focus on 3-D flow containing limited region of separation. We have found some new features of reattachment flows in a SEOC which have not been reported previously. One of the most important parameters determined in these experiments has shown the distance from the step to the point or region where separated shear layer reattaches to the wall (x_R). For a majority of experiments where the boundary layer is believed to be fully developed and turbulent, x_R/H generally $5.5 < x_R/H < 7.5$[1]. The purposes of this work are 1)to investigate the accuracy of variational method, a math-physics formula to produce a 3-D velocity field based on a 2-D original data, 2) to investigate flow reattachment in a SEOC, and 3)to compare the reattachment flow in a SEOC with a BFS.

2.Experimental Arrangements and Procedures

The present experiments were carried out in a free surface water channel. The channel has a work section of 30.0 m long, 0.7 m wide and 0.12 m deep. The added parts to the channel are two prismatic obstacle each one is formed of a rectangle and a parabolic curve attached to the channel walls at the middle of the channel where the bed and walls are made of glasses. The obstacles were made of acrylic plate to provide the smoothness of the expansion. The expansion depth H, at each side of the channel was 5 cm and Reynolds number Re, based on H at separation($x = 0$) was about 1.4×10^4. A projector light was passed through a slit to produce a light sheet at the test sections, 5 mm in depth and approximately 40 cm in the streamwise direction. The light sheet was aimed at a mirror related to a stepping motor (see Fig. 1). To understand the charactristics of flow at $z/H = 0$– 1.4, four cameras were used to take pictures of three horizontal sections and one longitudinal section of the testing area. When the light sheet has illuminated section 1, only camera 1 should take a picture and when it has illuminated section 2, only camera 2 should take a picture and etc.

3.Interpolation Method and Variational Technique

To get a 3-D image of flow, the original three pictured sections which produce a 2-D velocity field should be increased to a volume using an interpolation method. A cubic spline function fitted over three single points, one from each section, was used to produce this volume. In the next step, variational technique is used to solve numerical equivalent of the flow in the integral approach. In most physical problems it would be formed based on energy consideration. Using this technique and an iteration method, say SOR, we could obtain 3-D velocity field over the domain of interest,a rectangular box confined on two sides by the channel bed and wall.For further information reader is referred to Kawanisi et al[2]. Here the roll of camera 4 is to provide a check point of created data by variational method, since at first, there is no data in x-z plane, the produced data should be compared to the measured one. Determination of an appropriate value for α_i in variational functional is important because it has a significant roll in the quantity of two velocity components, V and W. Variations of α_1 and α_2 in the range of, say 0.5–5.0, has no big effect on the U component of velocity. To provide this condition we used the following relations: $(W_{sec4} - W_{var} \cdot (U_m)_{sec4}/(U_m)_{var})^2 = min, W_{sec4} = W_{var} \cdot (U_m)_{sec4}/(U_m)_{var}$, where U_m is the average of streamwise velocity component over the intersection of section 4 and the rectangular box, and indexes sec4 and var are related to section 4 and variational data, respectively. Since these two relations are independent from each other sometimes satisfying these conditions needs personal judgements.

4. Results and Discussions

Although the geometry of a SEOC looks as simple as a BFS, the flow characteristics are much more complex. To predict the flow the length to reattachment is the most important parameter. Observing different photographs in different sections we found that $x_R/H \geq 6$. We couldn't determine the upper limit of this ratio because of the limitation area in the pictured sections, however it seems that the inclination of the dividing streamline toward the channel wall is larger for a BFS than a SEOC, this is due to the reversed flow produced by an adverse pressure gradient which is larger for a BFS. The point which should be considered in experimental procedures is that the Reynolds number has effect on the reattachment flow up to producing a turbulent boundary layer and after that it has no significant roll, however this is the expansion ratio, Y_1/Y_0, (see Fig.2), which plays an important roll, as increasing this ratio, the adverse pressure is increased[3]. The flapping effect in the recirculation region can be dramatically observed during the period of taking photographs.

A strong vortex generated in the recirculation region moves downstream and persist in the separated free-shear layer(zone I in Fig.3). This motion causes a shift in the reattachment point toward the downstream and, we believe, there will not occur reattachment in the far downstream. The edge of shear layer next to zone I has a wavy shape(Fig.3).As seen, this is due to vortical structures generated in the recirculation region, however it doesn't mean that all of these vortical structures necessarily can be seen at the same time,this confirms the existence of quasi-steady structures in the recirculation region. The largest vortical structures with a maximum size of H in diameter are appeared in $3 < x/H < 5$ and soon after that the size of vortical structures reduced to smaller sizes following the dividing streamline which trends toward the wall. Unlike the BFS, in a SEOC the inclination of outer edge of shear layer (zone III in Fig.3) doesn't trend toward the channel wall specially when we are going away from the bed. The largest vorticity values can be found in the largest velocity gradient where the dividing streamline is plotted. To show the combined effect of all of the vorticity components a surface graphics of enstrophy at $z/H = 0.4$ is given (see Fig.4). In Fig.5 an end view section of vorticity is shown. In this figure upward vectors shows the main positive vorticity which has a clockwise rotation almost over $y/H = 0$ and downward vorticity vectors, which take place on $y/H = -1$, both of these two show that the main vorticity component is ω_z and it seems that they are joined to each other at the bottom and upper parts. At these parts one can observe the dominant y component of vorticity, ω_y, which should be due to sweep and ejection. Because of the orientation of vortical structures along the channel wall vorticity component in the x direction is the weakest one. The magnitude of vorticity in the zone I is larger than the two other zones, since we are expected to have the stronger vorticity in the border of low and high velocity regions. Since at $x/H = 4.8$ still, we have a strong vortex along the expansion, we believe that the shear layer has a milder inclination toward the channel wall than in a BFS. Vortical structures in zone II almost follow the dividing streamline which can be seen from Fig. 6.

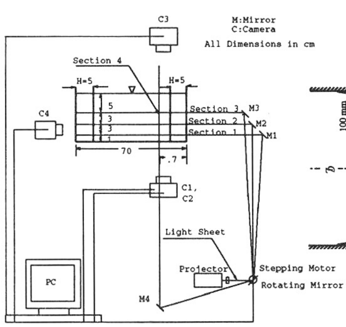

Fig. 1 Schematic sketch of experimental setup.

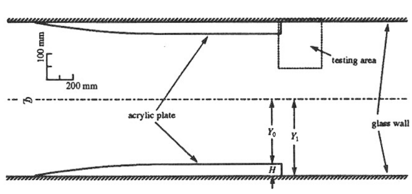

Fig. 2 Schematic of test section (plan view).

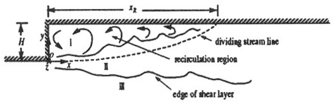

Fig. 3 Sudden expanded flow field: details of reattachment-length, recirculation region and shear-layer, specified by a dashed-rectangle in Fig. 2.

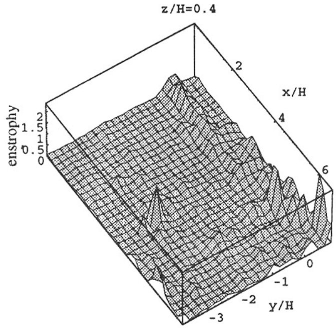

Fig. 4 Representation of detatching flow, higher enstraphy takes place on the border of detatchiment.

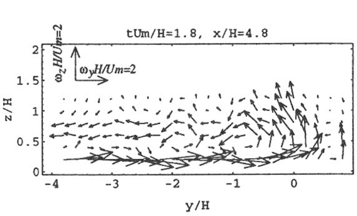

Fig. 5 End view of vorticity vector field represents the vortical structure generated in zone II (y/H=-1.0~0.4).

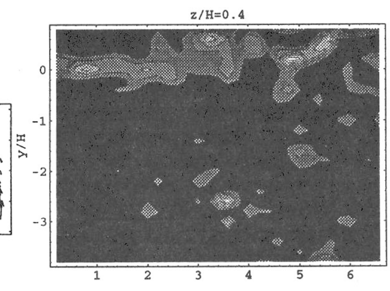

Fig. 6 Enstrophy distribution correspnded to Fig. 4: brighter area shows higher intensity of enstrophy.

References

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3) J. Kim,S.J.Kline, J. P. Johnston, "Investigation of a Reattaching Turbulent Shear Layer: Flow Over a Backward-Facing Step", Journal of Fluid Engineering, Vol.102, Sep., 1980.