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Original Paper

Flow characteristics over forward facing step and through abrupt contraction pipe and drag reduction

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Abstract

The flow through a circular pipe with an abrupt contraction has two distinguished vortex regions just before and after the contraction. The latter vortex makes the effective cross-sectional area of the downstream constracted pipe reduce, and then the flow resistance, drag, is increased.

In this study, first the flow chracteristics over the forward facing step (corresponds to a two dimensional case of an abrupt contraction pipe) and through abrapt constractin pipe and then the flow control, suppression, of the vortex over the forward facing step by a new simple method, mounting a small obstacle on the wall just before the step. As a result, a considerable drag reduction of the abrapt contrction pipe by the new simple method was made clear.

keywords: Forward facing step, Abrapt contraction pipe, Flow separation and control, Drag reduction

1. Introduction

The flow through an abrapt contraction pipe has two distinguished vortex regions just before and after the contraction (Fig. 2). The latter vortex causes the decrease of the effective cross-sectional area of downstream contracted pipe ($A_2 \rightarrow A_c$) and then this increases the flow resistance, drag. In order to reduce the flow resistance, the latter vortex should be controoled or suppressed. In general, making the step corner round or tapered pipe are used in order to reduce the flow resistance. But, these are high cost and take a lot of room especially for a large forward step and an abrapt contrction pipe. The forward facing step corresponds to a two-dimensional case of an abrupt contraction pipe, and there are some studies on separated flow over a forward facing step. For example, Tropea, et al [1] made clear the flow characteristics around an obstacle by detailed measurements by Laser Doppler Anemometry (LDA).

Furthermore, Taulbee et al.[3], Liou et al. [4] made a numerical analysis, Kiya et al.[5] studied about the flow over the forward facing step, Chiang et al. [6] made a numerical analysis about two-dimensional abrupt contraction flow passage, and Fukunishi et al.[7] showed the control of the vortex which appears on the forward facing step by causing a small vibration of a part of step corner.

In this study, first the flow chracteristics over a forward facing step and through an abrupt contrction pipe is examined experimentally and then the control or suppression of the vortex, vortex II, on the upper step surface is shown newly by a small obstacle which is mounted on the lower step surface (see Fig. 2). It is considered that making the separated flow from the small obstacle flows along a forward facing step, the vortex II will be controlled or suppressed. This leads to the drag reduction of an abrapt contrction pipe.

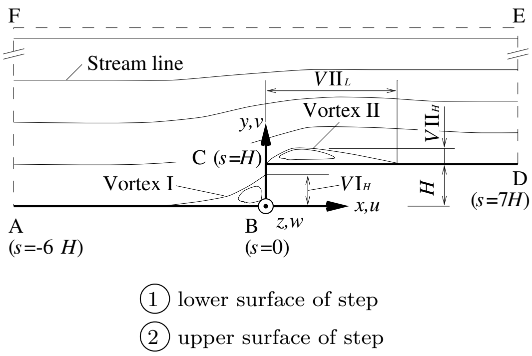


Fig. 1 Forward facing step

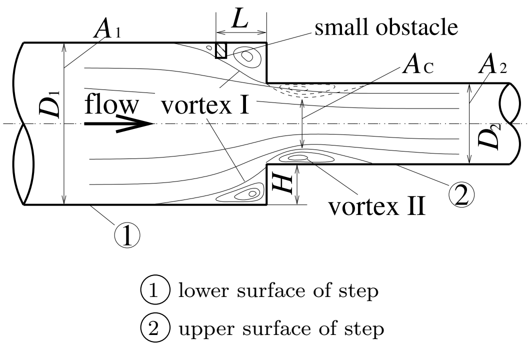


Fig. 2 Circular pipe with abrupt contraction

2. Experimental Set Up and Procedure

2.1 Forward Facing Step

The experimental set up for forward facing step is shown as Fig. 3. The water flow from the reservoir tank is intrduced into the test section having a bell-mouth at the inlet after passing through the straightener. The test section having 200 × 80mm rectangular cross section is made by transparent acrylic resin plate and the lngth is 1,320mm.

Figure 4 shows the details of the test section. The forward facing step is set in the test section. The step with a sharp edge of leading angle 27° and the lower surface of 6 times length of step height $H(= 20\text{mm})$ was mounted at the position of $40\text{mm}(= 2H)$ from the side wall I and of 710mm from the entrance of flow passage.

In order to control or suppress the separation vortex, vortex II, on the upper surface of step, the small obstacle (size: $0.2H \times 0.2H$, where H: step height) mounted on the lower surface was used (Fig. 4). The distance L from the step to the front of the small obstacle can be varied arbitrarily.

The flow velocity measurements by LDA was carried out for Reynolds numbers $Re = u_m H/\nu = 5,000$.

2.2 Abrupt Contraction Pipe

The experimental setup of abrupt contraction pipe is shown in Fig. 5. The water from the reservoir tank ① is introduced into the flow passage having a valve for control of flow rate ③, flow meter ④, straightener ⑤ and test section ⑦ (inner diameter $D_1 = 60[\text{mm}] = \text{const.}$). The test section has the bell-mouth ⑥ at the entrance and the straight part of $50D_1 = 3,000[\text{mm}]$ at upstream of the abrupt contraction. The water passed through the test section is backed to the reservoir tank ①.

The details of the test section is shown in Fig. 6. The contraction pipes with three contraction rates, $A_1/A_2 = 4$, 3.1 and 1.9 are used.

3. Result and Discussion

3.1 Flow Characteristics over Forward Facing Step

Figure 7(a) is photograph of visualized flow pattern by atracer method. The flow on the lower step surface separated from the surface and the vortex region, vortex I, on the lower step surface was formed. The flow separated from the step corner and it reattached on the upper step surface. Then on the upper step surface the vortex region, vortex II, was formed.

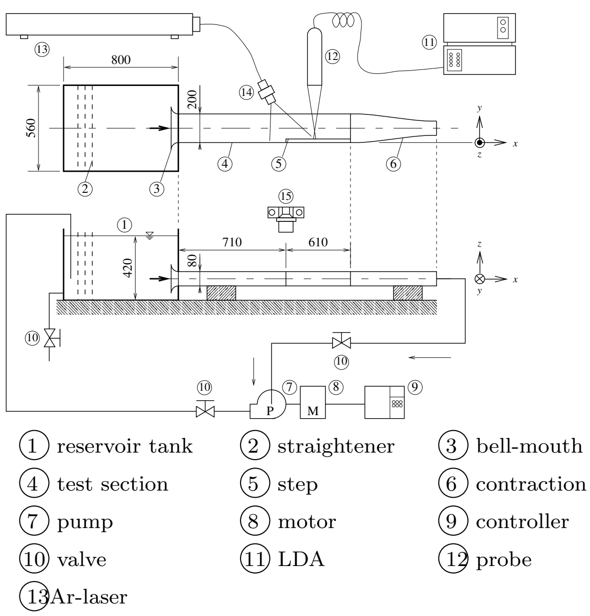


Fig. 3 Experimental setup (forward facing step)

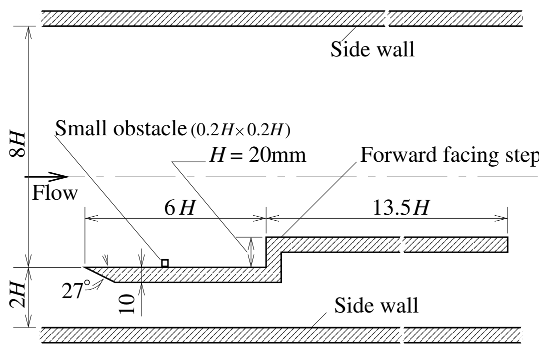
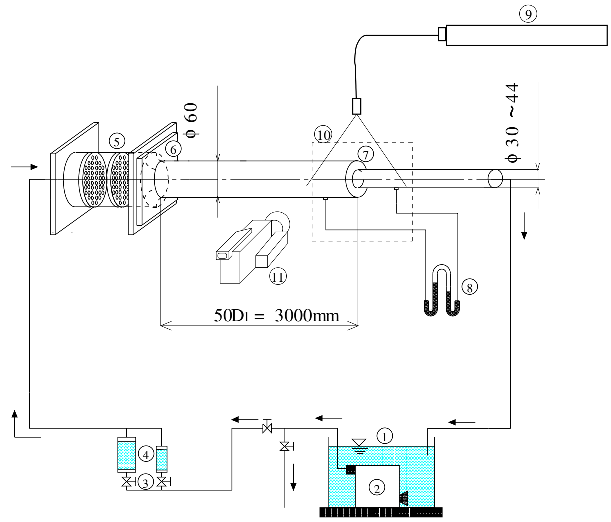


Fig. 4 Details of Test Section (forward facing step)



1 reservoir tank
2 pump
3 valve
4 flow meter
5 straightener
6 bell-mouth
7 test section
8 manometer
9 Ar-laser
10 laser light sheet
11 CCD-camera

Fig. 5 Experimental setup (abrupt contraction pipe)

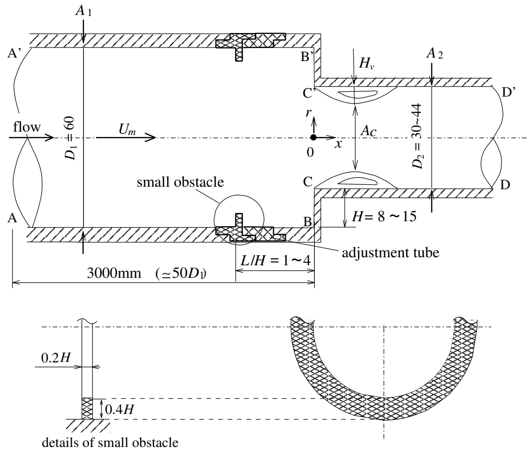
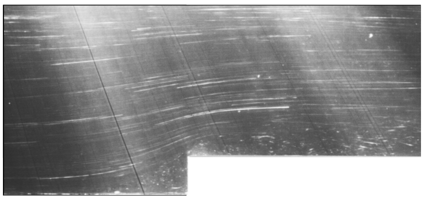
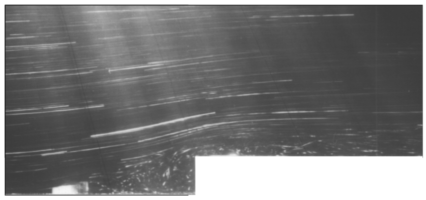


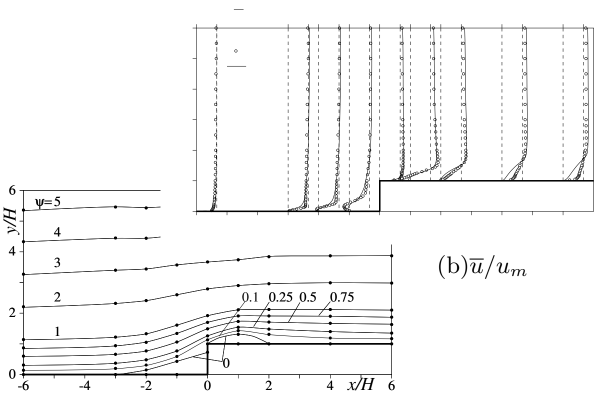
Fig. 6 Details of test section (abrupt contraction pipe)



(a) Visualized flow pattern

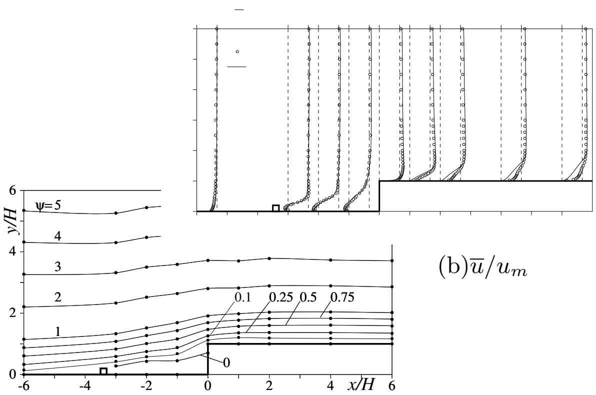


(a) Visualized flow pattern



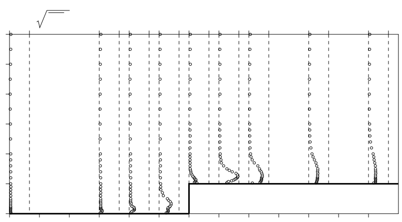
(b) $\overline{u}/u_m$

(c) Stream lines



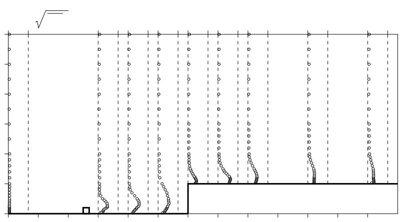
(b) $\overline{u}/u_m$

(c) Stream lines



(d) $\sqrt{\overline{u'^2}}/u_m$

Fig. 7 Flow characteristics



(d) $\sqrt{\overline{u'^2}}/u_m$

Fig. 8 Flow characteristics (Separation control by small obstacle, $L/H = 3.5$)

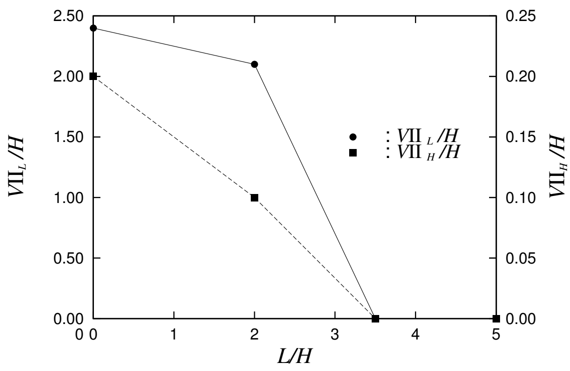


Fig. 9 Size of Vortex Region II

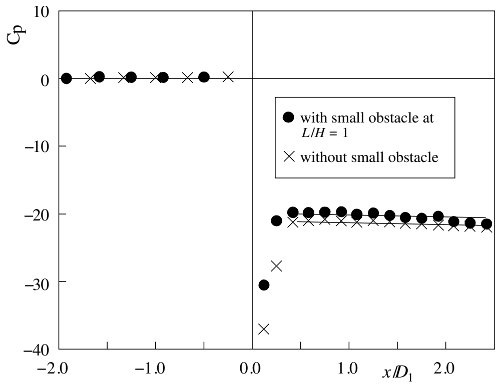


Fig. 10 Pressure distribution ($A_1/A_2 = 4.0$, Re $= 2 \times 10^4$)

Figures 7(b) and (c) show the velocity profile of $\overline{u}/u_m$ and stream lines, respectively. From the cross section of $x/H = -6$, the uniform is introduced, and there are two recirculating regions, vortices I and II, just before and after the step. The size of vortex I is of the length $VI_L/H = 2.4$ and height $VI_H/H = 0.75$. The vortex II is of $VII_L/H = 1.9$ and $VII_H/H \simeq 0.3$.

Figure 7(d) shows the turbulence intensity $\sqrt{\overline{u'^2}}/u_m$. Turbulence intensity becomes large near the separation stream line [see Fig.7(b)] with a large velocity gradient. Especially, at the downstream $x/H = 1$ of the step corner it takes a maximum value.

3.2 Control of Separated Flow by Small Obstacle

As mentioned before, vortices I and II are formed just before and after the step. In this section, in order to control or suppresse the formation of vortex II the effect of a small obstacle mounted on the lower surface is discussed.

Figure 8 shows the flow characteristics for $L/H = 3.5$. Figures 8(a)$\sim$(d) correspond to Figs.7(a)$\sim$(d), respectively. From the visualized flow pattern Fig.8(a), and stream line Figs.8(c), it is well known that the separated stream line from the small obstacle reattaches around the step corner accompanying vortex I between the lower surface but the vortex, vortex II which appears for the case (see Fig.7) without a small obstacle, on the upper surface disappears because the flow above the separated stream line flows along the upper surface. The turbulence intensity around the separated stream line increases but it over the step where there is no vortex decreases [see Fig.7(d)]. The formation of vortex II can be controlled or suppressed by a simple method by a small obstacle.

Figure 9 shows the size of vortex II. In Fig.9, the $L/H = 0$ means there is no obstacle. Both of the length VII_L/H and height VII_H/H decreased with increasing L/H, and it disappeares at $L/H = 3.5$.

3.3 Abrupt Contraction Pipe

3.3.1 Pressure Distribution

The pressure distribution along the pipe axis is shown in Fig. 10. Reynolds number is Re $= u_m D_1/\nu = 2 \times 10^4$. The pressure is measured by static pressure hole of diameter 0.8mm on the pipe wall. The pressure distribution of the upstream pipe is not changed magnificently, but it changes to low pressure discontinuously at the abrupt contraction ($x = 0$) and then pressure is recovered abruptly. At $x/D_1 > -0.5$, the pressure decreases with the gradient based on Brasius' equation:

$$\frac{\partial C_p}{\partial (x/D_1)} = -\lambda \left(\frac{D_1}{D_2}\right)^5 = -0.7 \tag{1}$$

where, $\lambda = 0.3164(D_1/D_2)^{1/4}$.

In the case of the small obstacle ($L/H = 1$), the pressure reduction rate at $0 < x/D_1 < 0.5$ is smaller than the case of without a small obstacle, and the pressure after recovery is lager about 10% than the case of without a small obstacle. It depends on the effect of suppression of vortex II on the upper step surface.

3.3.2 Flow Resistance, Drag

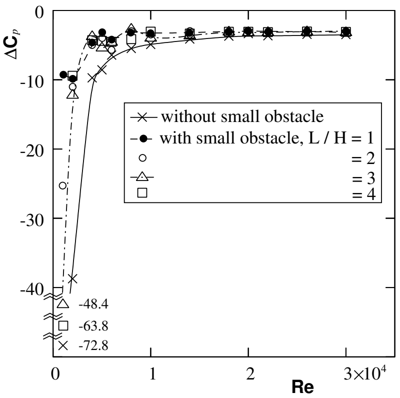
Effects of Reynolds Number The flow resistances, drag reduction, ΔC_p for contraction rates $A_1/A_2 = 1.9$, 3.1 and 4.0 and Reynolds number of $0 \leq$ Re $\leq 3 \times 10^4$ are shown in Fig 11 (a) $\sim$ (c).

The flow resistance ΔC_p is defined by

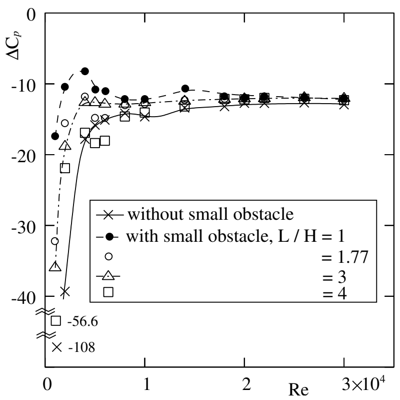
$$\Delta C_p = \frac{2\Delta p}{\rho u_m} \tag{2}$$

where, ΔC_p: pressure drop between the position of $x = -75 \pm 6$mm and $x = 75$mm.

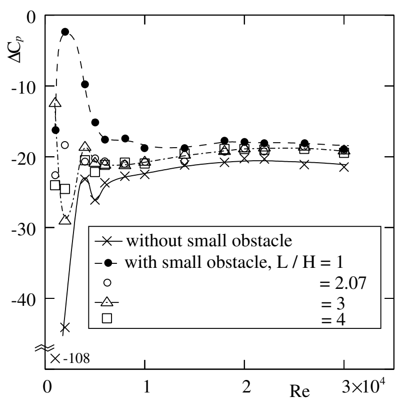
For each contraction rate, ΔC_p for the small obstacle approaches to it without small obstacle. Especially, in the case of $A_1/A_2 = 1.9$ and 3.1, ΔC_p are almost same for both cases of with and without small obstacle.



(a) $A_1/A_2 = 1.9$

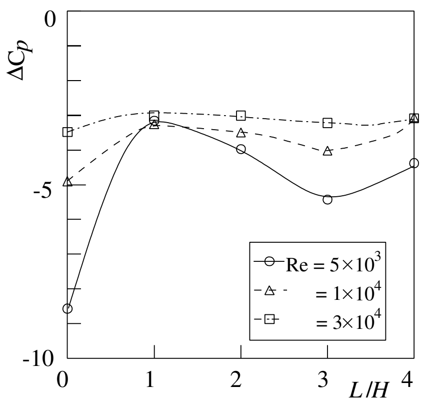


(b) $A_1/A_2 = 3.1$

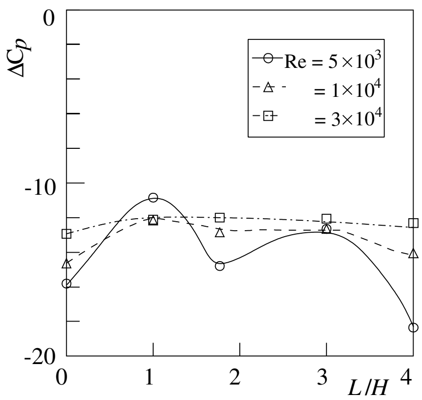


(c) $A_1/A_2 = 4.0$

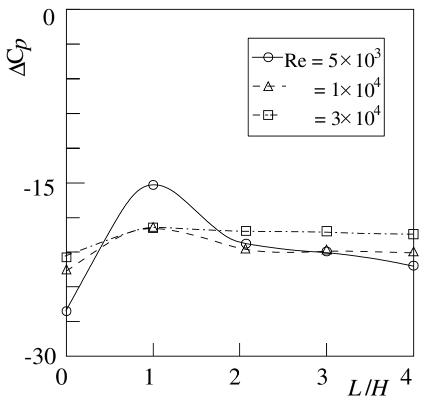
Fig. 11 Effects of Re number on flow resistance



(a) $A_1/A_2 = 1.9$



(a) $A_1/A_2 = 3.1$



(c) $A_1/A_2 = 4.0$

Fig. 12 Effects of L/H on flow resistance

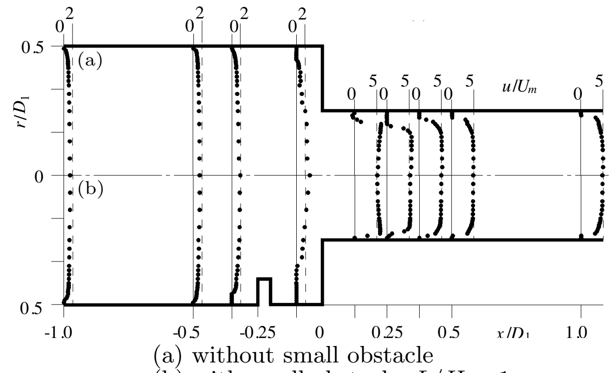
Optimum Location of Small Obstacle The effects of location of small obstacle L/H on the flow resistance ΔC_p are shown in Fig 12 (a) $\sim$ (c).

The flow resistance takes a minimum at $L/H = 1$ for each case. For example, at $Re = 10 \times 10^4$, flow resistances are reduced by 33, 16 and 16% for the contraction rates $A_1/A_2 = 1.9$, 3.1 and 4.0, respectively. It depends on suppression or minimization of vortex region II on the upper step surface by mounting a small obstacle. The separated flow from a small obstacle flows along the upper step surface as mentioned before. This will be made clear in the following.

3.3.3 Velocity Distribution

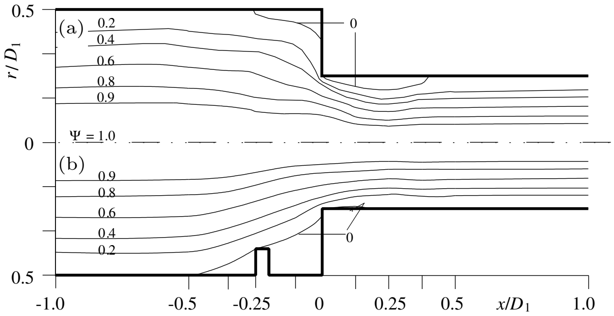
Abrupt Contraction Pipe The velocity distribution of u and streamlines for the contraction rate $A_1/A_2 = 4$ and Reynolds number $\mathrm{Re} = 5 \times 10^3$ are shown in Fig. 12(a), 13(a), respectively. Since the flow pattern is axisymmetric only the half region in radial direction is shown. A fully developed and reversed flows are observed at the cross section $x/D_1 = -1$ and around $x/D_1 = 0.1$, respectively. The flow separates on the lower step surface at $x/D_1 = -0.25$ and reattaches on the vertical step surface at $r/D_1 \simeq 0.4$. The vortex region, vortex I, is formed on the upper step surface of length $0.25D_1$ and height $0.1D_1$. There is the reversed flow also at $x/D_1 = 0.125$, 0.25 and 0.375 on the upper step surface. The separated flow from the step corner reattaches at $x/D_1 = 0.4$, and the vortex region, vortex II, of length $0.4D_1$ and height $0.01D_1$ is formed. The vortex II of height $0.05D_1$ reduces the effective cross-sectional area of down stream constracted pipe by about 36% and then the flow resistance will be larger.

The turbulence intensity distribution $\sqrt{u'}/U_m$ is shown in Fig. 14(a). Above the upper step surface, it takes a maximum near the separation stream line because of a large velocity gradient.



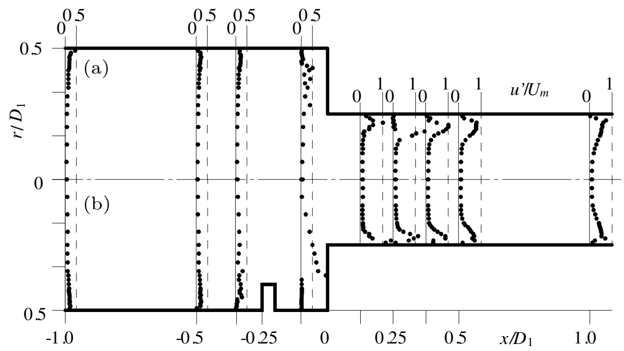
(a) without small obstacle
(b) with small obstacle, $L/H = 1$

Fig. 13 Velocity distribution, u/U_m
($A_1/A_2 = 4.0$, $L/H = 1$, $\mathrm{Re} = 5 \times 10^3$)



(a) without small obstacle
(b) with small obstacle, $L/H = 1$

Fig. 14 Stream line
($A_1/A_2 = 4.0$, $L/H = 1$, $\mathrm{Re} = 5 \times 10^3$)

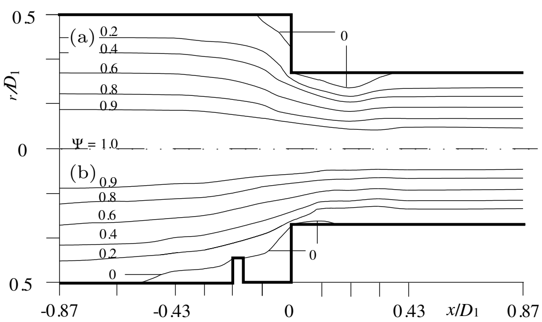


(a) without small obstacle
(b) with small obstacle, $L/H = 1$

Fig. 15 Turbulence intensity, u'/U_m
($A_1/A_2 = 4.0$, $L/H = 1$, $\mathrm{Re} = 5 \times 10^3$)

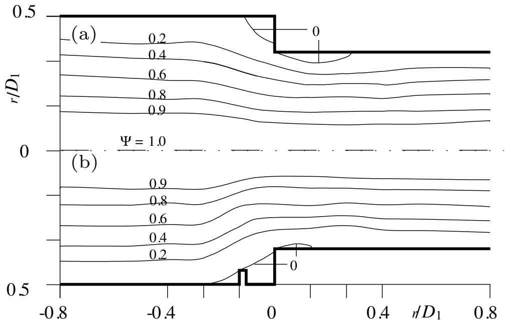
Effects of Small Obstacle It will be shown that $L/H = 1.0$ is an optimum position of small obstacle in order to minimize the flow resistance.

The velocity distribution u and stream lines are shown in Figs. 12(b) and 13(b),



(a) without small obstacle
(b) with small obstacle, $L/H = 1$

Fig. 16 Stream line
($A_1/A_2 = 3.1$, $L/H = 1$, $\mathrm{Re} = 5 \times 10^3$)



(a) without small obstacle
(b) with small obstacle, $L/H = 1$

Fig. 17 Stream line
($A_1/A_2 = 1.9$, $L/H = 1$, $\mathrm{Re} = 5 \times 10^3$)

respectively.

As mentioned before, the vortex region II on the upper step surface almost disappears when there is the small obstacle. The turbulence intensity distribution $\sqrt{\overline{u'}}/U_m$ is shown in Fig.14(b). Because of suppression of vortex region II, its maximum position of approaches to the upper step surface than the case of without small obstacle.

The stream lines for $A_1/A_2 = 3.1$ and 1.9 are shown in Figs.15 and 16, respectively. For each case, vortex region II is much smaller than case of without the small obstacle.

4. Conclusion

The flow characteristics over the forward facing step and through the abrupt contraction pipe are made clear by the flow visulization, measurements of mean and fluctuating velocity distributions using LDA and pressure distributuion. A simple flow control method by a small obstacle to reduce the flow resistance, drag, was proposed newly.

The major results are as follows.

1. The vortex region, vortex II, on the upper surface of forward facing step can be suppressed by mounting a small obstacle (height: $0.2H$) on the lower step surface. The size of vortex II is decreased with increasing L/H, and at $L/H = 3.5$ it disappeared almost because the separated flow from the small obstacle flows along the upper step surface.

2. Mounting small obstacle (height: $0.4H$) on the lower step surface of abrupt contraction pipe, vortex region II is suppressed and made smaller. In the case of $L/H = 1$, the vortex region II is almost disappeared, because the separated flow from a small obstacle flows along the upper step surface.

3. The flow resistance of abrupt contraction pipe takes a minimum for mounting a small obstacle at $L/H = 1$, because vortex region II is suppressed. The reduction rates of flow resistance are 33%, 16% and 16% for the pipe of contraction rates $A_1/A_2 = 1.9$, 3.1 and 4.0, respectively.

4. The effects of a small obstacle on the flow resistance is decreased with increasing Reynolds number. For the contraction rate $A_1/A_2 = 1.9$ and 3.1, the reduction rate of flow resistance is almost zero at $\mathrm{Re} \simeq 3 \times 10^4$.

References

[1] Tropea,C.D. and Gackstatter,R., The Flow Over Two-Dimensional Surface-Meounted Obstacle at Low Reynolds Numbers, *Trans. ASME*, *J. Fluids Eng.*, **107**-4, (1985), 489-494.

[2] Barrows,J.F. Upstream Separation Point for an Internal Corner in a Two-Dimensional Channel Flow, *Trans. ASME*, *J. Application Mechanics*, **30**-4, (1963), 505-508.

[3] Taulbee,D.B. and Robertson, J.M, Tuebulent Separation Analysis Ahead of a Step, *Trans. ASME*, *J. Basic Engineering*, **94**-3, (1972), 544-550.

[4] Liou,T.-M. and Kao,C.-F., Symmetric and Asymmetric Turbulent Flows in a Rectangular Duct With a Pair of Applied Mechanics, *Trans. ASME*, *J. Fluids Engineering*, **110**, (1963), 505-508.

[5] Kiya,M. and Nozawa,T., Turblence Structure in the Leading Edge Separation Zone of a Blunt Circular Cylinder, Trans.JSME, **53**-488B, (1986), 1183-1189,

[6] Chiang,T.P., Bifurcations of Flow Through Plane Symmetric Channel Contraction, *Trans. ASME*, *J. Fluids Engineering*, **424**, (2002), 444-451.

[7] Fukunishi, Y., Kobayashi, R., Kikuchi, S. and Taniguchi, H., Active Control of a Separation-Reattachment Flow after a Forward Facing Step, Trans. JSME, **63**-605B, (1997), 76-81.