Flow around Turbulence Promoters in Parallel Channel, (II)

Shedding Vortex around Cylinder

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Effects of walls on shedding vortex in developed channel flow were investigated putting a cylinder at the center of channels or on a wall for the value of $w/d$ from 2 to 4. Results were compared with the uniform flow result.

When a cylinder was put at the center of the channels, non-dimensional frequency plotted against Reynolds number agreed with the uniform flow result at low Reynolds number. However, it increased rapidly with Reynolds number, then it lay considerably above the uniform flow results at high Reynolds number. When a cylinder was put on a wall, non-dimensional frequency was considerably lower than the uniform flow result in the cases of $w/d=3$ and 4. In the case of $w/d=2$, however, frequency was higher than the uniform flow result at high Reynolds number. In all cases in the present study, the transition Reynolds number increased with decrease in the value of $w/d$.

These results indicate that the increase in shedding frequency was due to the shift in velocity distribution from Poiseuille parabola in the wake region, which obviously increased with Reynolds number and with decrease in channel width.

KEYWORDS: Karman vortex, Strouhal number, shedding frequency, circular cylinder, turbulence promoter, parallel channel laminar flow, hot wire, flow visualization, wall effect

I. INTRODUCTION

Flow characteristics around a bluff body are closely related to heat transfer characteristics. Many investigators have studied flow around a circular cylinder in uniform flow\(^{(1)}{}\sim{}^{(4)}\). In practice, effects of walls on the flow pattern must be considered, for in many cases flow is confined within two walls. Particularly, the effects will increase with increase in the ratio of the cylinder diameter to channel width $d/w$. This is the case of channel with turbulence promoters on the wall, which are effective device for improvement of heat transfer in many areas such as High Temperature Gas Cooled Reactor. The author et al.\(^{(5)}\) reported the flow pattern around cylinder-type turbulence promoters on the wall in parallel channel. The results showed that the flow pattern around promoters was considerably different from that around a cylinder in uniform flow.

The effects of walls on the flow pattern around bluff body have been studied by several investigators. Most of them treated large Reynolds number flow at $Re>10^4$. Suzuki et al.\(^{(6)}\), Hiwada et al.\(^{(7)}\) and Richter et al.\(^{(8)}\) showed increase in Strouhal number with increase in the value of $d/w$. Okamoto et al.\(^{(9)}\) observed constant Strouhal number for the range of $d/w$ from 0.089 to 0.34 at $Re\sim{}3\times{}10^4$. Experiments for low Reynolds number

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was made by Okude(10), Nishioka et al.(11), Rosenhead et al.(12), Thom(13) and Taneda(14). Okude(10) and Nishioka et al.(11) treated the effects of walls perpendicular to the axial direction of cylinder. According to Okude(10), the regular and irregular shedding vortex modes were influenced by boundary layer developed from the inlet. Nishioka et al.(11) reported that the Reynolds number of incipient Karman vortex (which is called as the transition Reynolds number in the present study) increased with the value of \( d/w \).

Rosenhead et al.(12), Thom(13) and Taneda(14) studied the effects of walls parallel to axial direction of a cylinder. Rosenhead et al.(12) and Taneda(14) visualized the flow pattern by pushing a cylinder through the water in a parallel channel with a constant velocity. According to Taneda(14), the transition Reynolds number is about 60 when \( w/d=3 \), about 80 when \( w/d=2 \) and about 150 when \( w/d=1.5 \). According to the experiment made by Thom(13), who put a cylinder in a flow at the middle of a parallel channel, the transition Reynolds number was 46 and 62 with \( w/d=2 \) and 10 respectively.

Those studies described above, however, are concerning to the effects of walls in uniform flow. It seems that the flow characteristics around a bluff body such as frequency of shedding vortex will be different when the flow in a channel is fully-developed. The purpose of the present study is to investigate the effects of walls on the shedding vortex when a single cylinder is put in almost fully-developed channel flow.

II. EXPERIMENTAL APPARATUS AND PROEDURE

Experimental apparatus is shown in Fig. 1. The apparatus is the same open channel flow circuit that reported in the previous paper(15). The size is 2,130 mm in length, 100 mm in width and 55 mm in depth. The fluid is circulated by a screw. Three meshes and a honeycomb mesh 100 mm in length were installed to make flow profile symmetrical. Parallel channel consisted of two acrylic plates 1,500 mm in length. Distilled water and Spinox oil were used as a fluid for the experiment of uniform flow and channel flow respectively. A sheath heater was inserted just behind the screw to set up fluid temperature at an arbitrary degree up to 45°C. The diameter of cylinder was 16 mm for channel flow experiment and from 2.4 to 8.0 mm for uniform flow experiments. Flow velocity and velocity fluctuations were measured by a hot wire probe which consisted of gold-gilded tungsten wire 20 \( \mu \)m in diameter. Hot wire was inserted in the fluid at about 4~6 cylinder diameters from the cylinder. Clear and large velocity fluctuation of shedding vortex was observed at this situation. Frequency was measured by oscilloscope and spectrum analyzer. The frequencies measured by two methods agreed within about 3%. The channel width were 64, 48 and 32 mm in the channel flow experiment which corresponded to \( w/d=4, 3 \) and 2 respectively, and the width 100 mm in uniform flow experiment. In the case of the channel flow experiment, single promoter was set in the middle of the channel or on the wall at 1,000 mm downstream from the inlet. Reynolds number \( Re_d \) was varied from 50 to 650 in the uniform flow experiment and from 120 to 650 in the channel flow experiment. High Reynolds number was obtained by setting up the fluid temperature at an arbitrary temperature up to 45°C.

Figure 2 shows velocity distributions in channel at 1,000 mm downstream from the
inlet in the case of \( w = 32, 48 \) and 64 mm. Hot wire probe was situated about 1 cm beneath the fluid surface. Slight nonsymmetry in velocity distribution observed in the previous study\(^{(5)}\) when \( w/d = 3 \) almost vanished by inserting honeycomb mesh before the inlet. Flow was not fully-developed at 1,000 mm from the inlet when \( w/d = 4 \). The maximum deviation from the Poiseuille parabola at \( Re_d = 300 \) is less than 8.5% according to Shlihiting\(^{(15)}\). The velocity range of the fluid was 9.0~16 cm/s. Except this velocity range shedding vortex could not be detected by hot wire probe. This will be due to three-dimensional flow and surface waves for excessively high velocity or flow reversal and slow circulation of vortex for excessively low velocity.

III. RESULTS AND DISCUSSION

1. Uniform Flow Experiment

Figure 3(a) shows the relation between non-dimensional frequency and Reynolds number. The diameter of the cylinder was varied from 2.4 to 8.0 mm, this corresponds to \( w/d = 41.7 \) and 12.5 respectively. Solid line is quoted from Roshko\(^{(1)}\). The results of the present study are slightly lower than that of Roshko at low Reynolds number. However, the data of the present study almost agree with the solid line at high Reynolds number. For low Reynolds number, the plotted data

![Fig. 3 Results of uniform flow experiment](image)

(a) Non-dimensional frequency vs. Reynolds number
(b) Strouhal number vs. Reynolds number

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agree with the dotted line quoted from Friehe(18) and Hattori et al.(16). According to Roshko(1), Hattori et al.(16), Tritton(19) and Bloor(19), shedding vortex turns from regular mode to irregular mode at $Re_d=100-200$. In the present study, difference in gradient of the data is observed in the vicinity of $Re=150$ in Fig. 3(a). This difference in gradient can be probably due to the transition from the regular vortex to the irregular vortex. Photograph 1(a), (b) shows the wave signals from the hot wire probe. As seen from the photograph, regular sinusoidal wave is observed at $Re_d=78$, however, irregular wave is observed at $Re_d=157$.

![Wave signals from hot wire probe](image)

Photo. 1(a)–(e) Wave signals from hot wire probe

Typical examples of power spectra are shown in Fig. 4. Figure 4(a) is the case of uniform flow experiment. The scale for the power spectral density is arbitrary where as the frequency scale is in Hz. Only one peak is observed in the figure. The transition Reynolds number was about 60, in the case of $w/d=41.7$.

Figure 3(b) shows the relation between Strouhal number and $Re_d$. The present data for low Reynolds number are lower than the solid line quoted from Roshko(11). For low Reynolds number, the data of Hattori et al.(16) agree with the results of the present study. The results of other investigators, however, scattered considerably as seen in the figure.

2. Channel Flow Experiments

(1) $w/d=3$

Figure 5(a) shows the relation between non-dimensional frequency and Reynolds number with a cylinder at the center of the channel. The transition Reynolds number for shedding vortex was about 180-200. It was rather difficult to determine the transition Reynolds
number precisely, the reason of which would be described later. As is shown in the figure, the non-dimensional frequency almost agrees with that of uniform flow for low Reynolds number below $Re_d=300$. Non-dimensional frequency, however, increases for $Re_d>300$ and it lies above the results of uniform flow experiment. The relation between Strouhal number and Reynolds number is shown in Fig. 5(b).

The results of channel flow experiment for $w/d=3$ with a cylinder on the wall are shown in Fig. 6 (a), (b). The non-dimensional frequency shown in Fig. 6 (a) is lower with cylinder on the wall than with cylinder in the center of the channel. Particularly, the results lie below the broken line of uniform flow experiment for $Re_d<600$. Hot wire signals are shown in Photo. 1(c), (d) when Reynolds number is 500 and 476 respectively. Sinusoidal waves remains in the signals with the cylinder at the center of the channel, however, distorted waves that still retain periodicity are observed in the signals with a cylinder on the wall.

Figure 4 (b), (c) show the examples of power spectra in the case of $w/d=3$. Strong shedding peaks are observed in the figures.

The transition Reynolds number with a cylinder on the wall was about 180~200.
Fig. 5(a), (b) Results of channel flow experiment in case of \( w/d = 3 \) with cylinder at center of channel

Fig. 6(a), (b) Results of channel flow experiment in case of \( w/d = 3 \) with cylinder on wall
This is considerably higher than the result of the uniform flow experiment and almost same as the results when a cylinder was put at the center of the channel. It was difficult to determine the critical Reynolds number, because shear layer just behind the promoter often flows roughly periodically even though the shedding vortex is not observed, and hot wire probe detects the velocity fluctuations induced by the shear layer flow. The examples of the signal of the hot wire and power spectra of shear layer flow in the case of \( w/d = 2 \) are shown in Photo. 1(e) and Fig. 4(d). In this case, the hot wire signal shows sinusoidal waves similar to the signal of shedding vortex. Usually, velocity fluctuations induced by the shear layer flow were weak and excellent frequency could hardly be determined because of the existence of two or more peaks in the power spectra as seen in Photo. 1(d). In the vicinity of the transition Reynolds number, however, the shear layer flow grew into quasi-vortex then it was difficult to distinguish the signal of shedding vortex from that of shear layer flow.

In the previous paper\(^1\), it was reported that the shedding vortex pattern occurred at \( Re_w = 860 \sim 1,000 \) which corresponded to \( Re_d = 140 \sim 170 \). The transition Reynolds number is slightly higher in the present study than in the previous study. This difference seems to be partially due to the effect of honeycomb mesh which makes flow profile symmetrical and partially due to the difficulty in determining the transition Reynolds number as described before.

The irregularly shedding vortices pattern above \( Re_w \geq 2,000 \sim 3,000 \) observed in the flow visualization experiment\(^1\) could not be observed in Fig. 6. The reason will be that the averaging process executed in spectrum analyzing experiment cancelled the frequencies of irregularly generated vortices.

\( (2) \ w/d = 4 \) and 2

The non-dimensional frequencies are plotted as a function of Reynolds number for \( w/d = 4 \) and 2 in Fig. 7(a), (b) when a single cylinder is put at the center of the channels. As is seen from the figures, the plotted data almost agree with uniform flow data below \( Re_d = 375 \) for \( w/d = 4 \) and below \( Re_d = 280 \) for \( w/d = 2 \). Then the non-dimensional frequencies increase more rapidly than the uniform flow data with increase in Reynolds number in both cases. As is seen from Fig. 6, the flow in the channel with the ratio of \( w/d = 12.5 \) can be regarded as uniform flow. In the case of \( w/d = 4 \), however, the non-dimensional frequency deviates from the uniform flow data for high Reynolds number. It can be noted from these results that the Reynolds number above which non-dimensional frequency \( F \) deviates from the uniform flow data increases with increase in \( w/d \). Therefore the deviation of non-dimensional frequency from the uniform flow data occurs between \( w/d = 12.5 \) and 4. It can be said that the effect of walls is weak when Reynolds number is low, however, it becomes strong when Reynolds number is high. According to the experimental results of Rosenhead et al.\(^{12}\) increase in number of shedding vortices is observed at almost the same Reynolds number when the channel width is narrow. Generally, the width of wake region behind a cylinder decreases with increase in Reynolds number. This will indicate that the wall effect on vortex shed by a cylinder will decrease as Reynolds number increases. However, the differences in velocity distribution in wake region from Poiseuille parabola increase with Reynolds number and with decrease in channel width. This velocity distribution in wake will cause the increase in shedding frequency. The transition Reynolds number was about 170\sim 180 when \( w/d = 4 \) and 220\sim 260 when \( w/d = 2 \) with a cylinder at the center of the channel. The non-dimensional
The non-dimensional frequencies are plotted as a function of Reynolds number in Fig. 8 for \( w/d = 2, 3 \) and 4 with a single cylinder at the center of the channels. As is seen from the figure, the data for three cases agree well for comparatively high Reynolds number for \( Re_d \geq 400 \). These data are represented by the best fitted line

\[
F = 0.453 Re_d - 71.4 . \tag{1}
\]

The non-dimensional frequencies are plotted in Fig. 9 for three cases with a single cylinder on the wall. In the cases of \( w/d = 3 \) and 4, the data lie below the data of uniform flow for \( Re_d < 600 \). Particularly, the deviation from the data of uniform flow is much larger for low Reynolds number. It is noticeable from the figure that both results for \( w/d = 3 \) and 4 agree well. The best fitted line of these data is

\[
F = 0.271 Re_d - 44.0 . \tag{2}
\]

In the case of \( w/d = 2 \), however, the
results were different from those of \( w/d = 3 \) and 4. The non-dimensional frequency is a little smaller than the uniform flow data for \( Re_d \leq 360 \). It increases rapidly and lies above the uniform flow data as seen from Fig. 9. This is similar to the results with a cylinder at the center of the channel.

The maximum fluid velocity at the cylinder is lower than the center velocity in the cases of \( w/d = 3 \) and 4. Therefore the virtual Reynolds number is lower than the nominal Reynolds number based on the center velocity. Figure 10 shows the comparison of the replotted data of a cylinder on the wall using modified Reynolds number based on the velocity at the upper edge of the cylinder with the data of a cylinder at the center of the channel. The ratio of the velocity at the upper edge of the cylinder to the center velocity is 0.75, 0.889 and 1.0 for \( w/d = 4 \), 3 and 2 respectively. The data with a cylinder at the center of the channel are represented by Eq. (1) which is shown by the solid line in the figure. The replotted data for \( w/d = 3 \) are slightly lower than the solid line. However, the replotted data for \( w/d = 4 \) and 2 agree well with the solid line. In the case of \( w/d = 3 \), usage of modified Reynolds number based on the velocity at \( 3/4 \) of cylinder diameter produces good agreement with the solid line.

Other effects must be considered for the decrease in shedding frequency in the case of a cylinder on the wall. The wall suppresses the generation of shedding vortices. According to Taneda\(^{(14)}\), wave length of the vortex behind a cylinder in the vicinity of the wall is lengthened when the cylinder moves with constant velocity.

The effect of shear flow must be also considered. Kiya et al.\(^{(17)}\) studied the effect of shear flow on Karman vortex shed by a cylinder. They indicate that the transition Reynolds
number and Strouhal number increase with increase in shear parameter. Further experiments will be required to quantify these effects on the shedding vortex.

Photograph 2 shows the flow patterns around a single cylinder on the wall in the cases of $w/d=2$, 3, 4 and 5. As seen from the figure in the case of $w/d=5$, shedding vortices grow larger in the flow direction and the second wave is seen to reach center of the channel. When $w/d$ is small, the walls prevent the vortex growth as is seen from the Photo. 2(a). Accordingly, the distortions of velocity distribution in wake are large when channel width is small. This will induce the increase in frequency as is shown in Fig. 9.

The transition Reynolds number with a cylinder on the wall is about $Re_d=180$ when $w/d=4$ and about $Re_d=200\sim250$ when $w/d=2$. These values agree with the results with a cylinder at the center of the channel. These results indicate that the transition Reynolds number increases with decrease in $w/d$.

IV. CONCLUSION

(1) The relation between non-dimensional frequency and Reynolds number in channel flow experiment with a cylinder at the center of the channel agrees with that in uniform flow experiment for low Reynolds number. For higher Reynolds number, however, non-dimensional frequency considerably increases with Reynolds number and it lies above the results of uniform flow experiment. The deviation of non-dimensional frequency from the uniform flow data occurs between $w/d=4$ and 12.5.

(2) When a single cylinder is put on the wall, non-dimensional frequency is considerably lower than that of uniform flow experiment below $Re_d\leq600$ in the cases of $w/d=3$ and 4. However, when $w/d=2$, non-dimensional frequency is considerably higher than the uniform flow case for $Re_d\geq360$. The replotted data using modified Reynolds number based on the velocity at the upper edge of the cylinder in the case of a cylinder on the wall agreed well with the data of a cylinder at the center of the channel.

(3) The results indicate that the increase in the shedding frequency at higher Reynolds number in narrow channel is due to the shifts in velocity distribution from Poiseuille parabola which increase with Reynolds number and with decrease in channel width.

(4) The transition Reynolds number increases with decrease in $w/d$. The transition Reynolds number with a cylinder at the center of the channel almost agrees with that with a cylinder on the wall.
[NOMENCLATURE]

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<th>Symbol</th>
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<td>$n$</td>
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REFERENCES