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Experimental investigation of the mutual interference flow of two circular cylinders by flow visualization

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Abstract. In order to understand the aspect of the mutual interference flow from two circular cylinders, the visual observation experiment was performed by use a water flow apparatus. The purpose of this study is accumulation of the basic image data for comparing with numerical computation or previous experimental results. In this report, the intervals of two circular cylinders were varied, the visualization experiment was performed, and the vortex shedding characteristics and the flow pattern in each case were investigated. The cylinder setting conditions were seven kinds (the position of the rear-side circular cylinder is changed). The cylinder diameter ratios were four kinds (D/d=1.0, 1.67, 2.5 and 5.0). The variation of Reynolds number was three kinds (Re=548.7, 1200 and 2500). The dye oozing streak method was used in this visualization experiment. Although the previous PIV experimental result and present result obtained the same flow feature, the aspect of an interference flow became clear by changing the color of tracer ink.

1 Introduction

Flow visualization is one of the useful study tools which can overlook the behaviour and phenomenon of fluid visually. The behaviour of fluid is shown by a stream line, a particle pass line, or a streak line, and the aspect of the flow is grasped by them. If the flow is a steady flow which does not change in time, those characteristic lines are in agreement. However, if the flow is an unsteady flow which changes in time, they are not in agreement and show a respectively different aspect. The case where the Karman vortex street produced behind a circular cylinder is expressed with the stream line, the particle pass line, and the streak line as an example of the unsteady flow known well is mentioned. Since the aspect of the flow which changes with approach methods of visualization in the unsteady flow is observed, when solving one flow phenomenon, it becomes important to change the visualization method and an observation viewpoint and to observe the phenomenon. However, there are few examples which compared the result obtained by the flow visualization by a different technique about the same unsteady flow phenomenon. In the aspect of the interference flow from two bodies, it is one of the most interesting matters to get to know the aspect of the flow by the difference in the visualization technique. As the study relevant to the interference problem of two bodies, Zdravkovich [1] introduces the studies that solve the drag and lift in the tandem arrangement case and parallel arrangement case and influence of two identical cylinders on the frequency of vortex shedding. Strykowski and Sreenivasan [2] deal experimentally and numerically the influence of the small cylinder (rear cylinder) and the formation of the vortex street behind the main cylinder at low Reynolds numbers. In their work indicate that there are positions of secondary small cylinder (rear cylinder) in which it can control the vortex street. Choi et al. [3] classify methods of flow control for the bluff cylinder and present results of comparing regions of attenuating instabilities using a small secondary cylinder. Mittal and Raghuvanshi [4] solve the influence of a small secondary cylinder on the main cylinder (primary cylinder) using numerical simulations. They compare with their results and previous experimental results and focus on the causes of the influence of the control cylinders on the main cylinder. Yokoi and Hirao [5-9] is reporting the result of the study shown by the streak line about the vortex shedding from the circular cylinder which is oscillating in the direction of flow using the flow visualization technique based on a pouring streak method. Rut et al. [10, 11] is reporting the result of study which showed the interference flow from two circular cylinders arranged staggered using the flow visualization technique based on a suspension method by the particle pass line. Then, the visualization experiment by the streak line method was performed on the same conditions as a previous experiment for the database creation in comparison with the previous experimental result [10].

In this study, the position and diameter ratio of two circular cylinders which are arranged staggered were varied using the closed circuit water channel apparatus, the tracer ink of different colour was made to ooze from each circular cylinder, and flow visualization by the streak method was performed. As a result, the aspect of

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Fig. 1. Aspect of experimental apparatus

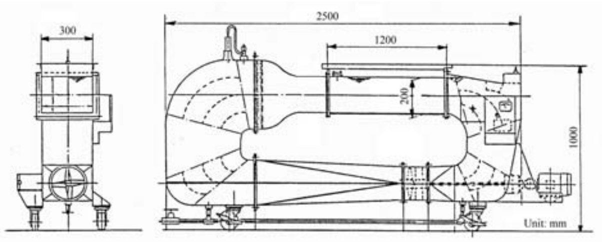


Fig. 2. Schematic diagram of closed circuit water channel

vortex shedding from each circular cylinder and the aspect of mutual interference flow were shown vividly.

2 Experimental apparatus and method

2.1 Outline of experimental apparatus

The experimental apparatus consists of a closed circuit water channel experimental apparatus, a visualization equipment, and an image record equipment. The aspect of experimental apparatus is shown in Fig. 1. The closed circuit water channel is a vertical circulation type of 2.5m in length, 0.3m in width, and 1m in height, and the volume of water is 0.4 tons. The water channel consisted of water flow generation equipment (1 axial flow type pump), rectification device, test section and 4 corner parts with guide vanes. The test section is 1.2m in length, 0.3m in width, 0.2m in depth, and the flume structure with the surface of the water. The test section is a product made from transparent acrylics. The maximum flow velocity in the test section was 1.3m/s. The schematic diagram of the closed circuit water channel is shown in Fig. 2.

The visualization apparatus consists of a tracer ink feed unit and a lighting installation. The ink tank is installed above the water surface, and a set of the clamps and opening-and-closing clips for flow regulation are formed in the vinyl tube which connects the circular cylinder to the ink tank.

As for the lighting installation, one halogen light of 500W and one stroboscope were used. Here, the halogen light was used as a main light source, and the stroboscope was used as a sub light source. And the stroboscope was used for measurement of vortex shedding frequency.

Fig. 3. Test circular cylinders, 4mm, 6mm, 10mm, 20mm

The video recording apparatus consists of a small size 3CCD video camera, a video recorder, and a monitor TV. Photography of an image installed a mirror aslant under the test section, and recorded the aspect of the flow projected on the mirror. Since the photography from the test section bottom side is not influenced by water surface wave for an observation picture, it is convenient.

2.2 Test cylinders

The length of all test circular cylinders is 300mm. As for the outer diameter, 4mm, 6mm, 10mm, and 20mm are prepared. The screw for circular cylinder fixation (M4) is prepared in the circular cylinder end, and the tracer ink introduction way is provided in the inside of the circular cylinder from the section of the screw to the tracer oozing port on the surface of circular cylinder. Two tracer ports for visualization were provided in the position of ±60 degrees from the cylinder stagnation point. They are located near 100mm from the circular cylinder other end. When installing the circular cylinder in the water tank test section, the tracer oozing position is 100mm under the water surface. The arrangement of circular cylinders is shown in Table 1. For convenience, front side and rear side cylinders are called the "1st cylinder" and "2nd cylinder", respectively.

In order to reduce mixture by tracer oozing, the depth positions of the oozing port differ in the 1st cylinder and the 2nd cylinder. The oozing port of 1st cylinder is provided in the water surface side, and the oozing port of 2nd cylinder is provided in the bottom side. The gap between both is 2mm. The photograph of these circular cylinders is shown in Fig 3.

2.3 Flow visualization method

The flow visualization technique used in this experiment is a pouring streak method. Tracer ink is led to the inside of the circular cylinder using a vinyl tube from a tracer tank, and it carries out by adjusting the valve travel of the clamp which provided that the tracer ink of the grade which does not destroy a boundary layer from the oozing port on the circular cylinder surface oozed in the middle of the vinyl tube. The used tracer ink is the poster color thinned moderately. "Pink" and "turquoise blue" were

Table 1 Setting positions of 2nd cylinder

D/d	1.0, 1.67, 2.5	5.0
	(*x/D*, *y/D*)	(*x/D*, *y/D*)
Posi1	(4.30, -1.20)	(4.05, 1.25)
Posi2	(3.20, -0.80)	(3.20, -0.80)
Posi3	(2.40, -0.80)	(2.40, -0.80)
Posi4	(1.95, -0.80)	(1.95, -0.80)
Posi5	(2.00, -0.60)	(2.00, -0.60)
Posi6	(1.50, -0.35)	(1.50, -0.35)
Posi7	(1.50, 0.00)	(1.50, 0.00)

used with the 1st cylinder and the 2nd cylinder, respectively. In the case of the single circular cylinder, the white poster color was used.

2.4 Experimental parameters

The main experiment parameters are Reynolds number *Re*, the diameter ratio of two circular cylinders *D/d*, and the arrangement position of two circular cylinders. Reynolds number *Re* is three kinds (*Re*=548.7, 1200 and 2500), and is obtained from the diameter of the 1st circular cylinder *D*, and main flow velocity *U*. The diameter ratios of two circular cylinders is four kinds (*D/d*=1.0, 1.67, 2.5 and 5.0). The combinations of the diameter of two circular cylinders are 10mm with 10mm, 10mm with 6mm, 10mm with 4mm, and 20mm with 4mm, respectively. Arrangement of two circular cylinders is seven kinds. The 1st cylinder position was put on origin (x, y) = (0, 0), and the position of the 2nd cylinder was changed as shown in Table 1.

2.5 Experimental procedure

As preparation, water is filled in the small closed circuit water channel, and condition is prepared so that experiment operation can be performed. The circular cylinder diameter ratio is determined. The 1st cylinder is installed in an origin, and the position of the 2nd cylinder is determined and attached in a circular cylinder attachment plate from the arrangement position of two circular cylinders. The plate equipped with circular cylinders is installed in the predetermined position of the test section. Test Reynolds number is set up by operating the axial flow pump of the closed circuit water channel. Quantity of the tracer ink which oozes from each circular cylinder is adjusted, and video recording of the flow pattern image of the visualization experiment is performed about 1 minute. If recording is completed, washing of the test section and exchange of water will be performed, and it will be set as the following test Reynolds number. If the variation of Reynolds number is completed, the arrangement position of two circular cylinders will be changed and the visualization experiment will be repeated in the same procedure. If the variation of the arrangement position of two circular cylinders is completed, the circular cylinder diameter ratio will be re-determined, and the visualization experiment will be gone on in the same procedure.

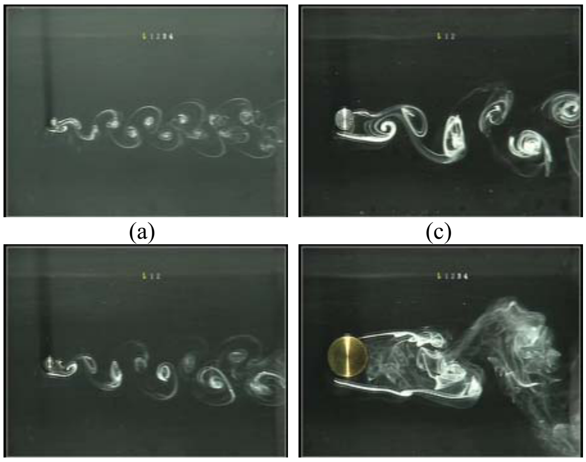


Fig. 4. Flow features of vortex shedding, single cylinder case, (a) *D*=4mm, (b) *D*=6mm, (c) *D*=10mm, (d) *D*=20mm

In video recording, photography of the plate which wrote the experimental condition before photography of the flow pattern was performed. The image data taken into the video recorder is copied to DVD, it reproduces with a personal computer, and a still picture is created by capturing operation.

3 Experimental results and discussion

3.1 Single circular cylinder case

Visual observation of the vortex shedding from a single circular cylinder was performed for operating evaluation of the experiment equipment. The photographs of the instantaneously flow pattern from the circular cylinder of each diameter are shown in Fig. 4. Here, the main flow velocity *U* is in the same state (*U*= 0.0556m/s). In each photograph, it is shown that vortices are alternatery shed from the circular cylinder and Karman vortex street is formed in the wake. It seems on photograph that the number of the vortexes of the Karman vortex formed with increase of the circular cylinder diameter *D* is decreasing. In the experiment of each circular cylinder, the luminescence period of a stroboscope was synchronized with the vortex shedding period, the Karman vortex shedding frequency *f* was measured, and it determined for a Strouhal number *St*. The Strouhal number is defined by *St=fD/U* based on the outer diameter of cylinder *D* and vortex shedding frequency *f*. As a result, the Strouhal number of each circular cylinder was about 0.21. Generally it is well known that the Strouhal number of circular cylinder is about 0.2. Since the value by experiment equivalent to the general known value was obtained, it turns out that the apparatus and the measurement technique of this experiment are appropriate.

3.2 Visualized flow pattern of Two cylinders

It is one of the most interesting things of this study to conduct visualization investigation of an aspect that install another circular cylinder behind cylinder and the

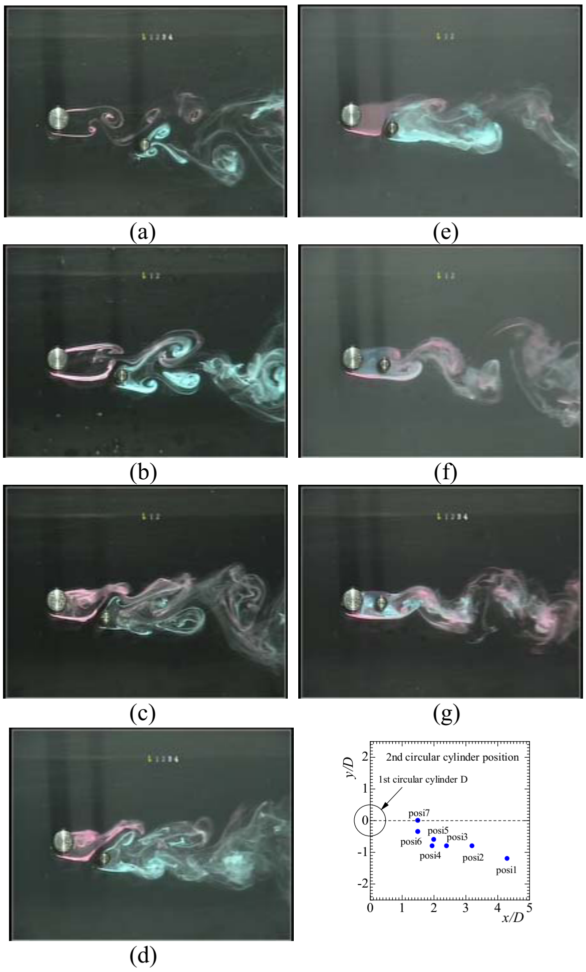


Fig. 5. Aspect of the flow when varying the position of 2nd cylinder, *Re*=548.7, *D/d*=1.67, (a) Posi1, (b) Posi2, (c) Posi3, (d) Posi4, (e) Posi5, (f) Posi6, (g) Posi7

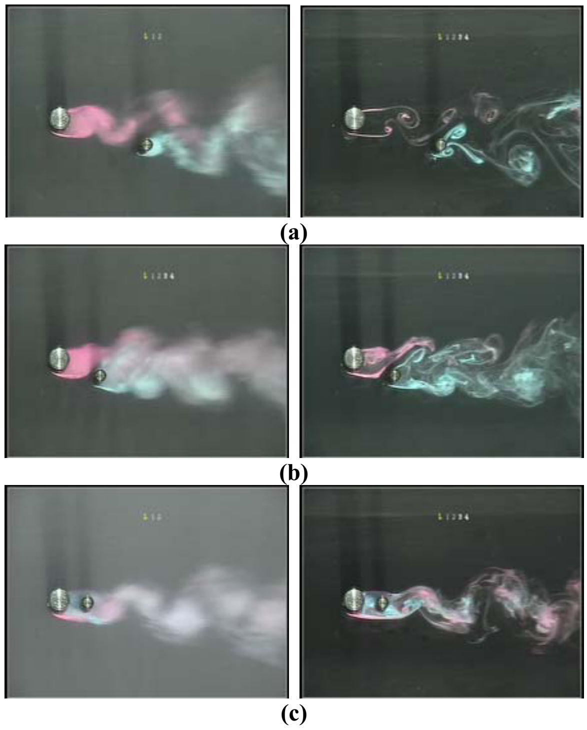
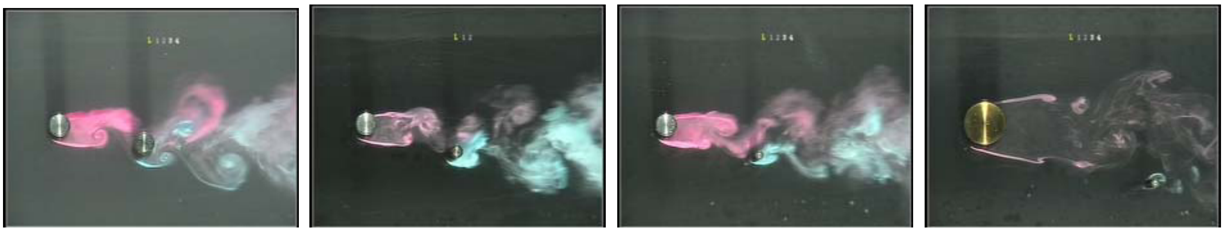


Fig. 6. Aspect of the flow when varying the flow velocity, (a) Posi1, *Re*=2500, 548.7, (b) Posi4, *Re*=2500, 548.7, (c) Posi7, *Re*=2500, 548.7,

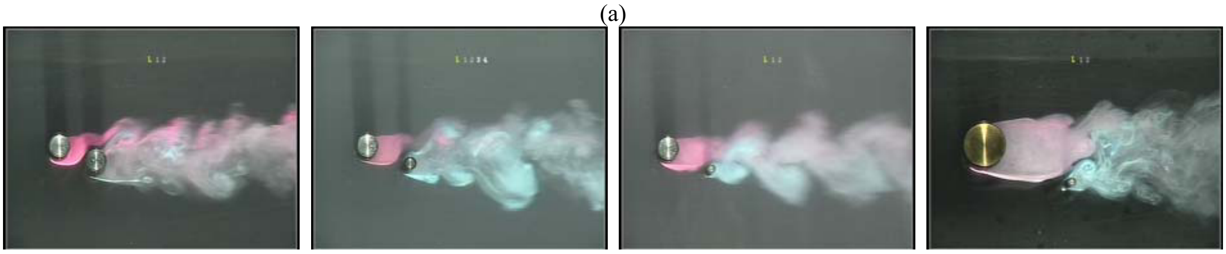
vortex flow is controlled. It was observed that the aspect of the flow of the 2nd cylinder completely differs from the aspect of the flow when the 2nd cylinder is placed independently through all experimental conditions. In staggered arrangement like this study, flow pattern can divide roughly into the following three types by the behaviour of the separating shear layer of the 1st cylinder by the side of the 2nd cylinder. (1) The state completely rolled by the separating shear layer before the 2nd cylinder. (2) The state of colliding with the 2nd cylinder before having been rolled by the separating shear layer since the 2nd cylinder is located in the outside of the separating shear layer. (3) The state where the flow from the 2nd cylinder is taken into the re-circulation flow of the 1st cylinder since the 2nd cylinder is located inside the separating shear layer. Figure 5 shows the aspect of the flow when varying the position of the 2nd cylinder in circular cylinder diameter ratio *D/d*=1.67 and Reynolds number *Re*=548.7, as an example. In "Posi1" case, the vortex is alternately discharged from the 1st cylinder, and the vortex by the side of the 2nd cylinder has collided with the 2nd cylinder. It has united with the vortex street which could draw near to the 1st cylinder side the vortex shedding from the 2nd cylinder under the influence, and was discharged from the 1st cylinder. In "Posi2" case, before having been rolled by the separating shear layer discharged from the 1st cylinder, it has collided with the 2nd cylinder. Therefore, the Karman vortex was not produced from the 1st cylinder, but the vortex shedding from the 1st cylinder has assimilated to the vortex shedding of the 2nd cylinder. In "Posi3" case, the separating shear layer from the 1st cylinder is flowing into the re-circulation region behind the 1st cylinder. In "Posi4" case and "Posi5" case which the position of the 2nd cylinder approaches, the phenomenon seems to be more remarkable. In "Posi6" case or "Posi7" case, the 2nd cylinder is placed inside roll up of the separating shear layer discharged from 1st cylinder. Therefore, the separating shear layer from 2nd cylinder is carried to the re-circulation flow of the 1st cylinder, and forms the stagnation region. The vortex shedding of two circular cylinders forms the Karman vortex just like the vortex shedding from one compound body.

In the range of the Reynolds number as for which the value of the Strouhal number becomes almost constant, roll up of the separating shear layer occurs generally in the same position. So, even when varying the Reynolds number in the experiment range, it is expected that the same flow pattern is obtained. Figure 6 shows the flow pattern of circular cylinder arrangement in which the flow pattern of three types mentioned above is shown. Here, it is circular cylinder diameter ratio *D/d*=1.67 and Reynolds number *Re*=2500. It turns out that the aspect of an interference flow does not change even if it changes Reynolds number compared with Fig. 5.

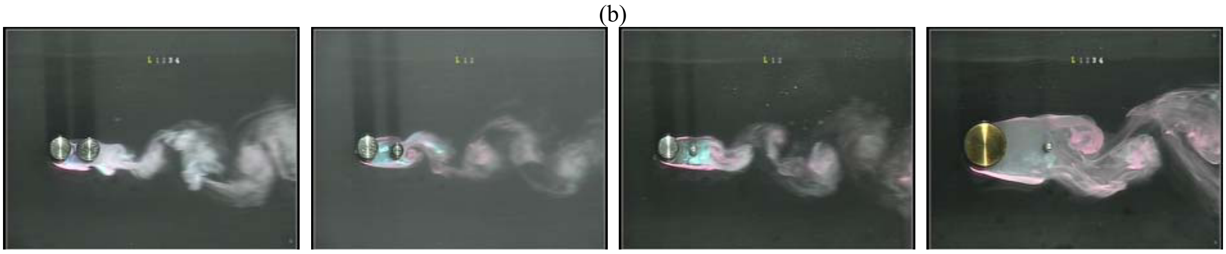
If its attention is paid to the behaviour of the separating shear layer of 1st cylinder, it will be expected that the aspect of an interference flow does not change



(a)

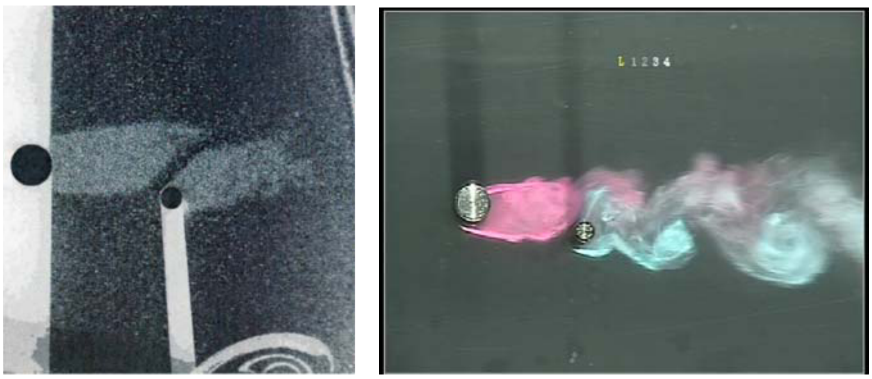


(b)

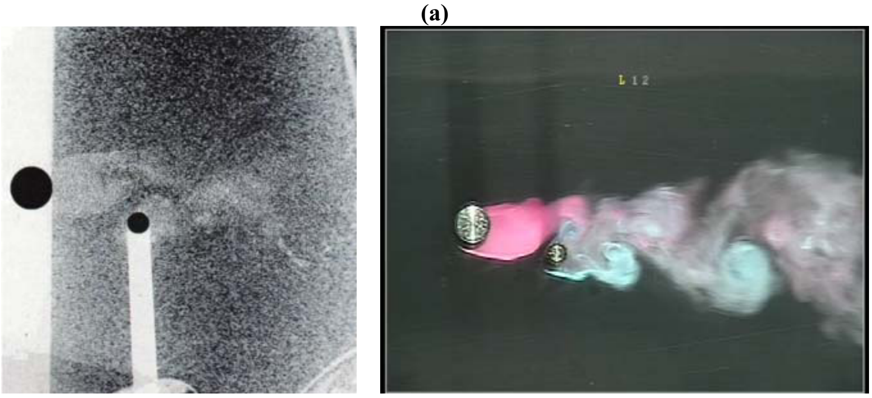


(c)

Fig. 7. Aspect of the flow when varying the cylinder diameter ratio *D/d* in *Re*=1200, (a) Posi1, *D/d*=1.0, 1.67, 2.5, 5.0, (b) Posi4, *D/d*=1.0, 1.67, 2.5, 5.0, (c) Posi7, *D/d*=1.0, 1.67, 2.5, 5.0,



(a)



(b)

Fig. 8. Comparison of the visualization technique in the particle pass method and the streak method, left-hand side visualization photograph is in the particle pass method in reference 6, (a) *Re*=1394, *D/d*=2, Posi2 and *Re*=1200, *D/d*=1.67, Posi2, (b) *Re*=1394, *D/d*=2, Posi3 and *Re*=1200, *D/d*=1.67, Posi3

even if it changes the diameter ratio *D/d*. Figure 7 shows the result of having changed the circular cylinder diameter ratio *D/d* in the situation which constitutes the typical flow pattern, respectively. When the position which the 2nd cylinder places is the same, it turns out that the aspect of an interference flow does not change even if it changes the diameter ratio *D/d*.

3.3 Comparison of aspect of flow by different visualization technique

It is also one of the most interesting things of this study to compare the result of having visualized the same phenomenon by different technique. Figure 8 shows a previous visualization result [10] and the visualization result obtained in this experiment. Here, although both have some difference at experimental conditions, it is a comparatively near case. The object of the comparison is in the state where the circulation region existed behind the 1st cylinder, and the direction of the vortex shedding from the 2nd cylinder has turned to the 1st cylinder side. The previous visualization technique [10] is based on the PIV technique by particle mixing, and shows movement of fluid by the particle pass line. On the other hand, present visualization technique is a pouring streak method by tracer ink oozing, and shows movement of fluid by the streak line. The particle pass line is the route which the same particles follow, and the streak line is the aspect of different particles which follow the same route. So, at the unsteady flow field, visible aspects differ in both. However, in the aspect of the flow of the 1st cylinder behind, and the aspect of the flow of the 2nd cylinder behind, even if it uses the different visualization technique, it is visible to the same aspect. This matter means that there is little fluctuation like the steady flow in the flow of this region.

4 Conclusions

Visualization observation of the flow around two circular cylinders which arranged staggered was carried out using the streak line method. The following conclusions were obtained.

(1) The aspect of interference flow changes with the position of 2nd cylinder.

(2) Even if Reynolds number changes, the aspect of an interference flow does not change.

(3) When the position of the 2nd cylinder is the same, even if the diameter ratio changes, the aspect of the interference flow does not change.

(4) The flow of the circulation region around two circular cylinders has little fluctuation so that it can be regarded as the steady flow.

References

1. M. M. Zdravkovich, J. Fluids Eng. **99**(4). 618-633(1977)
2. P. J. Strykowski, K. R. Sreenivasan, J. Fluid Mech. **218**, 71-107(1990)
3. H. Choi, I. Lee, W. P. Jeon, Annu. Rev. Fluid Mech. **40**, 113-139(2008)
4. S. Mittal, A. Raghuvanshi, Int. J. Numer. Math. Fluids **35**, 421-447(2001)
5. Y. Yokoi, K. Hirao, J. Fluid Science and Technology **4**-2, 401-414(2009)
6. Y. Yokoi, K. Hirao, EPJ Web of Conf. **45**, 01098(2013)
7. Y. Yokoi, K. Hirao, EPJ Web of Conf. **67**, 02131(2014)
8. Y. Yokoi, K. Hirao, J. Fluid Science and Technology **9**-3, 0057(2014)
9. Y. Yokoi, K. Hirao, EPJ Web of Conf. **92**, 02116(2015)
10. R. Vitkovicova, J. Nozicka, J. Cizek, V. Skala, EPJ Web of Conf. **92**, 02110(2015)
11. R. Vitkovicova, Vladislav Skala, EPJ Web of Conf. **114**, 02138(2016)