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FLOW AROUND TWO SIDE-BY-SIDE CIRCULAR CYLINDERS WITH INTERMEDIATE SPACED NEAR A PLANE WALL

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Abstract

The flow characteristic around two circular cylinders in side-by-side arrangement near a plane wall was investigated experimentally and numerically. The lower cylinder was embedded in a turbulent boundary layer whose thickness is about fifty percent from the cylinder diameter. The Reynolds number based on the diameter of single cylinder was 53000. The pressure distributions along the surface of the cylinder and the plane wall were measured for the gap-to-diameter of cylinder ratio $G/D = 0.2$ and the center to center spacing between the two cylinders was constantly maintained at $T/D = 1.5$, where G was the gap between lower cylinder surface and plane wall, while T was transversal distance among two circular cylinders. A flow

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pattern between cylinders was visualized with the 2D-URANS numerical simulation with k-ω SST as a turbulence viscous model. In fact, an evolution of pressure distributions in circular cylinders, especially at the lower cylinder, is influenced by a plane wall which is located near them. The gap flow is biased to one side, resulting in the formation of narrow wake behind one cylinder and a wide wake behind the other.

Nomenclature

C_D	drag coefficient
C_L	lift coefficient
C_p	pressure coefficient
p	static pressure (Pa)
$p_\sim$	free stream static pressure (Pa)
r	radius of cylinder (m)
D	diameter of cylinder (m)
G	gap distances from a bottom surface cylinder and plane wall (m)
T	tranversal distances between cylinder centers (m)
$U_\sim$	free stream velocity (ms^{-1})

Greek symbols

θ	circumferential angle on the cylinder (deg)
ρ	density of free stream (kgm^{-3})

0. Introduction

Flow around a circular cylinder is still an interesting topic in a fluid research, particularly, for the flow cross the circular cylinders in a group.

Zdravkovich [14], an expert in this object, has worked through his book deeply concerned with the flow phenomenon and the influencing parameters of flow around a circular cylinder. As the group, an existence of one cylinder affects the other cylinder, which is called *flow interference*, could cause some drastic change in fluid forces and some unexpected flow phenomena on its. One of the circular cylinders in the group is two circular cylinders in side-by-side arrangement. Moreover, this array which is located near a plane wall is an interesting topic to be investigated. This configuration can be found in many engineering applications such as element in offshore structures, undersea pipe-lines and in tube arrays of heat exchangers.

There are many studies about flow around a pair of two circular cylinders in side-by-side configuration in a centerline experimentally (Zdravkovich and Pridden [13] and Zdravkovich [11]), numerically (Meneghini et al. [7]) and flow visualization (Sumner et al. [9] and Mahbub et al. [5]). The author (Zdravkovich [11]) classified flow around two circular cylinders in side-by-side arrangement becoming very closed proximity $(1.0 < T/D < 1.2)$; intermediate spaced $(T/D = 1.2\text{-}2.2)$ and a spaced sufficiently far apart $(T/D > 2.7)$. At $T/D = 1.2\text{-}2.2$, the other authors (Zdravkovich and Pridden [13]) found the intermittency of the high and low drag values which did not cease but persisted for a longer time at one value. The remarkable feature of the interference between the two cylinders was that the drag of the two cylinders in side-by-side configuration is always less than twice the drag of the single cylinder. Zdravkovich [11] stated that $1.2 < T/D < 2$ to 2.2, narrow wake "NW" and wide wake "WW" were formed behind the cylinders, respectively, and could interchange positions. The flow was bistable while the gap flow formed a jet biased towards the narrow wake but could switch in the opposite direction too. Also, it produced always larger drag, lift and Strouhal number behind the cylinder with the narrow near-wake. That result was made more clear with Sumner et al.'s [9] work, which through a visualization or PIV technique, found the biased flow pattern, which means that flows in gap deflected in one side and the deflection angle becomes smaller when increasing pitch ratio.

The authors (Mahbub et al. [5]) found that in the bistable flow regime, $T/D = 0.1\text{-}1.5,$ the difference between the magnitudes of C_D for modes "NW" and "WW" was larger for small spacing. In the range of $T/D =$ $0.10\text{-}0.20$ and 1.20-1.50 (where T was gap spacing between cylinders; and D diameter), they found that the mean C_D value of the cylinders was greater than that of single cylinder. While at $T/D = 0.1,$ they found the lift coefficient was interesting, –0.12 and 0.65 for modes "NW" and "WW", respectively. It means that there were attractive forces also possible for two side-by-side cylinders in the bistable flow regime. This was showed through the pressure coefficient $C_p,$ the stagnation point shifted towards the inner side at 330° instead of 0° and this was a cause of repulsive lift force. In the case of mode "NW", there was a big difference between the pressure at the inside surface and the outside surface. The pressure at the inside surface was more negative than that at the outside surface, so that it is directed toward the inside. The values of C_D and C_L which were determined from integrating the surface pressures were 1.72 and –0.14, respectively, for mode "NW" and 1.21 and 0.61, respectively, for mode "WW". The pressure distribution indicated that the outer shear layer could be expected to separate from the cylinder at $\theta = 60^\circ$ and 65° for modes "WW" and "NW", respectively, while gap flow separation can be expected at about $\theta = 240^\circ$ and 200° for modes "WW" and "NW", respectively. A flow visualization showed that an earlier separation of the gap flow occurred from the lower cylinder and that the gap flow was directed along the surface of the upper cylinder, and finally, the gap flow separates near the base of the cylinder. While the pressure distribution for $T/D = 0.5,$ at which C_D for both modes was minimum, the trends in variation of C_p for modes "NW" and "WW" were almost the same except for a difference in pressures in the base region. At this spacing, the stagnation point was at $\theta = 340^\circ$.

According to the results of flow visualization of Lin et al. [3], if a cylinder is located near a plane wall, then the stagnation point will move to lower-side of cylinder, and it is moved far from 0° as a position of the cylinder closer to the plane wall. An existence of the plane wall made a recirculation region on its upstream the cylinder, that makes a flow on a gap was constricted. The scale of recirculation eddies was larger as a position of the cylinder closer to the plane wall. Yuwono et al. [10] researched two circular cylinders in tandem arrangement near a plane wall at $G/D \leq 0.2$, also found there was not a stagnation point with $C_p = 1$ in a front-side of upstream cylinder. This was caused of blockage effect of flow on a gap, that a large part of fluid flow to upper-side of the cylinder. Beside that, those separation points were down-side compared with its position in a centerline. Grummy et al. [1] have investigated the four circular cylinders in equispaced arrangement near a plane wall with $L/D = 1.5$ and $G/D = 0.2$. They found a flow interaction between the upper cylinder and the lower cylinder, also the lower cylinder and the plane wall. While behind the downstream cylinders occurred a bistable flow, which means narrow and wide wakes were formed behind the cylinders.

However, as far as we know, there is no study published in journal concerning an interaction between two circular cylinders in side-by-side arrangement is located near a plane wall. This study would focus on two side-by-side circular cylinders arrangement with intermediate spaced, $T/D = 1.5$, which is located near plane wall for $G/D = 0.2$. The measurements of pressure distribution on cylinders and the wall, respectively, would be reported here at Reynolds number of 5.3×10^4 (based on diameter cylinder D and the free stream velocity $U_{\sim}$).

1. Experimental Apparatus and Methods

The experiments were performed in an open-circuit subsonic wind tunnel with a test-section of 660mm in height, 660mm in width and 1800mm in length. The free stream turbulent intensity in test-section was 4% at 13m/s.

Figure 1 shows a sketch of the coordinate systems and a schematic diagram of the experimental set-up, and computational domain in this study. The diameter and aspect ratio (L/D) of two circular cylinders which is made from PVC tubing were 60mm and 11%, respectively. A smooth flat plate 10mm in thickness and 1400mm in length was installed 128mm above the bottom surface of the test-section. The leading edge of the plate was sharp-edged with an angle of 30°. The lower circular cylinder was located at 625mm from the leading edge of the flat plate and the boundary layer formed over the flat plate had a thickness of 30mm. During experiments, the free stream velocity $(U_{\sim})$ was fixed at 13m/s and the corresponding Reynolds number based on the diameter of the cylinder was about 5.3×10^4.

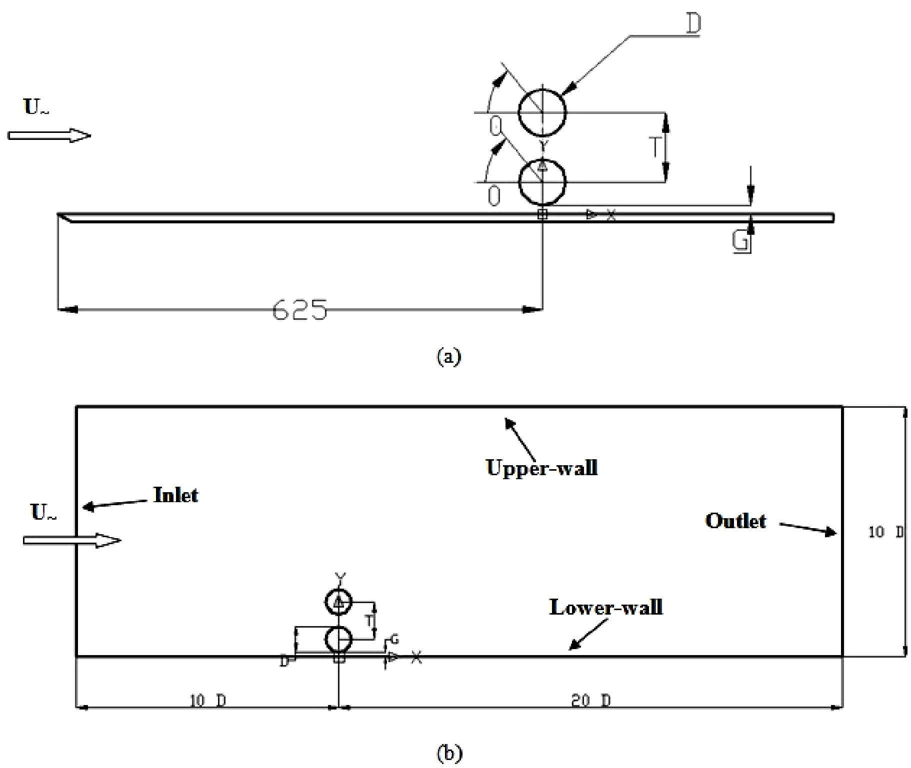

Figure 1. Sketch of: (a) the coordinate systems and a schematic diagram of experimental set-up and (b) computational domain and boundary conditions.

The coordinates X and Y denoted the streamwise distance from the cylinder and the vertical distance from the bottom plate, respectively; G represented the gap distance between the bottom of cylinder and the flat plate; and T represented the transversal distance between the centers of cylinder.

To measure the pressure distributions on the cylinders surface and on the flat plate were installed the 4 pressure taps with interval 90° on the cylinders wall and ends of them were equipped with rotator mechanism so that be rotated the cylinders every 5°, while the 221 pressure taps with interval 5mm started from 100mm of leading edge on the flat plate. The pressure taps were connected to pressure transmitter (PX655-05BDI) and data acquisition logger (OM-DAQPRO-5300). The pressure transmitter was calibrated with inclined kerosene manometer.

The experimental results were expressed in terms of dimensionless pressure, drag and lift coefficients. The pressure coefficient C_p was expressed in the following form:

$$C_p = \frac{p - p_\sim}{\frac{1}{2}\rho u_\sim^2}. \tag{1}$$

The drag and lift coefficients of cylinders were evaluated from the surface pressure distribution. If the contribution of skin friction on aerodynamic forces was negligibly small, then the drag force could be represented by the form drag component. The drag coefficient C_D and lift coefficient C_L were obtained as follows:

$$C_D = \frac{1}{2}\int_0^{2\pi} C_p(\theta)\cos(\theta)d\theta, \tag{2}$$

$$C_L = -\frac{1}{2}\int_0^{2\pi} C_p(\theta)\sin(\theta)d\theta \tag{3}$$

and both of these equations were done using Simpson's rules.

The numerical simulation 2-D URANS, with k-ω SST as a turbulence viscous model, the technique was employed to visualize the gap effect on the flow interaction between the wake behind the upper and lower cylinders and the flat plate boundary layer. It used a commercial software, FLUENT, and run based on a second order finite volume discretization and the SIMPLE pressure correction technique.

In order to test the reliability of measuring system, the pressure distribution on single cylinder was measured and compared with the result published in the literature. According to evaluation from the surface pressure distribution, drag pressure coefficient (C_{dp}) and base pressure coefficient (C_{pb}) had agreed quite well with Igarashi [2] (Figure 2 and Table 1).

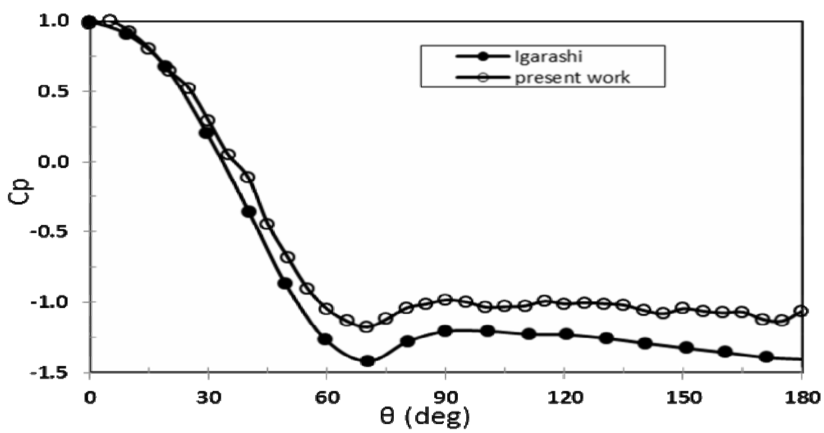

Figure 2. Comparison between present work $(Re = 4.913 \times 10^4)$ and Igarashi $(Re = 3.5 \times 10^4)$ in pressure distribution of a single circular cylinder.

Table 1. Comparison between present experiment and Igarashi in a single circular cylinder

	Re	C_{pb}	C_{dp}
Igarashi	$Re = 3.5 \times 10^4$	−1.40	1.26
Present work	$Re = 4.913 \times 10^4$	−1.01	1.10

The large differenced between the blockage ratio (9.1% vs. 0.125%), aspect ratio (11% vs. 3%) and the turbulent intensity (4% vs. 0.55-0.6%) of present experiment and Igarashi [2] might be the major reasons for the noted discrepancy.

2. Experimental and Numerical Result

A nature of flow pattern around two circular cylinders in side-by-side arrangement near a plane wall is evaluated through a distribution of pressure coefficient (C_p). Figure 3 shows a result of the pressure coefficient around the lower cylinder of side-by-side arrangement near a plane wall at $T/D = 1.5$ and $G/D = 0.2$. It can be seen in the figure that the stagnation point towards the inner side at 5° instead of 0°, while Mahbub et al. [5] found the stagnation point at 20° for the same ratio of the center to center spacing between the two cylinders, but its arrangement was located in centerline. This difference is caused by the plane wall which is located near the lower cylinder and that makes acceleration of flow in upper-side and bottom-side of the lower cylinder. This is shown from the difference of minimum peak of pressure value between the present work and result of Mahbub et al. [5], and that is also agree with Lin et al. [3]. Although including the bistable flow regime, there is a little difference between the pressure at the inside surface and the outside surface. The pressure distributions indicate that the outer shear layer can be expected to separate from the cylinder at $\theta = 260^\circ$, while gap flow separation can be expected at about $\theta = 110^\circ$. It occurs early than an arrangement positioned in a centerline. The values of C_D and C_L which are determined from integrating the surface pressure are 2.219 and 0.013, respectively, while Mahbub et al.'s [5] results are 1.142 and 0.430. This is agreed with Zdravkovich [12] result that a value of drag coefficient depends on G/δ ratio, which δ is a boundary layer thickness. These authors also found that a value of lift coefficient was affected by G/D ratio.

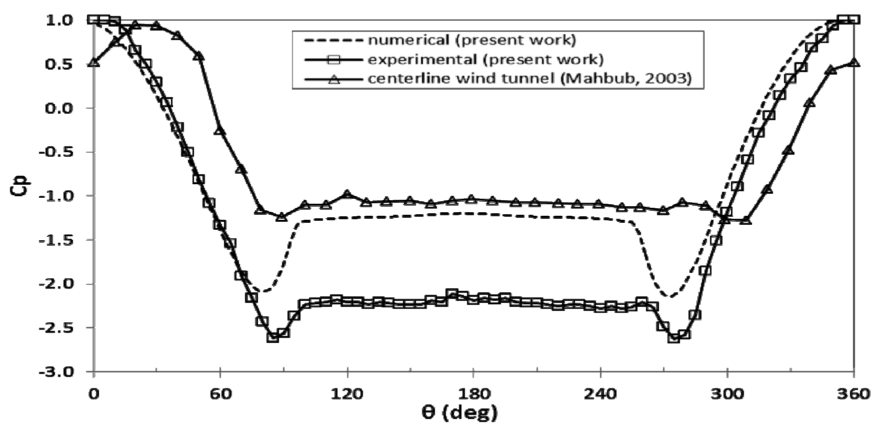

Figure 3. Pressure coefficient C_p, distributions for $T/D = 1.5$ around the lower cylinder.

Figure 3 also shows that the numerical result does not agree completely with the experimental result. Based on the numerical result, the flow is accelerated in the lower side so the stagnation point that towards the outer side (in the gap between cylinder and plane wall) at $\theta = 354^{\circ}$, it is contrary to the experimental result.

Figure 4 shows a result of the pressure coefficient around the upper cylinder compared with an arrangement in centerline. It can be seen that the stagnation point towards the inner side (gap) at 345°, while Mahbub et al. [5] found the stagnation point at 340°. But, there is only a little difference position of stagnation point between the upper cylinder for an arrangement near a plane wall and an arrangement in centerline. This is caused by, in arrangement near plane wall, partly a flow momentum in lower cylinder deflect toward to upper-side that makes a flow momentum in a spacing of cylinders is higher, and finally added a flow acceleration on flow around the upper cylinder. This is showed from a higher minimum pressure of peak value which is compared than an arrangement in centerline. The pressure distributions indicated that the outer shear layer could be expected to separate from the cylinder at $\theta = 75^{\circ}$, while in a gap, flow separation can be expected at about $\theta = 265^{\circ}$. These occured late compared to an arrangement in centerline, which were $\theta = 70^{\circ}$ and $\theta = 260^{\circ}$, respectively. The values of C_D and C_L which are determined from integrating the surface pressures 1.225 and 0.349, respectively, while 0.98 and 0.314 for an arrangement positioned in centerline. This is agreed with Zdravkovich [12] that a value of drag coefficient and lift coefficient tend to be not change when in an outside of boundary layer thickness.

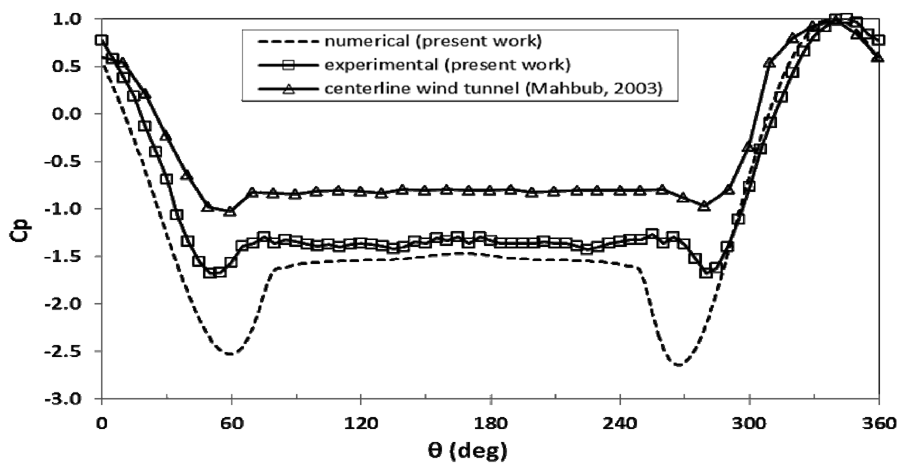

Figure 4. Pressure coefficient C_p, distributions for $T/D = 1.5$ around the upper cylinder.

As indicated in Figure 4, the comparison of numerical result and experimental result gives an enough agreement in separation point at the outer shear layer and stagnation point and at gap flow separation shear layer.

Figure 5 shows the pressure distribution along the plane wall which is measured from $-8.75 \leq x/D \leq 9.6$. An existence of the lower cylinder gives a blockage effect at the gap between lower side of the lower cylinder and the plane wall. It causes the flow decelerated when will enter a gap (it is showed by positive value of C_p). While in the gap, it occurs a high acceleration on flow which is showed by negative value C_p. Starting at about $x/D = 2.5$, flow tends to reattach on a wall until at the rear side. This condition is caused of a high flow momentum in a gap (between the cylinders) which forms a jet of flow push deflected flow reattachement to wall. As the flow moves downstream, the negative pressure recovers to static pressure. Figure 5 also shows that the numerical result indicates a good agreement with the experimental result.

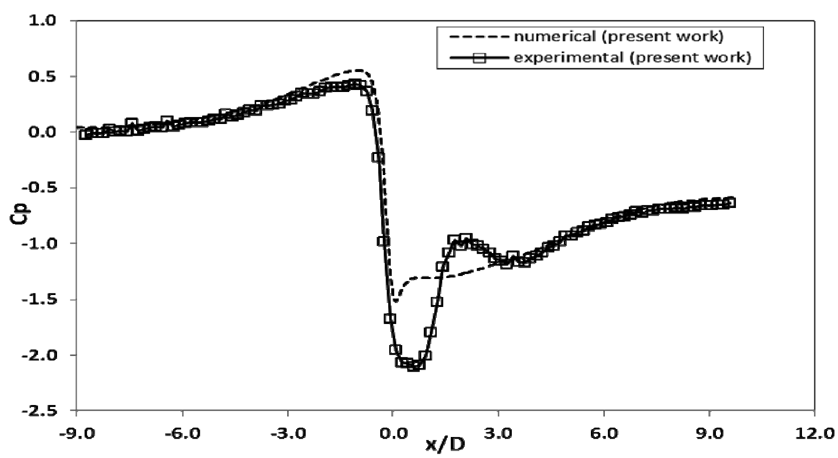

Figure 5. Pressure coefficient C_p, distributions along the plane wall.

3. Flow Visualization

The results of flow visualization indicate a biased flow phenomenon in this arrangement (Figure 6). It occurs narrow wake "NW" behind the upper cylinder and wide wake "WW" behind the lower cylinder. The plane wall causes accelerated flow in bottom-side of the lower cylinder. It causes a stagnation point of its shifts toward a front-side, and make a different position with the upper cylinder. Figure 6 also shows the eddy circulation in plane wall in the upstream cylinder, it forces the flow came to tend upwards and causing stagnation point moved to the upper-side. Through a visualization too, it is showed partly of flow momentum in gap between the cylinders makes a deflected flow from gap (between bottom-side of the lower cylinder and the wall) reattach on wall.

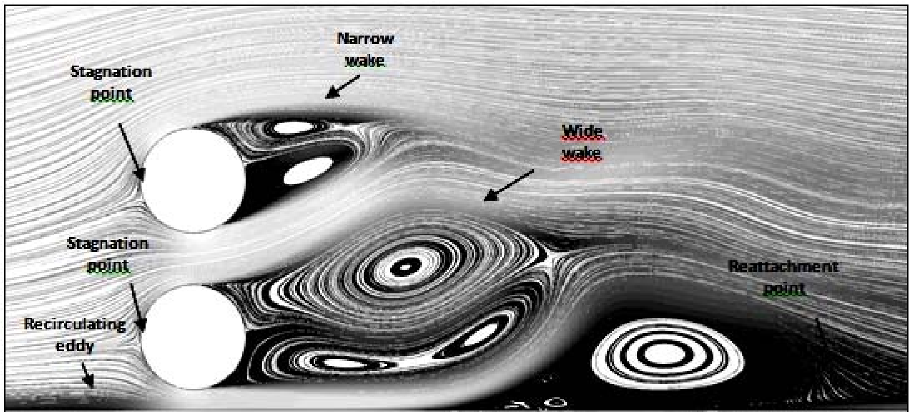

Figure 6. Visualization result with velocity pathline, $t = 0.076$s.

4. Conclusions

The result of this investigation may be summarized as follows: (i) flow interaction between lower cylinder and plane wall produces a different stagnation point in the lower cylinder and the upper cylinder. This is caused of a recirculating eddies which form in plane wall upstream of its and (ii) flow interaction between lower cylinder and plane wall produces reattachment flow on the wall started at $x/D = 2.5$.

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