 Characteristics of a Flow around Two Circular Cylinders of Different Diameters Arranged in Tandem *

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Experimental investigations on the characteristics of a flow around two circular cylinders of different diameters with the ratio \(d_2/d_1=0.68\) arranged in tandem were carried out. Reynolds number defined by the diameter of the first cylinder was varied in the range of \(3.3 \times 10^5 \leq Re \leq 5.8 \times 10^6\), and the longitudinal spacing between the axes of the cylinders in the interval of \(0.9 \leq L/d_1 \leq 4.0\).

The reattachment of a separated shear layer from the first cylinder, the jump phenomenon and the bistable flow at the critical region were confirmed in the same manner as the case of two cylinders of equal diameters. The differences between the two cases were discussed. Flow patterns were divided according to the spacing and Reynolds number. Characteristics of those flow patterns and effects of the Reynolds number were clarified.

1. Introduction

A simple experimental model of tube banks with two circular cylinders arranged in tandem in a cross flow has been investigated by many workers for a long time. Recently Zdravkovich(1) reviewed a number of investigations in this field. The author(2) has investigated experimentally the characteristics of a flow around two cylinders arranged in tandem in the range of subcritical Reynolds numbers. The experiments were performed as a function of the spacing ratio of the two cylinders and Reynolds number. From the results, in the case where quasi-stationary vortices are formed between the cylinders up to the critical spacing of \(L/d=3.5\), it is clear that a change in the flow structure around the two cylinders occurs at the spacing of \(L/d=1.1\), 1.6, 2.3 and 3.1. Particularly, the dependency of the Reynolds number was recognized in the range of \(1.1 \leq L/d \leq 2.0\). The bistable flow in the critical spacing was clarified.

Most of the former investigations on two cylinders arranged in tandem are concerned with the case of equal diameters. For engineering uses, it seems important to clarify the characteristics of a flow around two cylinders of different diameters. There are, however, few investigations on two cylinders of different diameters. Novak(3) measured the frequency of the vortex shedding behind two cylinders. The ratios \(d_2/d_1\) were 0.5 and 2.0, where \(d_1\) and \(d_2\) are the diameters of the upstream and downstream cylinders, respectively. Hiwada, et al.(4) investigated fluid flow and heat transfer around the downstream cylinder in the range of the ratios \(0.13 \leq d_1/d_2 \leq 0.52\). In their case, the smaller cylinder placed ahead of the larger one, acts as a turbulence promoter. The flow field differs remarkably from those of the cases in the range of \(0.6 \leq d_1/d_2 \leq 1\) and \(d_1/d_2 \geq 1\). The author(5) has reported that the flow around two cylinders of different diameters with the ratio \(d_2/d_1 = 0.68\) presents a jump phenomenon in the same manner as one of same diameter. The critical spacing ratio is small and the changes of the drag coefficient and Strouhal number at the spacing are not drastic. Below the critical spacing, a change of the flow structure occurs at the spacings of \(L/d = 1.1\) and 1.7. However, the flow characteristics has not been clarified completely, and there still remain a number of unclarified points concerned.

From the aforementioned viewpoint, a detailed experimental investigation was carried out on a flow around two cylinders of different diameters. The smaller cylinder was placed downstream of the big one. The purpose of this paper is to verify the occurrence of reattachment of the separated shear layers from the upstream cylinder onto the downstream one, the jump phenomenon, the bistable flow and the effects of the Reynolds number. The results are compared with those of the case of equal diameters.

Nomenclature

- \(C_D\) : drag coefficient = \(\frac{1}{2} C_D \cos \phi \phi\)
- \(C_p\) : pressure coefficient = \((p-p_0)/0.5 \rho \omega_0^2\)
- \(C_p^b\) : base pressure coefficient at \(\phi = 180^\circ\)
- \(C_{pg}\) : gap pressure coefficient at \(\phi = 0^\circ\) on second cylinder
- \(d\) : diameter of circular cylinder
- \(f\) : vortex shedding frequency
- \(L\) : longitudinal spacing between the axes of the cylinders
- \(P_0\) : static pressure at free stream
- \(p\) : pressure or time-averaged pressure
- \(p'\) : fluctuation pressure

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2. Experimental apparatus and procedure

The configuration is shown in Fig. 1. The upstream and downstream cylinders arranged in tandem in a uniform flow having its width H, are denoted by the subscripts 1 and 2 respectively. Let L be the longitudinal spacing between the centers of the two cylinders. The first cylinder is d1 = 50 mm in diameter and the second one d2 = 34 mm; the ratio d2/d1 is 0.68. Tests were carried out in a wind tunnel whose test section was 600 mm × 150 mm (H = 600 mm). The free stream velocity \( u_0 \) varied from 4 m/s to 10 m/s, and the turbulence intensity was 0.5% in this range. The Reynolds numbers defined by the diameter of the first cylinder were in the range of \( 1.3 \times 10^6 \leq \text{Re} \leq 5.8 \times 10^6 \). The effects of the spacings and the Reynolds number on the flow characteristics around the two cylinders were investigated. The pressure distributions around the cylinders were measured by a manometer, with the cylinders having a pressure tap of 1.0 mm in diameter rotated. And pressure fluctuations were measured by a semi-conductor pressure converter connected with the pressure tap of 0.6 mm in diameter. The Strouhal numbers of the vortex shedding from the cylinders were obtained from a frequency analysis of the velocity fluctuations measured by an anemometer in the wake of the second cylinder. Flow visualizations were performed by a smoke wind tunnel and an oil-film method. Furthermore, simultaneous measurements of the velocity fluctuation and the pressure fluctuation were carried out in a wind tunnel whose test section was 400 mm × 150 mm (H = 400 mm). From the results of Novak (4) for d2/d1 = 0.50, it was impossible to ascertain the vortex shedding of the second cylinder up to L/d1 = 7.0. The characteristic length of the Strouhal number and the Reynolds number is therefore the diameter of the first cylinder, d1.

3. Experimental results and discussions

3.1 Pressure distribution

The pressure distributions around the two cylinders at Re = 3.2 × 10^6 are shown in Fig. 2 (a) and (b) for various spacings. For the spacings of L/d1 ≥ 1.0, the base pressure on the first cylinder \( C_{b1} \) increases the most and the pressure around the second cylinder presents a flat distribution. In this case, there is no reattachment of the shear layer from the first cylinder onto the second cylinder. Those profiles of the second cylinder have no existence in case of two cylinders with equal diameters. This cause can be considered that the second cylinder is far away from the two shear layers from the first cylinder. At the spacing of L/d1 = 1.1, the pressure coefficient on the rear surface of the first cylinder has a minimum value and rises ranging between \( \phi = \)

![Fig. 1 Coordinate system and symbols](image1)

![Fig. 2 Pressure distribution around two cylinders](image2)
160° and 180°. The profile of the front surface of the second cylinder shows a reattachment of the shear layer and the gap pressure coefficient has a minimum value still lower than the base pressure coefficient of the first cylinder. As the spacings increase from \( L/d_1 = 1.2 \) to 1.8, the base pressure coefficient of the first cylinder, the gap and base pressure coefficient of the second cylinder gradually rise, away from the point of maximum value of the pressure coefficient, that is to say, the reattachment point of the separated shear layer moves forward. And as the spacings increase \( L/d_1 = 2.2, 3.0 \) and 4.0, the jump phenomenon takes place and the value of the base pressure of the first cylinder gradually falls and approaches that of the single cylinder. For the second cylinder, the position of the maximum pressure coefficient moves forward and the pressure coefficient of the front stagnation region increases remarkably. At the spacing \( L/d_1 = 4.0 \), the position of the maximum pressure coefficient is at the stagnation point of the cylinder. The values of the base pressure coefficient \( C_{pb2} \) decreases to -1.2 as the spacing increases. In the case of equal diameters beyond the critical spacing, the curve of the second cylinder has a maximum value at the front stagnation point. On the contrary, in the case of different diameters \( (d_2/d_1 = 0.68) \), the front stagnation point on the second cylinder is not the position of the maximum pressure. The profile looks as if the reattachment point moved forward in the reattachment flow. This fact is due to the critical spacing \( (L/d_1)_{cr} \) for different diameters being between 2.0 and 2.6, and smaller than that for equal diameters between 3.5 and 3.8.

### 3.2 Base pressure coefficient and drag coefficient

The effects of the spacing on the gap pressure \( C_{pg} \) and the base pressure \( C_{pb2} \) of the second cylinder are shown in Fig. 3 for three Reynolds numbers. The two coefficients are nearly equal up to the spacing of \( L/d_1 = 1.0 \), but the difference \( (C_{pb2} - C_{pg}) \) becomes very large above \( L/d_1 = 1.1 \), and then the inequality is reversed in the range of spacings \( 2.0 \leq L/d_1 \leq 2.2 \). This fact means that a jump phenomenon takes place at this spacing. The flow at the critical spacing is a bistable flow\(^{(2)}\): two different values of \( C_{pg} \) and \( C_{pb2} \) may appear intermittently. The difference between the two values of \( C_{pb2} \) is large, but that of \( C_{pg} \) is small in the critical region. The effect of the Reynolds number on \( C_{pg} \) is not remarkable except in the range of small spacings. On the other hand, the value of \( C_{pb2} \) decreases as the Reynolds number decreases in the range of spacings \( 1.1 \leq L/d_1 \leq 1.8 \) and beyond the critical spacing. Such tendency is remarkable for the region above the critical spacing. The critical spacing decreases as the Reynolds number increases and the value of \( (L/d_1)_{cr} \) is between 2.1 and 2.6 in this range of Reynolds numbers.

The drag coefficients obtained by integration of the pressure distributions are shown in Fig. 4. Compared with the case of equal diameters, the drag coefficients of the first cylinder, \( C_{p1} \), change complicatedly with the spacing ratios. The coefficients decrease considerably up to the spacing \( L/d_1 = 1.0 \), and increase drastically at \( L/d_1 = 1.1 \) due to interference of the two cylinders. Up to \( L/d_1 = 1.6 \), the drag force decreases as the spacing increases, but it increases above \( L/d_1 = 1.7 \). At the critical spacing, there is no discontinuous change recognized in the case of identical cylinders. Contrary to the second cylinder, the drag coefficient, \( C_{p2} \), is minus up to the critical spacing, so that the drag force acts as a thrust. While it is negligible small at the spacings \( L/d_1 = 1.0 \), the value is nearly constant between -0.4 and -0.5 in the range of \( 1.1 \leq L/d_1 \leq 1.6 \). The difference of the two drag forces between the critical spacing is small compared to the case of the same diameter.

### 3.3 Pressure fluctuation

![Fig. 3 Base and gap pressure coefficients of the second cylinder](image)

![Fig. 4 Drag coefficients of two cylinders](image)
The distributions of the R.M.S. (root mean square) pressure fluctuations on the surface of the two cylinders are shown in Figs. 5 (a) and (b) at \( Re = 3.2 \times 10^6 \). From the figure (b) the changes of the flow pattern around the second cylinder due to the spacing are not so complicated as in the case of equal diameters\(^1\). In case of different diameters (\( d_2/d_1 = 0.68 \)), the flow patterns are clearly classified into three types according to the magnitude and the profiles of the R.M.S. values. These patterns are associated with reattachment of the separated shear layer from the first cylinder onto the second one and a jump phenomenon; they correspond to the typical profiles of the pressure distribution. First pattern is a flow without reattachment for \( L/d_1 = 0.9 \) and 1.0, the R.M.S. values being small with flat distribution along the circumference of the cylinder. Second pattern is a flow with reattachment for \( L/d_1 = 1.1, 1.4 \) and 1.8. The values of the R.M.S. increase, and the profiles have three peaks at the positions of \( \phi = 35^\circ, 40^\circ, 75^\circ \) and \( 115^\circ \). The larger the values of peak angle for peak, the higher the peak value. But the third peak for \( L/d_1 = 1.8 \) disappears. Third pattern is a jumped flow for \( L/d_1 = 2.2, 3.0 \) and 4.0, and the R.M.S. values are considerably large. The profiles have two peaks at \( \phi = 40^\circ \) and \( 110^\circ \), and the first peak is higher than the second peak. But for \( L/d_1 = 4.0 \), the second peak disappears. The second and third patterns in present experiment have one to one correspondence to the patterns B and F in the case of equal diameters\(^2\). The first pattern, however, has not been pointed out before and it is found to be a new pattern. Next, the results of the first cylinder are compared with the flow patterns of the second cylinder. The pressure fluctuation of the first pattern is small on the circumference. For the third pattern of \( L/d_1 = 2.2 \) appearing above the critical spacing, the values of the R.M.S. are slightly lower than those of the single cylinder. The value on the circumference of the cylinder increases as the spacing increases. For \( L/d_1 = 3.0 \) and 4.0, the profiles overlap with that of a single cylinder. This means that thereafter the second cylinder has no effect on the first one. The second pattern is intermediate between the first and third patterns. The profile of \( L/d_1 = 1.1 \) overlaps in many parts with that of \( L/d_1 = 2.2 \). As the spacing increases, the profiles of the second pattern approach that of the first one.

### 3.4 Strouhal number

Vortex shedding frequencies behind the second cylinder are shown in Fig. 6. The results for two cylinders of different diameters with the ratio \( d_2/d_1 = 0.50 \), at \( Re = 1.0 \times 10^6 \) by Novak\(^3\) and author's previous report\(^2\) are given for comparison. For small spacings, the effect of the ratio of the two cylinder diameters is not clear and the values of the Strouhal number are nearly equal to or larger than those of the single cylinder. As the spacing increases, the effect of the interference of the second...
cylinder increases in proportion to the value of the ratio $d_2/d_1$, and the Strouhal number becomes lower than that of the single cylinder. The effect of the Reynolds number on the Strouhal number can be explained more in detail. For the first pattern, the Strouhal number of equal diameter is independent of the Reynolds number, but that of different diameters decreases as the Reynolds number increases. On the contrary, for the second pattern, it shows a similar tendency in both cases concerning the ratios of cylinder diameters. There is a remarkable effect of the Reynolds number for small spacings: the Strouhal number decreases as the Reynolds number increases. As the spacing increases, the effect of the Reynolds number gradually reduces and vanishes at the spacings of $L/d_1=1.7$ to 1.8. Just behind the critical spacing, there is no effect of the Reynolds number. Beyond $L/d_1=2.8$, the effect appears; the Strouhal number slightly reduces as the Reynolds number increases. It is characteristic of the case of different diameters that the Strouhal number does not show a discontinuous change at the critical spacing. This is closely related to the dilatory changes of the characteristics of the flow around two cylinders at about the critical spacing. The characteristics are related to the base pressure coefficient of the first cylinder, $C_{pb1}$, the gap pressure coefficient of the second one, $C_{pg}$, and the drag coefficients of the two cylinders $C_{d1}$ and $C_{d2}$.

3.5 Reynolds number effects

According to the results mentioned above, there are two types of the effects of Reynolds number. One is accompanied with a change of the flow pattern, and in the other the flow pattern remains unchanged but the flow characteristics change. From this viewpoint, the effects of the Reynolds number on the drag coefficients of the second cylinder are investigated in detail. The results are shown in Fig. 7. Up to the spacing $L/d_1=1.0$, the drag coefficient is slightly minus, so that the drag force acts as a thrust. The thrust increases only slightly as the Reynolds number increases. At the spacing $L/d_1=1.1$, a reattachment of the separated shear layer from the first cylinder onto the second one takes place, the thrust increases drastically at $Re=2.0\times10^4$, and the value jumps to about 0.5. Up to the spacing $L/d_1=1.5$, the thrust reduces only slightly as the Reynolds number increases. Beyond this spacing, there is no effect of the Reynolds number up to the critical spacing. At the critical spacing is recognized a bistable nature of the phenomenon that two flow patterns may intermittently occur; i.e., two different values of drag coefficients as shown in Fig. 7. Thrust and drag forces act intermittently upon the second cylinder. The bistable flow appears at a specific spacing and a specific Reynolds number and the critical Reynolds number reduces as the critical spacing increases. On the contrary, just over the critical spacing there is no effect of the Reynolds number on the drag force. Beyond the spacing of $L/d_1=2.3$, the drag force decreases as the Reynolds number increases. Cooper obtained the same results in the case of equal diameters. Next, the pressure distributions and the R.M.S. pressure fluctuation distributions around the second cylinder are investigated for the
3.6 Bistable flow

As shown in the previous sections, in the case of different diameters, a bistable flow appears at the critical spacing in the same manner as in the case of equal diameters. Figure 10 shows the pressure fluctuation at $\phi = 50^\circ$ on the second cylinder about critical spacings for $Re = 3.2 \times 10^5$. For $L/d_1 = 1.9$, it shows a reattachment flow where the pressure fluctuation is small due to the formation of quasi-stationary vortices between the two cylinders. The signal trace of $L/d_1 = 2.1$ presents intermittently large fluctuations. It takes a bistable flow in which a reattachment and a jump phenomenon appears alternately. At the spacing of $L/d_1 = 2.2$, it shows a jumped flow. Figures 11 (a) and (b) show examples of the time-averaged pressure distributions and the distributions of R.M.S. pressure fluctuations around the second cylinder in two patterns for a bistable flow. At the critical spacing of $L/d_1 = 2.1$, the two distributions of a reattachment flow and a jumped flow agree well with those of $L/d_1 = 1.9$ and 2.2 respectively.

3.7 Flow visualization

A typical flow visualization using a smoke wind tunnel at $Re = 1.9 \times 10^5$ is shown in Fig. 12: (a) photographs of long-exposure and (b) instantaneous photographs. At the spacing of $L/d_1 = 1.0$, the second cylinder is located on the inner side of the separated shear layers from the first one. These shear layers extend downstream, and the vortex formation region shift downstream. At the spacings of $L/d_1 = 1.2$ and 1.6, the separated vortices adhere to the rear surface of the
second cylinder due to the interaction of two cylinders and are shed at regular intervals. From the photographs in the figure, the locations where the two smoke lines of the outer shear layers overlap each other crosswise in the centerline of the wake are seen to be at the same distance from the second cylinder. For L/d₁=2.0, the location shifts remarkably downstream. This indicates that the flow characteristics of the second pattern vary at L/d₁=1.6. The photographs of L/d₁=2.2 show a bistable flow: a reattachment and a jumped phenomenon. The flows at the spacings of L/d₁=3.0 and 4.0 are jumped flows.

Figure 13 shows examples of the surface flow patterns on the second cylinder as taken by oil-film method. At the spacing of L/d₁=1.2, the reattachment point R and two separation points S₁ and S₂ on both sides of the position of R appear in the same manner of L/d₁=1.1 as shown in Fig. 8. For L/d₁=1.8, the reattachment point R and the separation point on the downstream S₂ are not clear. This is associated with irregularity of the flow and shift of the position of the vortex formation region toward downstream compared with those of L/d₁=1.2, and the disappearance of the third peak at the point S₂ on the pressure fluctuations as seen in Fig. 5. For jumped flows at the spacings of L/d₁=3.0 and 4.0, the difference of spacing ratios appears clearly and then the surface oil-flow patterns correspond to the pressure distributions as seen in Fig. 2. The second cylinder lies in the periodic flow outside of the shear layers from the first one, then the position of the maximum pressure is the stagnation point of the flow around the cylinder (point ST). The two points ST move forward as the spacings increase, and coincide with each other at the spacing of L/d₁=4.0. At the same time, the separation point S₂ moves forward together with the point ST. As is seen near the point of φ=0° in the front surface of the cylinder in Fig. 13(a), the photographs present a pattern of the separation point for L/d₁=2.2, a pattern of front stagnation region, and a pattern of sharp front stagnation. The

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**Fig. 11** Bistable flow: second cylinder

**Fig. 12** Flow visualization by smoke wind tunnel at Re=1.9×10⁶

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direction of the flow in the front surface for \(L/d_1 = 4.0\) is completely opposite to that for \(L/d_1 = 2.2\).

3.8 Fluid flow around the cylinders

Figure 14 shows the velocity \(u\) at \(\phi = 1\) mm distant from the wall and the fluctuation component of the pressure \(p'\) on the second cylinder. At the spacing of \(L/d_1 = 1.0\), \(u\) and \(p'\) are small along the circumference and the flow around the cylinder is stagnant. As the spacing increases to \(L/d_1 = 1.2\) and 1.8, it is seen that the separated shear layers from the first cylinder reattach intermittently onto the second one. At \(L/d_1 = 1.2\), the maximum velocity in the reattachment region is higher than the velocity of the free stream, and the pressure on the wall decreases at the same time. When the shear layer separated from the wall forms a vortex at the rear of the cylinder, a fluid flow and a pressure fluctuation caused by the vortex are clearly noticed at \(\phi = 120^\circ\). But this phenomenon is not recognized at the spacing of \(L/d_1 = 1.8\). The formation of the third peak on the profiles of the R.M.S. values of pressure fluctuations shown in Fig. 5 is due to the above mentioned reason. In the front surface region where the inner shear layer reattaches, the maximum velocity is almost the same as the velocity of the free stream and fluctuates periodically with the vortex shedding frequency. The pressure fluctuation makes a very complicated change, whereas \(u\) and \(p'\) in rear surface region change with the reattachment of the shear layer. It is seen temporarily that a remarkable recovery of the pressure from \(\phi = 60^\circ\) to \(40^\circ\) takes place at the reattachment. This can be explained as follows: when the vortex attached to one side of the rear surface is shed and the outer shear layer of the other side rolls up in the front region of the second cylinder, the stagnation point of the flow around the cylinder is formed about that position in front surface. At the spacing of \(L/d_1 = 1.8\), the reattachment takes long time but its duration is short. And the length of the shear layer from the separation point to the reattachment point increases, and therefore, the values of \(u\) and \(p'\) decrease.

3.9 Classification of flow patterns

The flow patterns around two cylinders can be classified according to the longitudinal spacing and Reynolds number. The results and sketches of the flow patterns are shown in Figs. 15 and 16. Pattern A is

![Fig. 13 Surface oil-flow patterns on the second cylinder at \(Re = 5.1 \times 10^4\)](image)

![Fig. 14 Oscillograms of velocity and pressure fluctuation around second cylinder](image)

![Fig. 15 Classification of flow patterns](image)
such a perfect separation type that the
separated shear layer from the first cylin-
der does not reattach onto the second one.
The flow around the second cylinder becom-
estagnant because the vortex formation re-
gion is shifted downstream. As far the drag
coefficient, the value of $C_D$ decreases
and that of $C_D$ is nearly zero. The Strouhal
number is closer to that of the single cylin-
der. Pattern $B_2$ corresponds to the case of
reattachment of the shear layer onto the
second cylinder. The flow around the second
cylinder becomes regular because the shed-
ding vortices attached on the rear surface
of the cylinder are accompanied with reat-
tachment of the outer shear layer from the
first one onto the front surface. The gap
pressure coefficients between the two cylin-
ders decrease remarkably. While the drag
coefficient $C_D$ increases, $C_D$ acts as a
large thrust. The R.M.S. values of the
pressure fluctuation on the second cylinder
increase and their profiles have three peaks:
one is near the reattachment point and the
other two are at the separation points of the
both sides. The Strouhal number decreases
remarkably. Pattern $B_2$ too represents a
reattachment flow, but the flow characteris-
tics are different from those of pattern $B_1$.
The differences can be seen on the relation
between the spacings and the drag coeffi-
cients, the effects of the Reynolds number
on the Strouhal number and the disappear-
ance or appearance of the third peak of the
pressure fluctuation on the second cylinder.
These differences depend on the difference
in the position of the vortex formation re-
gion. Pattern $C$ is a bistable flow which
presents alternately a reattachment and a
jump phenomenon in the transition region of
the two patterns $B_2$ and $D$. The variations
of the flow characteristics in the critical
region are not drastic because the critical
spacing is small. Pattern $D$ is a jumped
flow. For $L/d_1 = 3.0$, it shows a tendency of
the transition region. Patterns $A$, $B_1$, $B_2$,
$C$ and $D$ have one to one correspondence to
the patterns $A$, $B$, $C$ and $D$ in the case of
equal diameters of the two cylinders.

4. Conclusions

Experimental investigations on the
characteristics of a flow around two circu-
lar cylinders of different diameters ar-
ranged in tandem were carried out in the
range of Reynolds numbers $1.3 \times 10^4 \leq \Re \leq
5.8 \times 10^4$, defined by the diameter of the
first cylinder. The smaller cylinder was
placed downstream of the big one, the ratio
of the diameters being 0.68. The following
conclusions have been obtained.

(1) The flow patterns vary with an
increasing of the spacing of the axes of the
cylinders in the same manner as in the case
of equal diameters as follows: First pattern
is a complete separation type (pattern $A$
) in which the separated shear layer from the
first cylinder does not reattach onto the
second one. Second and third patterns are
reattachment flows (patterns $B_1$ and $B_2$
) in which the shear layer reattaches onto the
second cylinder. Near the critical spacings,
a bistable flow (pattern $C$) is observed.
The last pattern is a jumped flow (pattern
$D$) in which the shear layer rolls up in
front of the second cylinder.

(2) The flow fields of the patterns $A$
and $B_1$ are considerably different from the
case of equal diameters. The critical spac-
ing is remarkably short and the changes of the
flow characteristics below and beyond
the critical spacing are considerably dull,
unlike the case of equal diameters.

(3) The flow patterns can be classi-
fied according to the spacing and Reynolds
number, and the characteristics of those
patterns are clarified.

(4) The spacings changing its own flow
pattern increase as the Reynolds number
decreases. The effects of the Reynolds
number differ among those patterns, parti-
cularly the effects are remarkable in the
pattern $B_1$.

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