STUDIES ON WAKE VORTICES (III): EXPERIMENTAL INVESTIGATION OF THE WAKE BEHIND A SPHERE AT LOW REYNOLDS NUMBERS

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STUDIES ON WAKE VORTICES (III)

EXPERIMENTAL INVESTIGATION OF THE WAKE BEHIND A SPHERE AT LOW REYNOLDS NUMBERS

By Sadatoshi TANEDA

Wakes produced by a sphere moving in a tank of water were photographically investigated at Reynolds numbers from 5 to 300. Main results obtained are as follows.

1. The critical Reynolds number at which the permanent vortex-ring begins to form in the rear of a sphere is about 24.
2. The size of vortex-ring is nearly proportional to the logarithm of the Reynolds number.
3. The wake behind a sphere begins to oscillate at the rear of the permanent vortex-ring when Reynolds number of about 130 is reached.

1. Introduction. Up to the present, many theoretical and experimental investigations have been carried out concerning the viscous flow past a shere. It is well known that when Reynolds number is sufficiently low, the theoretical calculations of the flow around a sphere can approximately be made by the methods of Stokes and Oseen or by other appropriate ones.[1)2)3)]

However, the interest of the experimentalists have centered, in the past, mainly round the problem of the drag and no observations seems to have yet been made concerning the flow pattern for the case of Reynolds number lower than 150. (Reynolds number, R, is Ud/ν; where U is the model speed, d is the diameter of the sphere and ν is kinematic viscosity.)

In the present report, detailed photographic observations of the velocity field in the wake immediately behind a sphere, at Reynolds numbers from 5 to 300, are described, together with some remarks about the apparatus and the experimental technique concerned.

2. Apparatus and Experimental Method. The experiments were carried out with the glass water tank of 100 cm in length, 20 cm in breadth and 30 cm in depth. A general description of the apparatus and an account of the experimental technique was given in the previous paper,[4)] and so need not be repeated here.

Various modifications, however, were made in the apparatus. In order to eliminate the very small vibrations of the carriage, the base of the gear box was separated from the foundation of the water tank and the nut, which was attached to the carriage and engaged with the lead screw, was allowed "*play*" in a direction normal to the axis of the lead screw. As the result of a careful adjustment, a sufficiently smooth and uniform velocity

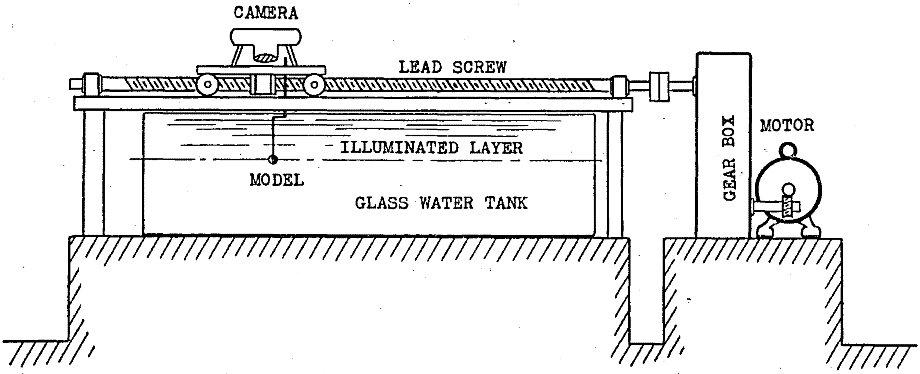


Fig. 1. Schematic diagram of the apparatus.

of the carriage was obtained. Fig. 1 shows the general arrangement of the apparatus.

Steel ball-bearings of three different sizes were used as the model. The ball was attached to one end of a fine piano wire serving as a support. The piano wire was 0.5 mm in diameter and 15 mm in length, and it was fixed to the carriage through a steel needle. In Table I the size of the models are given.

Table I.

Sphere			
d(mm)	d^*(mm)	d^*/d	F_0/F
19.82	0.5	1/40	1/190
15.08	0.5	1/30	1/330
9.52	0.3	1/32	1/840

d : Diameter of the sphere
d^*: Diameter of the support
F_0: Sectional area of the sphere
F : Cross-sectional area of the water tank

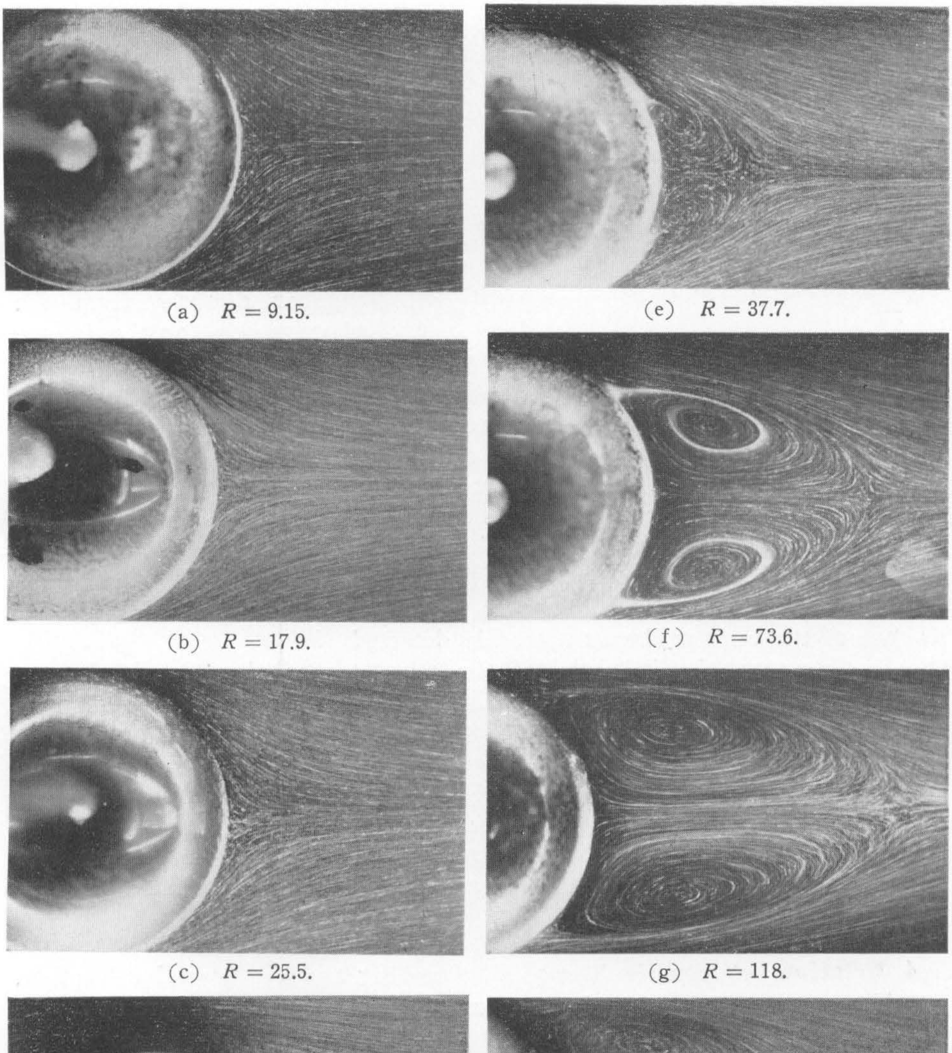
The method of illumination was the same as in ultramicroscopy. A sheet of intense light from incandescent lamps behind a narrow slit was made to pass through a horizontal plane, containing the center of the sphere on it. The illuminated object was photographed from above with a camera fixed to the carriage.

3. Critical Reynolds Number at which Permanent Vortex-Ring begins to form.

Concerning this problem there has been no experimental investigation except that by Nisi & Porter,[5] and little is known of the accurate value of the critical Reynolds number.

The present experiment was made by means of aluminium dust method. Before beginning the experiment, a great care was taken to allow the water to become sensibly still and to prevent small air bubbles from attaching to the surface of the sphere. Many photographs of the stream-lines immediately behind the sphere were taken at various Reynolds numbers by making long duration of the exposure. In Photo 1 some of the photographs obtained are shown.

As is seen from the photographs, when the Reynolds number is lower than 22, the flow around the sphere is perfectly laminar and vortex-ring can be found nowhere. When Reynolds number of about 25 is reached, however, a small permanent vortex-ring appeares in the neighborhood of



(a) $R = 9.15$.

(e) $R = 37.7$.

(b) $R = 17.9$.

(f) $R = 73.6$.

(c) $R = 25.5$.

(g) $R = 118$.

(d) $R = 26.8$.

(h) $R = 133$.

Photo 1. Photographs showing flow pattern in the wake immediately behind a sphere.

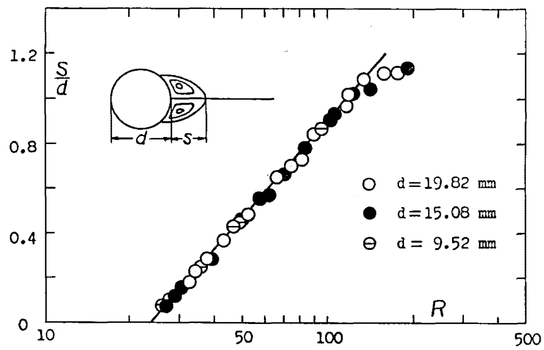


Fig. 2. Plot of s/d against $\log R$. (Sphere)

the rear stagnation point. As the Reynolds number is increased further it grows and becomes more and more elongated in the flow direction. In Fig. 2 the size of vortex-ring is plotted against the Reynolds number.

It is very difficult to determine the critical Reynolds number directly from the photographs for the following reasons; (1) the dimension of vortex-ring is still very small, (2) the vortex-ring appears in the neighborhood of the rear stagnation point where the velocity of the flow is extremely small. However, it can be estimated from Fig. 2 that the critical Reynolds number, at which the permanent vortex-ring begins to form, is about 24. It should be noticed that this value of Reynolds number 24 far exceeds the range in which approximations of Stokes or Oseen is valid.

The present experiments were carried out at $F_0/F<1/190$, where F_0 is the cross-sectional area of the sphere and F is that of the tank. The influence of the tank wall was scarecely detected.

Furthermore, the influence of the support was also tested. It was observed that a slight asymmetry of the flow pattern was caused by the presence of the support; namely the separation point just behind the support was moved slightly forward. Of course, the smaller the diameter of the support was, as compared with that of the sphere, the less its influence was. In the present experiment the measurements were made at $d^*/d<1/30$, where d^* is the diameter of the support and d is that of the sphere, and it was confirmed that the support effect was nearly negligible in determining the critical Reynolds number.

4. Relation between the Size of Vortex-Ring and the Reynolds Number.

The permanent vortex-ring appears in the rear of a sphere at $R=24$ and, as the Reynolds number is increased, it grows and becomes more and more elongated in the flow direction.

As will be seen from Fig. 2 the size of vortex-ring is nearly proportional to the logarithm of the Reynolds number.

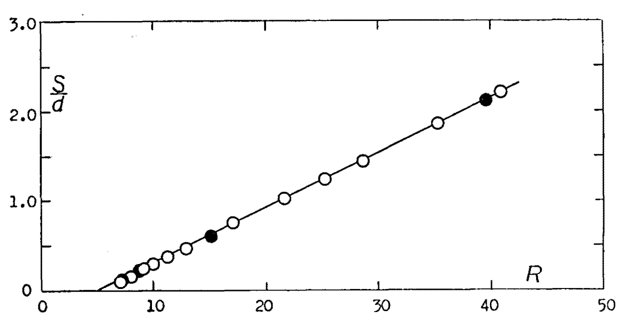


Fig. 3. Plot of s/d against R (Circular cylinder).

On the other hand, in the case of a circular cylinder, as was shown in the previous paper,[4] the size of twin-vortices is proportional to the Reynolds number itself. (see Fig. 3.)

Thus there is a conspicuous difference between the two cases of a sphere (three dimension) and a circular cylinder (two dimension).

The location of the center of the vortex-ring was also determined at various Reynolds numbers. When R was small, it was rather difficult to locate photographically the accurate position of a vortex center. Therefore the measurements were made only at $R > 50$. The results are shown in Fig. 4.

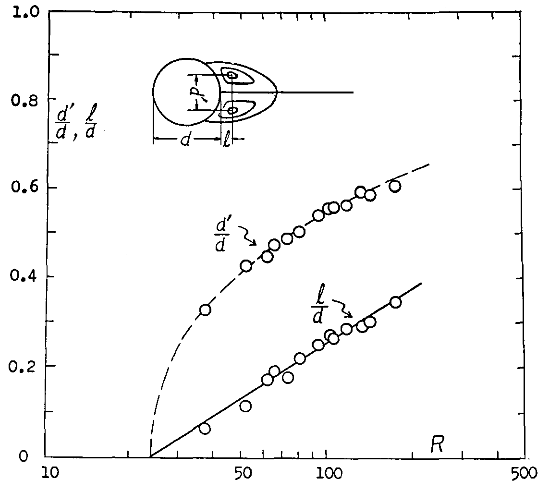


Fig. 4. Position of the vortex center.

5. Reynolds Number at which Vortex-Ring begins to oscillate. The experiments concerning the oscillation of the permanent vortex-ring behind a sphere were carried out in the past by Schmiedel (1928)[6] and Möller (1938),[7] but comparatively little is known of the critical Reynolds number at which the oscillation begins.

As can be seen from the Photo 1, the permanent vortex-ring becomes larger as the Reynolds number is increased, but the flow of fluid around a sphere is sensibly stationary so far as Reynolds number is less than about 130. When Reynolds number of about 130 is reached, however, the faint periodic pulsative motion with a very long period occurs at the rear of the vortex-ring. And as the Reynolds number is increased further, the oscillation becomes more and more conspicuous.

The flow behind the vortex-ring, however, was found to be perfectory laminar until Reynolds number of about 200 is reached. Moreover it was observed that the front part of the vortex-ring was stably attached to the sphere up to $R \doteqdot 300$ or so.

The process of development of the wake behind a sphere is illustrated in Fig. 5.

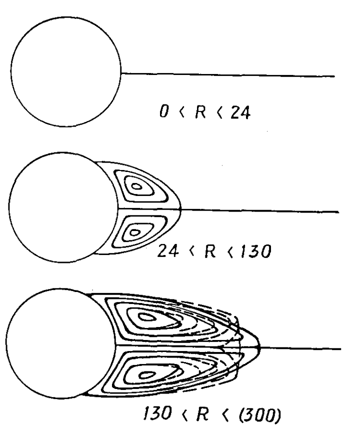


Fig. 5. Process of the development of the wake behind a sphere.

As for the flow around a sphere at Reynolds numbers exceeding 150, the detailed experiments have been reported by Möller in 1938.[7]

6. Position of Separation. The position at which the separation occurs was determined by examining the photographs at Reynolds numbers between about 60 and 300.

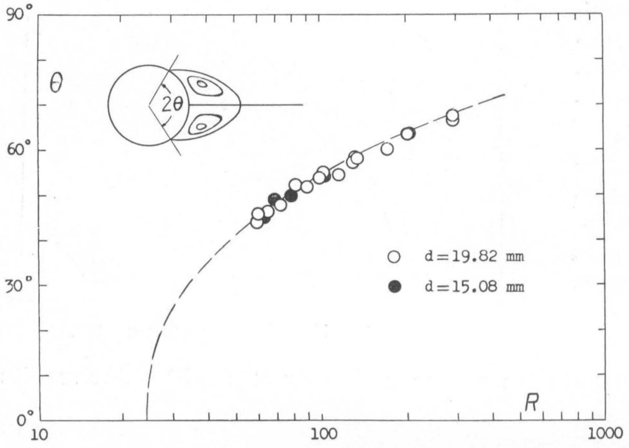
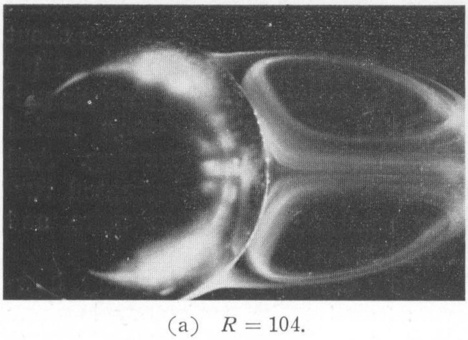
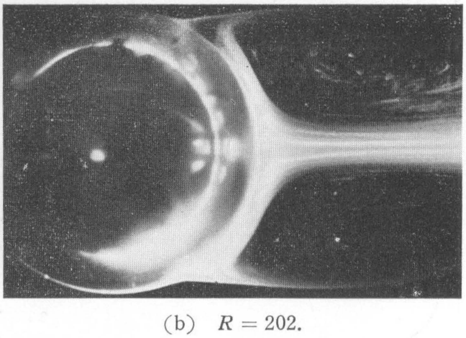


Fig. 6. Position of the separation.

The experiments were made mainly by means of condensed milk method. When a sphere thinly coated with condensed milk is set in motion in water, the milk melts in the wake little by little and reveals the separation point clearly. When Reynolds number was small, it was considerably difficult to determine the separation point, because the stream-lines in the immediate neighborhood of the separation point were not clear. Therefore the measurements were made at $R > 60$. The results are shown graphically in Fig. 6, and some of the records are shown in Photo 2.



(a) $R = 104$.



(b) $R = 202$.

Photo 2. Photographs obtained by means of condensed milk method.

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