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STANDING TWIN-VORTICES BEHIND A THIN FLAT PLATE NORMAL TO THE FLOW

By

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The aluminum dust visualization technique was used to study the wake behind a thin flat plate placed perpendicular to the uniform flow at Reynolds numbers ranging from 0.1 to 30 (the Reynolds number is Ud/ν, where U is the flow speed, d is the plate length and ν the kinematic viscosity).

The critical Reynolds number at which the standing twin-vortices first make their appearance is about 0.4. As the Reynolds number is increased, the standing twin-vortices grow in size and become more and more elongated in the flow direction. The length of the twin-vortices is nearly proportional to the Reynolds number when the twin-vortices are not so small. At a Reynolds number of about 25, the flow starts to become unsteady and the wake begins to form the Kármán vortex street. The positions of the vortex centers are given also.

1. Introduction

The standing eddies are formed in the rear of bluff obstacles at an intermediate Reynolds number range [1)~8)], where the exact Navier-Stokes equations are insoluble. Oseen's as well as Stokes' solutions are invalid in this range, because they are limited by the linearizing approximations [9),10)]. Boundary layer theory approximations also give no information about the flow at the rear of the bluff bodies. Since Thom [11)] (1933), however, numerical methods have been successfully used by many investigators [12)~17)] to solve the Navier-Stokes equations for the problem of standing eddies behind circular cylinders and spheres.

In the case of a flat plate normal to the flow, on the other hand, little seems to be known of the standing eddies. The present paper is concerned with the standing twin-vortices which are formed in the rear of a thin flat plate placed normal to the uniform flow. The case of a flat plate is not so simple as the others, because there are the effect of the thickness and the effect of the shape of the plate edges to take into account. In order to eliminate these effects the present experiments were carried out with the very thin test plate.

2. Apparatus and experimental method

The experiments were carried out with a glass sided glycerine-water solution tank 200 cm in length, 40 cm in width and 40 cm in depth. A carriage to which a test plate was fixed upright was moved uniformly along rails mounted horizontally over the water tank by means of a nut engaging on a lead screw. The velocity of the carriage could be varied continuously between 0.1 and 10 cm/s by means of a 100 watt a. c. motor and a stepless reduction gear. General arrangement of the apparatus is shown in Fig. 1. A thickness gauge 1.30 cm in length, 0.02 cm in thickness and 250 cm in span was used as the test plate. The ratio of the plate length to the tank width was 0.0325 and the ratio of the plate thickness to the plate length was 0.0154.

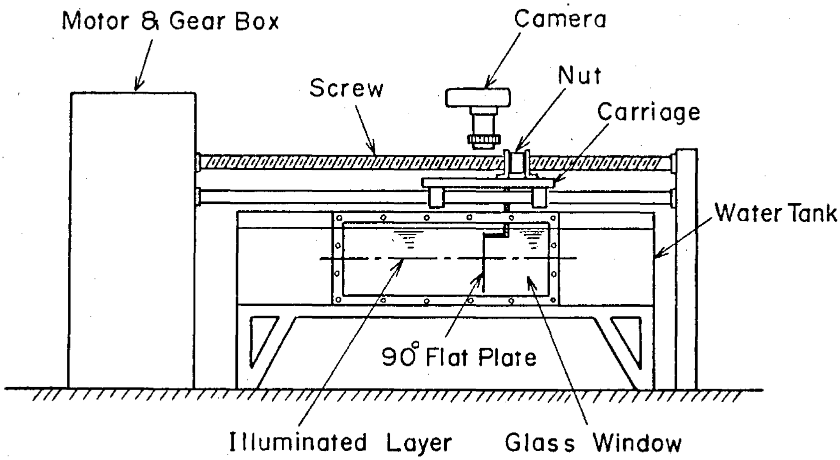

Fig. 1. Schematic diagram of the apparatus.

In order to visualize the motion of fluid a small quantity of aluminum dust was suspended uniformly in the fluid. The method of illumination was the same as in ultramicroscopy. A sheet of intense light from twenty 100 watt incandescent lamps was passed horizontally across the test plate, and the scattered light was photographed from above with a camera fixed to the carriage. A great care was taken to allow the water to become sensibly still before beginning each experiment.

3. Experimental results

Many photographs of the flow past a thin flat plate at 90° incidence were obtained at Reynolds numbers ranging from 0.1 to 30. Some examples of the photographs obtained are shown in Photo. 1~6, and the results of measurements made on the twin-vortices are tabulated in Table I.

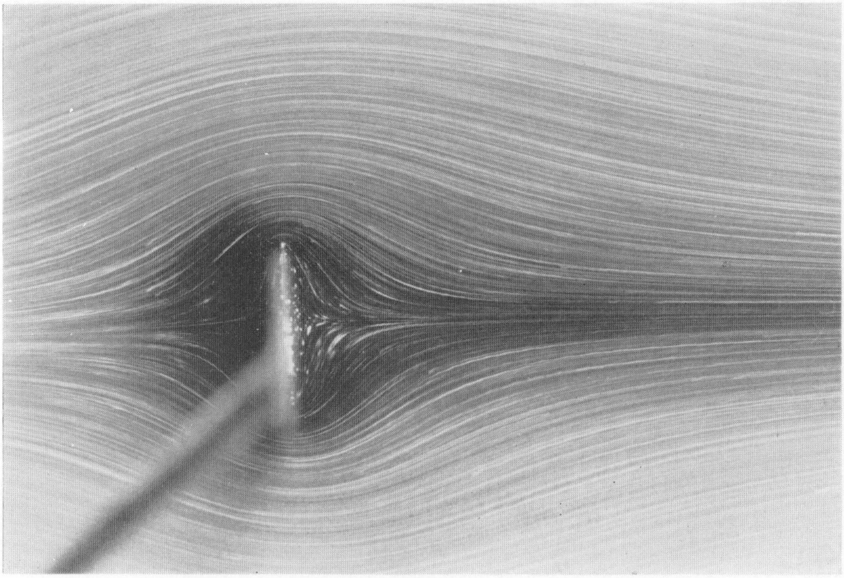

Photo. 1. R=0.334 (d/B=0.0325, t/d=0.0154)

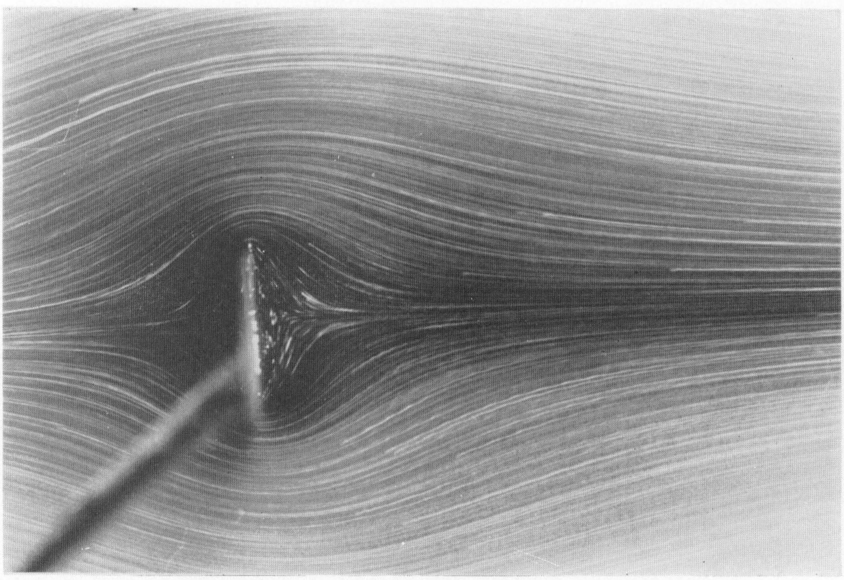

Photo. 2. R=0.440 (d/B=0.0325, t/d=0.0154)

(*Facing p.* 156)

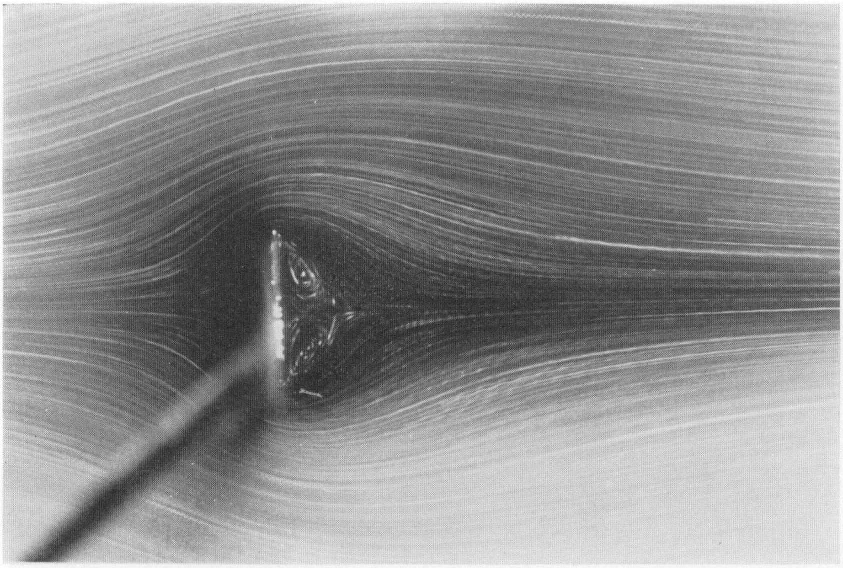

Photo. 3. R=1.89 (d/B=0.0325, t/d=0.0154)

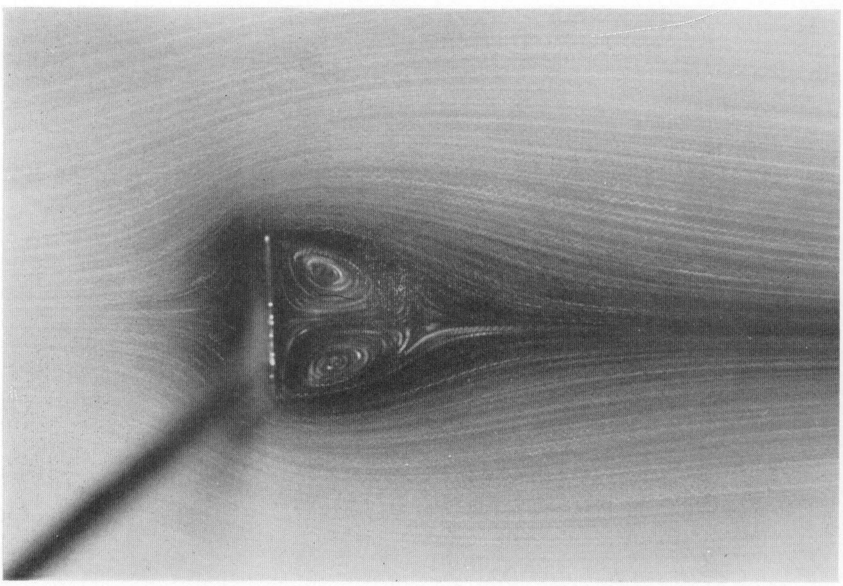

Photo. 4. R=6.68 (d/B=0.0325, t/d=0.0154)

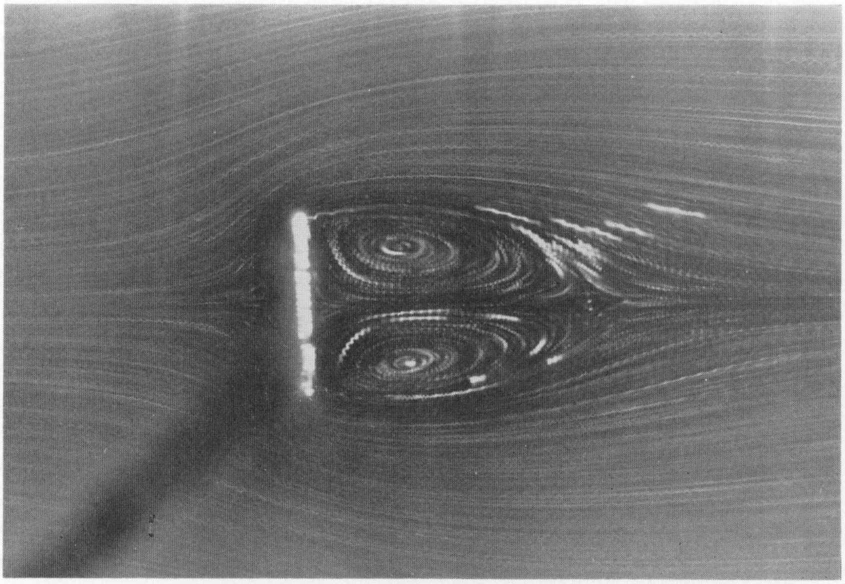

Photo. 5. R=13.3 (d/B=0.0325, t/d=0.0154)

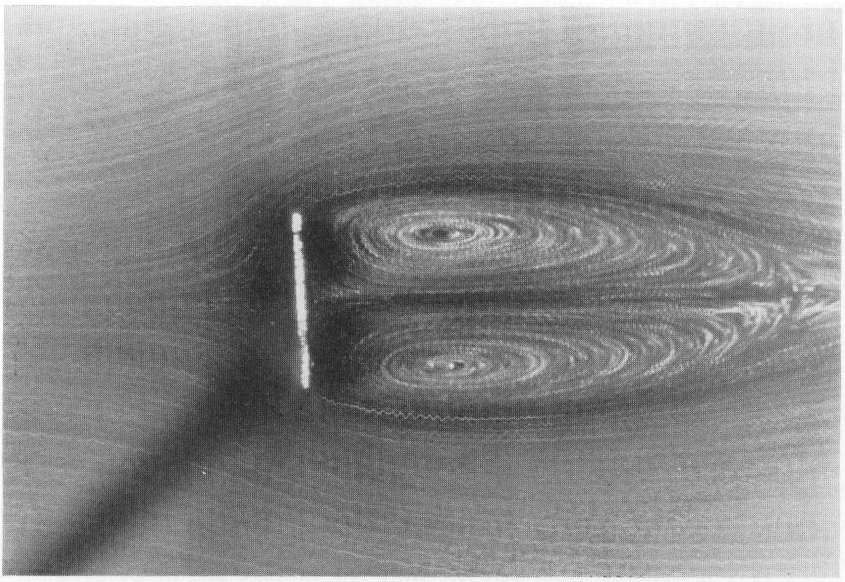

Photo. 6. R=22.6(d/B=0.0325, t/d=0.0154)

Table I. Experimental results (d/B=0.0325, t/d=0.0154)

R	s/d	d*/d	s*/d	s*/s	R	s/d	d*/d	s*/d	s*/s
0.334	0	—	—	—	5.92	0.79	0.561	0.362	0.452
0.336	0	—	—	—	6.68	0.87	0.577	0.369	0.418
0.440	—	—	—	—	6.68	0.885	0.592	0.369	0.418
0.85	—	—	—	—	7.12	0.94	0.600	0.385	0.410
0.92	0.216	—	—	—	7.17	0.96	0.600	0.392	0.408
1.16	0.225	—	—	—	7.49	0.96	0.600	0.392	0.412
1.28	0.25	—	—	—	8.05	1.05	0.616	0.446	0.423
1.36	0.28	0.46	0.146	0.528	8.86	1.17	0.631	0.469	0.399
1.36	0.29	—	—	—	9.00	1.21	0.638	0.462	0.375
1.89	0.35	0.507	0.161	0.457	9.95	1.17	0.616	0.454	0.388
2.40	0.42	0.507	0.192	0.455	10.0	1.30	0.654	0.477	0.365
2.49	0.38	0.500	0.192	0.500	10.1	1.23	0.623	0.462	0.375
2.72	0.44	0.500	0.215	0.491	10.15	1.30	0.654	0.485	0.371
2.90	0.48	0.515	0.223	0.433	10.2	1.23	0.623	0.454	0.375
3.00	0.45	0.500	0.223	0.500	10.36	1.23	0.616	0.462	0.373
3.38	0.52	0.515	0.238	0.442	10.36	1.25	0.623	0.462	0.370
3.50	0.50	0.500	0.238	0.477	12.8	1.69	0.692	0.592	0.350
3.74	0.55	0.500	—	—	13.3	1.65	0.685	0.577	0.348
4.00	0.585	0.538	0.269	0.460	17.6	2.19	0.738	0.670	0.311
4.21	0.61	0.530	0.269	0.443	22.6	2.85	0.777	0.830	0.292
4.42	0.615	0.538	0.277	0.450	22.8	2.92	0.800	0.885	0.295
5.02	0.69	0.538	0.308	0.444	23.5	3.08	0.800	0.885	0.287
5.26	0.73	0.538	0.330	0.453	23.5	2.92	0.800	0.810	0.276
5.35	0.72	0.546	0.330	0.458	26.0	3.36	0.846	0.962	0.284
5.71	0.75	0.538	0.338	0.450					

d: plate length B: tank width
t: plate thickness R: Reynolds number
s: length of twin-vortices
d*: distance between two vortex centers
s*: distance between plate and vortex center

3-1 The critical Reynolds number at which the standing twin-vortices first make their appearance

For very small values of the Reynolds number, the flow around the thin 90° plate is perfectly laminar and does not show any signs of separation. The critical Reynolds number at which the standing twin-vortices first make their appearance in the rear of the thin 90° flat plate is about 0.4 (see Fig. 2 and Fig. 3). It should be noted that the critical Reynolds number of the 90° plate is much smaller than that of the circular cylinder.

When the Reynolds number is higher than this critical value of 0.4, the

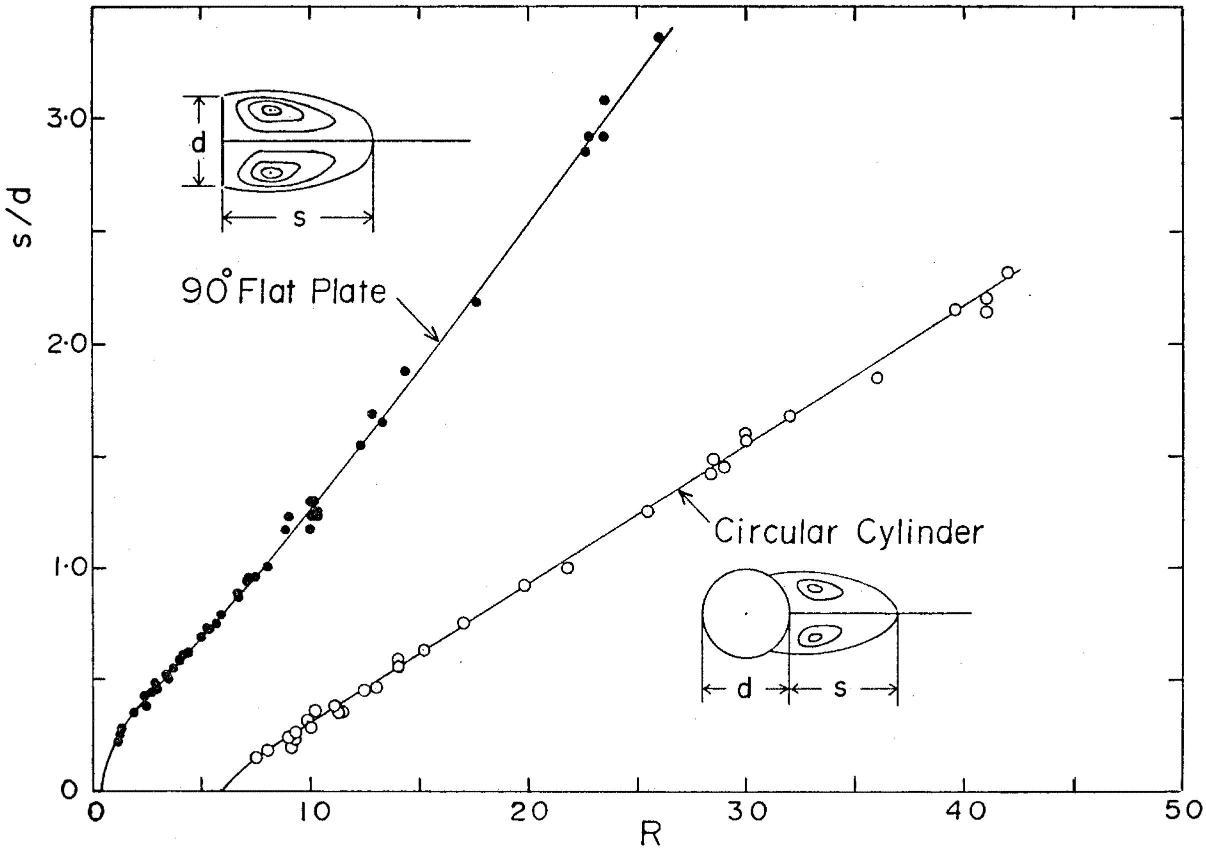

Fig. 2. The length of the twin-vortices plotted against the Reynolds number ($d/B=0.0325$, $t/d=0.0154$ for the 90° flat plate and $d/B \leqq 0.03$ for the circular cylinder).

flow always separates at the two edges. As the Reynolds number is increased further, the standing twin-vortices grow in size.

In order to eliminate the effect of the wall, the present experiments were carried out at d/B = 0. 0325, where d is the plate length and B is the tank width. Moreover, both the thickness effect and the shape effect must be taken into account, since the section of the test plate used was rectangular. However, considering that the ratio of the plate thickness to the plate length is very small (t/d = 0. 0154, where t is the plate thickness), these effects are supposed to be very small in the present experiments.

3-2 The length of the standing twin-vortices

The standing vortices are formed in the rear of the 90° thin plate for the Reynolds number higher than about 0. 4. They grow in size and become more and more elongated in the flow direction as the Reynolds number is increased.

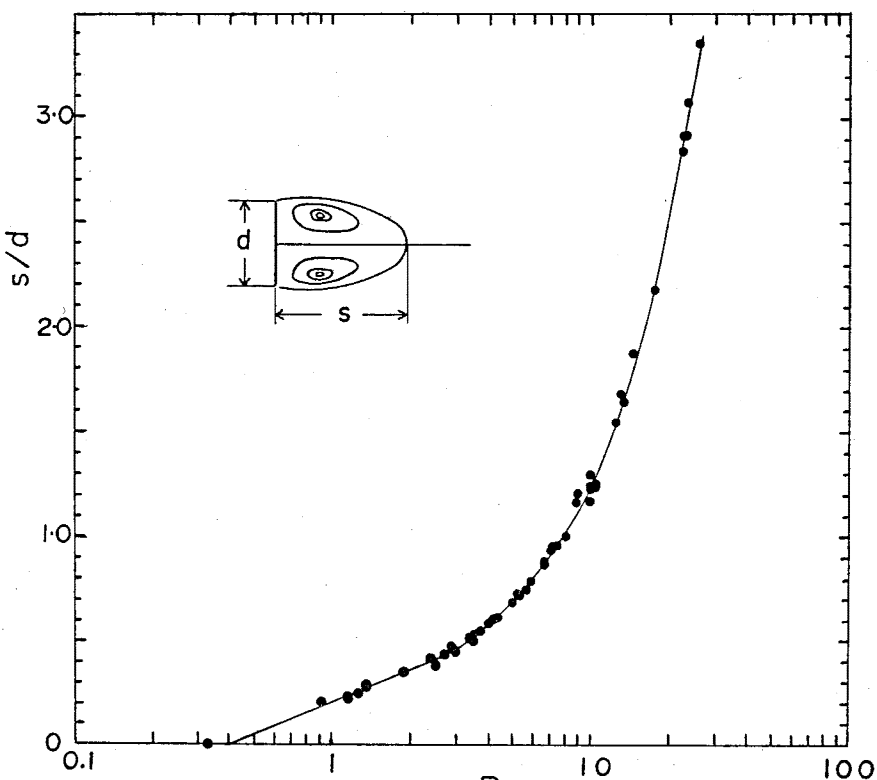

Fig. 3. The length of the twin-vortices plotted against the logarithm of the Reynolds number (d/B=0. 0325, t/d=0. 0154).

The length of the twin-vortices is plotted against the Reynolds number in Fig. 2. The length of the twin-vortices behind the circular cylinder is also plotted in the same figure for the comparison. From Fig. 2 it will be seen that when the twin-vortices are not so small the length of the twin-vortices is approximately represented as a linear function of the Reynolds number both for the 90° plate and for the circular cylinder. It should be noted, however, that the lines do not pass through the origin. In Fig. 3 the length of the twin-vortices behind the 90° plate is plotted against the logarithm of the Reynolds number. As will be seen, the length of the twin-vortices is approximately represented as a linear function of the logarithm of the Reynolds number when the twin-vortices are small.

At the Reynolds number of about 25 the wake begins to oscillate and forms the Kármán vortex street.

3-3 The locus of the vortex centers

The position of vortex centers of the twin-vortices is shown graphically in Fig. 4~6. In Fig. 4 the distance between two vortex centers of the standing twin-vortices is plotted against the Reynolds number. When the twin-vortices are small the value of d^*/d is about 0.5 (d^* is the distance between the two vortex centers), but it increases gradually up to about 0.8 as the Reynolds number is increased. In Fig. 5 the distance between the plate and

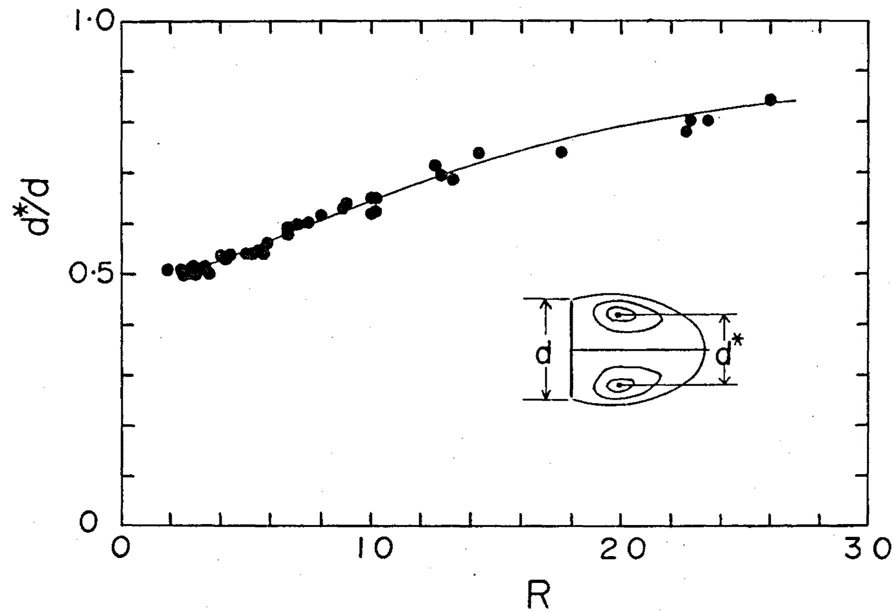

Fig. 4. The distance between the two vortex-centers plotted against the Reynolds number ($d/B=0.0325$, $t/d=0.0154$).

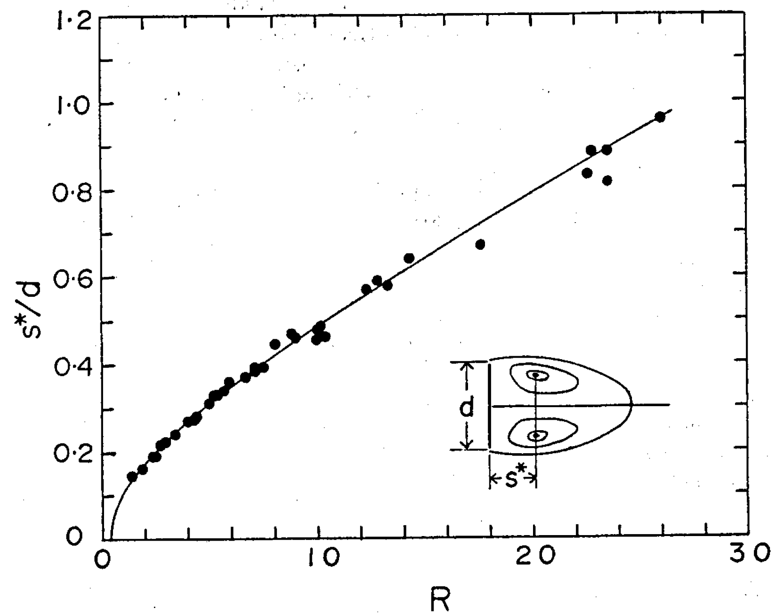

Fig. 5. The distance between the plate and the vortex-center (d/B=0.0325, t/d=0.0154).

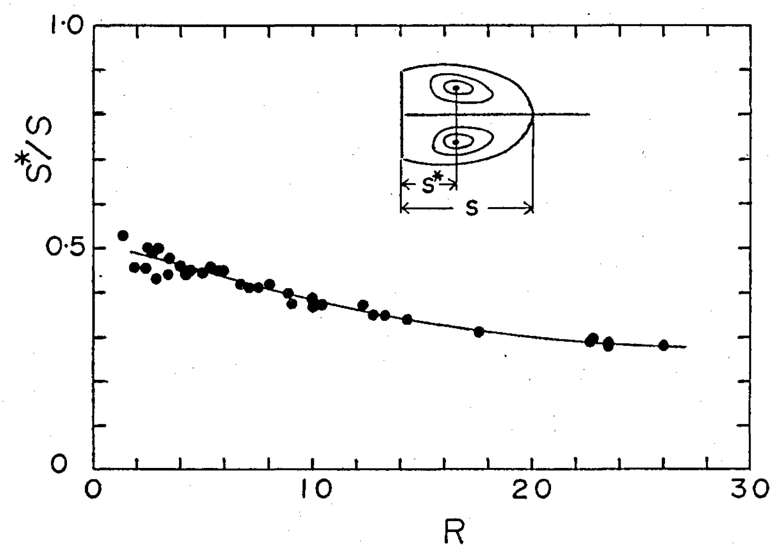

Fig. 6. The ratio of the distance between the plate and the vortex-center to the length of the twin-vortices (d/B=0.0325, t/d=0.0154).

the vortex center is plotted against the Reynolds number. And in Fig. 6 the value of s*/s is plotted against the Reynolds number, where s* is the distance between the plate and the vortex center and s is the length of the twin-vortices. It will be seen that when the twin-vortices are small the value of s*/s is about 0.5, but it decreases gradually as the Reynolds number is increased.

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