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An experimental investigation of the end effects on the wake of a circular cylinder towed through water at low Reynolds numbers

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At low Reynolds numbers, three-dimensional features are frequently observed in the vortices shed behind a basically two-dimensional circular cylinder. This paper deals with the dependence of the configuration of the vortices on various end constructions. The cylinder is towed at a uniform speed in a water tank and simple flow visualization is used. It is found that the three-dimensional structure of the wake depends strongly on the flow configuration at each end of the cylinder. The boundary condition imposed on the nascent vortex lines determines the subsequent behaviour of the shed vortices. Consequently, the vortex street can be rendered more nearly two-dimensional by allowing the vortices to link outside the boundary as they approach that boundary normally. This is the case for the water–air interface when the water surface is clean. In the case of a contaminated water surface or of a solid surface acting as a boundary to the vortex street, the vortices link between themselves underneath the water surface and a strong interaction takes place behind the end of the cylinder. The subsequent effect is a bowing of the vortices towards the end of the cylinder. The free-end effect at the bottom end of the cylinder induces a strong bowing of the vortices towards that end and causes the wake to contract. It follows from the effect of surface contamination that the study of vortex wakes by the spreading of some surface contaminants might not necessarily show the true behaviour of the wake below the surface. It is postulated that slantwise shedding arises from a difference in the two end effects.

1. Introduction

The wake observed behind a basically two-dimensional body placed in a uniform stream is rarely two-dimensional, even at the lowest Reynolds number at which the vortex street is present. The three-dimensionality of the wake is often characterized by one or several of the following features. (*a*) The vortices shed behind the body are straight and parallel but inclined relative to the body axis: so-called slantwise shedding. This effect was observed by several workers, namely Tritton (1959), Berger (1964) and Koopmann (1967). (*b*) The vortices show a certain degree of waviness and sometimes a kink or an irregularity (Phillips 1956; Hama 1957; Tritton 1959; Gaster 1969; Gerrard 1978). (*c*) The vortices are bowed towards the ends of the body (Koopman 1967; Gerrard 1978).

The amount of three-dimensionality found in the wake usually increased with Reynolds number, with a tendency for the wake to be more two-dimensional at

Reynolds numbers less than about 80 (Phillips 1956; Tritton 1959). The importance of the effect of non-uniformity of the flow and of the presence of background motions on the waviness of the vortices was first stressed by Hama (1957). The irregularities sometimes displayed by the vortices at some spanwise position are induced by either the presence of a three-dimensionality along the body span or by the flow being non-uniform at that spanwise position (Tritton 1959; Gerrard 1966; Gaster 1969, 1971). Gerrard (1978) observed that the bowing of the vortices developed as the effect of the ends spread along the span when flow was started from rest. The frequently observed slantwise shedding remained unexplained. Berger & Wille (1972) suggested that it may be an intrinsic feature of the flow, although the magnitude of the effect may depend very much on the particular end construction of the body.

The reported observations of the three-dimensionalities taking place in the wake and of their relative magnitude display a large disparity. This is not surprising as the steady flow past a bluff body is extremely sensitive to the flow conditions that are particular to each experimental arrangement. This paper deals with the investigation of the effect of various end constructions on the wake structure of the body. The experiments are carried out in a water tank using a circular cylinder and observations are made by means of flow visualization of the wake. A preliminary analysis of the flow configuration that may take place near the ends of the body is made for the various end constructions. This analysis is matched afterwards with the observed behaviour of the wake near the ends. This method enables us to improve our understanding of the effect of the end construction on the observed wake structure.

2. Apparatus and method

The water tank used in our experiments is fully described by Anagnostopoulos & Gerrard (1976). It basically consists of a trough of water 4 m long, 75 cm wide and 40 cm deep. The circular cylinder was towed through the water at a constant speed, with its axis vertical. The speed constancy was checked to be within 1 %. Cylinders of diameter 1·00 cm and 1·27 cm were used and the length-to-diameter ratio varied between 25 and 30. The investigated Reynolds-number range extended between 60 and 200. The Reynolds number *Re* is based on the cylinder diameter.

Observation of the wake structure behind the body was achieved by flow visualization of the shed vortices. The back of the cylinder was coated with dye (ICI Edicol blue, food dye). The dye washes off the separation points and is concentrated in the rolled-up vortices. In most cases, the entire span of the cylinder was coated with dye. The end effects that are present in our experiments are due to the presence of the water free surface and to the bottom end of the cylinder.

The water tank was originally designed for a minimization of the background motions arising from convection currents (Anagnostopoulos & Gerrard 1976). This was achieved by insulating the water tank walls (excluding the working section) and the bottom surface, by covering the water surface with a thin layer of transparent oil so as to prevent any evaporation and by heating the water top layer by means of heating wires so as to impose a vertical temperature gradient and thus cancel any residual vertical motion over most of the depth of the tank. However, in the present experiments, since the effect of the free surface on the configuration of the vortices is investigated, the layer of oil was removed and the heating wires were not operative.

Two water surface conditions, clean water surface and contaminated water surface, were found to have a different effect on the structure of the wake. The contamination developed over a period of time resulting in the production of a very thin surface film which was of elastic and deformable structure, not easily ruptured. When the experiment was to be carried out with a clean water surface condition, the contamination was removed by means of detergent which was introduced at one end of the surface and which moved the thin layer to the other end of the tank where it was then drained out using an overflow tube. A more detailed account of this cleaning process and of the related water surface condition is given in § 4.1.

The effect of a solid surface at the top of the cylinder (i.e., an end plate) was also investigated. Consequently four principal end effects were investigated. (1) The effect of a clean water surface. (2) The effect of a contaminated water surface. (3) The effect of a solid surface. (4) The effect of a free end.

The end effect due to the water free surface was investigated with the cylinder projecting through the surface. The effect of a solid surface at the top end of the cylinder was produced by a partially immersed rectangular Perspex plate attached to the top end of the cylinder. The leading edge of the plate was at the front of the cylinder. Its streamwise length and its immersed depth were about 12 and 0·15 cylinder diameters, respectively. The end plate was not designed to do other than present a solid end surface. The effect of a free end on the configuration of the vortices was investigated for both ends of the circular cylinder. Flow visualization of the free-end effect was obtained by producing dye filament lines beyond the end of the cylinder. This was achieved by fixing to the end of the cylinder a thin rod which projected from the end parallel to the cylinder axis for several cylinder diameters. Spots of dye were attached to the thin rod. These produced smooth filament lines because the Reynolds number of the flow past the thin rod was low enough for the wake to be steady. When observing the free-end effect at the top end, the cylinder was entirely submerged in the water and various distances between the top end of the cylinder and the water surface were tried. For this the cylinder was rigidly held at its bottom end by a horizontal rod which was itself supported, some distance away from the cylinder, by a vertical rod attached to the towing carriage. This towing construction had thus no influence on the flow at the top end. Varying the distance between the bottom end of a cylinder and the bottom surface of the tank allowed us to investigate both the effect of the free end on the bottom-end flow configuration and the effect of the solid surface of the tank.

Photographs of the vortices produced behind the circular cylinder were taken from the side through the transparent walls of the working section. The other side of the working section was covered with a white sheet ruled with vertical lines at 100 mm spacing and having rows of dots of the same spacing. Owing to the position of the camera being lower than that of the water surface level, a reflection of the flow visualization in the water surface is also produced on the photograph. Unused heating wires are visible in some photographs. The lighting was provided by two 500 W floodlights fixed at the back of the towing carriage and directed towards the back of the cylinder and the opposite side of the working section.

3. A preliminary analysis of the flow configuration at the ends of the circular cylinder

It is believed that a proper investigation of the various flow configurations that may take place at the ends of the bluff body is needed for each experimental arrangement so as to assist the understanding of the subsequent three-dimensional behaviour of the wake behind the body that is induced by the end effects. The importance of the flow configuration at the ends of the body on the pattern of the vortex shedding was stressed by Berger & Wille (1972).

Our investigation here will be restricted to the possible flows that may take place at both ends of a circular cylinder towed in a water tank, with its axis vertical and its top end penetrating the water surface. The boundary conditions for the vortices have to be satisfied at both ends of the cylinder and the eventual interaction between the boundary condition and the shape of the vortices has to be investigated.

It is known that vortices must form closed loops or extend to infinity except under some special circumstances in which they end at rotating surfaces. For the vortex to end at a surface, the no-slip condition requires that the surface be rotating so as to have a vorticity which exactly matches the vorticity of the fluid at that surface. When this is not possible, the vortex turns away from the surface.

The various end effects investigated in this paper result from one of the following three boundary configurations: (1) boundary between two fluid media (water–air interface), (2) boundary due to the presence of a solid surface moving with the body (end plate) or fixed relative to the free stream (wall) and (3) interaction in the same medium with a different flow (free-end effect). The effect of a boundary between two different fluids usually depends on the relative magnitude of the densities of the media and on whether the observations are made in the lower-density fluid or in the higher one. If the difference in density is relatively large then the vortices formed in the denser medium will go through the interface while the vortices formed in the lighter medium will deflect away from it. If the vortex goes through the water surface then the water surface will rotate and will deform slightly to produce a dimple. If the vortex were inclined to the water surface which it penetrated, the water surface would have to be tilted and yet remain plane far from the vortex, which is not possible. Therefore, the penetrating vortex can approach the water surface only at right angles.

In a steady flow past a bluff body it is expected that at the end of the body the vortices in the growing shear layer will link with the vortices of the opposite shear layer and with the next and opposite rolling-up vortex. The shed vortex will link with its two adjacent vortices of the opposite row. This link can be made as a 'bunch' of vortex filaments of small strength with a total strength equal to that of the shed vortex. The vortices of both boundary layers will link to one another, in pairs of equal strength, as soon as they are formed; however, the linking mechanism between the boundary-layer vortices is complex and depends entirely on the end construction. The conditions imposed by the end construction determine the manner in which vortex lines are linked as they are created and will then determine the subsequent linking between the separated shear layers and the rolled-up vortices.

If the vortices go through the water surface, the linking between the vortices will take place in the air medium. A solid boundary causes the vortex lines to turn away from it; therefore a complex linking mechanism is to be expected. The mechanism will certainly depend on the particular arrangement of that solid surface. In the case of an end plate, for example, the existence of a boundary layer on the solid surface has to be accounted for in the flow configuration that takes place at the end of the body.

The third case of an interaction in the same medium with a different flow applies to the bottom end effect of the cylinder with the end some distance away from the bottom surface of the tank. Two effects can be expected here: the difference in pressure between the region behind the bottom end of the cylinder and the free stream will induce a certain upwards deflection of the free stream behind the body. Also the existence of a boundary layer on the bottom end surface of the cylinder will play a role in the linking between the vortex lines of the boundary layers around the walls of the cylinder.

4. Results and discussion

In our experiments the background motions due to convection currents in the tank were not minimized. Consequently, a certain degree of waviness of the vortices and the occasional appearance of an irregularity (which we have called a knot) at some spanwise position were observed. However, these effects arising from the flow non-uniformity are independent of the end effects investigated here and in the following observations our main attention is concentrated on the effect of the various end constructions on the finite structure of the wake.

4.1. *Flow configuration near the water surface*

It was realized during these experimental investigations that the end boundary that is represented by the water surface behaved differently depending on its degree of contamination. This made the water–air interface act either as a fluid interface capable of rotation or as a solid surface. The water surface condition which we refer to here as a contaminated one is the condition which prevails when a visible thin film or when visible patches of contamination are present on the water surface. The water surface was considered to be clean when no such contamination was visible and when no surface-active substance such as detergent was present. The water surface was clean when freshly made of tap water and it remained so for a few hours before the development of the surface contamination made its presence felt. This development is a function of the tap water condition, of the cleanliness of the tank containing it and of the surrounding conditions. The presence of a few 'dust' particles, which often get deposited on the water surface, did not alter the water surface condition. When the water surface was observed to be contaminated the cleaning process which was adopted was to remove the contamination layer by introducing a very small amount of detergent (usually a few drops only) at one end of the tank and by removing the top layer of water which contained both contamination and detergent using an overflow tube at the opposite end of the tank. The top of the overflow tube was just below the water surface level in order to allow the water top layer to pass down the tube. The resulting water surface condition was then that of a clean water surface, free from contamination. The water was then, of course, given time to settle before the execution of a run. It was found that the presence of detergent at the water surface

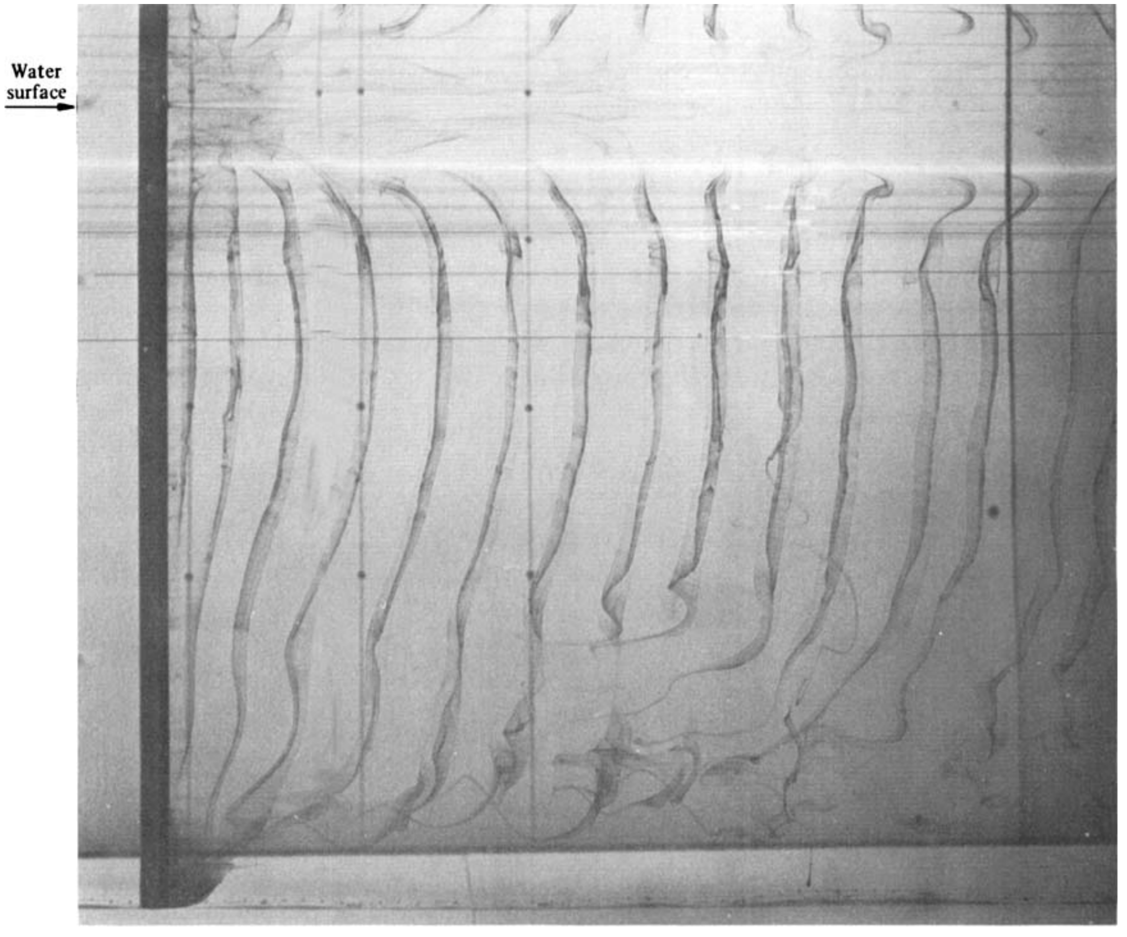

FIGURE 1. Effect of a contaminated water surface on the flow configuration of the wake. $Re = 127$.

did not noticeably alter the surface motions and still allowed the vortices to be shed perpendicularly to the water surface, as in the case of a clean water surface (which is described below). In a clean water surface when, occasionally, the dye was coated along the whole span of the cylinder the dye at the water surface was observed to follow faithfully the rotation beneath the surface as can be seen for instance in figures 6 and 8. This is because, although the dye is slightly surface-active and tends to spread on a clean water surface, it does so only moderately while the cylinder is being towed and follows the water surface rotation without inhibiting the penetration of the water surface by the vortices.

When the water surface is contaminated, it remains motionless after passage of the cylinder. Figure 1 shows the flow configuration behind the circular cylinder with a contaminated water surface. A straight and continuous line of dye on the water surface behind the cylinder is just visible and is evidence of the motionless behaviour of the surface. This line of dye remained straight even after a long time, during which the vortices in the body of the fluid had developed into large swirls. The linking between the forming vortex lines in the boundary layers and the subsequent links

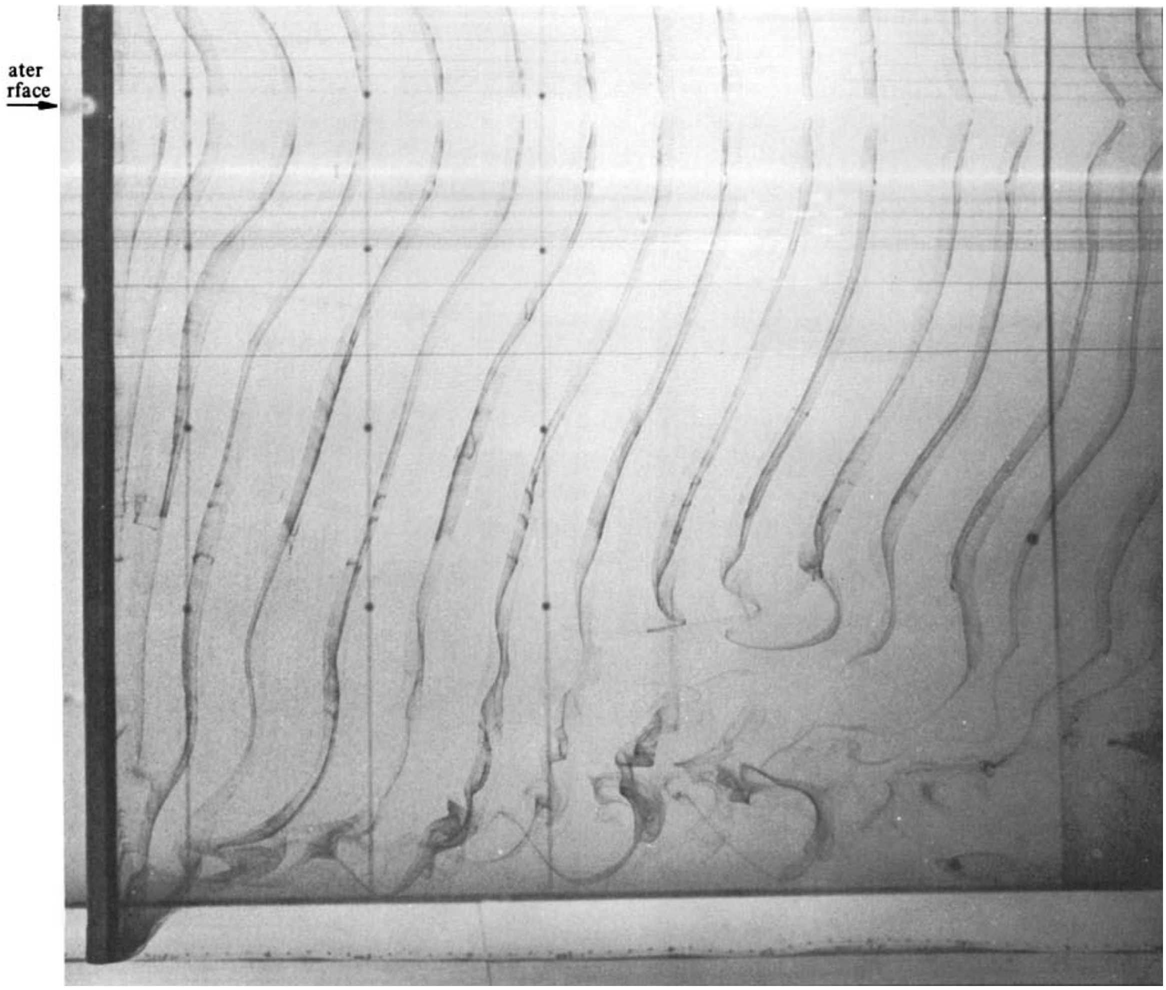

FIGURE 2. Effect of a clean water surface on the flow configuration of the wake. $Re = 127$.

between the vortices of the shear layers and the shed vortices take place underneath the water surface. It is suggested that because of the motionless nature of the contaminated water surface the boundary-layer vortex lines which far from the top end are parallel to the cylinder axis gradually point towards the front stagnation point just below the water surface. At this point they became linked with vortex lines of equal strengths and of opposite signs when they were formed. From figure 1 we see that the end effect of this linking mechanism extends for several cylinder diameters from the end. The vortices are thus bowed towards the top end of the cylinder. This bowing of the vortices can be seen to be decreasing with downstream distance. The top part of the vortices becomes then less visible and a gradual straightening-up takes place. The presence of a knot can also be seen on the figure as well as the free end effect at the bottom of the cylinder.

When the water surface is clean, it rotates with the vortices which are then perpendicular to the water surface. The vortices 'link up' in the air medium as soon as they are formed in the boundary layers. Figure 2 shows the effect of a clean water

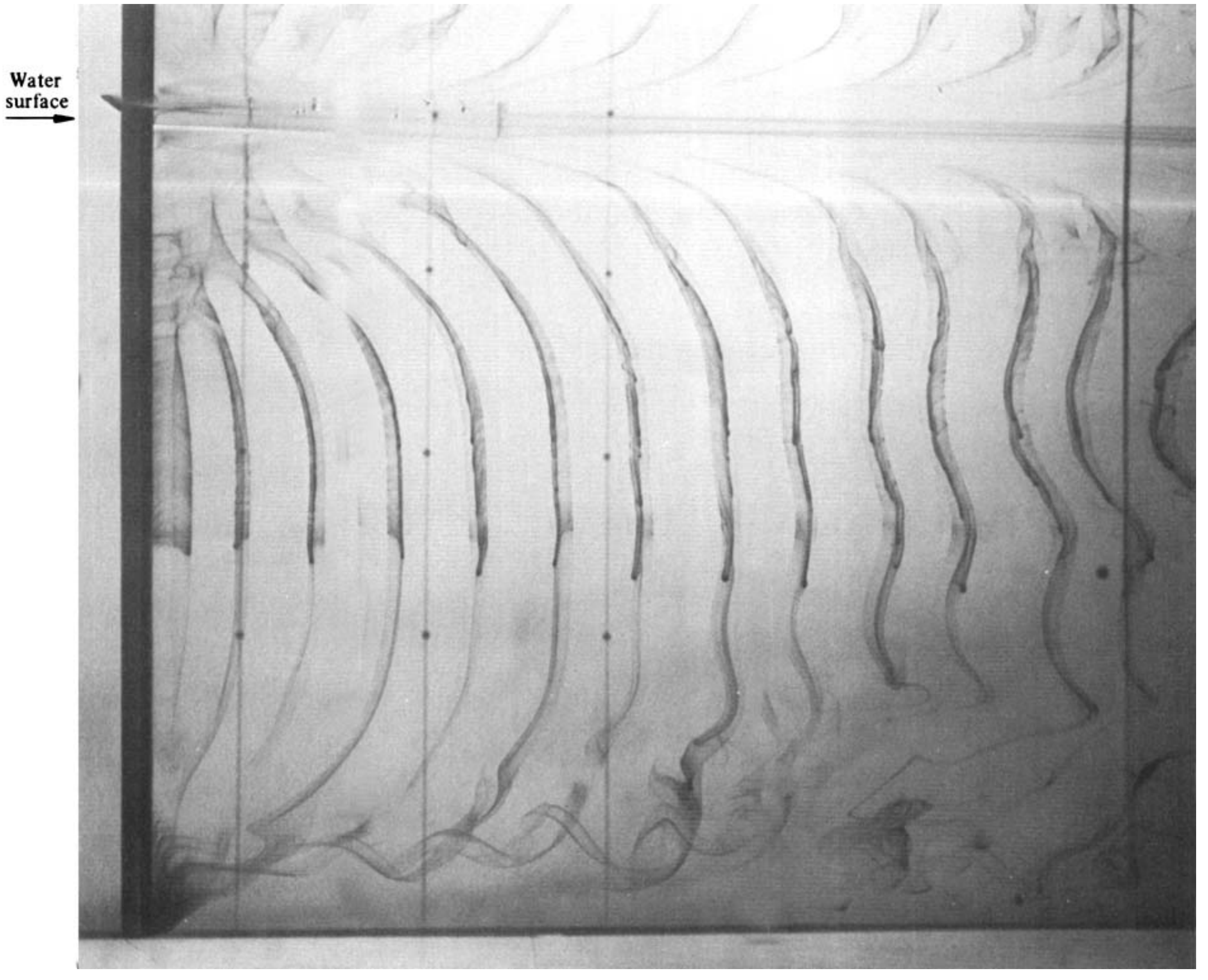

FIGURE 3. Effect of an end plate on the flow configuration of the wake. $Re = 100$. Water surface: clean. Plate half immersed in the water.

surface on the configuration of the vortices. The inclination of the vortices towards the bottom end of the cylinder is due to the free-end effect. When dye was introduced on the surface the rotation of the water surface in the near wake and at the positions of the shed vortices was clearly visible.

When the surface changed from one condition to another (i.e., from a clean condition to a contaminated condition) as the cylinder was towed along the tank, it was observed that the behaviour of the vortices changed correspondingly.

It is important to note that our designation of the water surface as clean does not mean that the water surface is truly clean in the chemical sense. The reason for this simplification lies in the nature of the present work. Since we are merely concerned with the effect of the water surface condition on the behaviour of the vortices formed below the surface, the critical parameter is not the surface tension but rather the shear elastic modulus of the surface which characterizes the ability of the surface to resist shear when no new surface is being produced. Such a modulus is zero for the case of a clean water surface (see Davies & Rideal 1963). Thus a water surface which

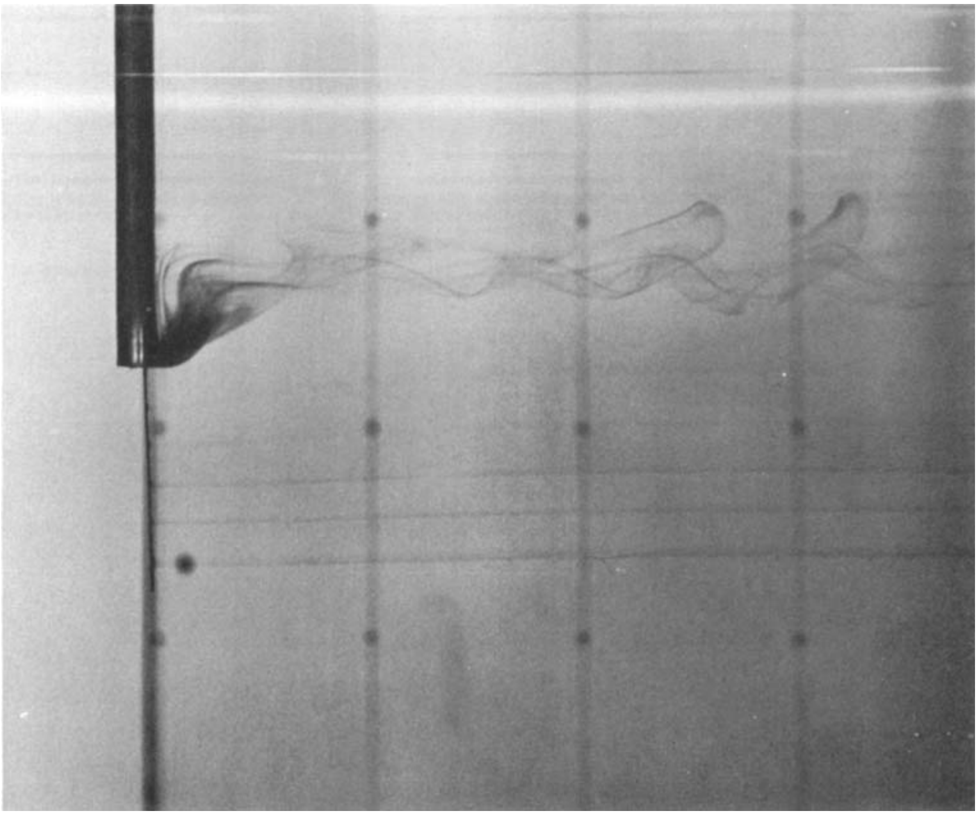

FIGURE 4. Free-end effect. $Re = 119$. Dye on bottom surface of cylinder and spots of dye along the thin rod below the cylinder.

looks clean is clean as far as this work is concerned as it presents no resistance to shear and allows the vortices to be shed perpendicularly to the water surface.

4.2. *Flow configuration near a solid surface*

The effect of an end plate attached to the top end of the cylinder can be seen in figure 3. The resulting flow configuration shows a bending of the vortices towards the plate even far downstream. The interactions between the vortices close behind the top end of the cylinder and the plate boundary layer are unclear: however it can be seen that these interactions have a major effect on the upper part of the vortices. Because of the clean water surface condition it might be expected that the vortices would go through the water surface some distance behind the plate, but this is not the case. The bending of the vortices lowers the top end of the vertical section of the vortices. The vertical sections of the vortices thus become less effective in inducing enough velocity at the water surface to make it rotate. The inclined sections of the vortices cannot produce significant surface rotation since the motion which they induce is inhibited by gravity, which tends to keep the surface nearly horizontal. The strong bowing of the vortices towards the top end of the cylinder because of the presence of the plate and towards the bottom end of the cylinder because of the free-end effect renders the vortices almost straight and parallel to the cylinder axis in

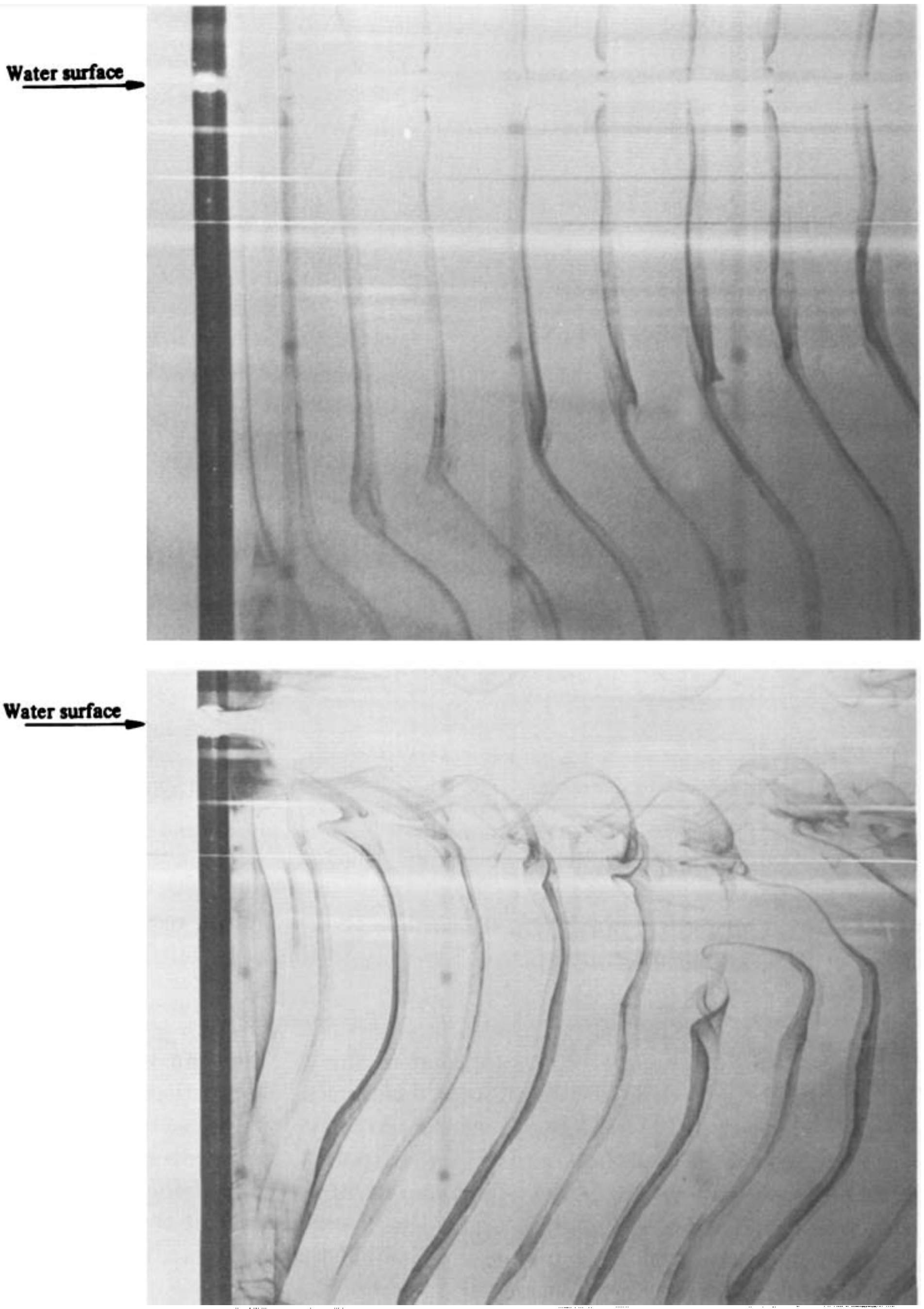

FIGURE 5. Effect of the distance between the top end of the cylinder and the water surface on the flow configuration near the top end. The water surface was clean in both cases. (i) Magnitude of gap was 0·20d; Re = 108. (ii) Magnitude of gap was 0·45d; Re = 109.

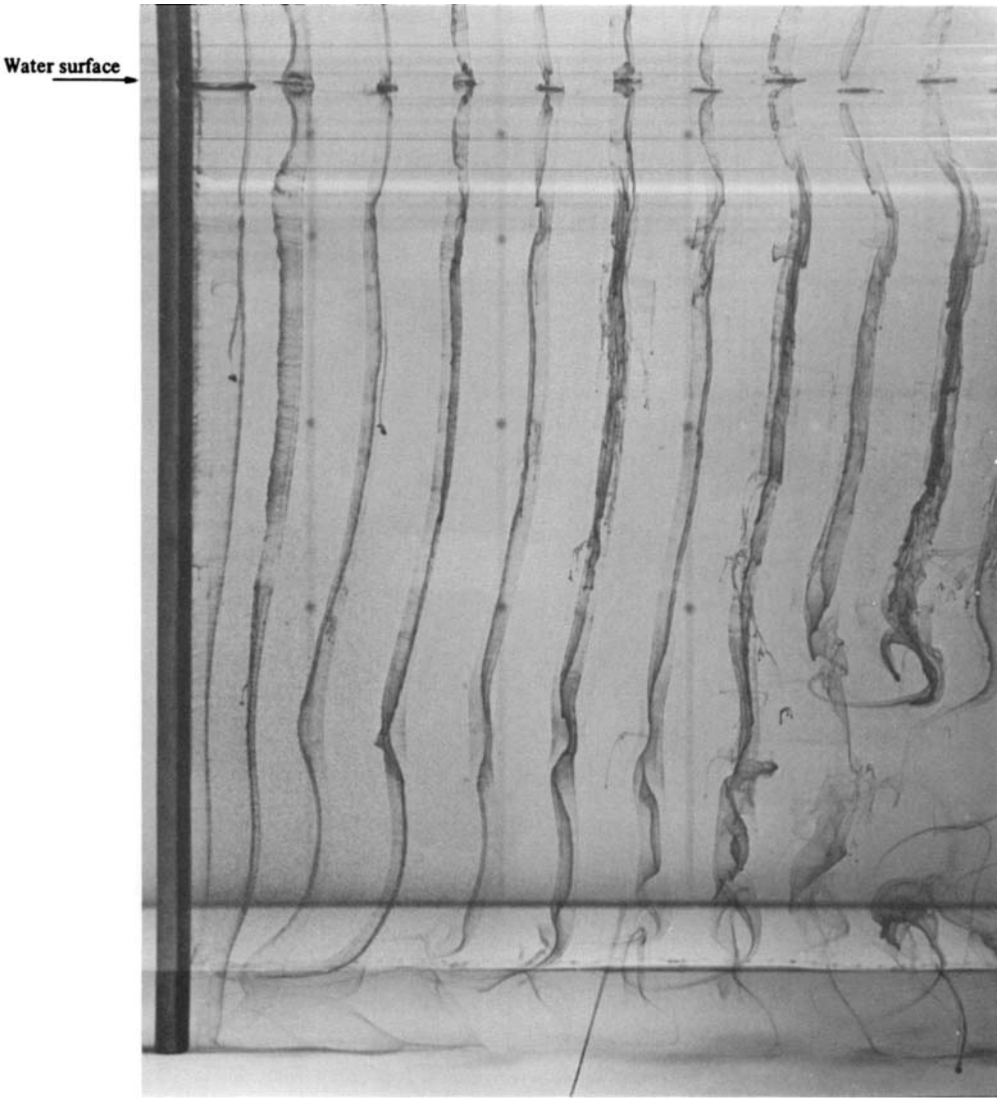

FIGURE 6. Wake behind a circular cylinder at $Re = 142$. Water surface: clean. Gap between bottom end of cylinder and bottom surface of the tank $= 0{\cdot}15d$.

their middle part. When only one end effect is present as in the case of the free end effect in figure 2, an inclination of the vortices is observed.

4.3. *Free-end effect and flow configuration near the bottom end*

The effect of a free end was investigated for both ends of the cylinder. Provided that the distance between the end of the cylinder and the boundary (i.e., water surface or bottom surface of the tank) was sufficiently large, the effect was similar in both cases. The main result was a suppression of the vortex shedding behind the end of the cylinder. Figure 4 shows the free-end effect at the bottom end of the cylinder. Vortex shedding only takes place 3 or 4 diameters above the end. The deflection of the free stream can be seen by the deflection of the line of dye produced by a spot

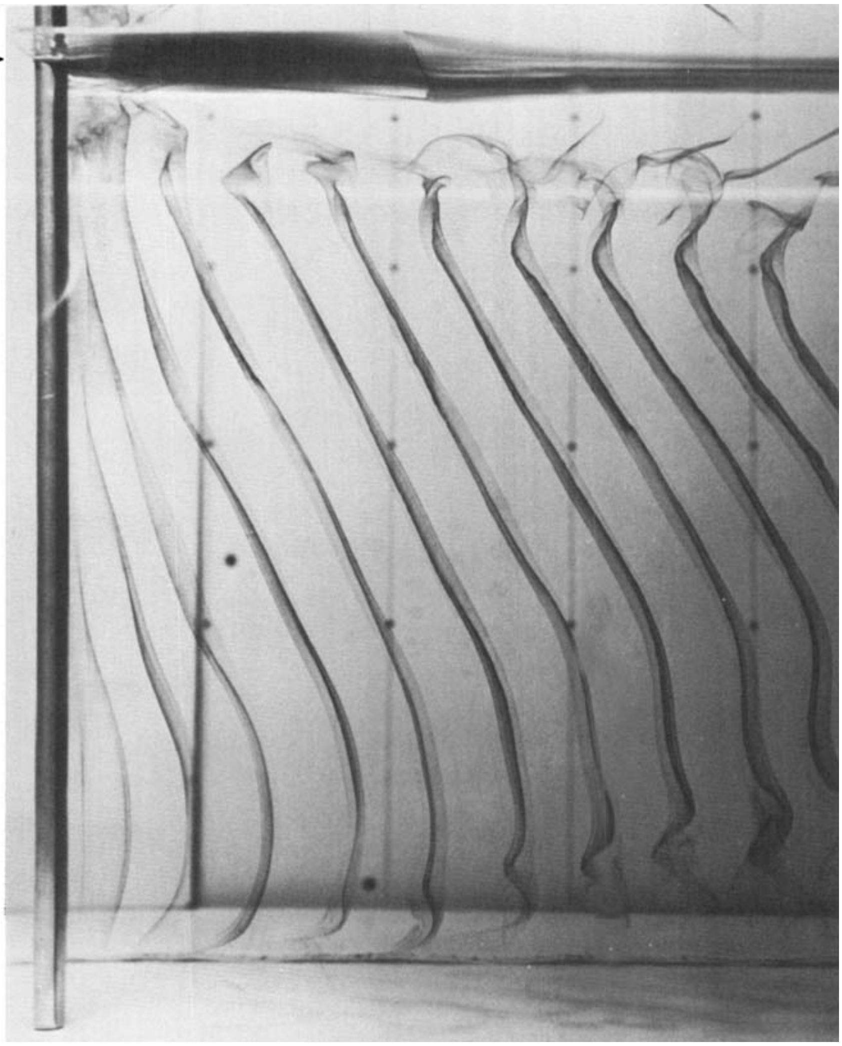

FIGURE 7. Wake behind a circular cylinder with a dominant top-end effect. $Re = 133$. Water surface: clean. End plate half immersed in the water. Gap between bottom end of the cylinder and bottom surface of tank $= 0{\cdot}15d$.

of dye placed one diameter away from the end. The other lines of dye, placed at further positions, are progressively less affected. The dye placed on the surface of the bottom end of the cylinder is drawn upwards into the wake, close behind the cylinder. This free-end effect at the bottom end of the cylinder can also be seen in figures 1, 2 and 3. It causes a bowing of the vortices towards the bottom end of the cylinder. A complex interaction between the lower sections of the vortices follows. A contraction of the wake is thus gradually obtained as the lowest sections of the vortices disappear with downstream distance through cancellation of their vorticity due to mixing. This contraction effect was also observed by Taneda (1952).

When the distance between the end of the cylinder and the boundary was reduced to a very small gap, the flow at the end changed dramatically. This occurred at a gap of about 0·2 of the cylinder diameter. That the significant length is reasonably expressed as a factor of the diameter was confirmed by observation on a cylinder with diameter of 3·5 cm. The following observations were then made.

With the top end of the cylinder just below the water surface the free-end effect is cancelled and with a clean water surface condition the vortices extend up to the top end of the cylinder and go through the water surface. This is contrary to the observation made by Taneda (1952) in a similar experimental arrangement. No details were however given on the water surface condition in his experiments. Figure 5 shows the top end effect with a small gap and a large gap, both with a clean water surface condition.

When the bottom end of the cylinder is just above the bottom surface of the tank (without touching it) the free-end effect is considerably reduced and no contraction of the wake is observed. The vortices extend to the level of the bottom end of the cylinder. This is shown in figure 6. The vortices in the near wake of the bottom end are almost straight and parallel to the body axis. Soon afterwards an irregularity always develops at about 3 diameters above the bottom end and the vortices then present the following configuration in their lower section: the vortex divides itself into four vortex filaments which link it to its two adjacent vortices at two different spanwise positions. One very close to the bottom surface of the tank and the other at the spanwise position where the irregularity takes place. The now reduced end effect takes place between 1 and 2 wavelengths downstream, causing the vortices to gradually point towards the cylinder. Once the vortices develop the double link to their adjacent vortices they become straight and parallel to the cylinder axis and their lower sections seem to present a stable configuration. This phenomenon was consistently observed and the irregularity always took place at the same spanwise position. The linking mechanism between the vortex lines at the bottom end of the cylinder and the subsequent interactions which arise in the near wake are not clearly understood. However, it can be seen that reducing the gap between the bottom end of the cylinder and the bottom surface of the tank to a minimum cancels the contraction of the wake and allows the vortices to be as straight as possible in their lower section and that a subsequent more two-dimensional flow is obtained.

4.4. *Other results*

The importance of background motions on the wake structure was also investigated. It was found that, even at the lowest Reynolds number at which a vortex street is present, the wake can be rendered three-dimensional by having a run only a few minutes after the previous one. On the other hand the wake can be kept almost two-dimensional at Reynolds numbers of up to about 180 by using the appropriate end constructions (i.e., a clean water surface and a very small distance between the bottom end of the cylinder and the bottom surface of the tank) and by allowing sufficient time for the water to settle after the previous run. This result can be seen on figure 6 where the Reynolds number was 142 (where there is, however, evidence of some background disturbance at about a third of the way up the cylinder).

Slantwise shedding was only observed to occur when one end effect was stronger than the other. The strong free-end effect at the bottom end of the cylinder was usually the cause of the inclination of the vortices relatively to the cylinder axis. The degree of inclination depended on the relative importance of the end effect. In

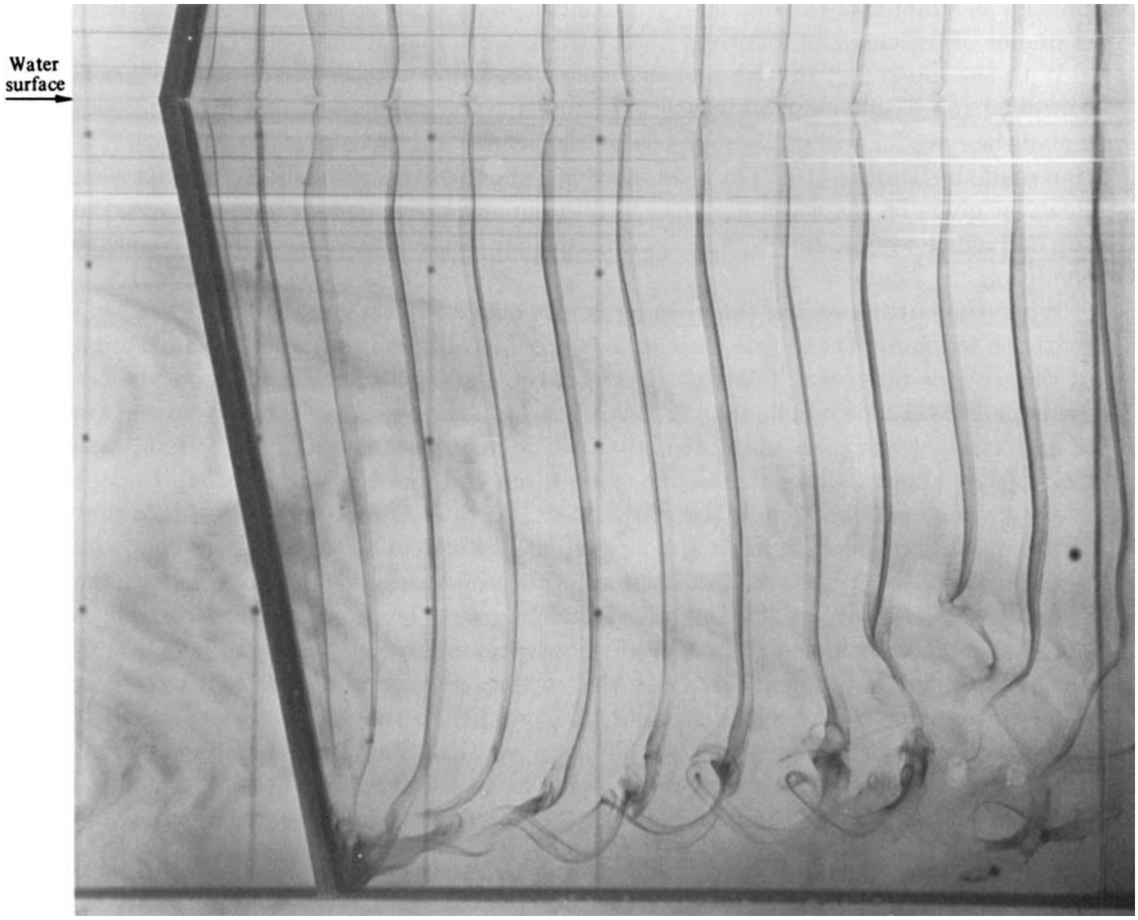

FIGURE 8. The wake configuration behind a yawed circular cylinder at $Re = 114$. Water surface: clean. Angle of yaw $= 10°$. Surface end leading.

order to check this the following experiment was carried out: a circular cylinder was towed with an end plate in a clean water surface condition as in the experiment in figure 3. The bottom end was, however, close to the bottom surface of the tank so as to reduce the bottom end effect. The dominant end effect is now that induced at the top of the cylinder by the end plate and vortices are expected to show a slantwise shedding towards the top end. Figure 7 shows that this is the case.

A clean water surface condition produces a flow configuration in the body of the fluid that is the exact half of the flow configuration that would be obtained behind a body made of the original bluff body and of its mirror image relative to the water surface. For a yawed circular cylinder the flow configuration is that of the one produced behind a V-shaped circular cylinder. For small angles of yaw (of up to about 20°) where the effect of the axial flow is small we investigated the interaction between the vortices shed behind the body and the water surface in a clean condition. The resulting flow configurations can be seen in figures 8 and 9 for both directions of yaw. The vortices behind the yawed cylinder with its leading end at the water surface (figure 8) are almost vertical and are perpendicular to the water surface even close

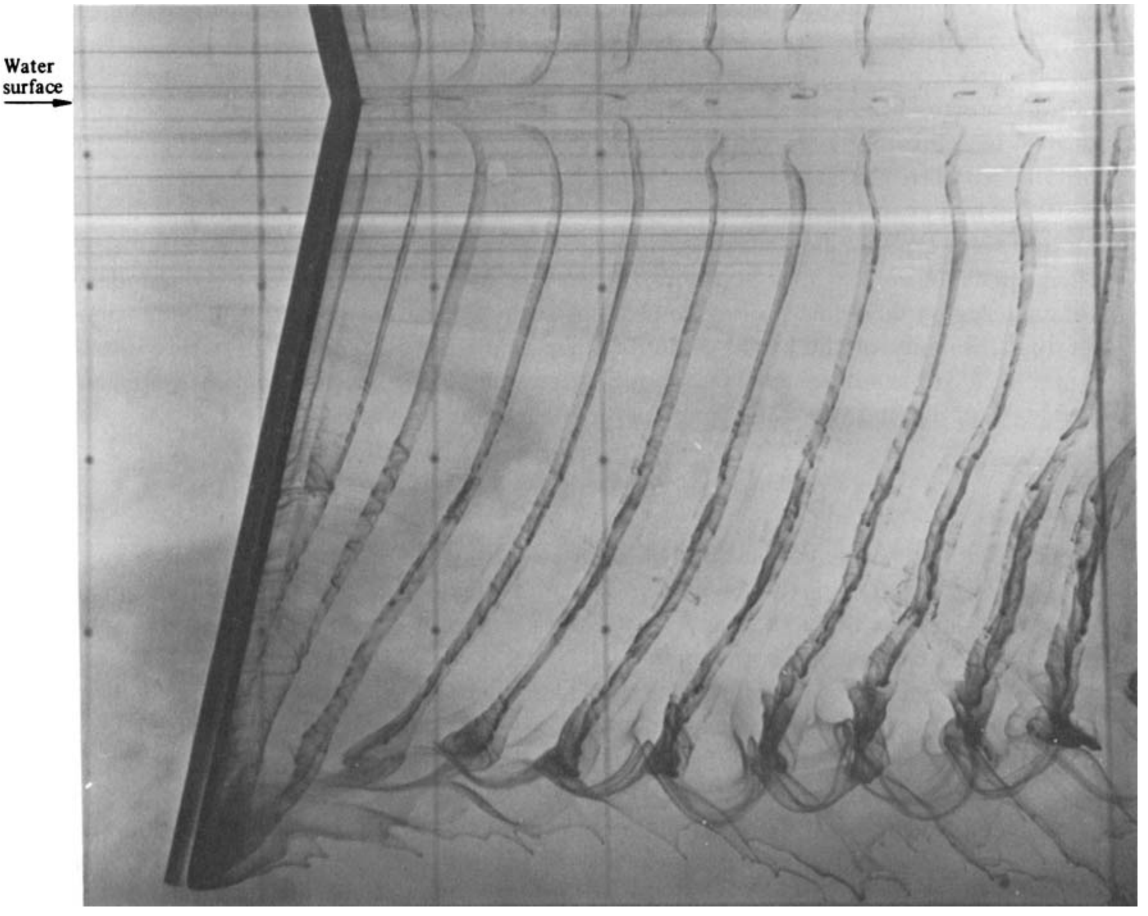

FIGURE 9. The wake configuration behind a yawed circular cylinder at $Re = 114$. Water surface: clean. Angle at yaw = 10°. Free end leading.

behind the body. The vortices behind the yawed cylinder with its bottom end being the leading end (figure 9) are not perpendicular to the water surface. Their interaction with the water surface is interesting; the vortex partly goes through the water surface while the remaining vorticity produces a vortex filament that is inclined below the water surface and links with its adjacent and also inclined vortex filaments. The rotation of the water surface is clearly visible, but the reduced amount of vorticity that is present at the water surface produces a vortex street that is similar to that observed at a lower Reynolds number. The rotation at the water surface can be seen to be weaker than that of the vortex underneath it. The difference between the surface effects in figures 8 and 9 is not due to differences in surface contamination. The photograph of figure 8 was taken after that of figure 9 without any disturbance to the surface. The effect was also repeatable. Experiments were also made with cylinders bent into a V-shape. The flow configuration behind the body pointing in the direction of motion was identical to that of figure 8 while the flow configuration behind the same model pointing in the reverse direction showed the vortices pointing towards the trailing end as in figure 9.

It can, therefore, be concluded that a vortex that is initially inclined at small angles to the normal of a clean water surface (or of any surface that is capable of rotation) will divide itself into two vortex filaments, one perpendicular to the water surface and one parallel to it. The resulting effect will be a lower-Reynolds-number vortex street at the water surface. A similar effect was observed when the vortex was initially perpendicular to a slightly contaminated water surface: the linking between the vortices takes place both below and above the water surface, resulting in a lower *Re* flow at the water surface. The surface contaminants produced by additives used for flow visualization must therefore be investigated to determine their effect on vortex lines at the water surface. When flow visualization is undertaken a vortex flow pattern can be produced which does not have the same motion as does the body of the liquid some distance below the surface. Even with a clean water surface the surface flow may not be the same as it is beneath the surface when the body producing the wake is not perpendicular to the surface.

5. Conclusions

The finite structure of a wake behind a two-dimensional bluff body is of a very complex nature. This is due to its sensitivity to the non-uniformities existing in the flow and along its body span and to the particular end constraints imposed on the flow by the experimental arrangement.

Our investigation of the effect of various end constructions on the wake structure behind a circular cylinder was carried out through observation of the wake using flow visualization. Our investigation was restricted to the low-Reynolds-number range ($60 < Re < 200$). It was found that the wake structure was strongly affected by the flow configuration near the ends of the body, which itself depended entirely on the constraints imposed by the end construction. These determine the manner in which the linking between the vortex lines forming in the boundary layers is allowed to take place. The investigated end effects were due to the following end constructions: (*a*) clean water surface, (*b*) contaminated water surface, (*c*) end plate at the top end of the cylinder, (*d*) free end at the bottom end of the cylinder, and (*e*) small gaps between a free end and the top and bottom surfaces.

A full analysis of the complex linking mechanism in the attached boundary layers and in the near wake has not been attempted. The details and the mechanics of the flow processes at the ends of the body still remain to be investigated. The main observations were the following.

(1) In the presence of a clean water surface, with the top end of the cylinder emerging out of the water, or ending just underneath the water surface, the vortices link between themselves in the air medium and are straight and vertical below the surface. In the context of the present work a clean water surface can be defined as one which allows vortices to pass completely through it. Such a water surface has a clean appearance free from a film or islands of oily surface contamination. The presence of detergent has no adverse effect. The clean water surface condition thus maintains the two-dimensionality of the vortices in the upper part of the wake.

(2) When the water surface is contaminated or in the presence of an end plate, the linking between the vortices takes place underneath the water surface and a certain amount of bowing in the vortices is present. Behind the top end of the body the dye is not concentrated in the vortex cores until some considerable distance downstream.

(3) The presence of the free stream at the bottom end of the cylinder has the most severe effect upon the two-dimensionality of the flow. It results in the strong bowing of the vortices towards that end and in a contraction of the wake.

(4) Slantwise shedding was only observed when the effect of one end was dominant. When the bending of the vortices is strong towards both ends of the cylinder straight and parallel shedding is obtained in the mid-span vicinity of the wake. It is consequently suggested that slantwise shedding is not an intrinsic feature of the wake of bluff bodies at low Reynolds numbers.

(5) The wake can be rendered more two-dimensional by having a clean water surface and by minimizing the distance between the bottom end of the cylinder and the bottom surface of the tank.

(6) Experiments with a yawed circular cylinder allowed us to investigate the interaction between a clean water surface and a vortex approaching that surface at a small angle to its normal. It was found that the vortex divides itself into two vortex filaments, one normal to the water surface and the other parallel to and below the surface. A similar effect was observed in the interaction between a slightly contaminated water surface and a vortex approaching that surface at a right angle.

Provided that the Reynolds number is below the range at which 'fingers' are observed (see Gerrard 1978), at a Reynolds number of about 180 in the present experiments, the observations reported in this paper were independent of the Reynolds number. The flow sensitivity to non-uniformities however increased with Reynolds number. At Reynolds numbers greater than 180 the configuration of the vortices changed altogether with the appearance of 'fingers'. The end effects however remained unchanged since they represent some intrinsic effects of the end constructions.

It seems, therefore, that if non-uniformities in the flow and along the body span are reduced to a minimum, then any three-dimensional features of the wake will depend entirely on the end constructions. The behaviour of the shed vortices depends on the boundary condition imposed on the vortex lines forming in the boundary layers. The way in which they are able to link with one another as they are formed in the boundary layers thus depends on the end construction and the subsequent flow configuration near the end of the body is determined by their interactions in the near wake and by any eventual flow added by the end effect. Consequently, the lack of homogeneity in published experimental results concerned with the bowing of the vortices towards the ends of the body and with the inclination of the vortices is understandable. It is unfortunate, however, that in most cases no proper investigation of the flow configuration taking place at the ends of the body was carried out. Attention was only paid to the resulting three-dimensional behaviour of the wake.

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