Study of Three-Dimensional Separation on a Spheroid at Incidence

By

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Summary: Experimental observation of flow separation on a spheroid at various angles of attack was carried out in low Reynolds number flow using a water channel by flow visualization method. Color oil method was adapted to make the surface separation pattern visible, and hydrogen bubble method was effective for visualization of the flow field around the model. The results have supported the three-dimensional separation criteria proposed by Maskell, Wang, and Han and Patel, and mechanism of the flow interaction with the longitudinal vortices along the body surface has been made clear.

§I. INTRODUCTION

In two-dimensional steady flow, the separation point of flow on the body surface coincides with the point at which the wall shear stress vanishes. The criterion of separation, conceived by Prandtl, is mathematically obvious, such that $\partial u/\partial y=0$ at the surface, and convenient to apply to real flows [*1*]. The separation point is characterized by several features as follows [*2*],

1) The flow near the surface is reversed.
2) The first order boundary-layer equations become singular at the separation point.
3) The boundary-layer thickness increases rapidly beyond the separation point.
4) The boundary-layer approximations become invalid, and the wall pressure distribution does not agree with that of given by the potential flow theory.

In two-dimensional steady flow, all these phenomena are well recognized, and this idea of separation has often been used for practical procedures of boundary-layer calculations.

In three-dimensional steady flow [*3*], the definition of the separation is not mathematically clear and it is generally known that flow separation from the body surface is not simple phenomena which only relate to the flow characteristics near the surface. Especially, three-dimensional flow separation is rarely associated with vanishing of wall shear stress, except in certain special cases. However, it is very important to identify the occurrence of separation, in order to apply the fluid dynamic analysis to real flow.

Recent studies on comprehensive definitions of the three-dimensional separation have revealed the relation of separation with observed skin friction lines. Various definitions of three-dimensional separation line observed are proposed as follows [*4*],

a) Line on which any component of wall shear stress vanishes.

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b) Envelope of limiting streamlines.

c) Colliding line of flows come from different directions.

d) Limiting streamlines joining onto a 'singular' point.

Any one of these definitions is not universally applicable, but has been used under certain restrictions. General concept of flow separation is illustrated in Fig. 1.

Maskell [5] is one of the pioneers in the study of three-dimensional separation. Based on observations of surface flow pattern, he proposed two basic types of separation; bubble type and free vortex type. Later, flow field past a body of revolution at incidence was studied by Wang [6], who introduced the concept of 'open' and 'closed' separation. The terms of 'open' and 'closed' separation in this paper are explained as illustrated in Fig. 2. The closed separation line is the one which forms a closed curve on the body and which passes through the singular points. Thus, this type of separation is also expressed by a term 'singular separation' since the separation line passes through or joins to the singular points at where the wall shear stress vanishes. This type of separation line divides the flow field into two different regions, one is the coming flow region and the other is the reverse flow region on the body surface. Along the open separation line, the surface streamline can be a coming line as well as a leaving one on the body surface. In this case, flow detachment from the surface is usually accompanied by formation of a longitudinal vortex [7].

Study reported here is conceived as visual investigation of overall separation features of the flow around a spheroid. Experimental apparatus and methods are described in §2.

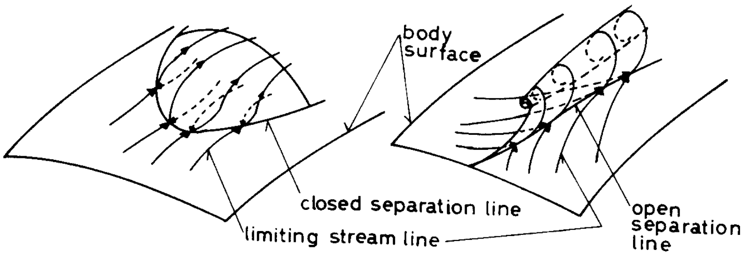


Fig. 1. Separation concepts.
a) Bubble, b) Free vortex layer.

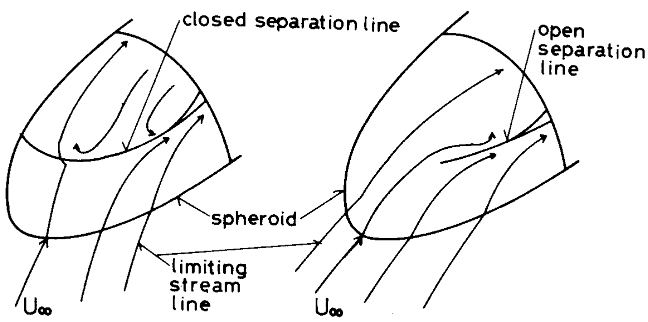


Fig. 2. Three-dimensional separation.
a) Closed separation, b) Open separation.

In §3 and §4, experimental results and discussions are presented respectively, and the conclusions are in §5.

§II. Experimental Apparatus and Methods

An open, low speed water channel with a working section of 50 cm high and 50 cm wide with free surface is used for the experiment. The Reynolds number, based on the free stream velocity and the major axis of the model, is 35,000~40,000 and 5,500~6,000 for oil flow and for hydrogen bubble visualizations respectively. The boundary layer, which develops along the surface of the body, is expected to be laminar everywhere during the experiment. A spheroid with the axis ratio of 4:1 is used as the model, that is, the major diameter is 24 cm and the minor one is 6 cm. Schematic diagram of the experimental apparatus is shown in Fig. 3. The model is held in the uniform flow by a rod of 5 mm in diameter at the center of the spheroid, as shown in the Figure. The incidence angle is adjusted in the range of 0°~55° by rotating the rod, and the separation pattern on the surface and the flow field around the body are observed by flow visualzation. Two kinds of visualization methods are used. In the first method, mixture of Rhodamine B and condensed milk is used to visualize the pattern on the model surface (oil flow method). Separation lines are represented by oil accumulation, where the wall shear stress vanishes. The place of accumulated oil slightly deviates from zero shear stress point due to dye's viscosity. Secondly, hydrogen bubble method is used to visualize the flow around the body. Fine copper wire of 0.1 mm in diameter is stretched vertically using a support and time lines of hydrogen bubble are generated applying intermittent pulsing electric current. In both methods, pictures of the flow field are taken using a motor driven camera.

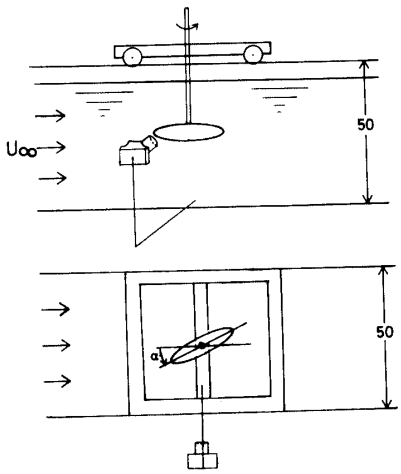


Fig. 3. Schematic Diagram of Experimental apparatus.

§III. Results

Depending on the incidence angle, the separation patterns are classified into three categories as follows:

A. First closed separation (small incidence, $\alpha=0°\sim5°$)

Figure 4 shows a series of pictures at small incidence. In the case of zero incidence in Fig. 4(a), the boundary layer is axisymmetric and separation is observed at the rear part. This first closed separation is basically agreed with Prandtl's criterion of separation.

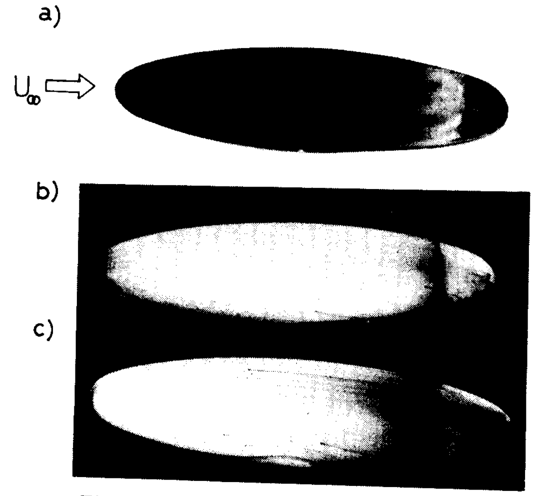


Fig. 4. Small incidence.
a) $\alpha=0°$, b) $\alpha=0°$, c) $\alpha=5°$.

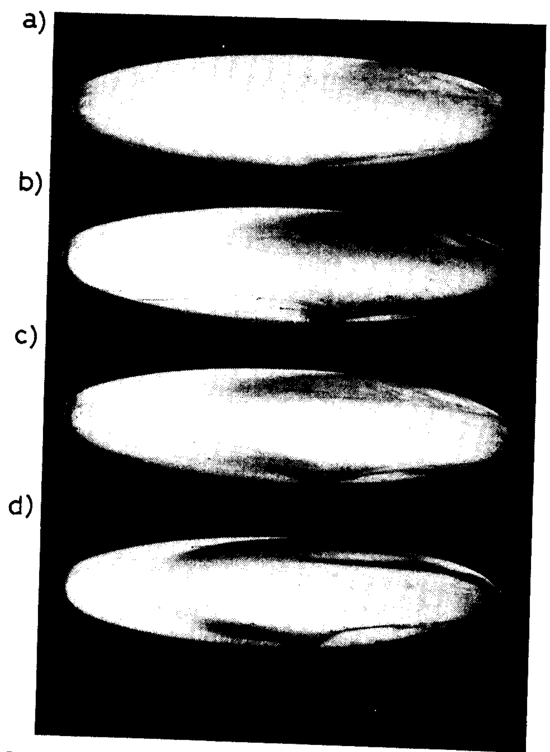


Fig. 5. Moderate incidence.
a) $\alpha=8°$, b) $\alpha=10°$, c) $\alpha=15°$, d) $\alpha=20°$.

This type of separation corresponds to the bubble type separation by Maskell or the closed separation by Wang. Figure 4(c) shows the surface pattern at an incidence of 5°. The line of axisymmetric separation slightly moves windward. It is recognized the leeward deflexion of the separation line, which implies reversal of the circumferential component of the velocity.

B. Open separation

B–1. Moderate incidence ($\alpha=8°\sim20°$)

A series of pictures of the observed flow pattern at moderate incidence is shown in Fig. 5. As increasing the incidence, greater deviation of the flow from the windward plane of symmetry and stronger convergence into the leeward plane over the nose region are recognized. As further increase of the incidence, the divergence of the separation line from the leeward plane appears to occur earlier, and separation line elongates to forward. (a~d)

B–2. High incidence ($\alpha=25°\sim35°$)

A series of the photographs taken at various angles of high incidence is shown in

a) b) c)

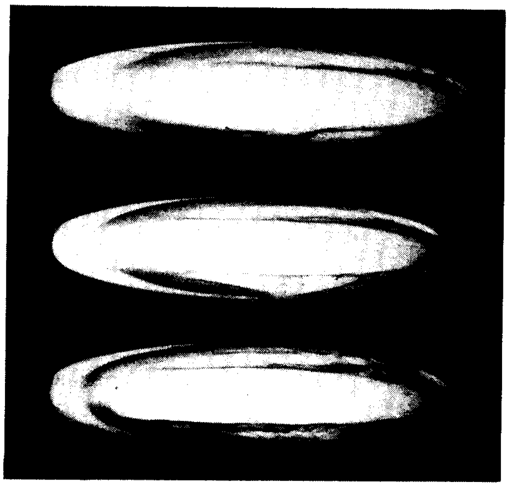
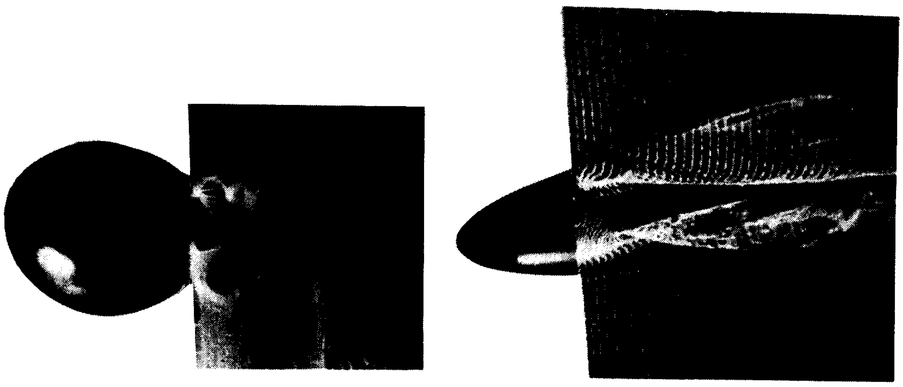


Fig. 6. High incidence.
a) $\alpha=25°$, b) $\alpha=30°$, c) $\alpha=35°$.



a) b)

Fig. 7. Longitudinal vortices along the spheroid. $\alpha=40°$, Re=5800.
a) Front view, b) Side view.

Fig. 6 of the incidence of $\alpha=25°\sim30°$. Both of separation and reattachment of the open type are observed. Two pairs of lines are recognized running from the nose to leeward along the model, the outer line corresponds to the open separation line and the inner one indicates the reattachment. The open separation is characterized by convergence of surface streamlines which are shown as the outer line, and the open reattachment lines located between them are identified by the divergence of the streamlines emanating from the outer lines. These features are clearly observed by hydrogen bubble which are generated at the 1/3 position of the body length. As shown in Fig. 7, two sheets of hydrogen bubble are rolled up in the opposite direction, as seen in the front view (a), and they flow down making a pair of longitudinal vortices, as seen in the side view (b).

C. Second closed separation

Extremely high incidence ($\alpha=40°\sim55°$)

A series of pictures at extremely high incidences is shown in Fig. 8. As the incidence increases, the region of the reversed flow grows gradually. At large incidences, the reversed flow penetrates upstream to considerable distance along the side of the body. But it remains anchored near the tail on the plane of symmetry. Figure 8(d) indicates that a pair of longitudinal vortices emanates from the line of the closed separation and leaves the surface.

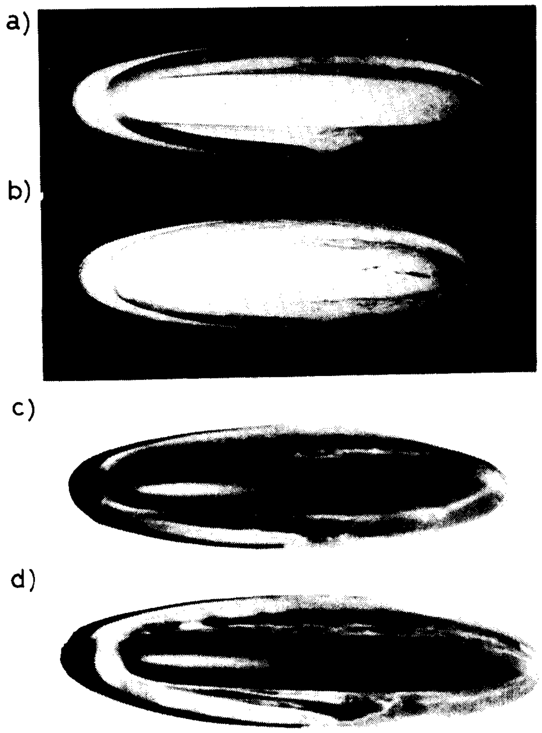


Fig. 8. Extremly high incidence.
a) $\alpha=40°$, b) $\alpha=45°$, c) $\alpha=50°$, d) $\alpha=55°$.

§IV. Discussions

It is considered that changes from the closed to open separations and from the open to closed ones are characteristic phenomena in three-dimensional flow. In the variation of the incidence of the flow to the spheroid, typical pattern varies from the closed to open ones and later from the open to closed ones again depending on generation and roll-up of the longitudinal vortices.

When the major axis of the spheroid inclined from the free stream direction at about 6°, the leeside separation point moves downstream and the separation line is curved`as shown in Fig. 9(a), and the branch CD bends forward. At moderate incidence (8°), the separation line breaks at a point between B and C, and the lower branch CD proceeds forward making the open separation line as shown in Fig. 9(b). Once the open separation occurs, there exist two tail vortices behind the separation lines AB and CD, which are not clearly visible.

At a high incidence, the singular separation point on the leeside symmetry plane jumps to a point near the front nose. Thus new feature of the open separation appears around the symmetry plane. The flow pattern forms locally a saddle point and the separated

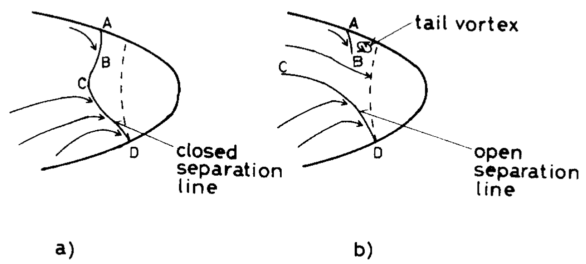


Fig. 9. From closed separation to open separation.
a) Cosed separation, b) Open separation.

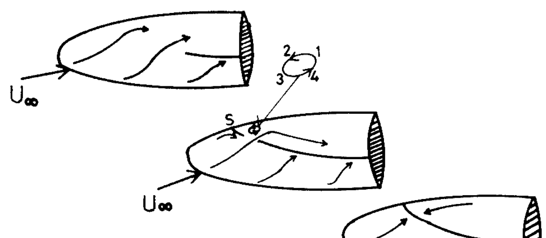


Fig. 10. Nose vortex.

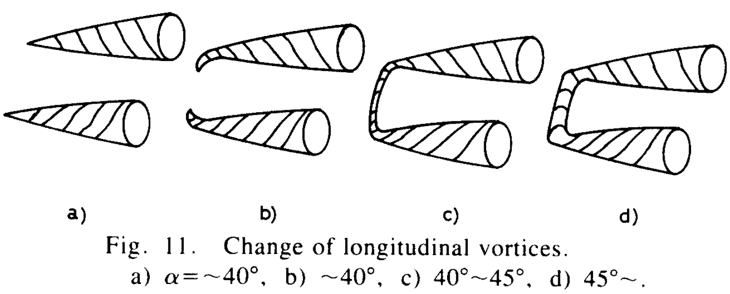


Fig. 11. Change of longitudinal vortices.
a) $\alpha = \sim 40°$, b) $\sim 40°$, c) $40° \sim 45°$, d) $45° \sim$.

region shrinks into a concentrated vortex at the nose, as shown in Fig. 10. With further increase of the incidence, the open separation line extends forward, then a local separation starts at the saddle point S. At this point, a counter clockwise vortex forms the reversed flow caused by the local separation near the point S along the upper path (1–2–3), while the open separation permits the flow to enter the leeside region along the lower path (3–4–1). When the incidence is increased further, the separation becomes again closed type, and the small vortex disappears. This vortex is expected only transitional from the open to the closed separation which is needed to compensate the flow field locally. Of course, actually a pair of such nose vortices is formed symmetrically on both sides of the plane of symmetry.

A pair of longitudinal vortices emanated along the lines of open separation, as schematically shown in Fig. 11, leaves from the surface into the flow field along the spheroid. Finally, a pair of longitudinal vortices is observed on the both sides and there vortices associate with the envelope of the open separation and the reattachment. In summary, (a) after the open separation occurs at a low incidence, a pair of longitudinal vortices exist backward along the body surface; (b) increasing the incidence, these vortices extend forward, and bend inside near the vortices of them; (c) at a high incidence, these vortices are connected each other at the center near the top of the body; (d) Finally, this connecting vortex grows thicker. Thus, angle of the separation pattern of the closed-open-closed path is completed by thus the incidence.

§V. Conclusions

Experimental observation of the flow pattern about a spheroid with 4:1 ratio of the major and minor axis is carried out using visualization mthods and the following results are obtained. Typical series of the side view of the surface separation pattern over a spheroid for various incidences is shown in Fig. 12. At zero incidence, the axisymmetric flow separates along a circumferential line at leeside of the body (a). With a small incidence, the separation lines tilts slightly (b).

At the region of small incidence, change from the closed to open separations evolves gradually. As the incidence increases, the leeside separation point moves downstream (c). At a incidence of about 6°, transition from the open to closed separation takes place. Meanwhile, the reverse flow along circumference of the body becomes strong. The separation line is approximately identified as the line of reversal flow, although it is located aft.

The open type of separation persists as the incidence to increase (from 8° to 40°, d~f). The separation line stretches forward, while the basic pattern remains same.

As the increasing incidence (about 45°, g), the separation becomes completely closed. Thereafter obvious change in the flow pattern does not occur. As the incidence increases, the separation has cyclic change of the closed to the open and again to the closed type. For the 4:1 spheroid, the range of incidence for the cycle runs from 0° to 45°. The transition from the closed to the open type takes place at about 6° and one to the closed type is about 45°.

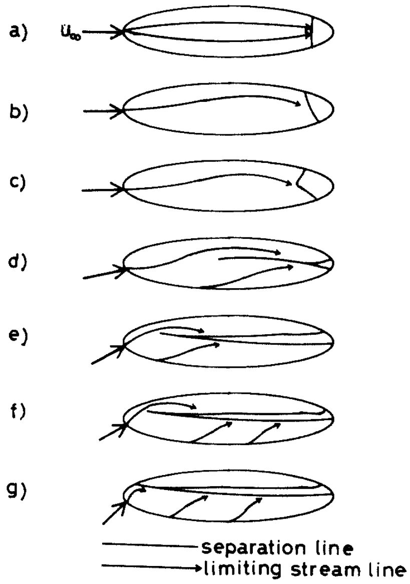


Fig. 12. Sequence of separation patterns. (Side view)
a) $\alpha=0°$, b) $\alpha=5°$, c) $\alpha=8°$, d) $\alpha=15°$.
e) $\alpha=30°$, f) $\alpha=40°$, g) $\alpha=45°$.

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