VISUALIZATION OF FLOW PAST A SPHERE NEAR ITS CRITICAL REYNOLDS NUMBER

VIJAY H. ARAKERI and H. S. GOVINDA RAM

Indian Institute of Science, Bangalore 560012, India.

ABSTRACT

Boundary layer flow visualization studies on a smooth sphere in the Reynolds number range of 1.0×10^5 to 3.5×10^5 are reported. The studies were conducted in a water tunnel facility using the schlieren method of flow visualization. The observations unambiguously show that at subcritical Reynolds numbers ($\sim 10^5$) only laminar separation exists at about 80°; whereas, at supercritical Reynolds numbers ($\sim 3 \times 10^5$) first laminar separation exists at about 101° followed by reattachment at about 112° and subsequently turbulent separation takes place at about 135°.

INTRODUCTION

IT is well known[1] that the drag coefficient of a circular cylinder or sphere decreases suddenly by an order of magnitude at a Reynolds number of approximately 3×10^5. The Reynolds number at which this phenomenon is observed to take place is commonly referred to as the critical Reynolds number. Prior to the work of Roshko[2] on a circular cylinder the explanation provided for the critical phenomenon was as follows. At subcritical Reynolds number laminar separation takes place at about 80° without reattachment resulting in substantial form drag. At supercritical Reynolds number turbulent transition takes place prior to 80° with now delayed turbulent separation at about 120° resulting in appreciably reduced form drag. However, the work of Roshko[2] seemed to show that at supercritical Reynolds numbers the flow is even more complicated than presumed with both laminar separation followed by reattachment and turbulent separation occurring simultaneously. In addition, it was suggested that turbulent separation alone occurs only at Reynolds numbers exceeding one million. Studies by Achenbach[3] and more recently by Taneda[4] seem to indicate similar flow regimes for flow past a smooth sphere as well. However, even the careful work of Achenbach[3] leaves the reader in some doubt as to the exact nature of separated flow past a sphere at supercritical Reynolds numbers. Therefore, it was felt that it would be worthwhile to provide clear photographic illustration of the nature of separated flow past a smooth sphere at and beyond supercritical Reynolds numbers.

EXPERIMENTAL METHODS

The experiments were carried out in a recirculating water tunnel having a closed working section with an internal diameter of 381 mm. The velocity in the test section can be varied from 2 to 20 m/s. The turbulence level has not been measured; however, in view of a high contraction ratio of 16 and a honeycomb flow straightner in the settling chamber the level is not expected to be excessively high*. The test sphere made of stainless steel was 39 mm in outer diamter (D) and had a tolerance of 0.1 mm when checked optically at 10 × magnification. The outer surface was highly polished and had a very smooth feel to the touch. The sphere which occupied only 1% of the throughflow area was securely mounted in the test section with a one bladed sting support (figure 1). The diameter of the sting immediately downstream of the sphere was 0.3 D. This was larger than desirable, but was necessary to facilitate the internal circulation of hot water the reasons for which are to be described later. It was found that alignment could be checked easily by observing cavitation pattern on the sphere. As will be
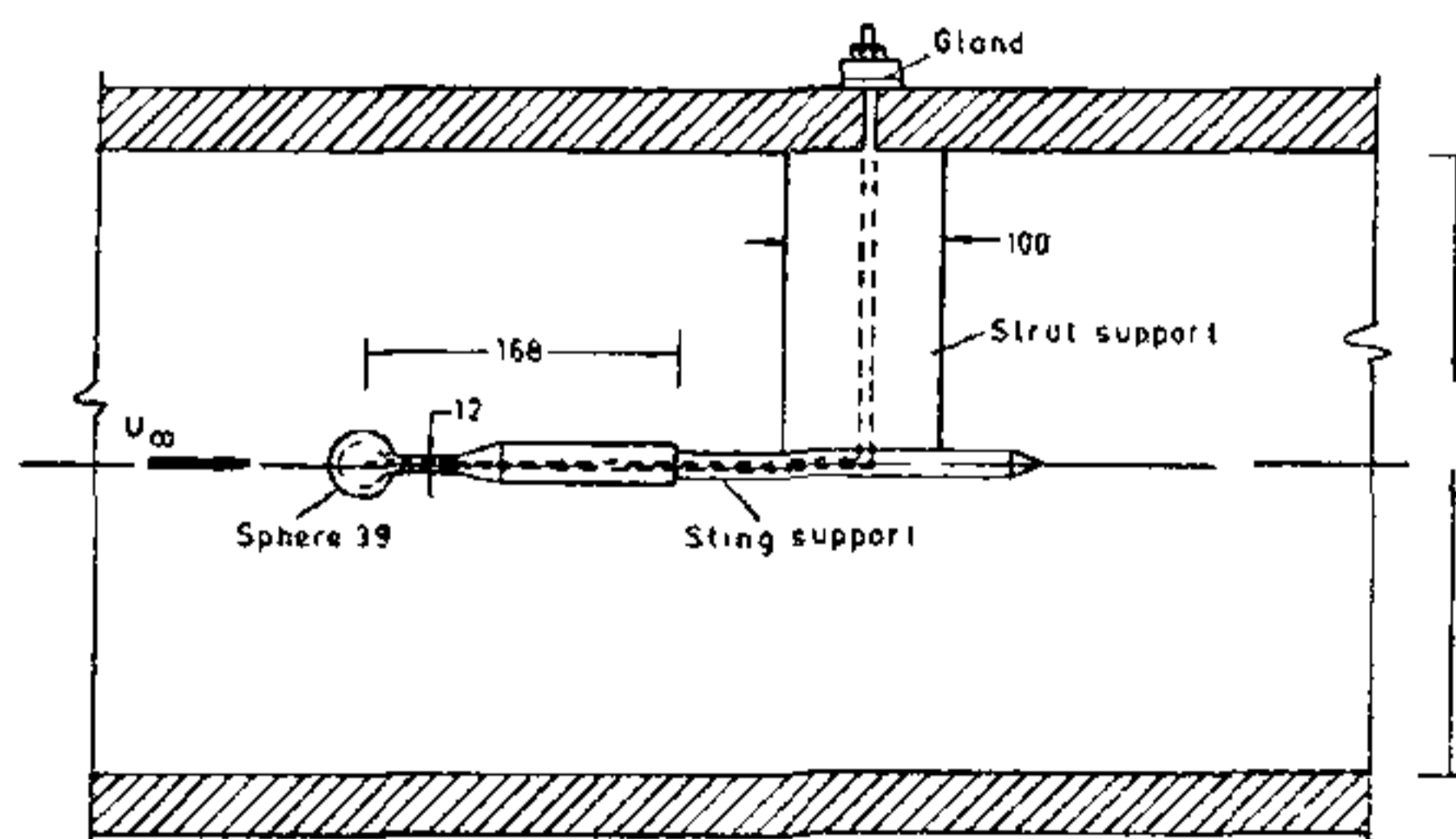

Figure 1. Sketch of the test section of the water tunnel with the test sphere. Dimensions are in mm.

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* We might note here that the turbulence level of a facility of similar design has been measured[5] to be about 0.2%.

seen later the flow visualization studies did show that the flow was symmetric indicating absence of any misalignment.

As noted earlier the schlieren method of flow visualization was utilized in the present work. The essential features of this method for use in water are described by Arakeri and Acosta[6]. The optical components and other details of the present schlieren set up were essentially similar to the set up described in the just noted reference. The density gradients necessary for the schlieren method in the present case were created by heating the sphere surface to slightly higher temperature than the free stream water temperature by internal circulation of hot water. One difficulty experienced in the present schlieren set-up was the optical distortion of the images caused by windows which were circular from inside. This was overcome by designing and fabricating a set of cylindrical correction lenses which were attached by adhesive tape to the flat side of opposing windows. It was also found that the quality of image improved substantially by adding a small amount of refractive index matching fluid (glycerine) between the correction lens and the flat surface of the window. However, even with these efforts a slight
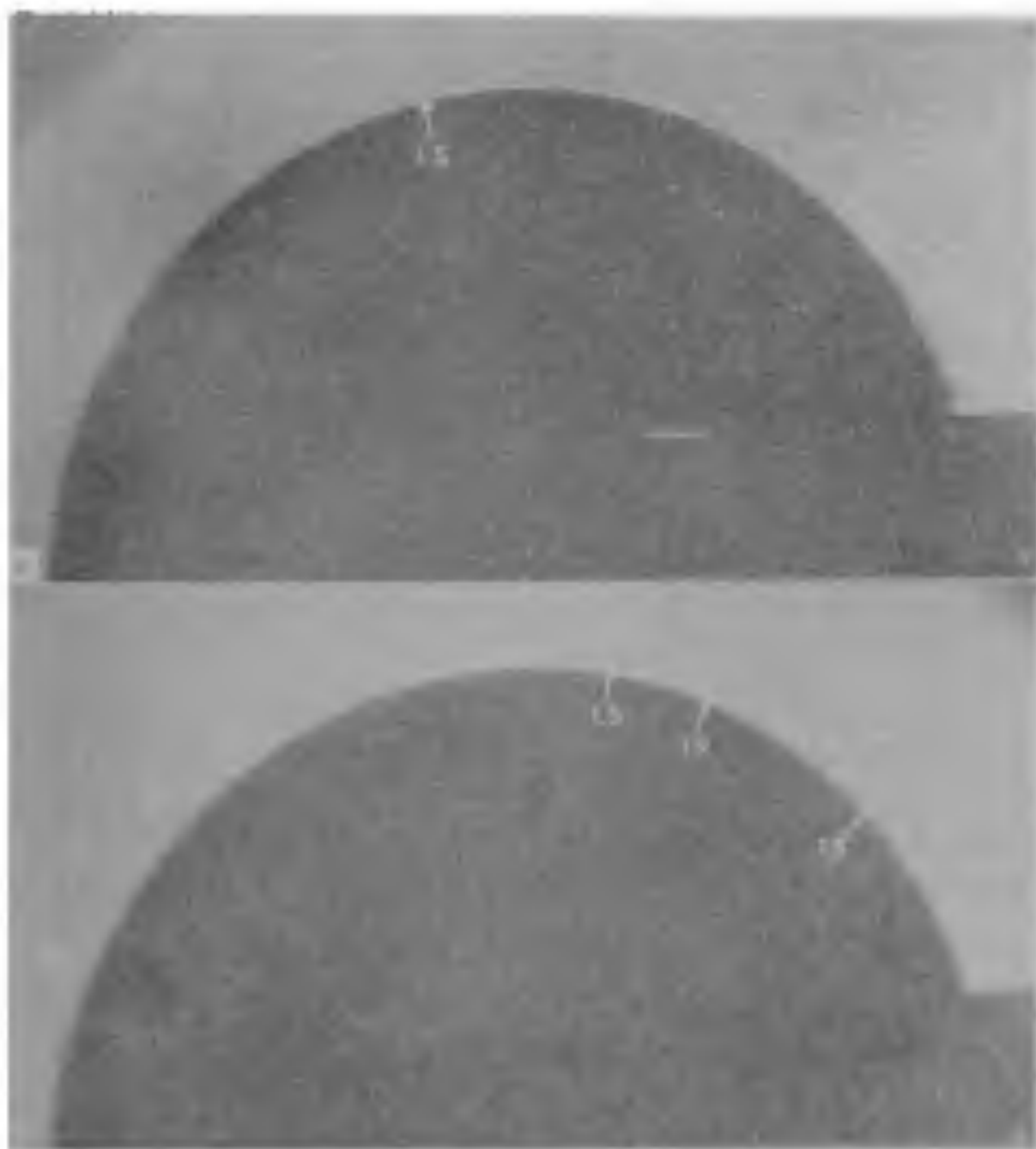

Figure 2. Separated flow past a sphere. (a) subcritical Reynolds number, $Re = 1.7 \times 10^5$; (b) supercritical Reynolds number, $Re = 3.3 \times 10^5$; LS is laminar separation, TR is turbulent reattachment and TS is turbulent separation. Flow is from left to right.

amount of distortion still persisted as seen from figure 2. In view of this a calibration negative was made by photographing a circular scale with angular markings and attached to the sphere. Photographs of the separated flow were obtained on two types of negatives namely 4″ × 5″ Kodak royal X-pan film having an ASA rating of 1250 and 10″ × 12″ Agfa Brovira having an ASA rating of 400. The former were used for exposing portion of the sphere in the region of interest and the latter for exposing the full sphere. Nominal magnification used was about 5 ×.

RESULTS AND DISCUSSION

A photograph of the separated flow past a sphere at subcritical Reynolds number[†] of 1.7×10^5 is shown in figure 2(a). It is evident that the flow separates in the forward portion of the sphere before 90°. The location of laminar separation was found to be 80° from the stagnation point. In figure 2(a) some details of the turbulent transition process on the free shear layer are also visible. The flow does not reattach subsequent to transition, resulting in a large turbulent wake. Pressure distribution measurements at limited locations (seven) after completion of the flow visualization studies confirmed that the flow was in the subcritical range at the Reynolds number of 1.7×10^5.

A dramatic change in the nature of separated flow past a sphere at a supercritical Reynolds number of 3.3×10^5 is shown in figure 2(b). Laminar separation location has now shifted downstream of 90° and subsequent to turbulent transition in the free shear layer the flow reattaches. The attached turbulent boundary layer (not clearly visible) separates further downstream (visible as marked). Therefore, as indicated in figure 2(b) three distinct phenomenon can be identified namely laminar separation (LS) at 101°, turbulent reattachment (TR) at 112° and turbulent separation‡ (TS) at 135°. We might note that detailed pressure distribution measurements of Fage[7] at a supercritical Reynolds number show an almost constant pressure region between presently observed locations of LS at 101° and TR at 112°. In addition, the same measurements show that a constant pressure region downstream of presently observed location of TS at 135°. Therefore, the photograph in figure 2(b)

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† Reynolds number, Re is defined as UD ν where U is the free stream velocity, D the diameter of the sphere and ν the kinematic viscosity of water at room temperature (25 C).

‡ This is not as clearly visible on the bottom side of the photograph.

clearly shows the physical flow characteristics of the separated flow past a sphere corresponding to the detailed pressure distribution measurements of Fage[7] at a supercritical Reynolds number.

Going through the critical range the position of laminar separation was observed to gradually shift downstream from its location at subcritical Reynolds number to its location at supercritical Reynolds number. This is illustrated from the series of photographs shown in figure 3. The presently observed trend of shift of separation location with increase in Reynolds number going through the critical range does agree well with the observations of Achenbach[3].

Besides showing some details of the separated flow the photographs in figure 3 give us some useful
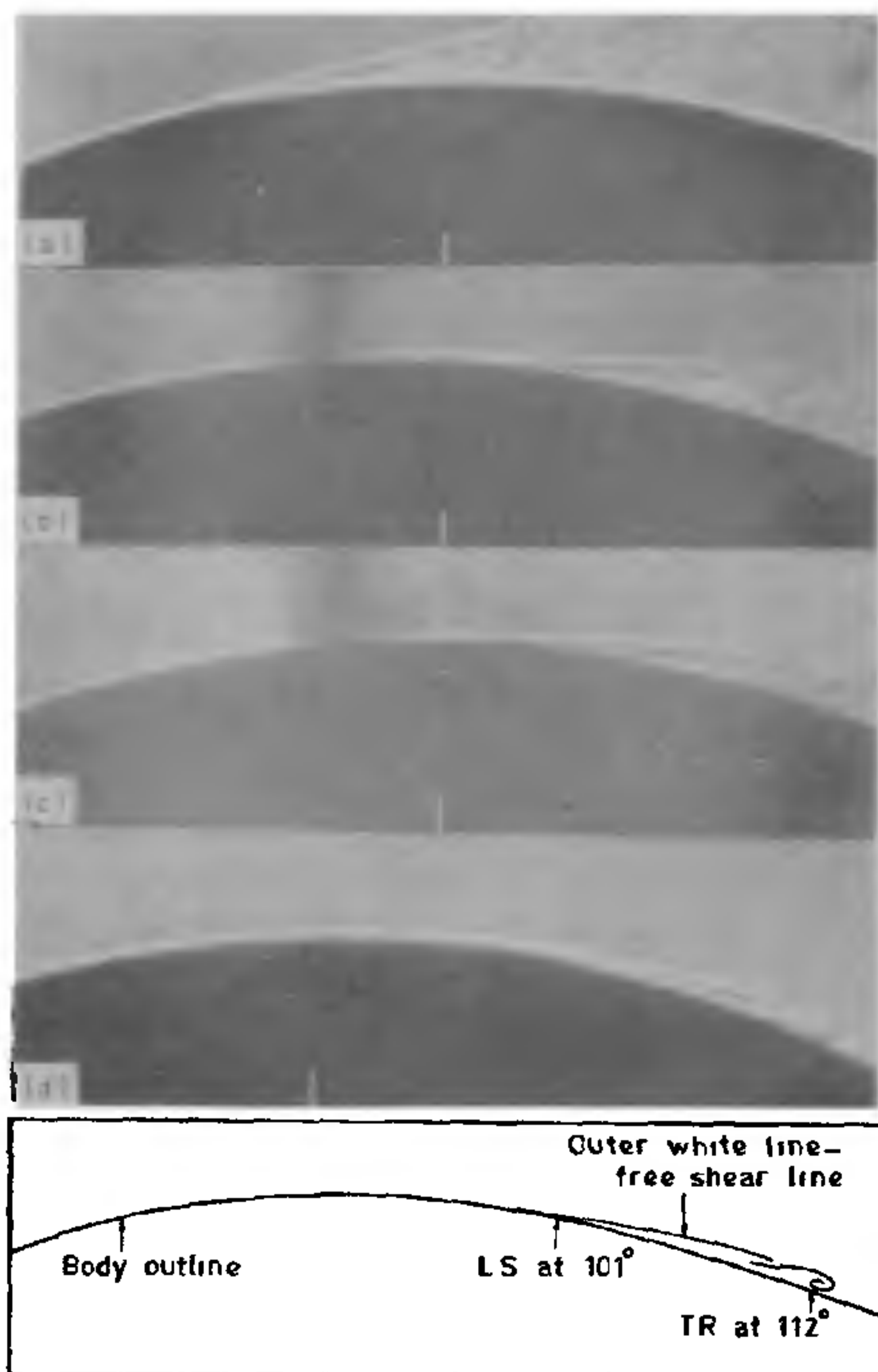
information on the nature of free streamline separation from a smooth body. Within the uncertainity of pin-pointing the location of separation the photographs show that the free streamline does detach tangentially from the body surface and also the curvature at the location of separation to be finite. Thus, we may infer from these photographs that the criterion of "smooth separation"[8] is a reasonable condition for predicting the location of free stream line detachment in potential flow modelling of such flows.

CONCLUDING REMARKS

The present flow visualization studies have shown that at subcritical Reynolds number the flow past a sphere consists of only laminar separation without reattachment resulting in a large turbulent wake, whereas at supercritical Reynolds numbers the flow consists of laminar separation with subsequent turbulent reattachment and finally turbulent separation further downstream. Eventhough such an interpretation has been indicated previously by other workers this has been done most unambiguously here. We are aware that the present study does indeed have some shortcomings: The free stream turbulence level could not be measured, the sting diameter had to be larger than desirable, some heating of the surface was required for the flow visualization etc. These are however, not expected to alter the basic conclusions of this study. This is evident from the generally good agreement obtained with previous studies.

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Figure 3. Shift of laminar separation location going through the critical Reynolds number range. (*a*) Re $= 1.7 \times 10^5$, LS at 80°; (*b*) Re $= 2.5 \times 10^5$, LS at 93°; (*c*) Re $= 2.8 \times 10^5$, LS at 95°; (*d*) Re $= 3.5 \times 10^5$, LS at 101°. Flow is from left to right.

1. Batchelor, G. K., *An introduction to fluid dynamics.* Cambridge University Press, 1973, p. 337.
2. Roshko, A., *J. Fluid Mech.*, 1961, **10**, 345.
3. Achenbach, E., *J. Fluid Mech.*, 1972, **54**, 565.
4. Taneda, S., *J. Fluid Mech.*, 1978, **85**, 187.
5. Barker, S. J., *J. Acoust. Soc. Am.*, 1976, **59**, 1095.
6. Arakeri, V. H. and Acosta, A. J., *J. Fluids Engg.*, 1973, **95**, 519.
7. Fage, A., *Aero Res. Counc. R. and M. No.* 1766, 1937.
8. Armstrong, A. H., *Memor. Arm. Res. Est. G. B. No.* 22/63, 1953.