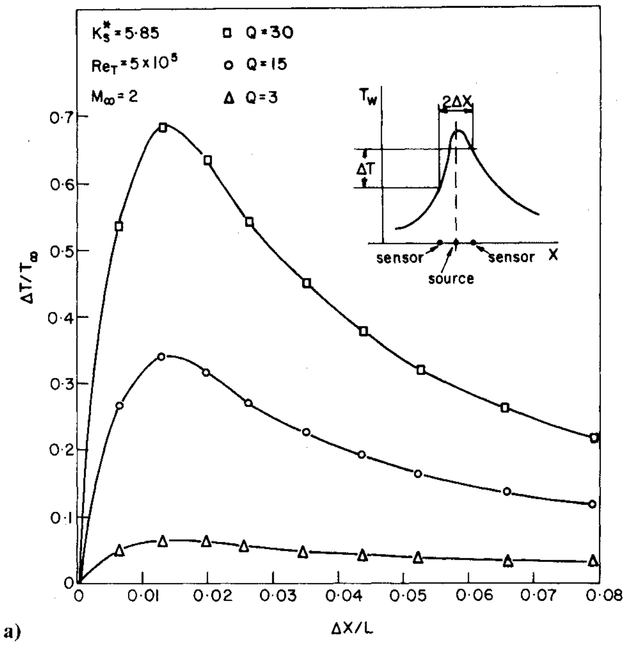
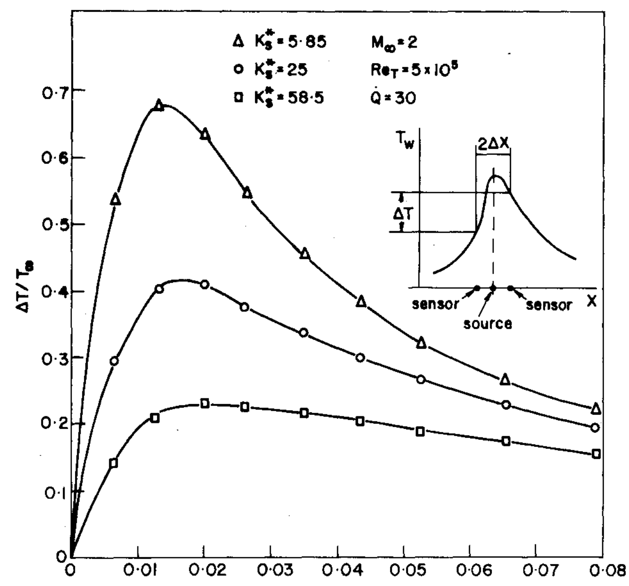


a)



b)

Fig. 3 Temperature differences between the upstream and downstream sensors as a function of their distance from the heat sources; a) effect of source strength, b) effect of conductivity.

malized depends only slightly on the source strength. Hence the distributions of ΔT vs $\Delta x/L$ (Fig. 3a) can be normalized to coincide with each other. The optimum location for the sensors (where maximum ΔT can be detected), is at $\Delta x/L = 0.013$, and is independent of the source strength. The calculations also show that when the Mach number is increased the maximum temperature difference is reduced, and its location $\Delta x/L$ moves toward the heat source. But the ΔT distribution becomes flatter and therefore the distance of the sensors $\Delta x/L$ can be increased without appreciable loss of gage sensitivity. As mentioned before, the effect of Mach number increase is to reduce the source influence on the flowfield. Hence, for higher Mach number flows the use of a stronger source is preferred in order to get detectable temperature differences without disturbing the flowfield.

Figure 3b shows the effect of conductivity ratios. An increase of solid conductivity lowers the temperature difference ΔT, and shifts the peak of the curve away from the source. It is therefore required that the gage material be of the lowest conductivity possible, even when the heater element is embedded under the surface as in the simulation.

The computational results indicate that the sensitivity of the gage increases with the increase of the source strength and the decrease of the conductivity of the solid substrate. The computations show that the heat source influence on the flow is minimal even in cases where measurements of significant temperature difference exist.

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Dry-Surface Coating Method for Visualization of Separation on a Bluff Body

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Introduction

AN indispensable aspect of any investigation of flow about a bluff body is the visualization of separation since it supplies an immediate physical insight into the overall flow structure. Methods of visualization of separation on a bluff body are useful when they: 1) apply over a wide range of Reynolds numbers and for incident laminar and/or turbulent streams; 2) produce an accurate trace of the separation line within a reasonable time period; and, 3) generate a permanent record available after the removal of the oncoming flow.

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The most common methods used at the present time to visualize the separation line on a bluff body placed in a wind tunnel airflow involve smoke, tufts, and a variety of wet-surface coatings. None of these visualization techniques meets all the necessary criteria. Smoke, due to its dispersion tendency, is limited by a maximum useful velocity, by the turbulence level in the incident airflow, and within the boundary layer. Tufts are insensitive at low velocity because of their stiffness and gravity effect.[1] Neither of these two methods can, moreover, generate a permanent record. Wet-surface coating techniques provide a permanent record but they are generally prone to earlier indication of separation on a bluff body.[2] This is due to the flow of the film sheet beneath the boundary layer induced by the airstream and, particularly, gravity. The dust method[3] is also afflicted by the same drawbacks since the body is initially smeared with a thin oil film to which the powder particles eventually adhere owing to the reverse flow within the wake. Similar errors are present when dust, which is introduced in the wake, deposits on an untreated surface as in the case of paraffin wax particles.[4] The error induced by the film motion becomes more critical with increasing bluffness of the body and it is largest in the case of a circular cylinder. In tests conducted in crossflow around a circular cylinder it was learned, for example, that the error due to the film motion in approximating the separation angle by a wet-surface coating method can be as high as 25%. In the light of the limitations imposed by the available techniques, a simple and relatively accurate dry-surface coating method for visualization of the separation on a circular cylinder or on any bluff body was developed.

Method Description

The dry-surface coating method for the visualization of the separation on a bluff body placed in a wind tunnel flow relies on the color reaction of the pH indicator contained in a thin film. This technique consists of the following basic five steps: 1) application to the surface of the body of an even thin coating composed of a versatile indicator and a paint carrier; 2) complete drying of the film in order to prevent its motion along the bluff body surface induced by the incident airstream and/or by gravity; 3) conditioning of the coating by an acidic solution for ensuring a suitable color reaction; 4) release into the body wake of a gas capable of producing a base as a result of its reaction with the solvent of the conditioning solution; and, 5) color reaction of this base with the film indicator according to its pH. The drying and subsequent conditioning of the coating are executed prior to exposing the body to the wind-tunnel airflow.

To start with, an indicator commonly known as Congo Red (sodium diphenyldiazo-bis-α-naphthylamine-sulfonate) was selected based on its color change over a wide range of pH values. Congo Red is a brownish-red powder whose color changes to either blue or deep red when exposed to a solution of a pH smaller than 3 or greater than 5, respectively.[5] Titanium white acrylic polymer water-thinned to the consistency of cream was used as the paint carrier, but any other water-soluble latex paint can be employed. Based on numerous trials it was found that a reddish mixture consisting of 1 part by volume of the Congo Red indicator to 30 parts of the paint carrier yields the best coating. In order to avoid permanent coating of the body, it is further desirable to apply the mixture to a thin, smooth cardboard sheet. An even thin film is readily obtained by spreading the mixture with a fine foam plastic roller. The complete drying of the film takes 10 min at most. Care is to be exercised in snugly wrapping without wrinkling the painted cardboard sheet over the body with its seam along the rear stagnation line.

In view of the initial reddish tint of the film and of the color properties of its Congo Red indicator, conditioning of the coating is necessary for ensuring the realization of two sharply contrasting colored sections on the body under the action of a base (pH$>$7) within the wake. This conditioning

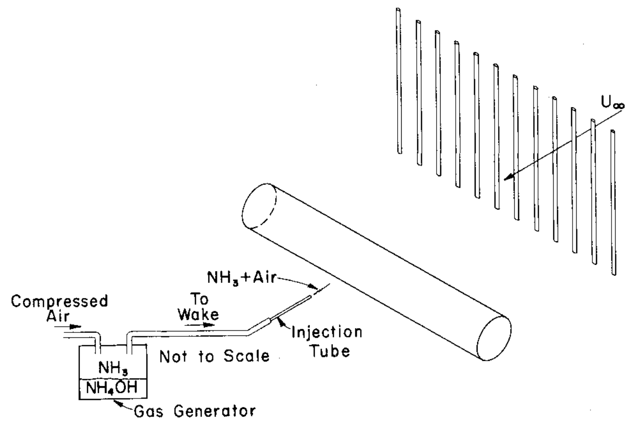


Fig. 1 Sketch of the experimental setup.

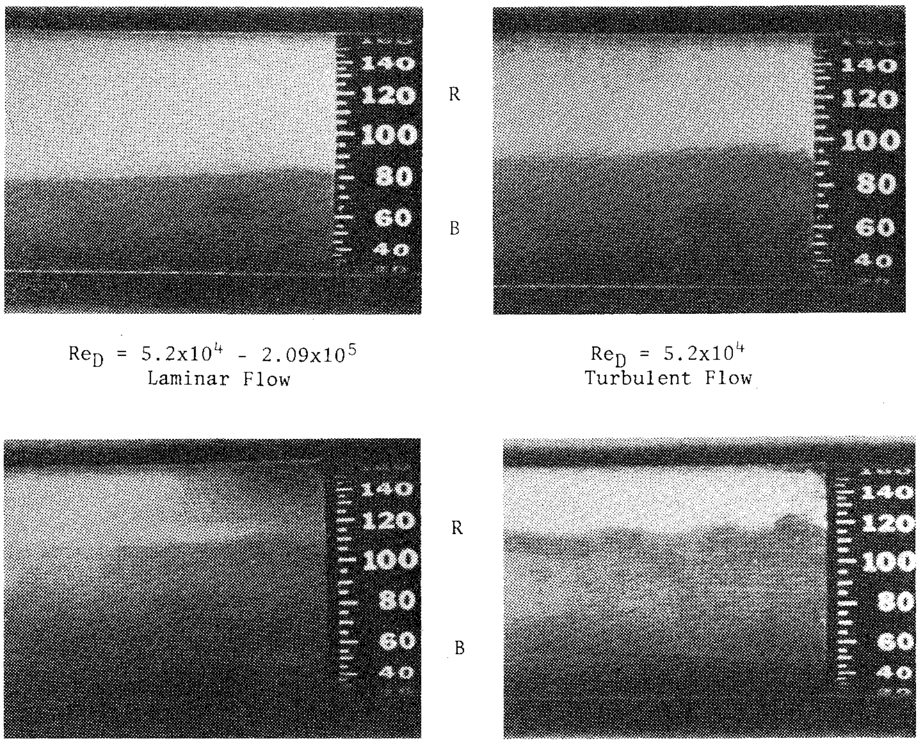
consists of spraying the coating with a strong hydrochloric acid solution (HCl) of a pH$<$3 that changes its original reddish color to blue. With the completion of this color change and the runoff of excess solution, the coating is enveloped by an extremely thin acidic solution sheath insensitive to both incident airstream and gravity effects. The coating is now ready to be exposed to the airflow.

Ammonia gas (NH_3) is next released in a regulated way along the centerline of the body wake. The ammonia gas was readily produced by means of a gas generator shown in Fig. 1. Ammonia gas emitted from the surface of an ammonium hydroxide solution [NH_4OH of 29% concentration by weight and of pH$>$11 (Ref. 6)] was conveyed from the generator by a continuous flow of compressed air. As the ammonia gas engulfed by the recirculating flow comes in contact with the coating of the wake region, it reacts with the solvent of the conditioning solution (i.e., with the water in the sheath of hydrochloric acid solution). Maintenance of a damp surface by applying a water mist furthers this reaction since it counteracts the evaporation of the solvent. The outcome of this reaction is the formation of a very thin film of ammonium hydroxide solution (NH_4OH) which is a base of a pH slightly greater than 11 (Ref. 6). Then the coating of the wake region quickly becomes deep red due to the color property of the Congo Red indicator while the rest of the film retains its original blue color.

The release of ammonia gas in the wake is continued until these two strongly contrasting colored regions on the body surface are delineated by a narrow transition band of several millimeters width. Generally, the time required to produce a clearly visible transition band amounts to only several minutes and, moreover, it decreases with increasing Reynolds number. The transition band demarcates the recirculating flow in the separated region from the upstream attached boundary layer and, therefore, it indicates the average location of the separation on the body. One then can view the centerline of this band as the separation line. A clear permanent record of the separation line is obtained since neither the two sharply different colors nor the demarcating transition band are affected by the removal of the airflow. This record is furthermore of consistently good photographic quality due to its color contrast. It is further important to stress that this dry-surface coating method is not restricted to any particular Reynolds-number range and it can be used for either oncoming laminar and/or turbulent crossflow.

Method Testing

The reliability of this dry-surface coating method was tested in visualizing the separation on a circular cylinder in both laminar and turbulent crossflows at subcritical cylinder-diameter Reynolds numbers Re_D ranging from 5.2×10^4 to 2.09×10^5. A circular cylinder 16 cm (6-1/4 in.) in diameter mounted across a $1.83\times1.83\times27$ m ($6\times6\times88$ ft) wind tunnel was used. Freestream turbulence was produced by



$Re_D = 5.2x10^4 - 2.09x10^5$
Laminar Flow

$Re_D = 5.2x10^4$
Turbulent Flow

$Re_D = 7.5x10^4$
Turbulent Flow

$Re_D = 1.25x10^5$
Turbulent Flow

Fig. 2 View of the separation angle on a circular cylinder in laminar and turbulent crossflow at subcritical Reynolds numbers; B: Blue, attached flow; R: Red, separated flow.

means of an upwind turbulence-generating grid.[7] The coating was applied to a cardboard sheet 600 μm (23.6 mils) thick of about the same surface roughness as the cylinder which, subsequently, was wrapped around the cylinder. Smooth entrainment of the ammonia gas by the recirculating flow in the wake was secured by appropriate selection of the diameter of the injection tube [7 mm (9/32 in.)] and by its positioning on the wake centerline (9 cm (3½ in.) downstream of the rear stagnation point). A sketch of the experimental arrangement including the turbulence-generating grid and the ammonia gas injection apparatus is provided in Fig. 1.

A transition band from the deep red color in the wake to a plain blue tint in the attached flow region evolved over a time period of at most 10 min. Its width varied with the Reynolds number but it never exceeded 7 mm (276 mils). This maximum width corresponds to an arc of 5 deg. The separation line was approximated by the centerline of the transition band and, therefore, the absolute error in estimating the separation angle was, at most, ± 2.5 deg.

A sample of the location of the separation line disclosed by this visualization technique is shown in Fig. 2. Four black-and-white still photographs reproduced from a color movie are presented in this figure. The color movies were taken using high-speed color-reversal film with the airflow on and off. Exactly similar images were obtained under both conditions owing to the permanency of the record. In the stills shown in Fig. 2 the dark and light areas represent the blue and red regions on the cylinder, respectively. A scale marking off angles at 5 deg intervals, with its origin at the forward stagnation point, is incorporated in the stills for convenient estimation of the separation angle.

A separation angle of about 80 deg was consistently revealed by the visualization over the entire Reynolds-number range in the case of incident laminar crossflow as clearly seen in Fig. 2a. In an oncoming turbulent crossflow, on the other hand, a continuous increase in the separation angle with augmenting Reynolds number was disclosed by the visualization. For instance, separation angles of about 95, 110, and 120 deg were recorded at Reynolds numbers of 5.2×10^4, 7.5×10^4, and 1.25×10^5, respectively, as distinctly observed in the stills given in Figs. 2b-d. These results were obtained with the turbulence-generating grid installed at an upwind distance of 10 cylinder diameters [160 cm (63 in.)].

In order to verify the accuracy of this visualization method, the separation angle was next estimated based on the distribution of the mean wall pressure under exactly similar flow conditions. The separation angle indicated by the visualization was in each case at most ± 3 deg from its counterpart deduced from the wall pressure distribution. Thus, this visualization method yields results which are within $\pm 4\%$ of the measured separation angles. It is thus apparent that this novel dry-surface coating method supplies a reasonably accurate visual indication of the separation angle on a bluff body.

Acknowledgment

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