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Flow Visualization in Wind Tunnels

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1. Introduction

Flow visualization is an experimental means of examining the flow patterns around a body or over its surface. The flow is "visualized" by introducing dye, smoke or pigment into the flow in the area under investigation. The primary advantage of such a method is its ability to provide a description of the flow over a model without a complicated data reduction and analysis. Smoke- flow visualization (described by Bradshaw, 1970 and Rae and Pope 1984) involves the injection of streams of vapor into the flow. The vapor follows filament lines (lines made up of all the fluid particles passing through the injection points) in steady flow the filament lines are identical to stream lines. (Lines everywhere tangent to the velocity vector). Smoke- flow visualization thus reveals the entire flow pattern around a body.
It is difficult to exaggerate the value of flow visualization. The ability to see flow pattern on a model often gives insight into a *solution to an aerodynamic problem*. Flow visualization can be divided into two broad categories the first is surface flow visualization when the visualization media is applied to the surface such as tufts and oil flow etc. The second type is off surface such as smoke and streams.
There are basically four methods of recording the flow visualization test. The first and the best but the least permanent method is for the scientist and the engineer to observe with his eyes. Because of the depth perception one can see a three dimensional picture. The other three common methods of recording the result of flow visualization are by film, either still or movie or television camera or video and magnetic tapes. It must be realized that all three of these methods are using a two dimensional medium to often record a three dimensional phenomena. This is especially fine when using a smoke or helium bubbles to trace flow stream lines pass the model. All three of these methods can be used either black and white or color. The photography methods while recording more time for developing and printing stills, when compared to video, yield higher resolution.

2. Flow visualization techniques

The present chapter will deal with the visualization of flow past different types of models like flat plates, delta wings, elliptical cones and rectangular bluff bodies using

- smoke wire technique
- laser light illumination technique
- surface flow visualization techniques

The results obtained are being discussed considering the importance of different techniques.

2.1 Flow visualization using smoke wire technique

Flow visualization is considered an important tool to understand the nature of flow field. Its proper utilization will provide reasonable information that will help in influencing the flow characteristics. This will eventually lead to better design modification leading to development of favorable pressures.

The visualization of the flow past the building models was made possible by using the above technique originally developed by Raspet and Moore in early 1950's and subsequently improved and used by Batill and Mueller [1], and was further improved by Stahl and Mahmood [2]. The procedure involves brushing a thin wire, which then forms a large number of small droplets. Heating the wire evaporates the oil with each droplet providing a fine streak-line in the flow. Under proper illumination the smoke streaks appear bright which can be observed and photographed This technique basically requires a fine wire of about 0.1mm in diameter of Nickel Chromium steel and suitable oil, which can vaporize quickly, and a DC current to heat the wire.. This technique was utilized, as it is very useful in studying separation especially in smooth and nominal boundary turbulent flows. The smoke-wire was placed at the upstream side of the building model to see the separating bubble from frontal edge and ground vortices at normal incidence, for both sharp and round edge model. For oblique incidences of 25° and 45° the smoke-wire was placed at a suitable position to note the separation of shear layer in the immediate vicinity of the leading edge corner where high suction pressures are developing. This technique provided a clear influence of rounding of roof edges on the separating shear layers that formed conical vortices. The influence due to change in the angle of incidence on the separation process for sharp and round edge models was found to be of interest. The smoke-wire could also be moved around the model to get useful information about the flow field.

2.1.1 Flow visualization in smooth flows, α =90°

The results from smoke wire technique for an angle of incidence of 90° for smooth flows are shown in Figure 1. These indicate that for a sharp edge model the flow incident on the front surface of the model divides into two parts. Part of the flow goes up and separates from the front edge with a large bubble and a re-circulation closer to leading edge, and the rest of the flow descends down and forms a vortex near the ground. In the model with a rounded edge, the flow does not have a sharp separation but a long bubble with a height smaller than that noted for the sharp edge model emerges. The balance flow goes down forming a vortex close to the ground in a way similar to that noted in the case of the sharp edge model. The difference between smooth flow and turbulent flow is visible in the separation of flow from the frontal edge. The height of the separation bubble is comparatively smaller in turbulent flow than the smooth flow.

2.1.2 Flow visualization in smooth flow at α = 45°, 25°

As the region near the leading edge corner is considered critical since maximum mean and peak suction pressures were recorded at hole # 50205(Texas tech University test building nomenclature), smoke wire technique was utilized to observe the flow past this region. Batill and Mueller [1] studied the transition in the flow on an airfoil using this technique. This technique was also successfully applied in studying the separation of flow past flat plates at various angles by Mahmood [2]. At incidence of α = 45° the smoke streaks incident on the side wall at a distance of about 15 to 20% of the length of the wall goes up and separates to from large separation bubble (bump) on the top surface of a sharp edge model as evident in Figure 1c. The remaining flow moved down resulting in re-circulation of flow, which persisted all along the length of wall. But as the rounding is increased, the size of the bump became smaller indicating the influence of rounding at a specific location. A bump smaller in size was noted for a round model with radius of 5mm. For a model with a radius of 10 mm, the smoke streaks remain almost attached to the roof and just slide over curved roof surface with a minimum possible separation, as shown in Figure 1d. Similar changes were noted for the flow at an of angle incidence of 25°. For this incidence angle the sharp edge model shows more separation and the height of separation of the vortex sheets decreased with increased rounding as evident in Figure 2.

For a sharp edge model a clear separation was visible at station 1 i.e., around 15 to 20% of the distance from leading edge corner, as shown in Figure 2a. But when round edge models were placed the height of separation reduced in proportion to the magnitude of rounding, especially for R=10 mm model, where the flow remained attached while moving from sidewall to the top surface, as shown in Figure 2c. This is in line with the observations made in smooth flow condition and is expected to influence the pressures that are developed on top surface of the model.

Since the influence of rounding was visible on both flows at oblique and normal incidence, its influence on the pressure characteristics was investigated and compared in both the cases.

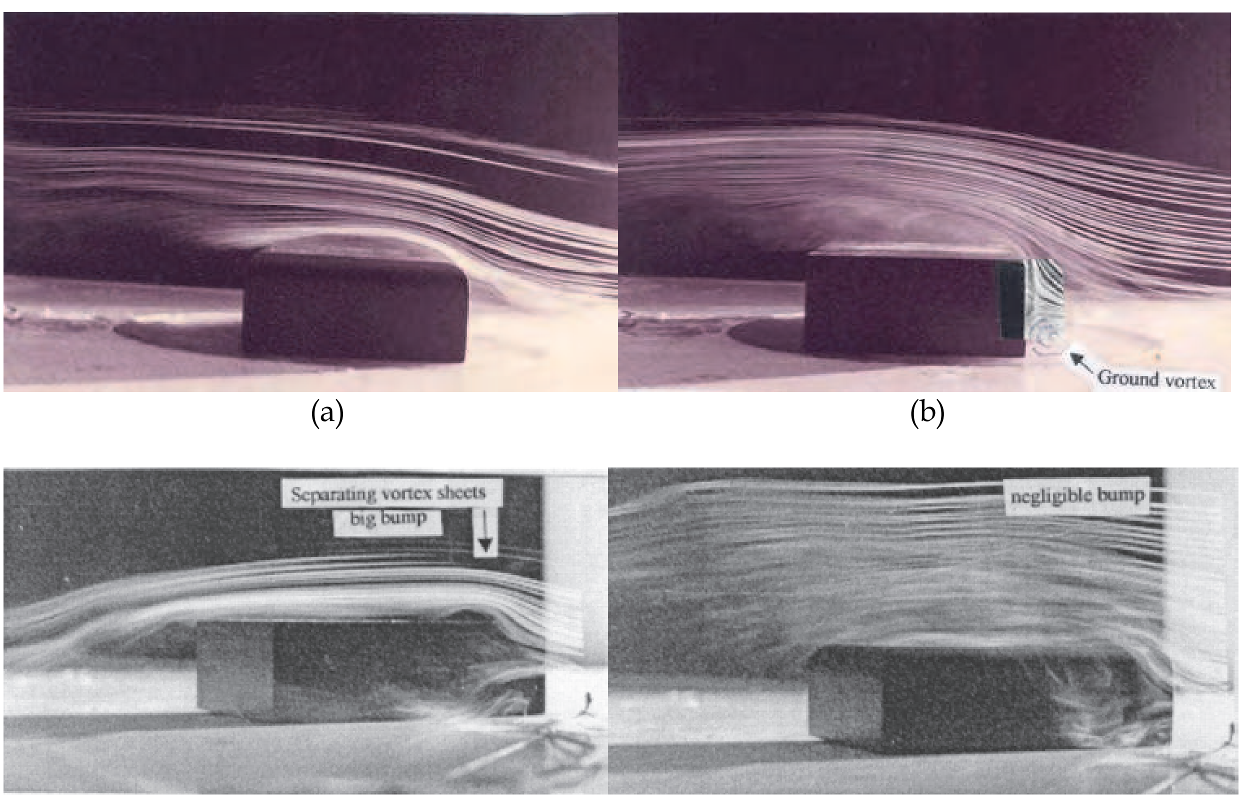
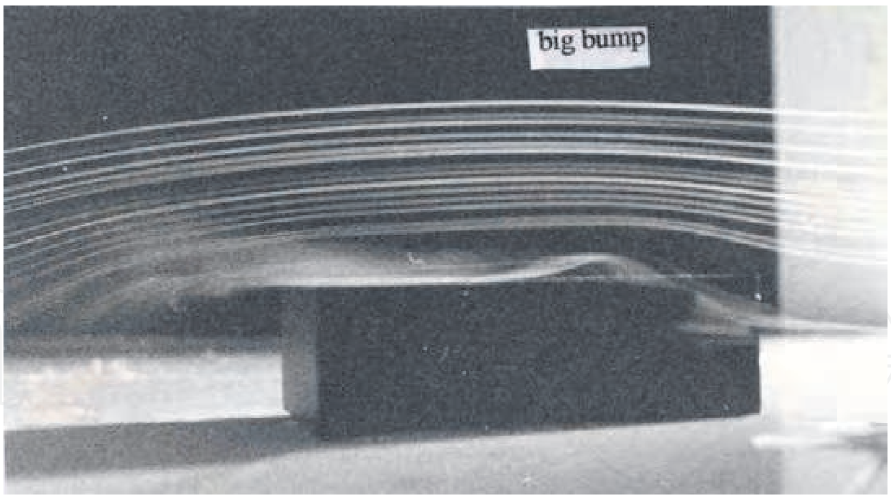
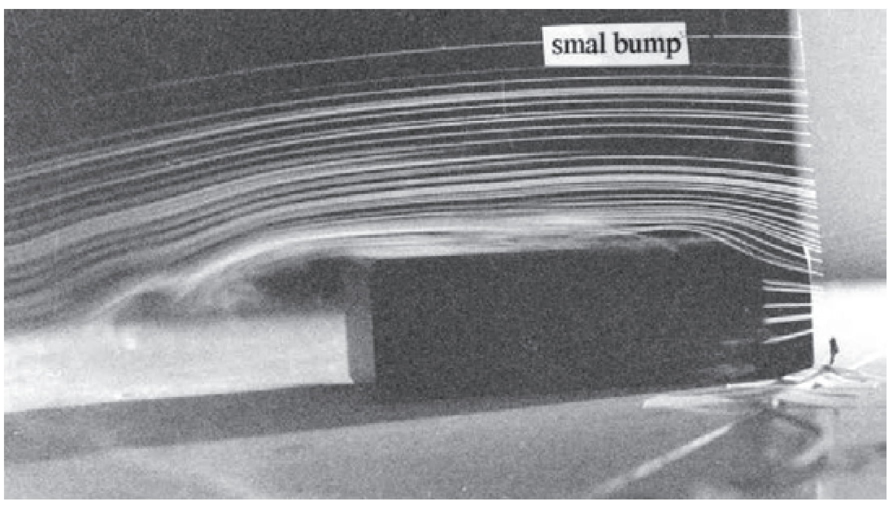


Fig. 1. Flow visualization using smoke-wire technique (smooth flow condition). View from front.

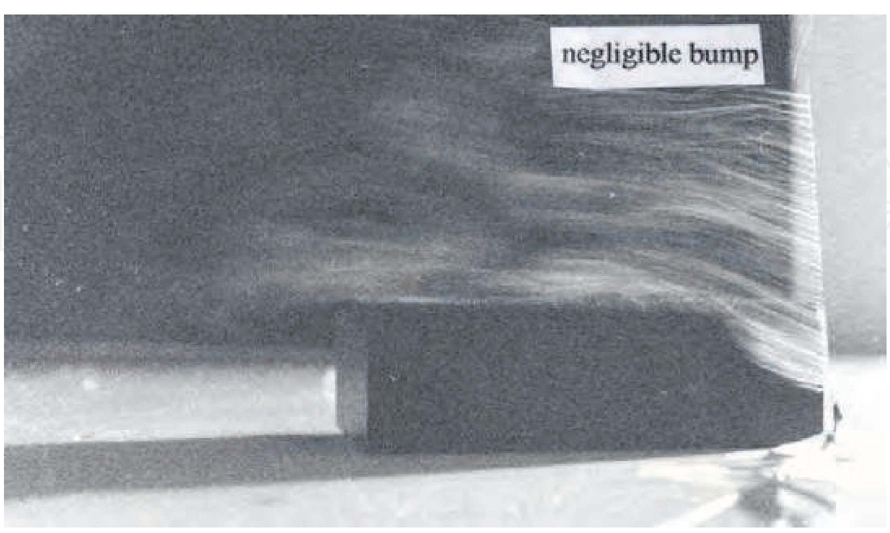
a. Sharp edge model α = 90°
b. Round edge model α = 10 mm, α = 90°
c. Sharp edge model α = 45°
d. Round edge model *R* = 10 mm, α = 45°



(a) Sharp edge model.



(b) Round edge model, R = 5.0 mm.



(c) Round edge model, R = 10.0 mm.

Fig. 2. Flow visualization using smoke-wire technique, α = 25° (smooth flow condition). View from front.

3. Flow visualization using laser light illumination technique

A smoke-probe was utilized to generate heavy smoke upstream side, which then passes over the model. A section of the flow was then made visible by using a laser-light sheet. This plane is generated by using a laser light source in conjunction with a lens system. This technique helped to study the flow on the top of the model. The near roof edge regions are considered important from pressure point of view, as corner vortices are said to exist there, which is a cause for severe suctions. The presence of corner vortices and the changes that take place in them when edges are rounded could also be studied. Still pictures at different stations were obtained by moving the laser light plane. This technique was used for all the flow conditions. A video recording of the flow was done and when played at slow rate provided useful details of the flow over the roof and could provide further information about the flow phenomenon.

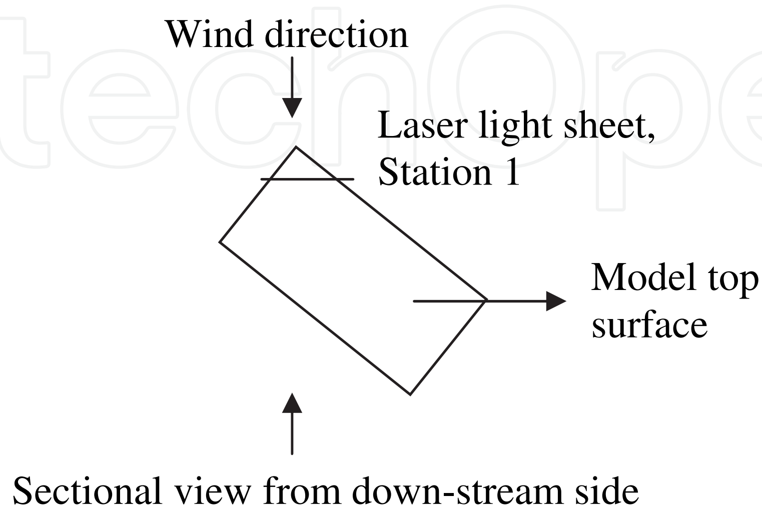
3.1 Flow visualization past building model in smooth flow at α=45°

The flow was visualized at two stations on the model top surface. Figures 3a and 3b show the section of the flow near the leading edge corner at station 1 (15-20% of the distance of the leading edge), whereas Figures 3c and 3d show the section of flow at station 2, which was at about 50% of the distance. Figures 3a and 3c show that there exist concentrated vortices springing from both the leading edges at station 1 and 2, respectively in the case of sharp edge models. A similar observation was also reported by Bienkiewicz and Sun [3] on a sharp edge cubical model when surface flow visualization was carried out in a turbulent boundary layer flow. Figure 3b shows some separation and rolling at station 1 for a round edge model with edge radius R=5 mm with a small vortex formation, where as at station 2 a big size vortex formed as, shown in Figure 3d. This had a diffused or burst nature, and could be observed during flow visualization. For model with a further rounded edge of R=10 mm, no separation was noted at station 1 where as proceeding towards the model end to station 2, formation of a vortex was noted which can be seen in Figure 3d. This had a loose core and a burst nature. A similar vortex with a loose core is usually observed for slender sharp edge delta wings at high incidence [4].

3.2 Flow visualization past elliptical cones and delta wings

As it was reported in the literature that the symmetry of vortex formation and the degree of asymmetry on elliptical cones is influenced by the thickness of the ellipses [5] and the theoretical predictions about the degree of asymmetry was also made. In order to study this phenomenon different elliptical cones whose base height to width ratio varied between 20% to 80% were taken. The model was placed in the wind tunnel using a suitable fixture. Smoke was generated upstream side of the model using a smoke probe. The laser light sheet illumination technique was then used to find flow characteristics. Fig 4 shows the vortices formation for 65% thick elliptical cone. The degree of asymmetry could be found when the plain of observation is bit normal to the axis of the cone. Similar results were reported on circular cones. Where it was possible to observe an asymmetric flow changing to almost symmetric one when a fin was fixed on the cone [6].
Experiments were conducted to study the asymmetry of vortex formation on a sharp edged delta wing of Aspect ratio A=0.56 in Ref [7]. It was observed that up to certain angle of attack symmetric vortex formation takes place as can be seen from Fig.5. These vortices

looked quite concentrated sitting on the wing. When the incidence angle was increased one vortex got burst and further increase in incidence angle resulted in bursting of both the vortices. The bursting of one of the vortices can be seen in Fig.6 and no vortex asymmetry was observed for this type of configuration. A study by Terry,N et al [8] shows extensive use of laser light illumination technique in visualizing the flow past an 80°Delta wing



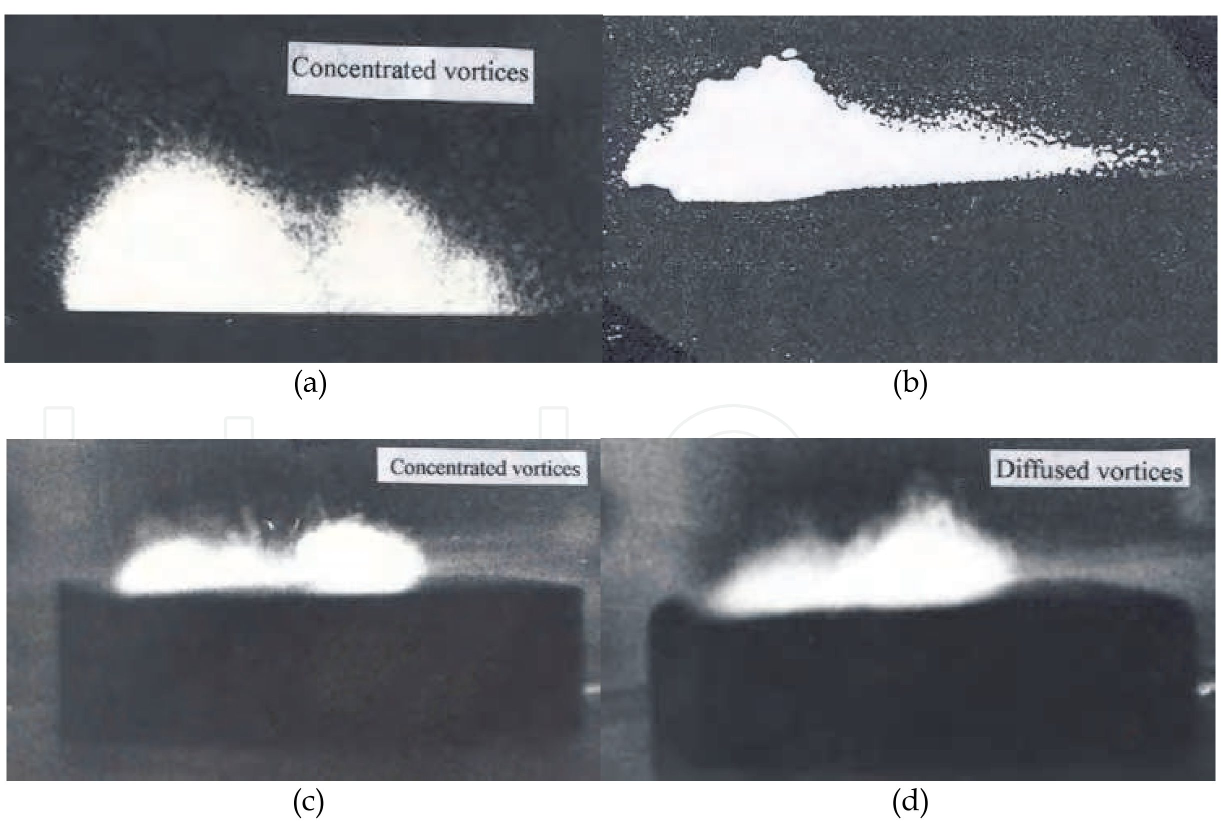


Fig. 3. Flow visualization (top surface) using laser light sheet illumination technique α = 45°. (a) Sharp edge model, (b) round edge model, R = 10.0 mm station 1 (15% of length), (c) sharp edge model, (d) round edge model, R = 10.0 mm station 2 (50% of length).

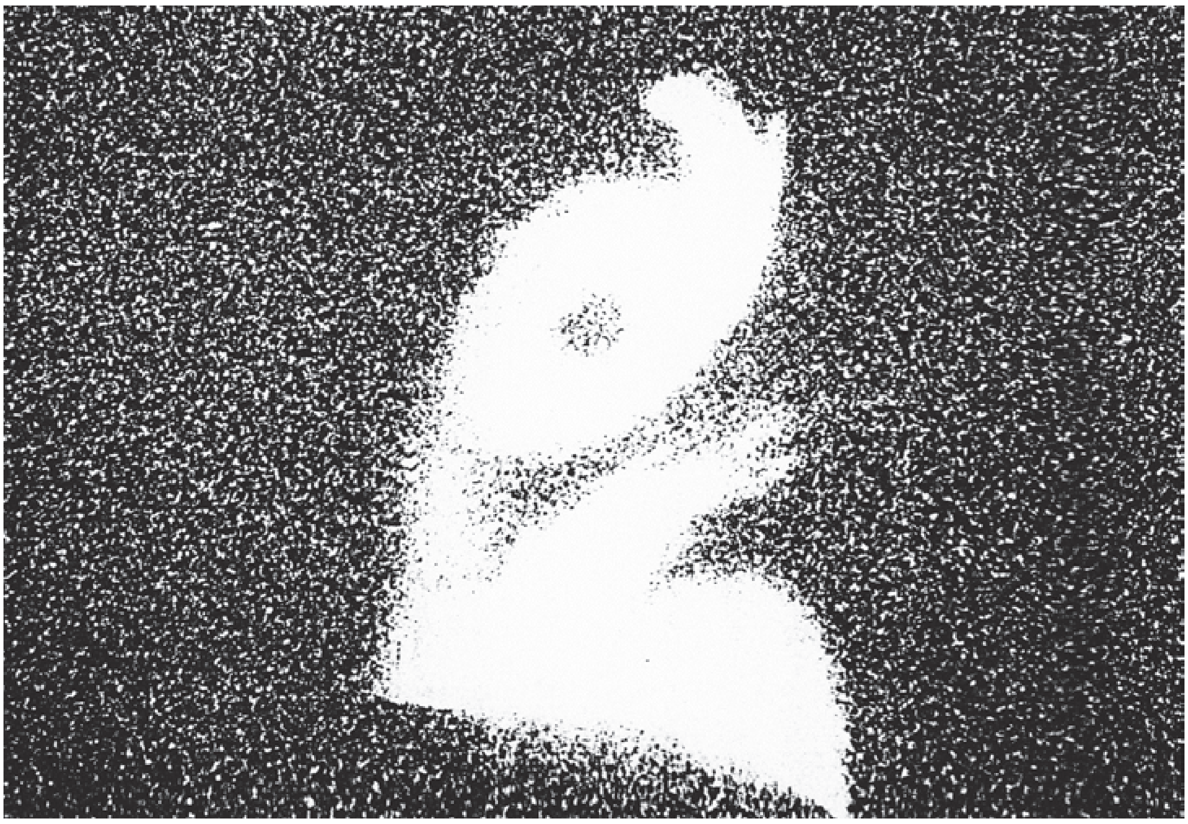


Fig. 4. Vortex formation behind elliptical cone thickness ratio=0.65, Reynolds number =132,000

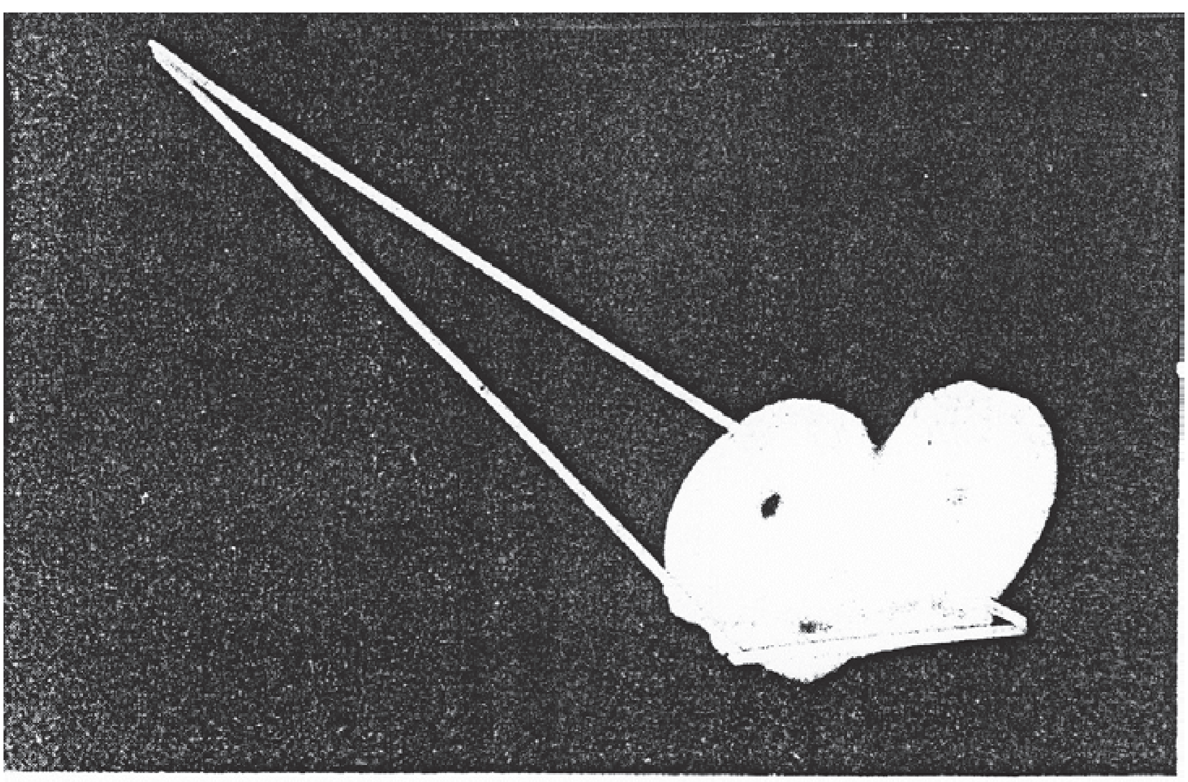


Fig. 5. Vortex formation behind Delta wing Aspect ratio=0.56, Reynolds number =132,000, α =30

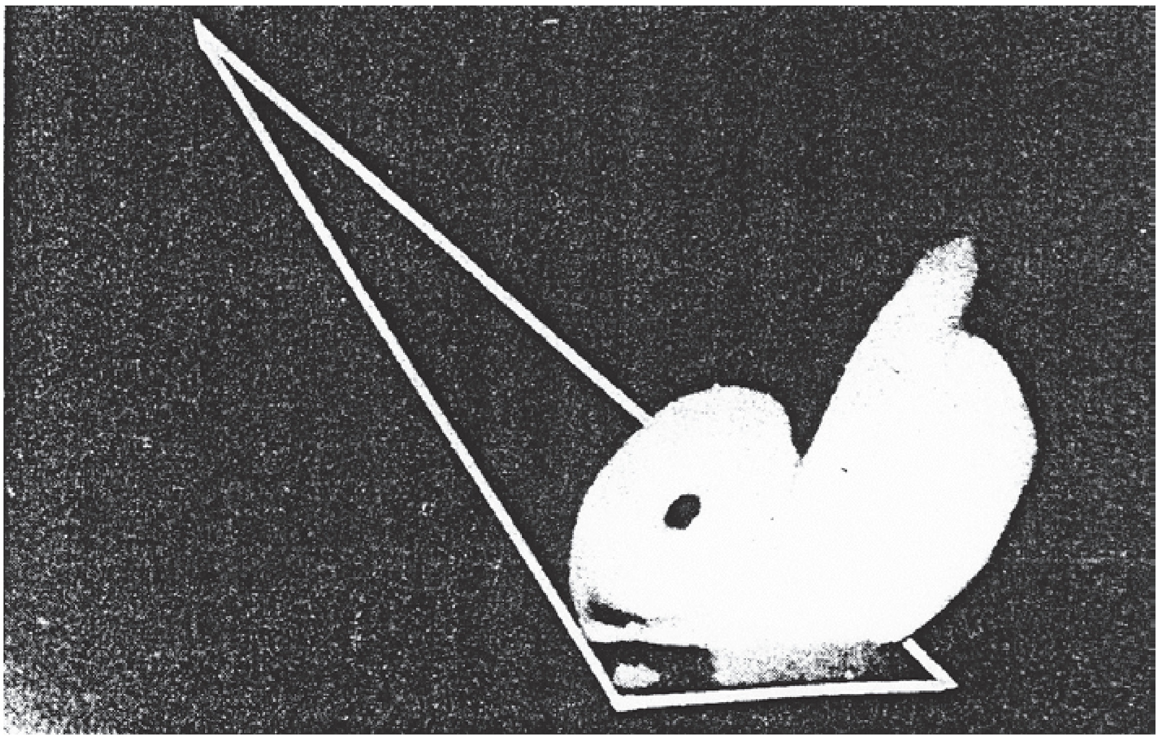


Fig. 6. Vortex formation behind Delta wing Aspect ratio=0.56, Reynolds number =132,000 α =35

4. Surface flow visualization technique

The study of the flow near the surface of the square plate model was carried out by using the chalk powder suspended in Kerosene oil and sprayed on the model. Figure7 shows the setup for surface flow visualization. When the flow passes the model the chalk and Kerosene mixture settles as per flow lines. The pattern of flow obtained revealed direction of surface streamlines and features like the separation of flow from the surface. The flow visualization experiments carried out by using different methods like smoke wire technique, smoke probe, surface flow etc., can be divided into two groups as one with $\alpha \leq 28°$ and another with $\alpha \geq 32°$as the incidence angle of around 30° is considered critical where a sudden drop in normal force occurs.

4.1 $\alpha \leq 28°$

Here the investigations are limited to angles of α = 26.5 and α = 28°. The flow is essentially divided into two parts, namely the wing center flow which is accompanied by separation and the wing tip flow Fig 8. In the latter case the flow is separating from side edges which form vortex sheets which curl up over the wing into the side edge vortices. The results from various flow visualization studies are shown in Figures 12-13,Here, for the above mentioned angles $\alpha \leq 28°$, the three dimensional separation bubble covers the central part of the plate and the flow is rotating inside the bubble, moving on the plate surface forward and outward, and frequently being drawn towards wing side edges. As a result of this induced transverse flows, considerable masses of air are involved in vortex motion along the side edges on the suction side as evident from Figs 8-9. Since the bubble is closing at a distance of about 0.1 C from trailing edge, some of the flow is observed as moving forward at this junction from movie film taken using a movie camera.

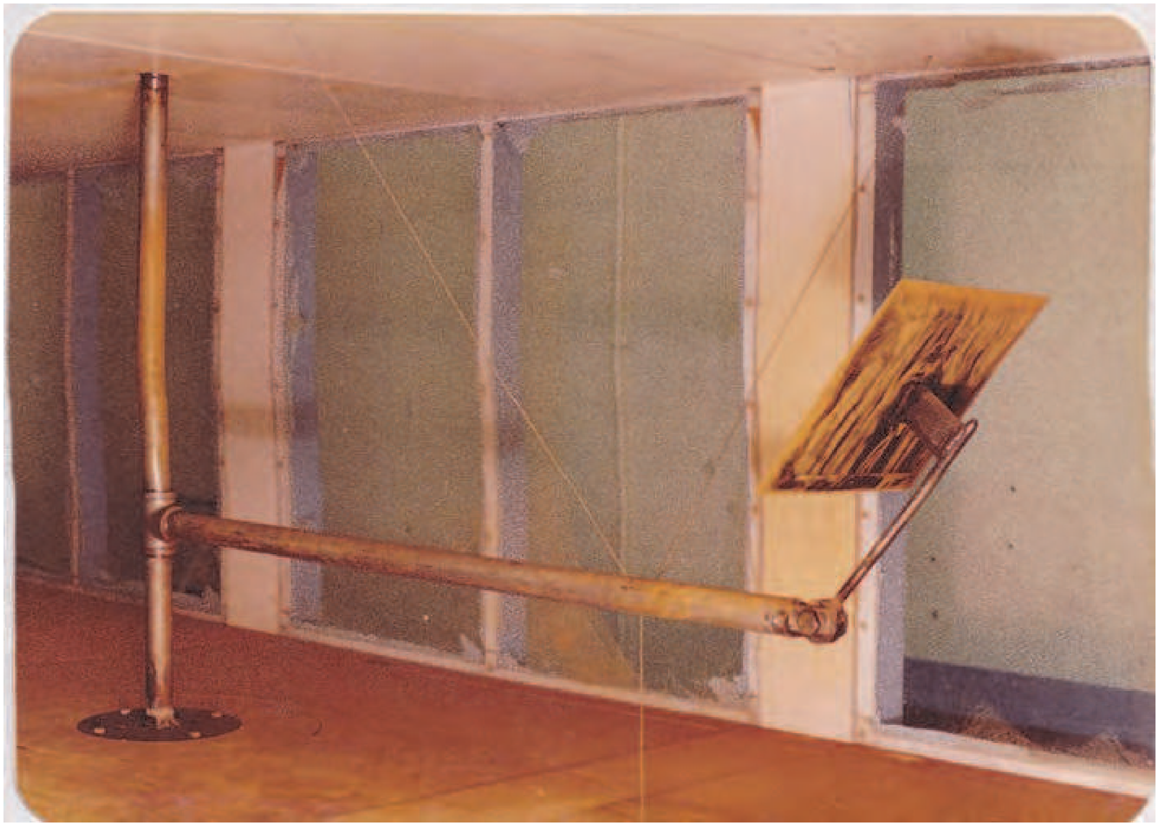


Fig. 7. Surface flow visualization setup

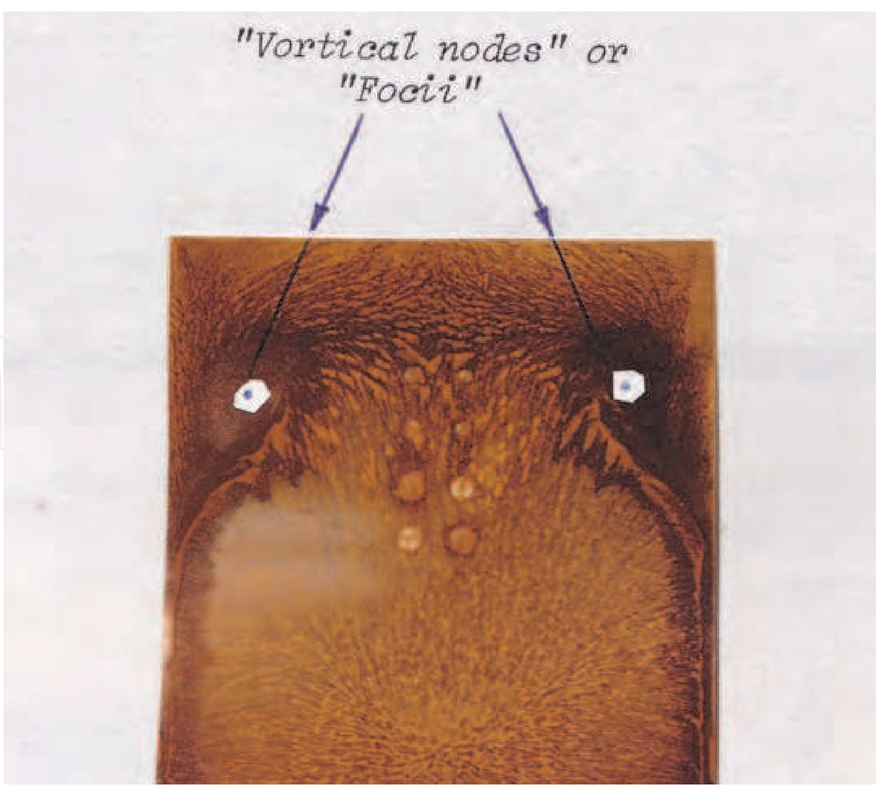


Fig. 8. Surface flow visualization on wake side of flat plate at α = 28°

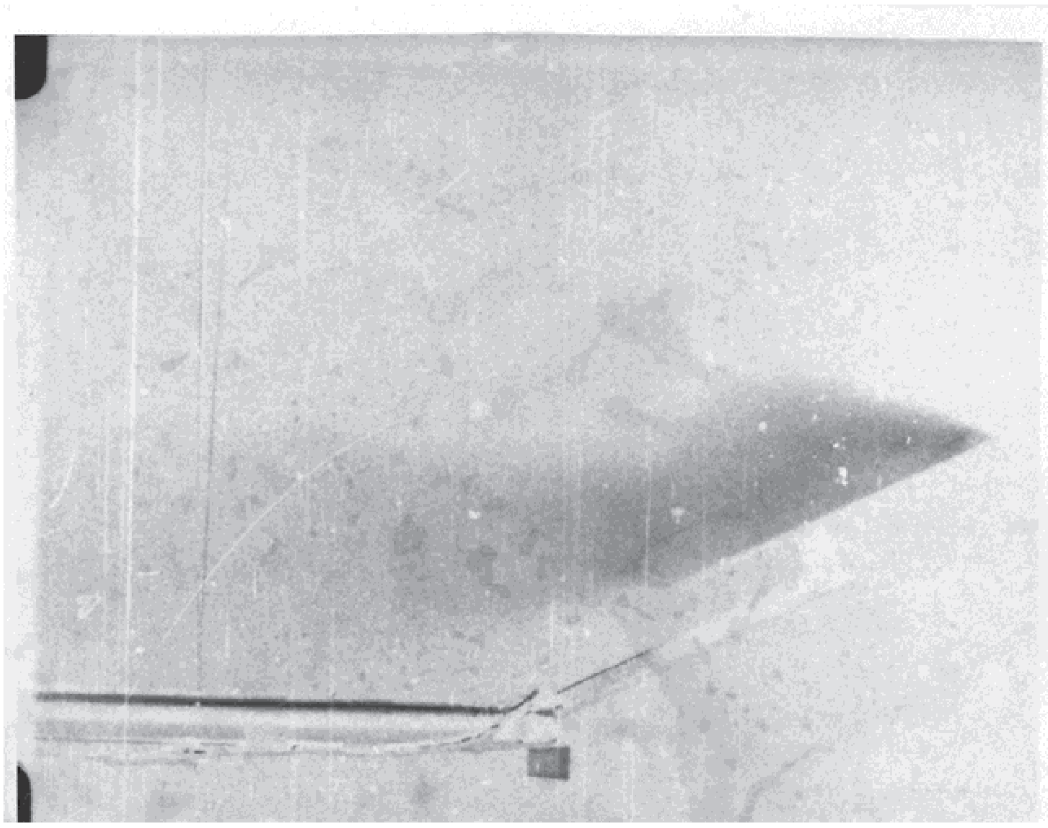


Fig. 9. Flow visualization inside of wake using smoke wire technique α = 28°

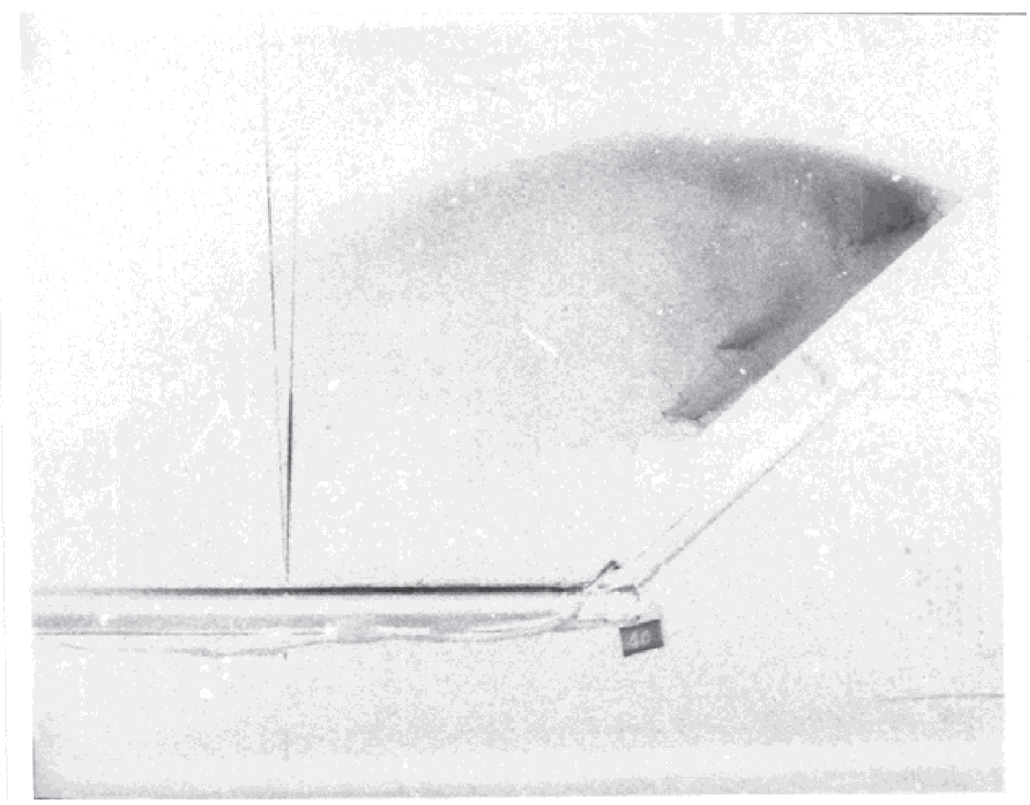


Fig. 10. Flow visualization inside of wake using smoke wire technique α = 32°

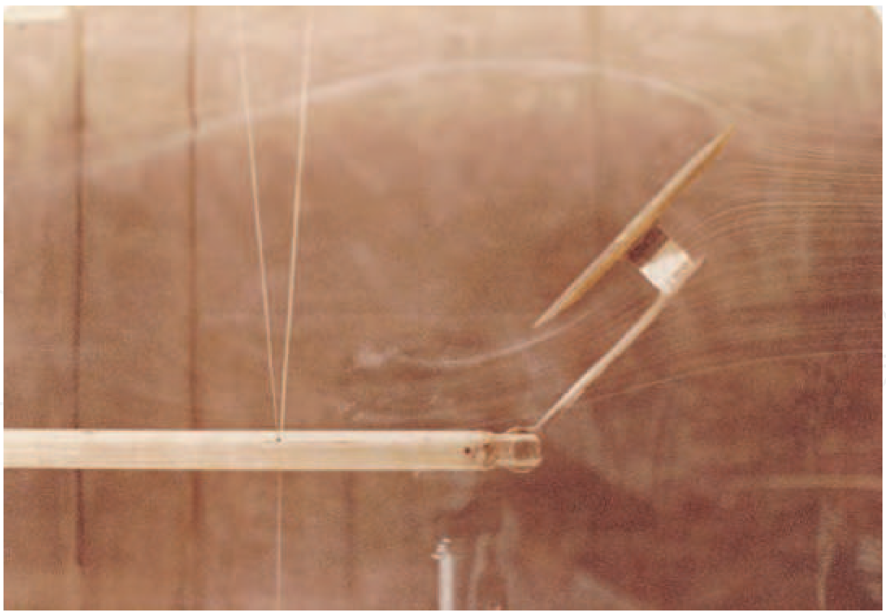


Fig. 11. Flow visualization using smoke wire technique α = 40°

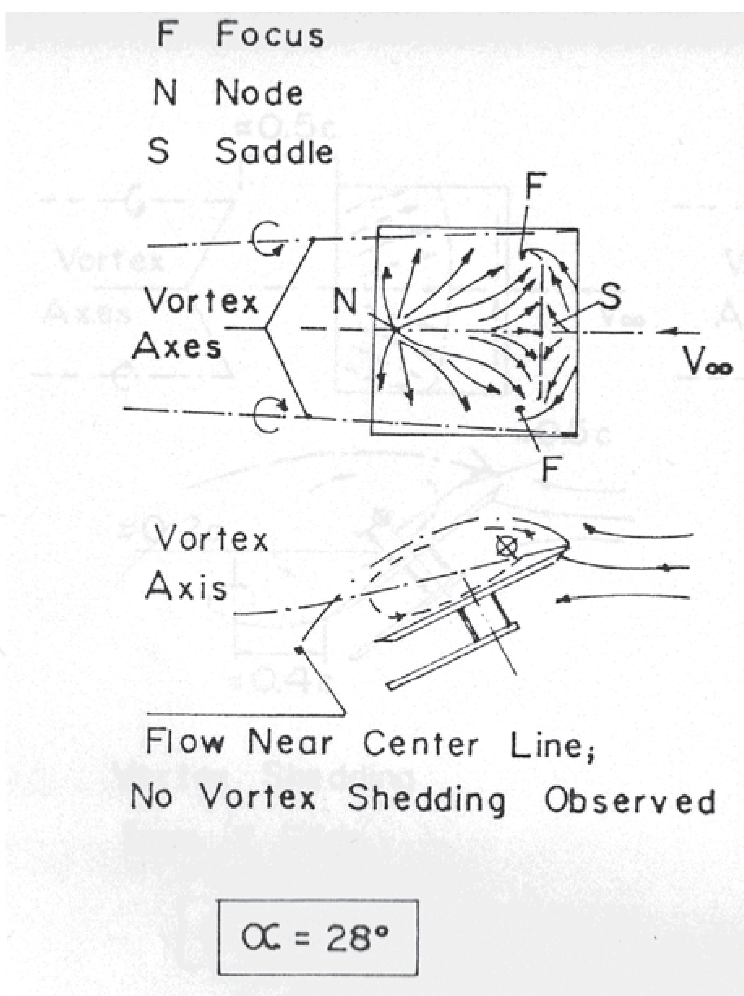


Fig. 12. Conjectured flow field on wake side of flat plate at sub critical incidence

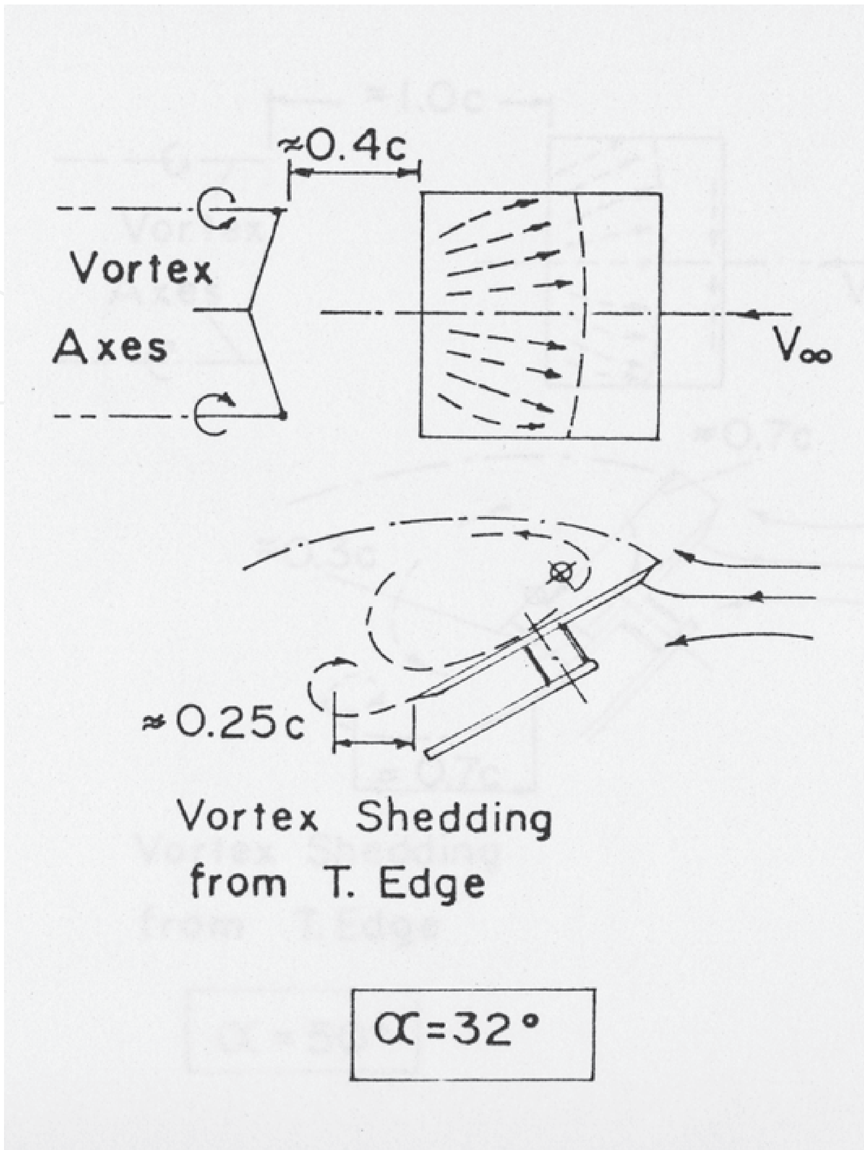


Fig. 13. Conjectured flow field on wake side of flat plate at super critical incidence

On the portion of the wing near the leading edge, on the suction side, heavy cross flows are induced which move to the side edges and bend into the stream direction. The axes of these side-edged vortices when traced reach the leading edge. The angle it makes is about half the angle of attack α which the plate makes with the stream direction. The core of the three dimensional bubble is near to the leading edge at a distance of about 0.25 C. There was no trailing edge vortex shedding observed for these incidences. The side-edge vortices extend downstream at least six to seven times chord. The diameter of these side edges vortices increases considerably with a little change in angle from α = 26.5° to α = 28°. The side-edge vortex core axis moves straight up to trailing edge when moving upstream, where it bends a little and again moves straight up to leading edge. From the outer wake flow pictures it is observed that the flow at the center seems to be just as big bubble trying to close about 0.1C to 0.2C from the trailing edge which is quite different from the angle α = 32° where the bubble closes well away from the trailing edge. Also the wake boundary is wavy for α = 28° where as for α = 32° it is quite sharp as seen in the Figs. 9 and 10

Fig. 14. Flow visualization on wake side using tuft probes.

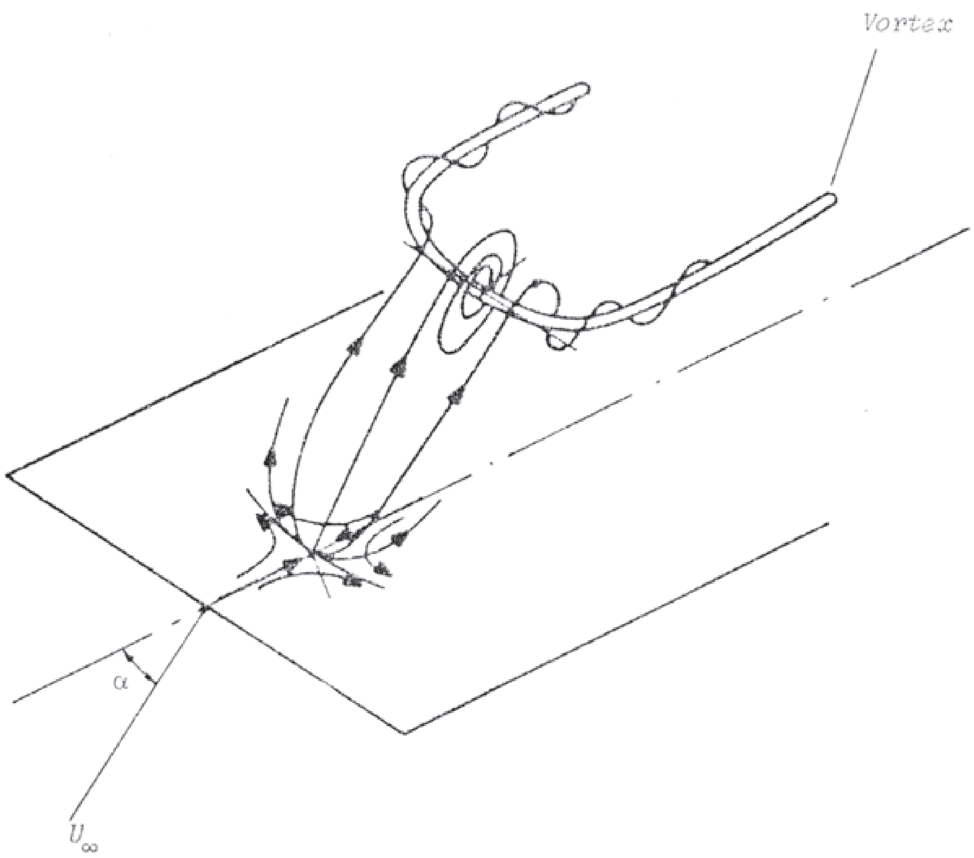


Fig. 15. Conjectured flow field on wake side of flat plate at sub critical incidence

The result of the variation flow visualization techniques have been used to construct the flow field as is shown in Figs12-13 and Fig.15 (“Flow visualization details”). This is what has been observed it is not an interpretation how the actual flow structure is. A first attempt has been made to get an idea of the flow field in the following way.

4.2 $\alpha \geq 32°$

For these incidences and higher up to $\alpha = 50$, it was observed that the wing centre flow is dominating the total span and the tip vortices are not present on the wing as shown in Fig.10, but appear further down the stream. The three dimensional bubble covers almost whole of the span with the appearance of trailing edge vortex shedding, and the flow is rotating inside this bubble. The flow near the plate surface is forward and spreading outward which is also noted from surface flow visualization pictures.

Trailing-edge vortex shedding and re-circulating flow was also observed by Calvert [9]. In the region near the leading edge on the suction side, the flow was observed as moving towards the plate centre from sides, and the flow which is moving forward is joining the main stream flow reaching from sides to form rotary motion like side edge vortices, the concentration of which is observed little downstream of the trailing edge. This distance increases gradually as the angle of incidence is increased. Also, it was found in the surface flow pictures that the two “eyes” had disappeared and with them the additional two vortices must have vanished there. For all these angles $\alpha \geq 32°$ trailing-edge vortex shedding was observed, and the frequency of vortex shedding was observed to increase as the angle of attack increases.

5. Conclusions

Flow visualization is considered an important tool to understand the nature of the flow field. Its proper utilization will provide reasonable information that will help in influencing flow characteristics. The above methods mentioned are not the only ways of understanding the flow but the results obtained using above methods highlight the usefulness of these flow visualization techniques.

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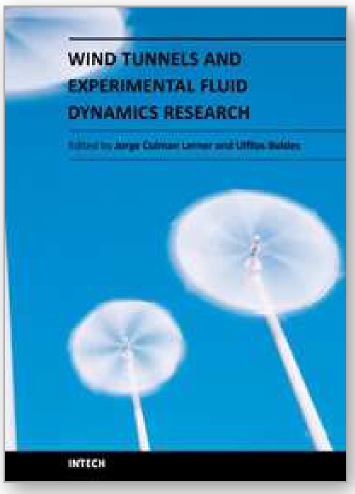

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The book â€œWind Tunnels and Experimental Fluid Dynamics Researchâ€ is comprised of 33 chapters divided in five sections. The first 12 chapters discuss wind tunnel facilities and experiments in incompressible flow, while the next seven chapters deal with building dynamics, flow control and fluid mechanics. Third section of the book is dedicated to chapters discussing aerodynamic field measurements and real full scale analysis (chapters 20-22). Chapters in the last two sections deal with turbulent structure analysis (chapters 23-25) and wind tunnels in compressible flow (chapters 26-33). Contributions from a large number of international experts make this publication a highly valuable resource in wind tunnels and fluid dynamics field of research.

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