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The Use of Dust Deposition as a Means of Flow Visualisation

By

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The Use of Dust Deposition as a means of Flow Visualisation

- By -

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SUMMARY

The use of dust deposition as a means of flow visualisation is compared with the volatile liquid method and the smoke filament method.

It is shown that the transition line indicated by the volatile liquid method occurs early in the transition region where the value of the skin friction is low. The transition line indicated by dust deposition, however, lies late in the transition region where the value of the skin friction is high. The use of a smoke filament as a method of flow visualisation is shown to be inaccurate as the filament promotes a premature transition.

A smoke generator is described which will produce a smoke of solid paraffin wax particles of 1 to 4 microns diameter. The smoke is produced in sufficient density to give visible wax deposits on the surfaces of an aerofoil mounted in a wind tunnel after a running time of only a few minutes.

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Replaces A.R.C.23,580.

1. Introduction

The deposition of dust particles from an airstream has frequently been observed to occur on the blades of wind tunnel and ventilating fans and on aerofoils mounted in wind tunnels. These deposits reveal various features of a flow pattern so that either the natural deposition of dust or the introduction into the flow of an artificially produced dust forms a useful technique of flow visualisation. The natural formation of dust deposits takes a considerable time but by introducing artificially produced dust into the airstream it is possible to observe the patterns after only a few minutes. Once formed, the dust deposit will remain visible for many days and is thus useful as a means of visualising the flow in a system which must be dismantled before the deposit can be observed.

Much research has been sponsored by the Safety in Mines Research Establishment into the removal of dust from airstreams and to explain the mechanism of deposition. E. G. Pereles in Ref. 1 and P. R. Owen in Ref. 2 have shown that the main factor controlling the deposition of dust from an airstream is the presence of turbulence in the flow. The eddy velocity given to the particles in the turbulent region of the flow is considered sufficient to carry the particles through the laminar sublayer to collide with the wall. E. G. Pereles has also shown that Brownian motion will only account for up to one-thousandth of the total amount of dust deposited on the wall, and that if the particles themselves carry a charge only those within a few diameters distance from the wall will be attracted to it by the formation of an image charge.

It is not certain why the particles stick to the walls. It may be that electrostatic attraction between the particle and the wall is an important relevant factor.

Dust deposition has been used as a means of flow visualisation at the Universities of Cambridge and Liverpool. At Cambridge University a duster shaken at the entry of a low speed wind tunnel caused a deposit to form on an aerofoil. This dust deposit showed the position of transition to turbulent flow, the existence of turbulence wedges downstream of surface protrusions and the path of the secondary flow vortex at the junction of the aerofoil with the wall. At Liverpool University M. M. Gibson[3] observed naturally occurring dust deposits on the four blades of a low speed wind tunnel. These deposits showed the presence of a large extent of laminar flow near the root of the fan blade.

In view of this, the present experiments were carried out to establish the relation between the dust deposits and the nature of the boundary-layer flow over the surface of an aerofoil. This work is at present being extended by the author by using dust deposition as a means of examining the boundary-layer flow over the blades of turbo machinery.

In the present report the dust deposit method of flow visualisation is compared with the smoke filament and the volatile liquid methods. For this comparison, the flow was studied over the suction surface of an aerofoil mounted in a wind tunnel at the two values of the Reynolds number, 3.8×10^5 and 5.5×10^5; the angle of attack being varied between $0°$ and $20°$.

2. The Artificial Production of Dust

Aerosols of sufficiently high particle concentration for experiments on the deposition of dust can be obtained by three methods: powdered dusts may be injected into an airstream, a solid of low melting point can be atomised while in the liquid state and a solid of low boiling point can be introduced into an airstream in the form of a vapour which subsequently condenses.

Talc and magnesium oxide can be obtained as fine dusts which are suitable for injection into an airstream. In both cases, however, the powder tends to coagulate into large heavy particles. Individual particles vary in magnitude from about 1.5 microns up to 5 microns and airborne groups of particles may occur with magnitudes of up to 30 microns.

The atomisation of molten paraffin wax produces spheres of 10 to 15 microns diameter. E. G. Pereles[1] compared the deposit on a wind tunnel wall of wax particles obtained by this method with the deposits of powdered coal of similar particle magnitude. The wax spheres were deposited as groups of many particles while the coal dust was deposited as single particles. It is thought that the wax spheres rolled along the surface until a collision with other spheres occurred and a large number of spheres became grouped together.

A particle generator in which a vapour is condensed to give small solid particles was designed by J. H. Preston and N. E. Sweeting at the National Physical Laboratory in 1943 (Ref. 4). In this generator paraffin wax was vaporised and the vapour was subsequently condensed by being mixed with a stream of cold air. The development of this solid particle smoke generator was abandoned as the particles were extremely flocculent and quickly blocked a pipe line of 1/4 in. diameter through which the smoke was to be conducted. Also on one occasion a vivid blue flash occurred in the condensing chamber of the generator, this being attributed to an electrostatic discharge.

The generator used in the present experiments was developed from a liquid paraffin smoke generator[4]. It is described in the Appendix and illustrated in Figs. 1 and 2. It will produce a dense white smoke of solid paraffin wax particles of magnitude 1 to 4 microns, a few particles up to 10 microns also occurring. The particle magnitude which occurred with the greatest frequency was about 1.6 microns*. No attempt was made to vary the particle magnitude although it is thought that this might be controlled by either altering the rate of flow of cold air into the condensing chamber of the smoke generator or by varying the diameter of the vaporiser nozzle.

The smoke was introduced into the airstream at the entry to the wind tunnel after being conducted there through neoprene tubing of 3/8 in. internal diameter. The length of the tubing was kept below 3 ft to avoid the occurrence of a blockage by deposition on the walls of the tube.

In the powdered dust method a large range of particle magnitudes may occur as the individual dust particles coagulate into groups before being injected into the airstream. This is overcome by the solid paraffin wax smoke particle method as individual particles are formed by condensation in an airstream and coagulation can only occur if the particles collide in the airstream. The particle magnitudes are thus more uniform when using in this latter method. However, once a particle has been deposited on the surface others tend to stick to it. The individually deposited particles then grow to give a deposit of groups which are larger than those particles existing in the airstream. These groups are smaller and more evenly distributed than the groups of wax spheres reported by E. G. Pereles as the particles do not roll along the surface.

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*<u>Measurement of the magnitude of paraffin wax particles</u>

The particles were deposited on a glass slide and the diameters of a number of particles were measured under a microscope of magnification 250.

The sample particles may have been larger than the airborne particles due to paraffin wax vapour condensing on the deposited particles causing them to grow.

3. Experimental Measurement of Transition

The aerofoil used in the experiments was section D* of the family of airscrew sections given in Ref. 5. The chord length of the aerofoil was 10 in. and its span was 16 in. It was mounted in a two-dimensional low speed wind tunnel and the experiments were carried out at two flow velocities giving values of the Reynolds number of 3.8×10^5 and 5.5×10^5.

The positions of transition to turbulent boundary-layer flow and of separation of the boundary layer on the suction surface of the aerofoil were observed at the two values of Reynolds number for angles of attack varying from 0° to 20° in 4° steps. Two methods of boundary-layer visualisation were used to compare with the solid particle method.

3.1 The volatile liquid method[6]

The surface of the aerofoil was smeared with a thin film of paraffin by wiping first with a wad of cotton wool soaked in paraffin and then with dry cotton wool to remove any excess liquid. The film evaporated more rapidly under a turbulent boundary layer than it did under either a laminar boundary layer or a separation bubble. Additionally it was found to evaporate more rapidly in that part of the laminar boundary-layer flow region near to the leading edge where the skin friction is high (Fig. 3).

The boundary of the leading-edge region of rapid evaporation was indistinct. There was, however, a distinct boundary where the transition occurred and the turbulent flow caused rapid evaporation. The resultant dry region gradually gave way to a liquid film as the evaporation mechanism was less efficient downstream of the transition (Fig. 4).

Separation of the boundary layer was shown by small waves of the liquid being swept towards the leading edge by the reversal of the flow direction. Also, at angles of attack greater than 4° a wavelet was observed just upstream of the transition indicating the presence of a separation bubble with turbulent reattachment.

To aid observation of the evaporation phenomena and particularly the wavelets at separation a beam of light was reflected from the surface. As the surface was of matt black finish the reflection of the light was poor from the dry regions whereas the wet regions made a good reflecting surface.

The indication of a laminar boundary layer was confirmed by adding small rough protrusions to the surface and observing the resulting transition wedges. These wedges showed up as a central wedge of rapid evaporation edged by two filaments of slow evaporation and they were clearly visible (Fig. 5).

3.2 The liquid paraffin smoke filament method[4]

Two holes of 1/10 in. diameter were drilled in the suction surface of the aerofoil at chordwise distances of 3/4 in. and 1 in. from the leading edge. The smoke was passed through the hollow frame of the aerofoil and was emitted at the two holes. The smoke filaments were observed against a black background, illuminated by a wedge of light at grazing incidence to the aerofoil surface.

The smoke filament was not easily observed at the separation of the boundary layer as it became dispersed in the turbulent boundary layer which preceded separation.

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*This section has been used in the design of the fans for three wind tunnels at the University of Liverpool.

The effect of the emission of a smoke filament upon the flow in the boundary layer was examined by allowing air to flow from one of the smoke holes and observing the effect upon the transition by using the volatile liquid method. Except when the amount of air flowing through the hole was almost negligible the air filament was observed to cause a premature transition. At such times a transition wedge was observed in the laminar flow region. Thus observations using a smoke filament can show premature transition even when the filament is reduced to an amount at which the smoke is just visible.

3.3 The dust deposit method

Paraffin wax smoke was introduced into the airflow close to the entry gauze of the wind tunnel. The smoke was allowed to pass through the gauze into the tunnel and after a time of five to seven minutes a distinct deposit of wax particles was formed on the aerofoil section. The smoke tended to concentrate in one area of the stream as it entered the tunnel at one point on the entry gauze. This resulted in the formation of a heavy paraffin wax deposit over part of the aerofoil and a light deposit over the remainder (Figs. 6, 7). Where a dense deposit was formed at the leading-edge transition to turbulent boundary-layer flow occurred prematurely by up to one-tenth of the chord length.

The distances of the transition from the leading edge were measured with a light deposit of wax which was only just visible. At the position of separation of the boundary layer a decrease in the density of the wax deposit occurred. This was only visible with dense deposits.

At the leading edge stagnation line there was an almost clear region containing a few small individual particles. Either side of this region on the upper and lower surfaces there were large particle growths where particles have become grouped together by collisions. This stagnation region pattern may be due to the rate of deposition of the wax being influenced by the value of the skin friction. The boundary layer is very thin just downstream of the leading edge and the skin friction is correspondingly high (Fig. 8).

3.4 The relation between the observed transition line and the transition region

The extent of the transition region of the boundary-layer flow over the suction surface of the aerofoil was obtained for a flow Reynolds number of 5.5×10^5 with the aerofoil at an angle of attack of 4°. To do that a 'Preston' tube of external diameter 0.025 in. and internal diameter 0.010 in. was set against the surface of the aerofoil and the total pressure at different distances from the leading edge was measured with reference to the static pressure measured at the wall of the working section 22.5 in. upstream of the leading edge of the aerofoil (Fig. 9).

Fig. 10 shows the chordwise distribution of the total pressure. On this graph are shown the positions of the transition determined by the volatile liquid and dust deposition methods. The shaded areas of the graph represent the range of the variation in the observed position of transition over the aerofoil. The single line in each shaded area represents the observed positions of transition along the line of the total pressure traverse.

4. Discussion of the Results

The results are shown in the graphs in which the position of the transition is plotted as a fraction of the chord length against the variation in the angle of attack (Fig. 11) and likewise for the position of separation (Fig. 12).

The measurements of the transition position show good agreement between the volatile liquid method and the dust deposit method. The smoke filament method shows transition to occur closer to the leading edge, the difference tending to increase with angle of attack. This is thought to be due, as previously suggested, to the disturbance of the boundary layer caused by the smokestream being ejected from a surface hole. However, this effect occurred in a region of adverse pressure gradient where the smoke filament is thought to be particularly sensitive to disturbances, and the error of this method may be negligible in favourable flow conditions. This view is supported by the increase in the observed error with the angle of attack.

The volatile liquid method shows transition to occur slightly nearer the leading edge than does the dust deposit method. This is due to the volatile liquid evaporating rapidly downstream from a point early in the transition region whereas the dust deposits do not occur until the local value of the skin friction is high, at a point near to the downstream end of the transition region (Fig. 10).

The liquid film does not appear to interfere with the flow and, provided that the dust is only just visible, the dust deposits also appear to have negligible effect on the boundary layer.

The measurements of the position of separation of the boundary layer show more scatter than do the transition measurements. This is thought to be due to the difficulty of determining the position of separation by these methods.

5. Conclusion

Dust deposition may be used to give an acceptable value for the position of transition to turbulent boundary-layer flow when the deposit is light and only just visible. This value agrees closely with the value obtained by the volatile liquid method but the smoke filament method was found to be inaccurate. The volatile liquid method shows a transition line early in the transition region and the dust deposit method gives a position close to the end of the transition region.

There was some scatter in the values obtained for the position of separation of the boundary layer and no means existed to assess which method is the most accurate. Separation was most easily observed by the volatile liquid method due to the ripples caused by the reversal of the flow after separation.

Both the volatile liquid method and the dust deposition method give a picture of the flow over the whole aerofoil and show the existence of turbulent transition wedges and vortices. The smoke filament only gives a picture of the flow along the streamline at which it is admitted and does not show the existence of turbulence wedges or vortices unless they occur on that filament line. It may then be difficult to distinguish between wedge transition and the normal transition line.

6. Suggestions for Further Work

The reason for the dust sticking to the surfaces after first being brought there by the flow phenomena has not been established. This may be due to electrostatic attraction and experiments on the magnitude of electrostatic charges existing on the dust particles and on the surfaces may lead to an explanation.

The solid particle smoke generator may provide a means of simulating icing conditions in wind tunnels.

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7. Notation

c	chord length of the aerofoil
P	dynamic pressure
p_s	static pressure
x	chordwise distance from the leading edge
U	free-stream velocity in the working section of the wind tunnel
ρ	density of air

Acknowledgements

I am indebted to Prof. J. H. Preston for suggesting these experiments and to the staff of the Department of Fluid Mechanics at the University of Liverpool for their invaluable assistance.

References

No.	Author(s)	Title, etc.
1	E. G. Pereles	The theory of dust deposition from a turbulent airstream by several mechanisms. Safety in Mines Research Establishment research report No.144. February, 1958.
2	P. R. Owen	Dust deposition from a turbulent airstream. Aerodynamic capture of particles. Pergamon Press, London. 1960
3	M. M. Gibson	The design of a wind tunnel for boundary-layer research. Ph.D.Thesis. Department of Fluid Mechanics, University of Liverpool. 1960.
4	J. H. Preston and N. E. Sweeting	An improved smoke generator for use in the visualisation of airflow, particularly boundary-layer flow at high Reynolds numbers. A.R.C. R. & M.2023. October, 1943.
5	A. Fage, C. N. H. Lock, R. G. Howard and H. Bateman	Experiments with a family of airscrews including the effect of tractor and pusher bodies. A.R.C. R. & M.829. November, 1922.
6	R. C. Pankhurst and D. W. Holder	Wind tunnel technique. Pitman, London. 1952.

APPENDIX/

APPENDIX

The Paraffin Wax Smoke Generator
(shown in Fig. 1)

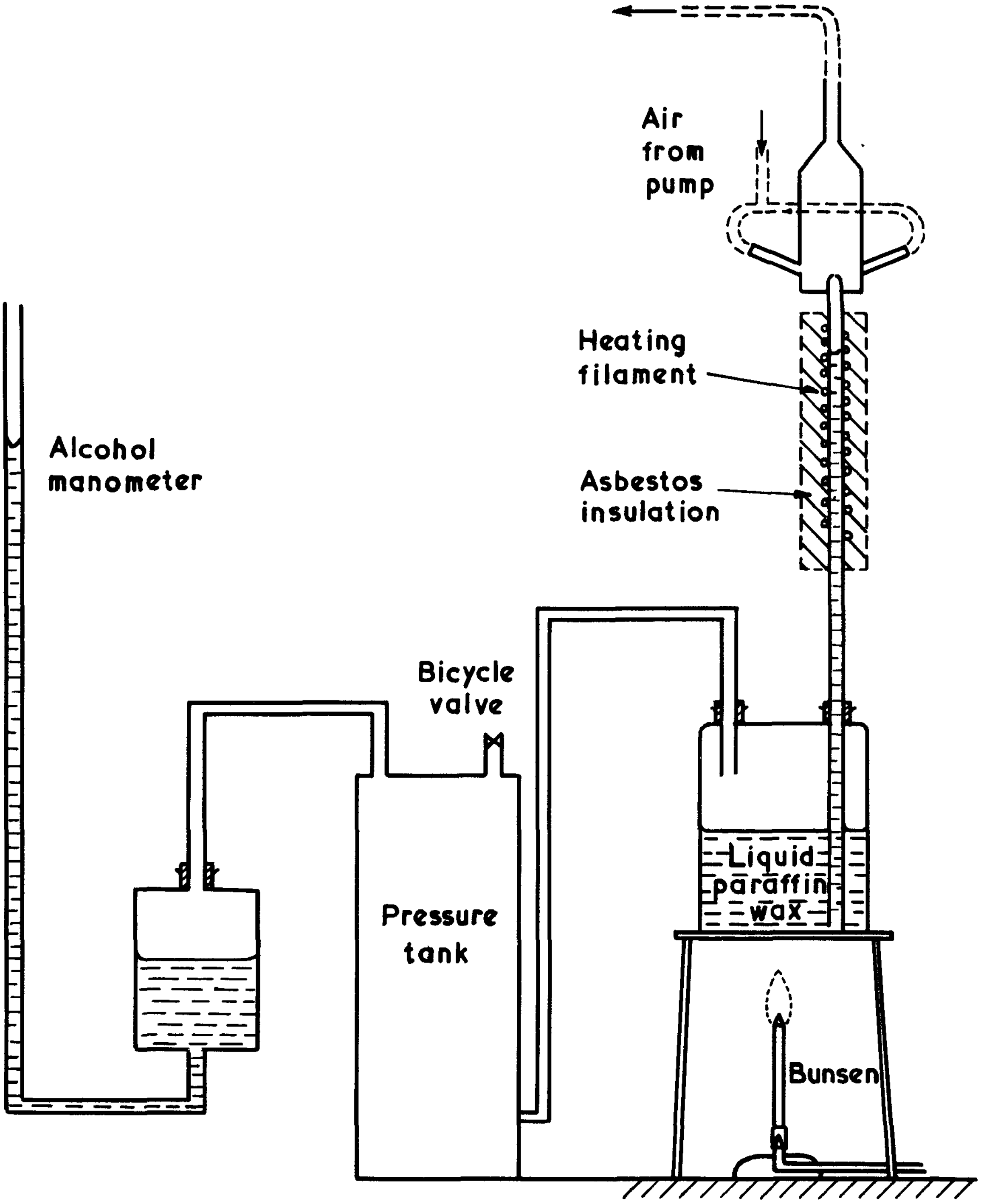
A reservoir of molten paraffin wax has the vertical tube of the vaporiser immersed in it. A pressure is applied to the reservoir which is sufficient to maintain the flow of the wax through the vaporiser with the liquid surface approximately level with the top of the heating filament. The paraffin wax vapour is mixed with cold air in the condensing chamber causing the vapour to condense into minute solid particles in a similar way to that by which snowflakes are formed. The particles are carried in the airflow and have the appearance of a dense white smoke.

Further constructional details of the generator are tabulated as follows:

Heating filament:	
'Vacrom' wire	
diameter	0.008 in.
length	20 ft
resistance	180 ohms
Heating potential:	
starting	205 volts
running	150-175 volts
Pressure applied to the reservoir:	
starting	30 cm of alcohol above atmospheric pressure
running	60-70 cm of alcohol above atmospheric pressure
Paraffin wax:	
melting point	38-56°C
boiling point	350-430°C

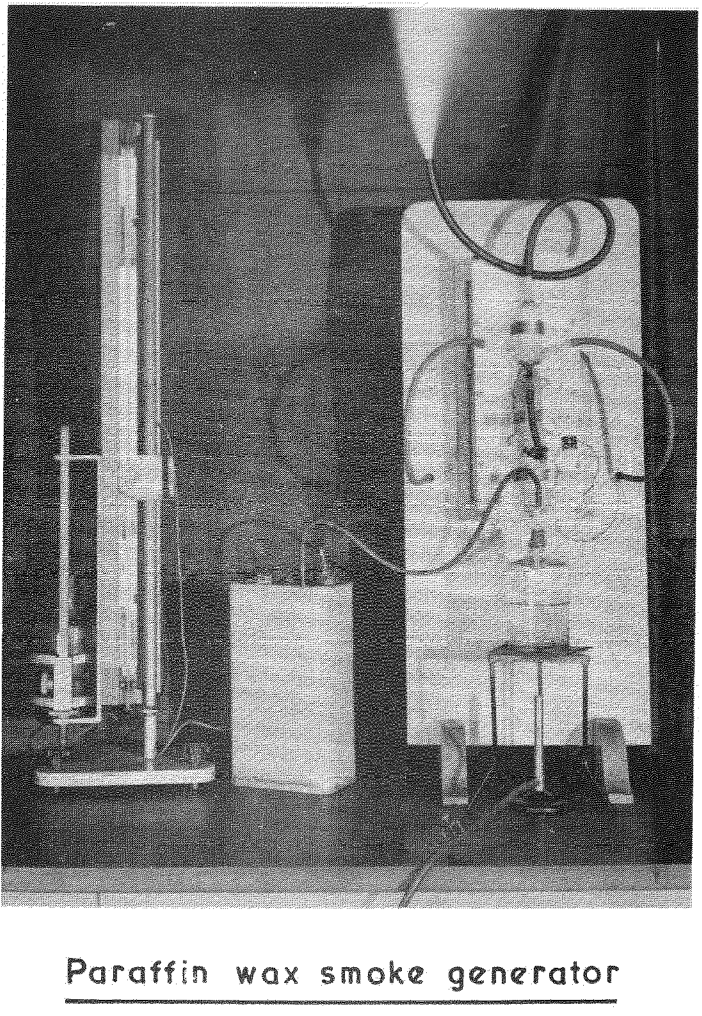
'Pyrex' glassware was used throughout the apparatus.

FIG. 1



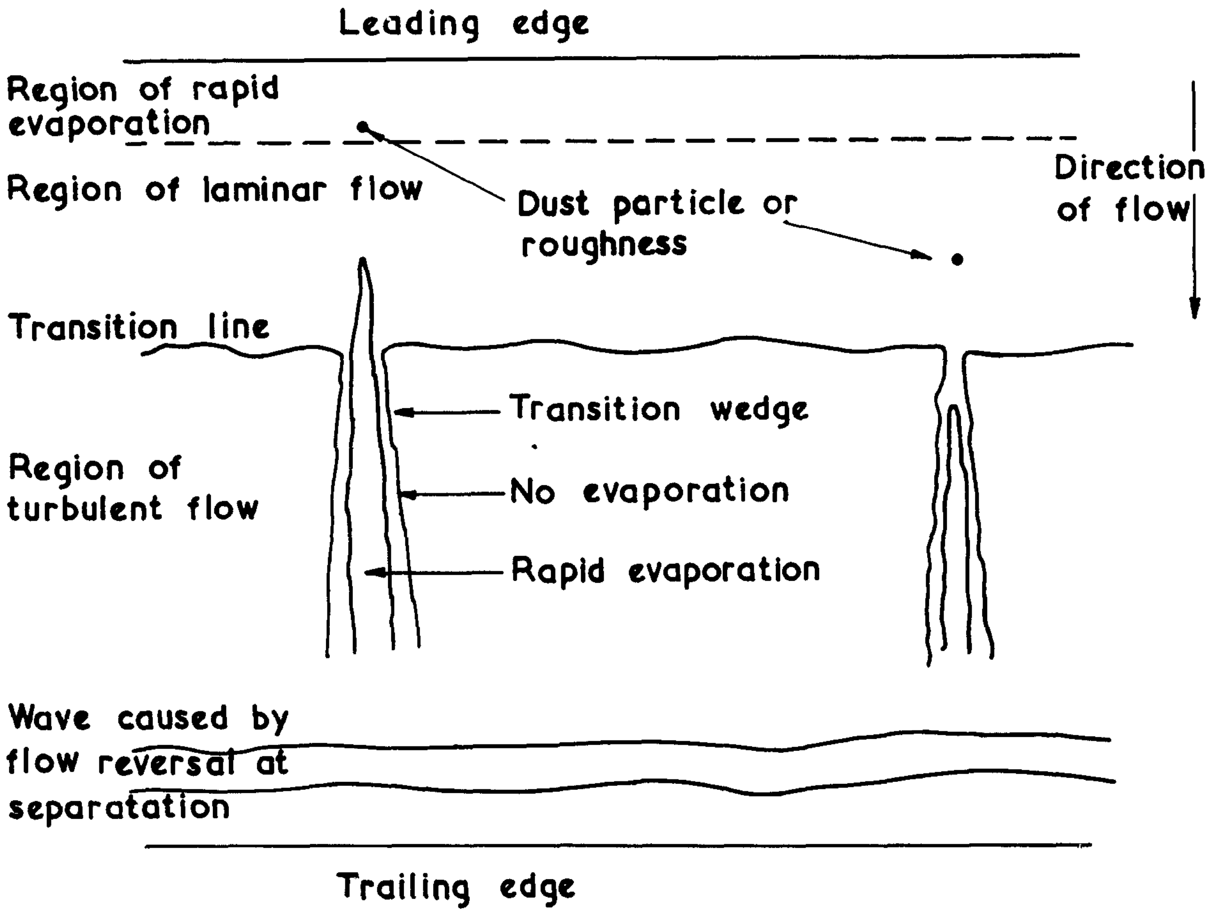
Paraffin-wax smoke generator

FIG. 2



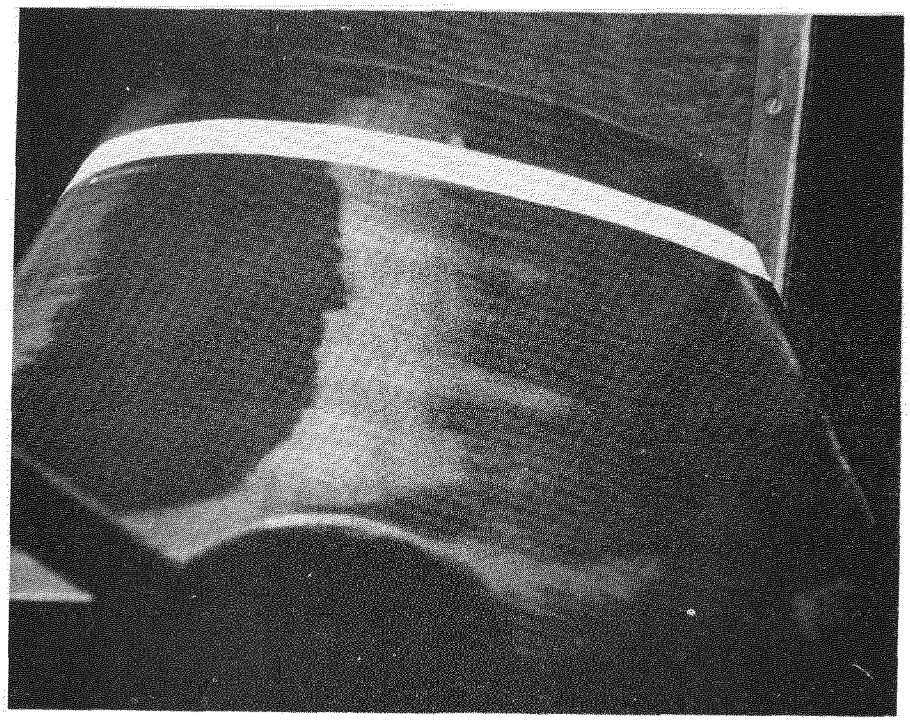
Paraffin wax smoke generator

FIG. 3.



The formation of turbulence wedges on the suction surface of the aerofoil shown by volatile-liquid method of flow visualisation.

FIG. 4

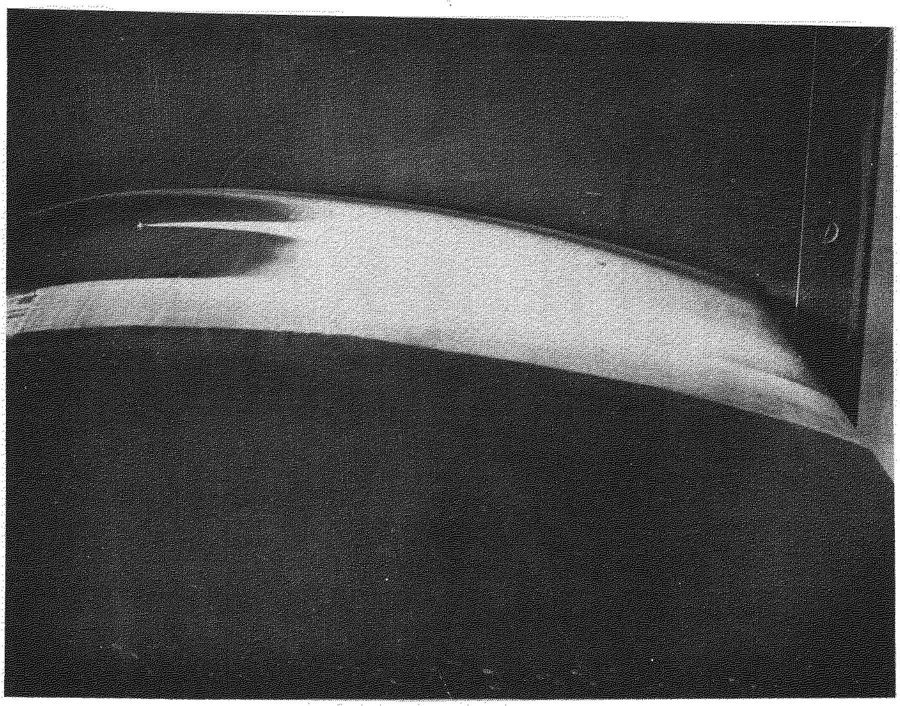


Transition indicated by the volatile liquid method

FIG. 5

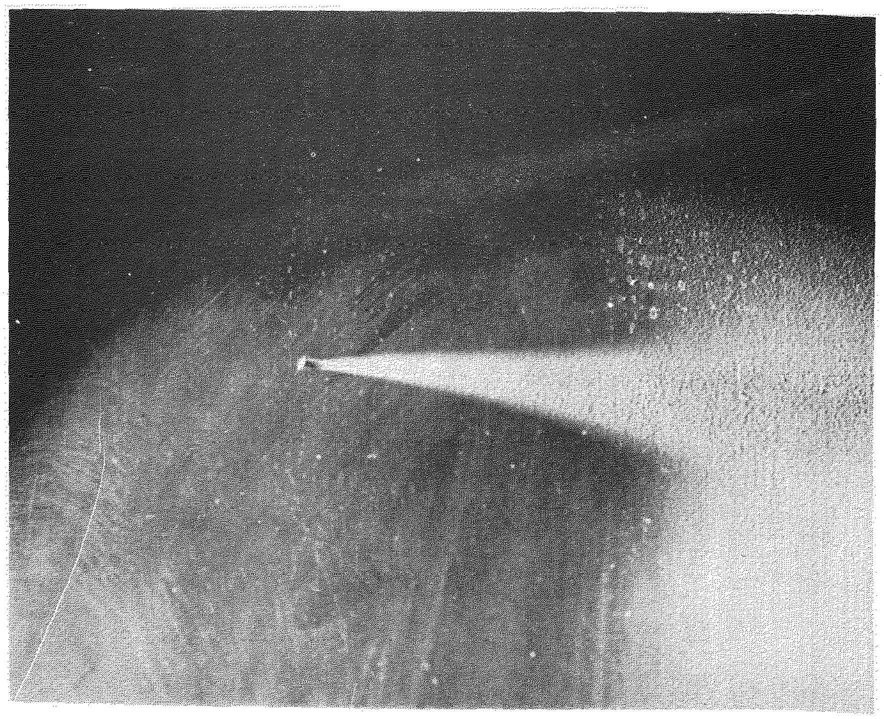
Transition indicated by the volatile liquid method showing transition wedges

FIG. 6



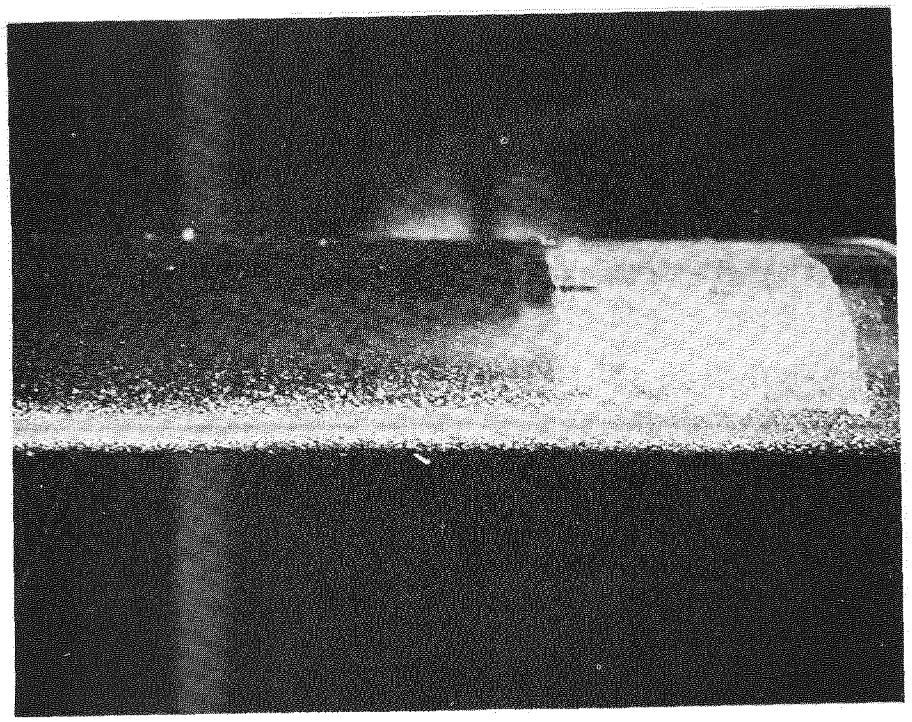
Transition indicated by a localised paraffin wax deposit

FIG. 7



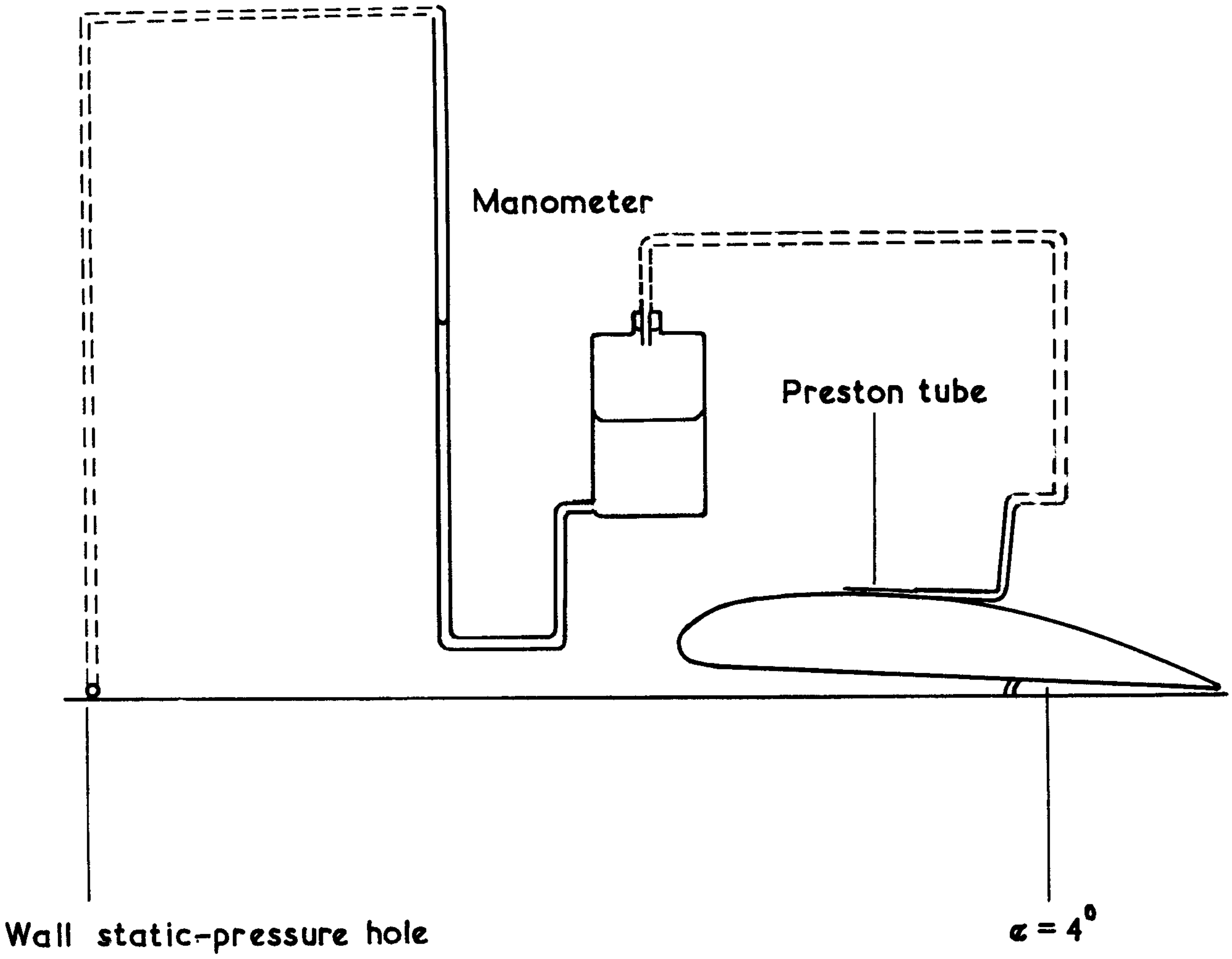
Transition wedge indicated by a parafin wax deposit

FIG. 8



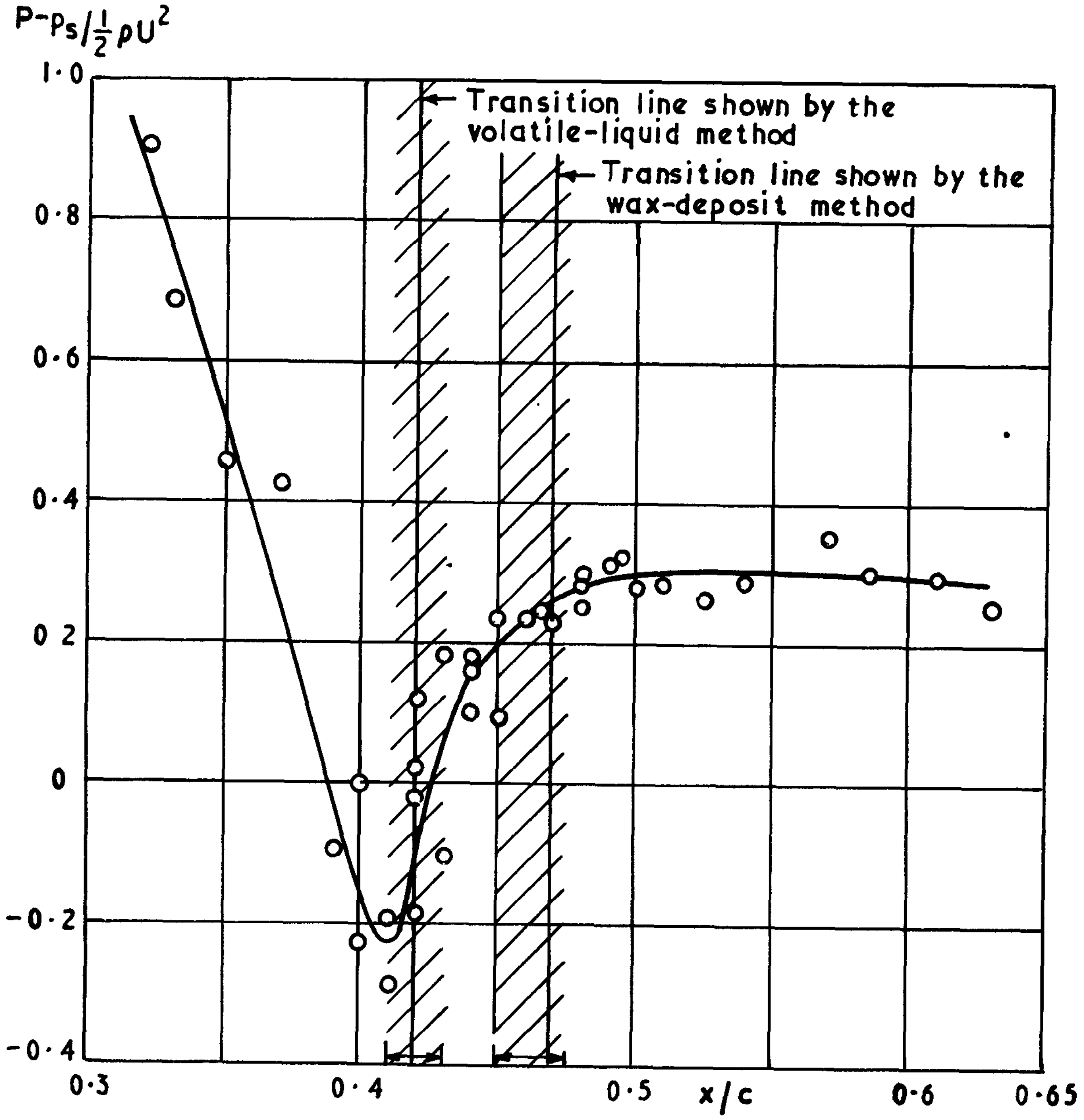
Leading edge paraffin wax deposit

FIG. 9.



Total-pressure measurement on the suction surface of the aerofoil

FIG. 10



Angle of attack = 4°

Flow Reynolds number = $5 \cdot 5 \times 10^5$

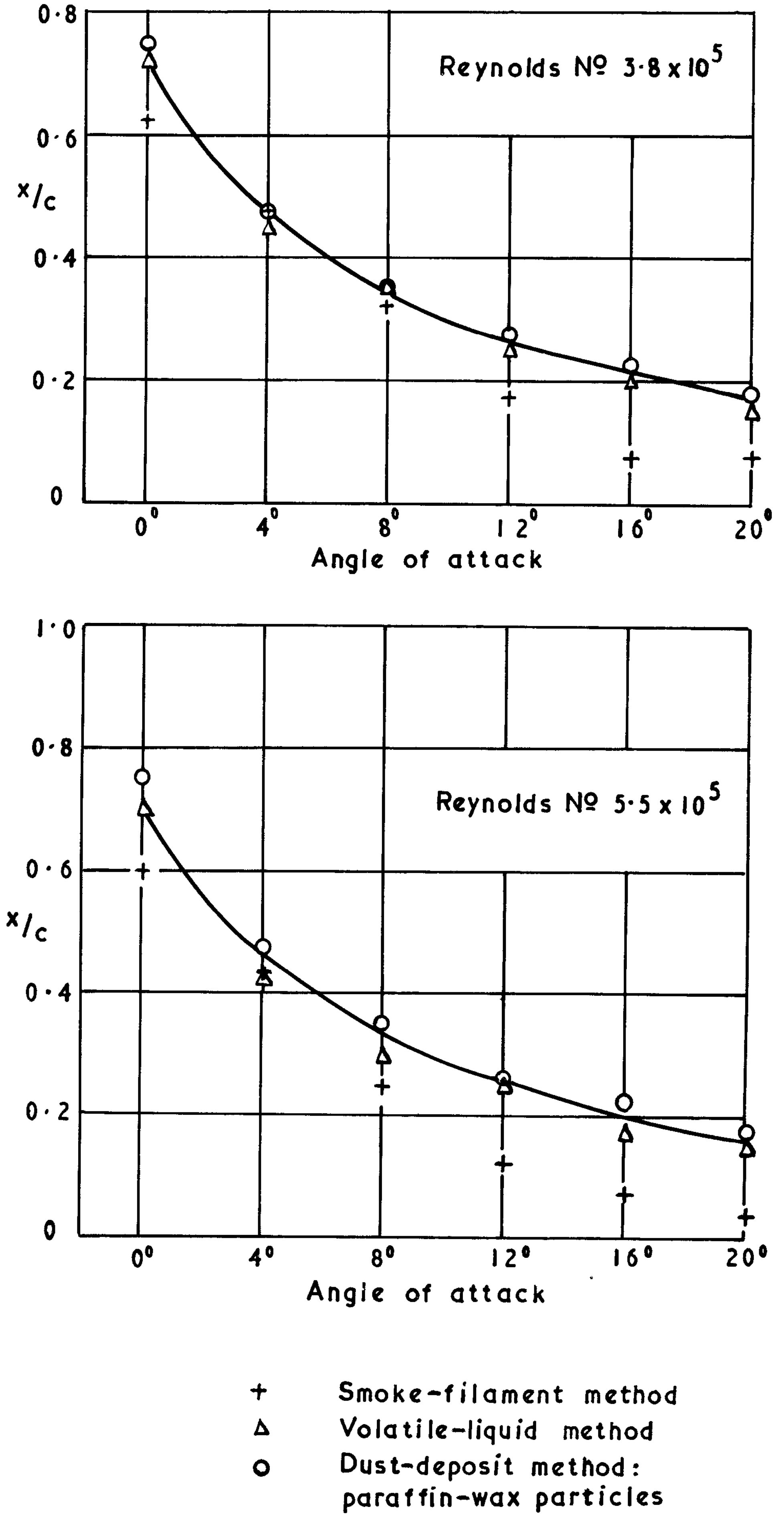
P is the total pressure measured at the surface by a pitot tube of 0·025 inches diameter

p_s is the wall static pressure

U is the free-stream velocity

The distribution of total pressure on the suction surface of the aerofoil.

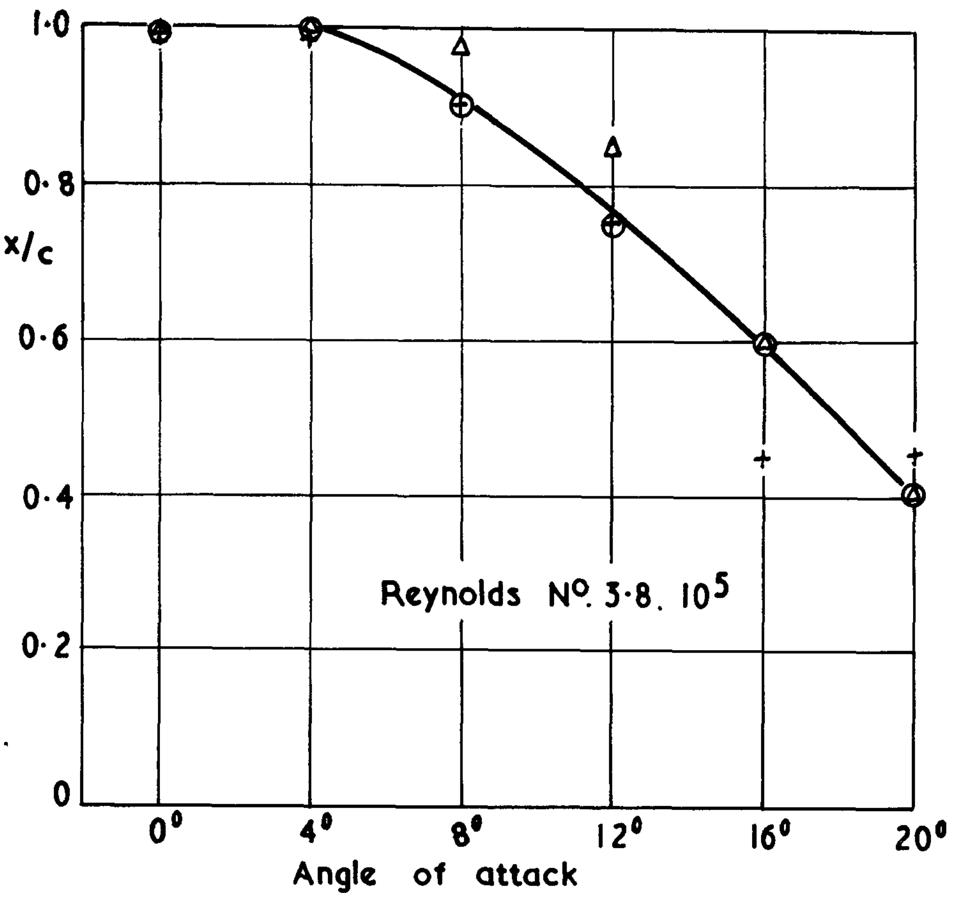
FIG. 11

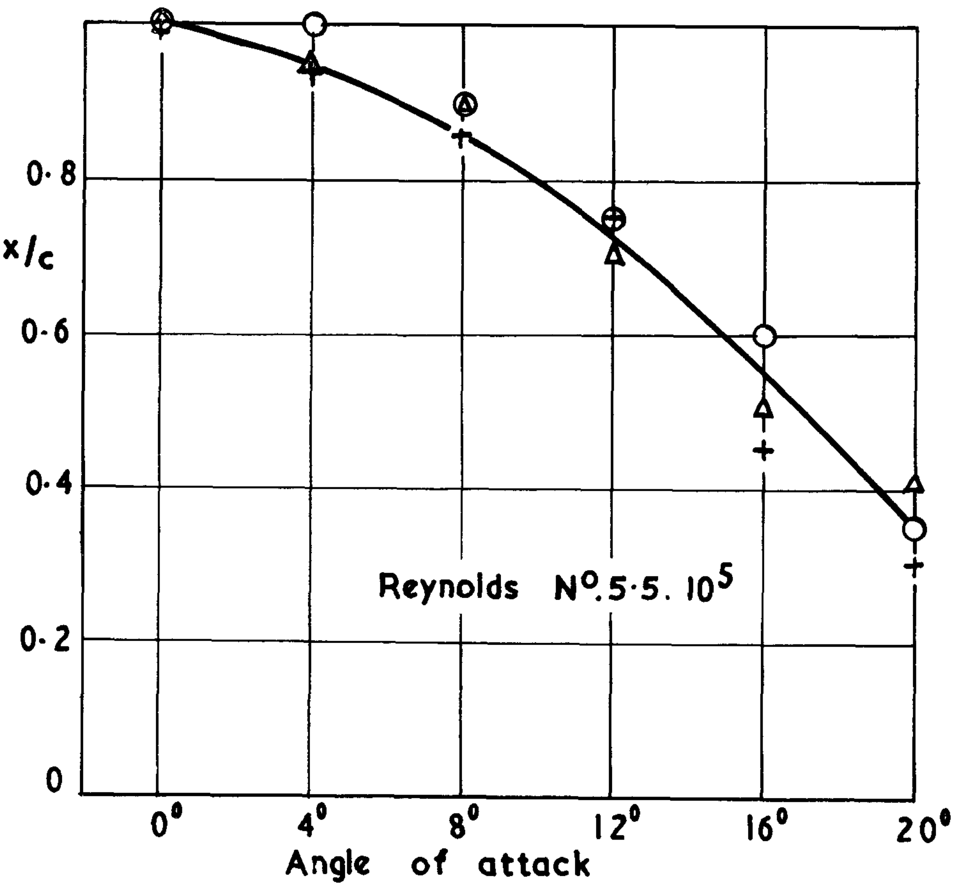


x/c is the ratio of the distance from the leading edge to the chord length.

The position of transition to turbulent boundary-layer flow on the suction surface of the aerofoil.

FIG.12.





The position of separation of the boundary layer on the suction surface of the aerofoil.

X Smoke-filament method.

Δ Volatile-liquid method.

O Dust-deposite method = paraffin-wax particles.

x/c is the ratio of the distance from the leading edge to the chord length of the aerofoil.

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