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A Preliminary Note on a Modified Type of Air Jet for Boundary Layer Control

by

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A Preliminary Note on a Modified Type of Air Jet for Boundary-Layer Control

- By -
R. A. Wallis, M.Eng.,
of the Department of Supply, Australia*

14th May, 1956

SUMMARY

An attempt has been made to develop a type of air jet which is capable of producing persistent vorticity for the purpose of delaying turbulent separation and, in particular, shock induced separation. Experiments with circular jets, suitably pitched and inclined at an angle to the surface in the cross flow direction, show considerable promise.

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1. List of Symbols Used

c	Aerofoil chord
C_Q	flow coefficient $\left(\dfrac{Q}{U_o c}\right)$
Q	air jet flow per ft of aerofoil span; cusecs at atmospheric pressure
u	velocity in boundary layer
U	velocity at edge of boundary layer
U_s	a velocity in the boundary layer as measured by a surface total head tube
U_o	velocity upstream of model
x	distance along chord from leading edge
y	distance normal to aerofoil surface at any point
α	aerofoil incidence

2. Introduction

With the use of discrete circular air jets, a measure of turbulent boundary-layer control has been achieved at low speeds on two-dimensional and finite wings, e.g., see References 1 to 3.

The possibility of developing air jets as a method of delaying the onset of shock-induced separation was mentioned in Ref.1. Some preliminary tests in the high speed tunnel at A.R.L., Melbourne, and a study of recent experimental data, however, suggest that air jets issuing normal to the surface might be relatively ineffective against this type of separation. Reasons for this assumption are now given.

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*On temporary service in the Aerodynamics Division, N.P.L.

When an air jet issues into a stream normal to the surface, two counter rotating vortices are induced, one on each spanwise edge of the jet. On the basis of experimental data, it is believed that these vortices play a major part in delaying turbulent separation. Since this vorticity is relatively weak, however, and does not persist in a discrete form for any appreciable distance downstream of the jet, the maximum improvement can only be obtained when the jets are carefully located in the adverse pressure gradient region. Upstream of shock waves the gradients are often favourable with the usual steep pressure rise occurring at the shock. Since the shock wave moves, with incidence and Mach number, over a large extent of the chord it is unlikely that air jets normal to the surface can be considered practical. This is due to the difficulty in locating air jets so that they meet the above requirements for optimum operation over the whole range of shock wave movement.

At this juncture it was decided to develop a type of air jet capable of producing a persistent type of vorticity similar to that associated with vane type vortex generators. This tacitly implies that the jet momentum must be used in a more direct manner than previously, that is, it must be introduced straight into the secondary motion. Such a device is likely to be more efficient and less sensitive as regards its location relative to the critical flow region.

This work is the preliminary part of a programme being carried out at W.P.I. for the purpose of studying the effect of air jets on shock-induced separation phenomena.

3. Scope of Tests

The scope of the present work is very limited as the experiments were designed mainly to provide a guide to the type of jet most suitable for further development.

An existing 12 in. chord, 12% thick, low drag type of two-dimensional aerofoil, was used for these tests in the low speed 1 ft × 1 ft wind tunnel. Two different incidences were investigated, namely 5° and 8°, in order to determine the influence of pressure gradient. With the exception of the smoke tests, all work was carried out at a speed of 80 ft/sec $(R \approx 0.5 \times 10^6)$.

The tests included flow visualization, surface tube measurements, and the experimental determination of selected boundary-layer profiles; no attempt was made to study, in detail, the type of vorticity present.

4. Types of Air Jet Used

Three types of jet, involving three general principles, were studied, namely:-

(a) Circular jets normal to the surface, which produce secondary flows by means of induced effects.

(b) Plane jets issuing normal to the surface through finite slits and arranged so that the long axis of each slit is at a moderate incidence to the general flow direction. This type of jet was suggested some time ago by colleagues in Australia.

(c) Circular jets inclined at 45° to the aerofoil surface in the spanwise direction but with no streamwise component. This configuration was based on the simple minded concept of introducing jet momentum directly into the cross flow direction.

> The angle chosen, namely 45°, provides a strong cross flow component together with an appreciable normal component to ensure penetration of the boundary layer. These tests should be interpreted as providing a check on the basic principles involved and not necessarily as defining the optimum configuration of jet.

No attempt was made to develop optimum arrangements although the configuations chosen were influenced by previous experience with vortex producing devices.

5. Experimental Details

Preliminary experiments disclosed that the test aerofoil was of the nose stalling variety and hence not suitable for providing a direct check on the effect of the various devices on turbulent separation from the trailing edge. However, since the tests were designed for the prime purpose of providing data regarding the general nature of the flow downstream of the devices, this feature was not considered to be important.

In addition to the jet configurations described in the previous Section, vane type vortex generators were included in order to form a basis of comparison for assessing the persistency of the vortices introduced by the air jets.

Since the tests were intended to be largely comparative, all arrangements were studied simultaneously by locating them at intervals along the span at the 25% chord station (see Fig.1). Only co-rotating configurations were tried as these had been shown to be the most successful in previous experiments with vane type generators[4]. The 45° inclined holes, metal vanes and air "vanes" were arranged in pairs with a "neutral" region between them; near each end of the aerofoil a jet, normal to the surface, was provided.

The slits were made $\frac{3}{8}$ in. long and $\frac{1}{32}$ in. wide and, in order to provide an approximately equal discharge area, the circular holes were formed with a 0.120 in. diameter drill. The vanes were of $\frac{1}{2}$ in. chord and $\frac{1}{8}$ in. span. A pitch of $\frac{3}{4}$ in. was arbitrarily chosen for the pairs, and the vanes and slits were given an incidence of 20°.

6. Results

6.1 Flow Visualization

Smoke introduced into the air supplying the jets demonstrated the existence of vortices for the cases of the air "vanes" and the inclined holes and, in addition, provided a rough measure of their field of influence. In general, the vortices showed no tendency to coalesce or leave the surface. The main body of the circular jets, issuing normal to the surface, was somewhat more removed from the surface in the vicinity of the trailing edge than in the cases just mentioned.

A mixture of titanium oxide and paraffin was applied to the surface after which the tunnel was run up to speed. Figs. 1(a) and 1(b) depict, for an incidence of 5°, the initial and final stages respectively in the development of the surface patterns. The first is an excellent demonstration of the regions of high and low surface velocities whilst the second illustrates the detailed flow pattern.

Except for differences in detail, the air "vanes" and the inclined jets produce one main, strong and persistent vortex per jet similar to that which trails from a single metal vane. It will be noticed, however, that the jets normal to the surface appear to have, in comparison, a relatively minor effect on the flow.

6.2/

6.2 Surface Tube Explorations

Since vortex generators transfer high energy air from just outside the boundary layer to regions near the surface, a surface total head tube might be expected to provide a measure of the effectiveness of this transfer mechanism. Measurements with such a tube were made at 87.5% chord, which was sufficiently far downstream to provide a check on the vortex persistency.

A preliminary spanwise traverse at this station indicated a large variation in total head but showed the static pressure to be substantially constant.

Results are given in Figs. 2 and 3 for incidences of 5° and 8°; the chordwise velocity distributions for these incidences are given in Fig.4. On comparing the results for the inclined jets and air "vanes" with those for the metal vanes, it will be seen that, in general, the overall effect is similar. For jets normal to the surface, the increase of velocity is very small.

At this point, a decision was made in favour of the inclined jets as they are simple and have a relatively high effectiveness. This does not mean that the air "vanes" and normal jets are necessarily inferior to inclined jets in all applications. However, from the viewpoint of persistency, which is the major consideration here, the inclined jets appear to give the best results.

6.3 Boundary-Layer Traverses

Boundary-layer traverses have been made at selected positions mainly for the purpose of determining whether the surface tube measurements are a valid basis for comparison. The obvious spanwise stations for such experiments are the peaks "C" and "F" and the troughs "B" and "E", (see Figs. 2 and 3); the results are presented in Figs. 5 to 8. For the cases investigated, it does appear that the surface tube is a reliable guide to the effectiveness of the devices. A traverse taken between "B" and "C", for $\alpha = 5^\circ$, gave a profile which possessed features intermediate between those of these two stations. Additional observations have been made in Section 6.5.

The relative improvements are greatest for the higher incidence of 8° and suggest that inclined jets will prove successful in delaying turbulent separation.

6.4 Effect of Flow Quantity

It will be noticed in Figs. 2 and 3 that the effectiveness of the inclined jets increases with flow quantity. This feature was investigated with the surface total head tube, the results of which are given in Figs.9 and 10. As might be expected, the slope of the lines becomes smaller as the flow quantity is increased. The value of C_Q at which maximum effectiveness is likely to be reached is not unreasonable from a practical point of view. These values of C_Q were not obtained by direct measurement but calculated from the static pressure difference between the box pressure and the aerofoil surface after suitable assumptions, based on previous work, had been made for the discharge coefficients of the holes.

6.5 Other Observations

Whilst too much speculation on the limited data presented would be unwise, it is felt some comments are in order.

Firstly,/

Firstly, although Figs. 1 to 3 suggest a marked similarity between the effects of the inclined jets and the metal vanes, Figs. 5 to 8 show a significant difference. In Figs. 5 and 7, the profile for "C" resembles a normal turbulent profile more closely than does the profile for "F"; preliminary yaw traverses at these stations showed a greater cross flow* in the boundary layer downstream of the vanes. The profiles in the trough "B" for the inclined jets (Figs. 6 and 8) indicate a relatively thick boundary layer although the momentum deficiency in the outer half is very small.

Secondly, there is a region of low velocity air on the left hand side of each pair of inclined jets, metal vanes or air "vanes" (see Figs. 2 and 3). This consists of "tired" air which is swept in this direction by the vortices and accumulates there in the absence of an adjacent vortex to sweep it away towards the free stream. These features are illustrated in Figs. 1(a) and 1(b); in the former, the initial accumulation of low velocity air adjoining the highly scrubbed regions is apparent, whilst, in the latter, heavy deposits of titanium oxide are visible in the regions corresponding to the spanwise locations "G", "H" and "J" shown on Fig.2. The conditions existing at these points do not normally arise in practice but the feature illustrates the function of the adjacent vortex in clearing away the low energy air swept into its sphere of influence. The boundary-layer profiles in the troughs "B" and "E" are a function of the interaction of one vortex with its neighbour and hence may be expected to exhibit appreciable differences with changes in pitch and configuration.

Lastly, an inspection of Figs. 7 and 8 shows a reduction in the displacement thickness of the initial layer when either inclined jets or metal vanes are used. This suggests that, although the skin friction drag may be increased by the devices, the form drag is reduced. This is in agreement with current explanations which have been put forward to explain the absence of increased drag when vortex generators are fitted to the upper surfaces of aircraft wings; the induced drag of the vanes and any increase in skin friction are roughly balanced by the reduction in form drag.

7. Conclusions

The data presented show that the simple concept of allowing the jets to issue with a component in the cross flow direction, produces persistent vorticity which has a favourable influence on the boundary layer mixing without incurring any appreciable drag penalties. Further study of this type of jet appears highly desirable.

Since vortex generators have been used successfully in delaying shock-induced separation, it appears extremely likely that the inclined type of air jet will also be effective.

The flow quantities used at a Reynolds number of 5×10^5 were very reasonable and lower values should be possible when due allowance is made for the expected decrease of C_Q with increasing Reynolds number.

References/

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*The magnitude of the yaw, however, was insufficient to warrant any special precautions being taken when reading the total head in the layer.

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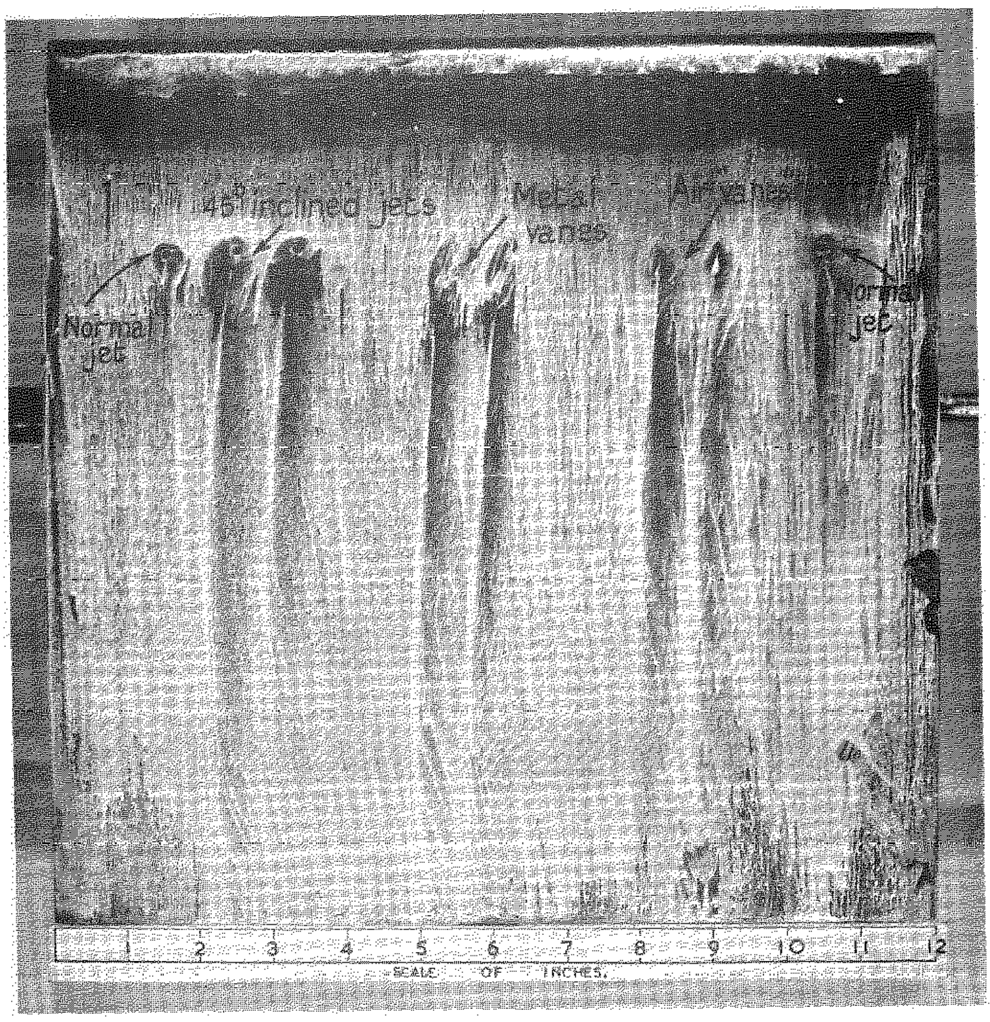
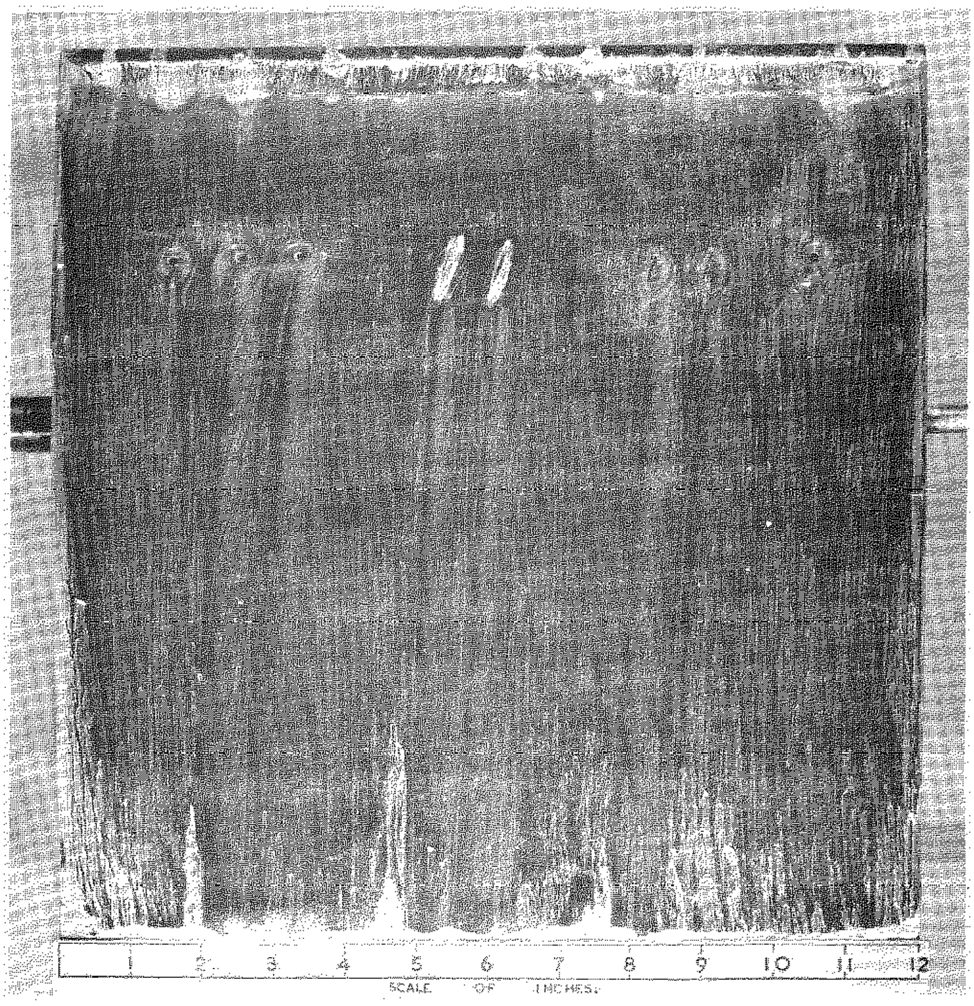
FIG. 1.

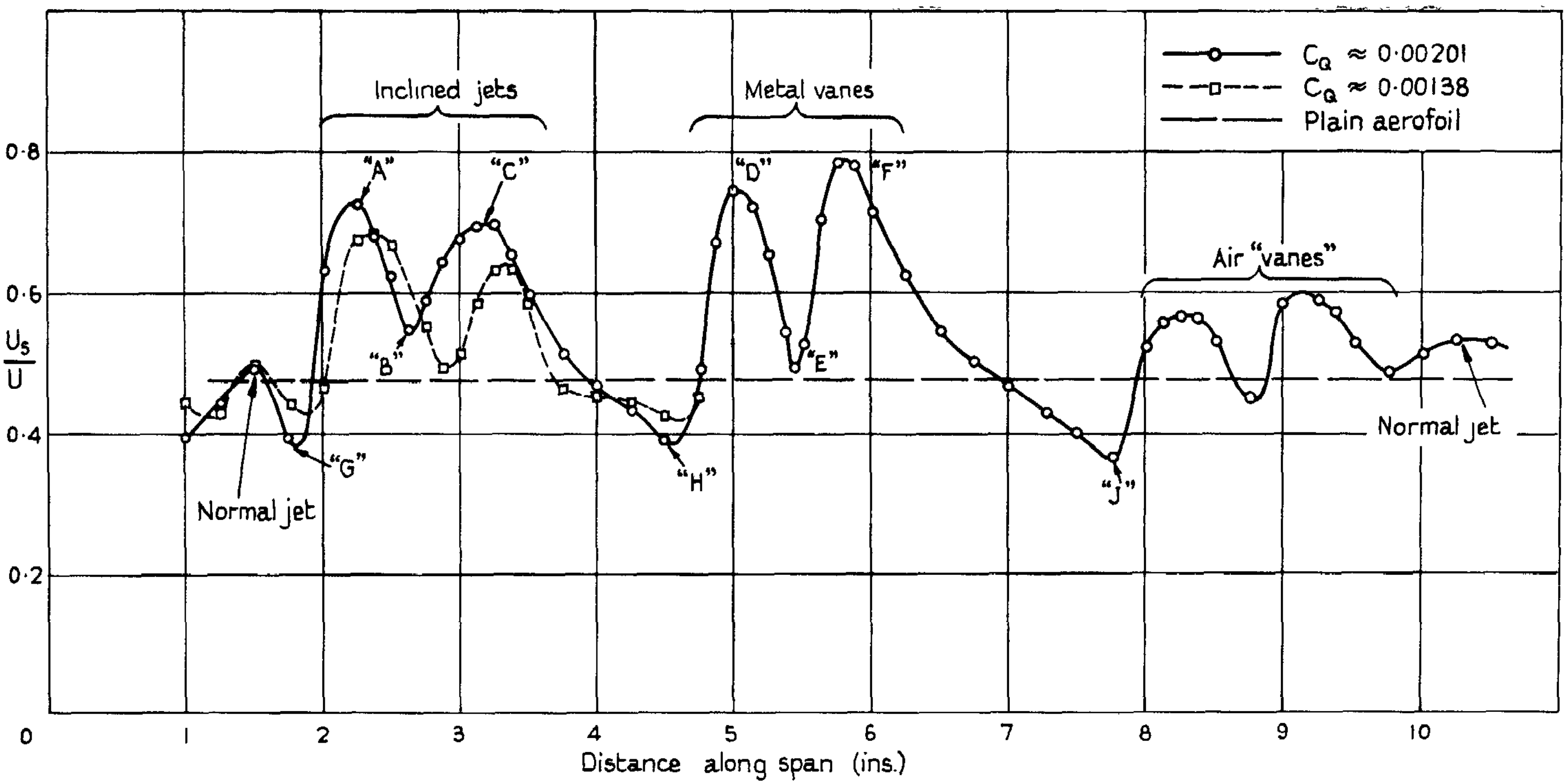
(a) Initial flow pattern showing regions of high scrubbing.



(b) Final flow pattern.



Flow patterns using titanium oxide.



Spanwise velocity distribution in boundary layer at fixed distance from surface.

$x/c = 0.875, \quad \alpha = 5°$

FIG. 2.

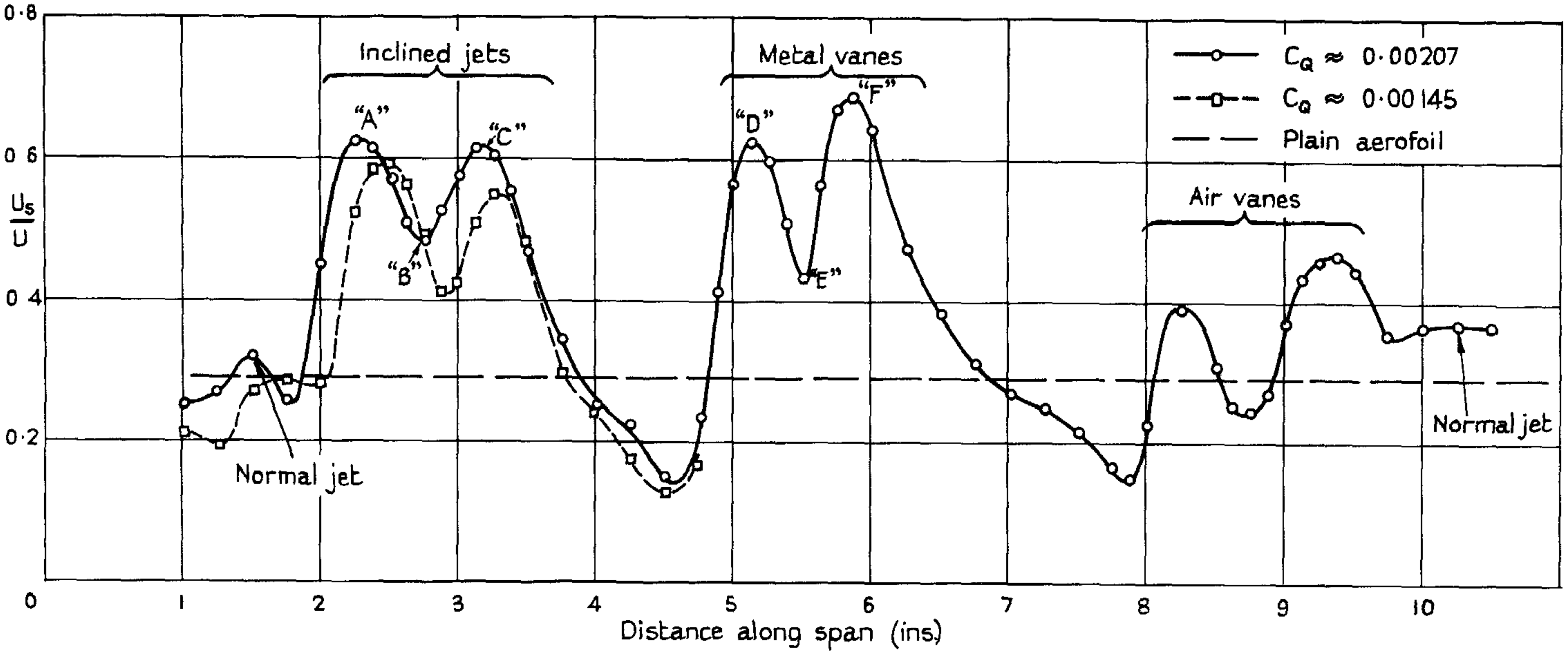
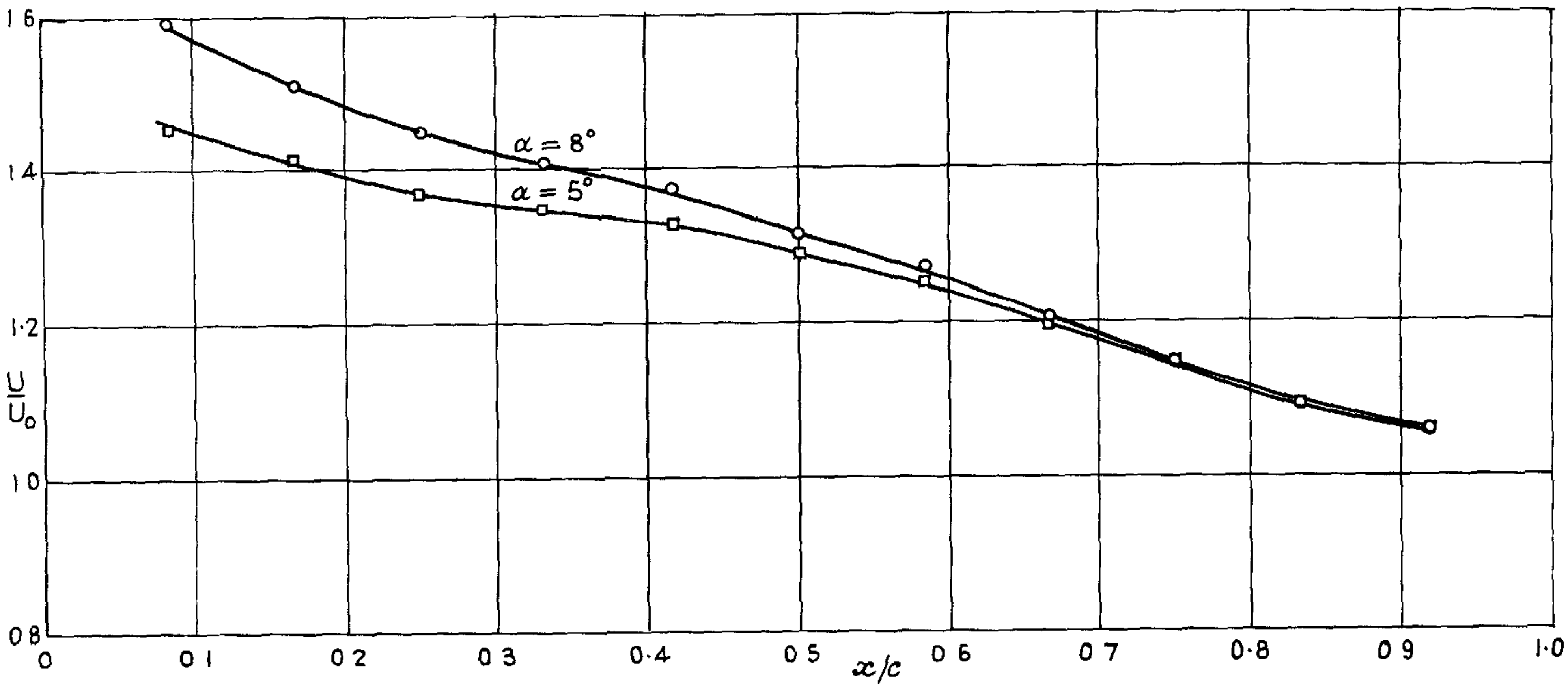


FIG. 3.

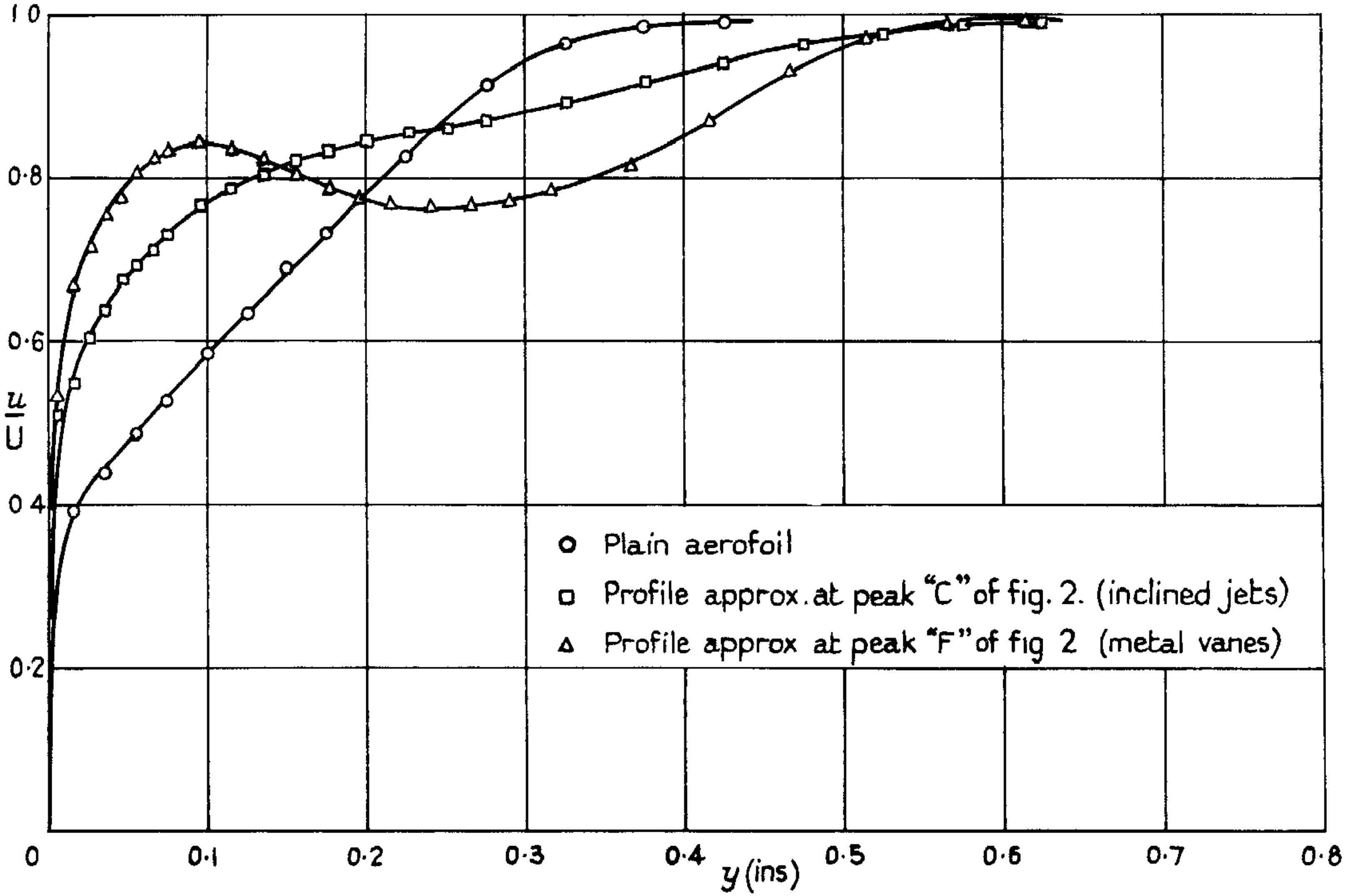
Spanwise velocity distribution in boundary layer at fixed distance from surface

$x/c = 0{\cdot}875, \ \alpha = 8°$

FIG. 4.



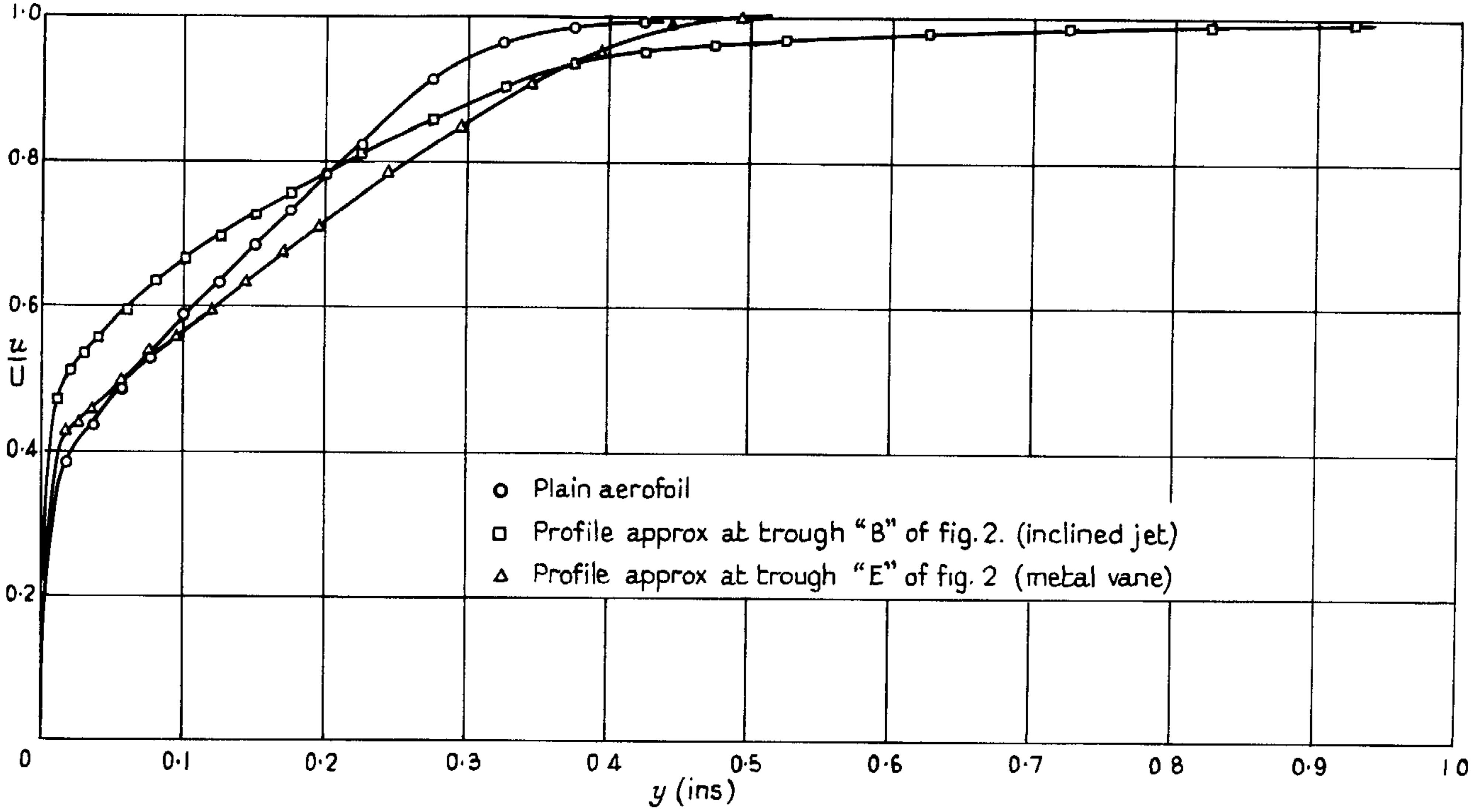
Chordwise velocity distributions for plain aerofoil.



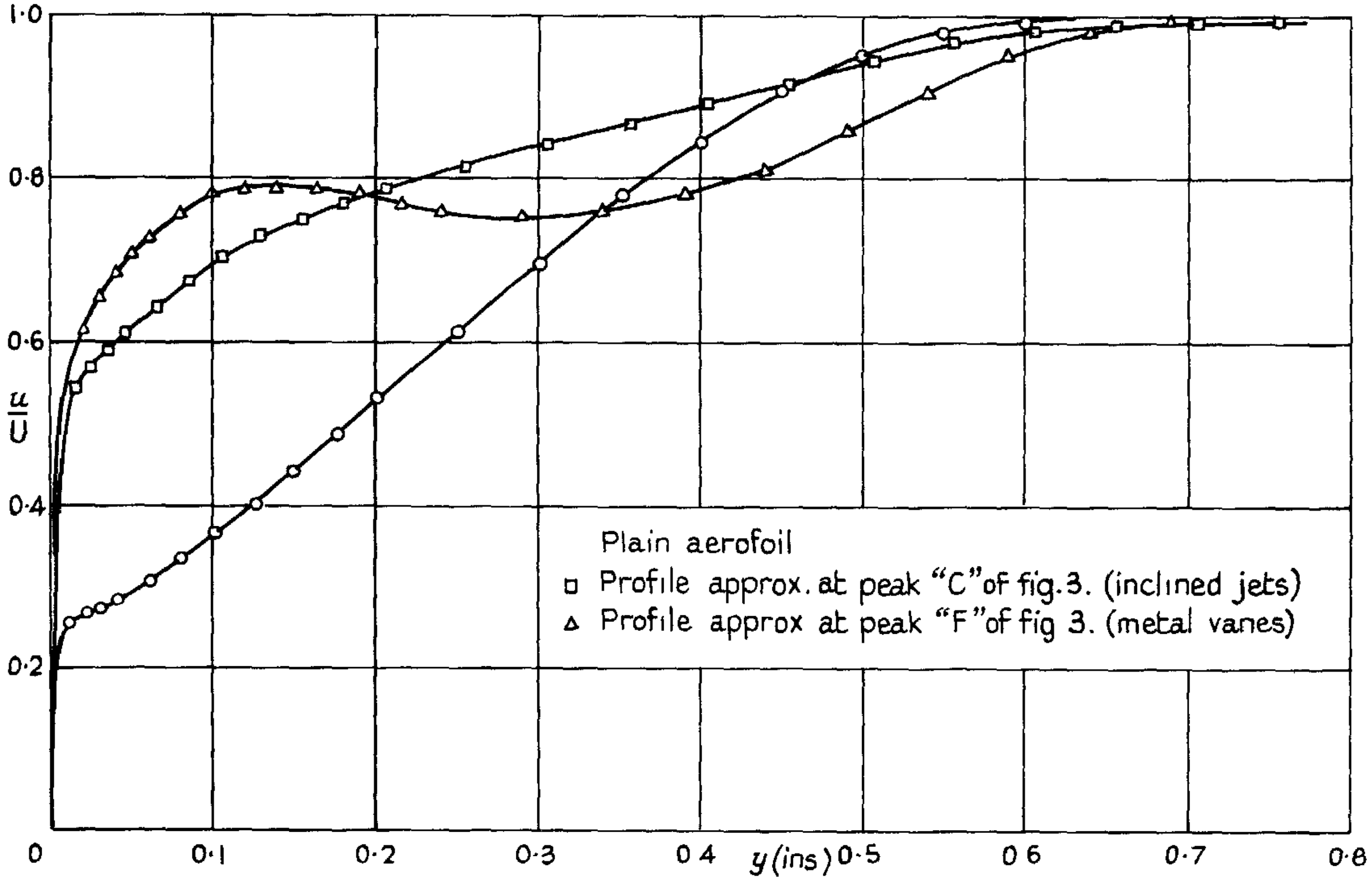
Boundary layer profiles at $x/c = 0{\cdot}875$ ($\alpha = 5°$, $C_Q = 0{\cdot}00201$)

Fig. 5.

Fig. 6.



Boundary layer profiles at $x/c = 0{\cdot}875$ ($\alpha = 5°$, $C_Q = 0{\cdot}00201$)



Boundary layer profiles at $x/c = 0{\cdot}875$ ($\alpha = 8°$, $C_Q = 0{\cdot}00207$)

FIG. 7.

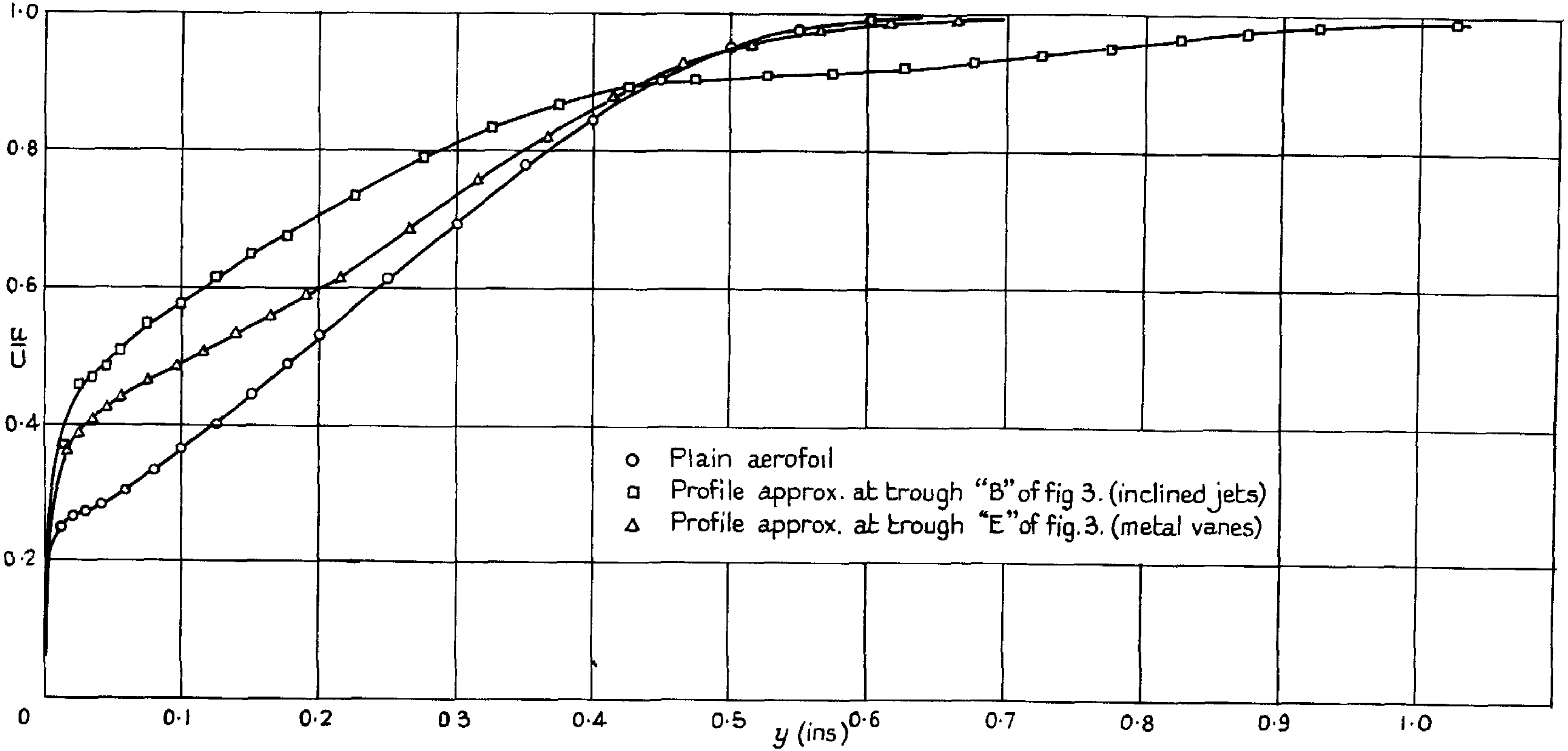
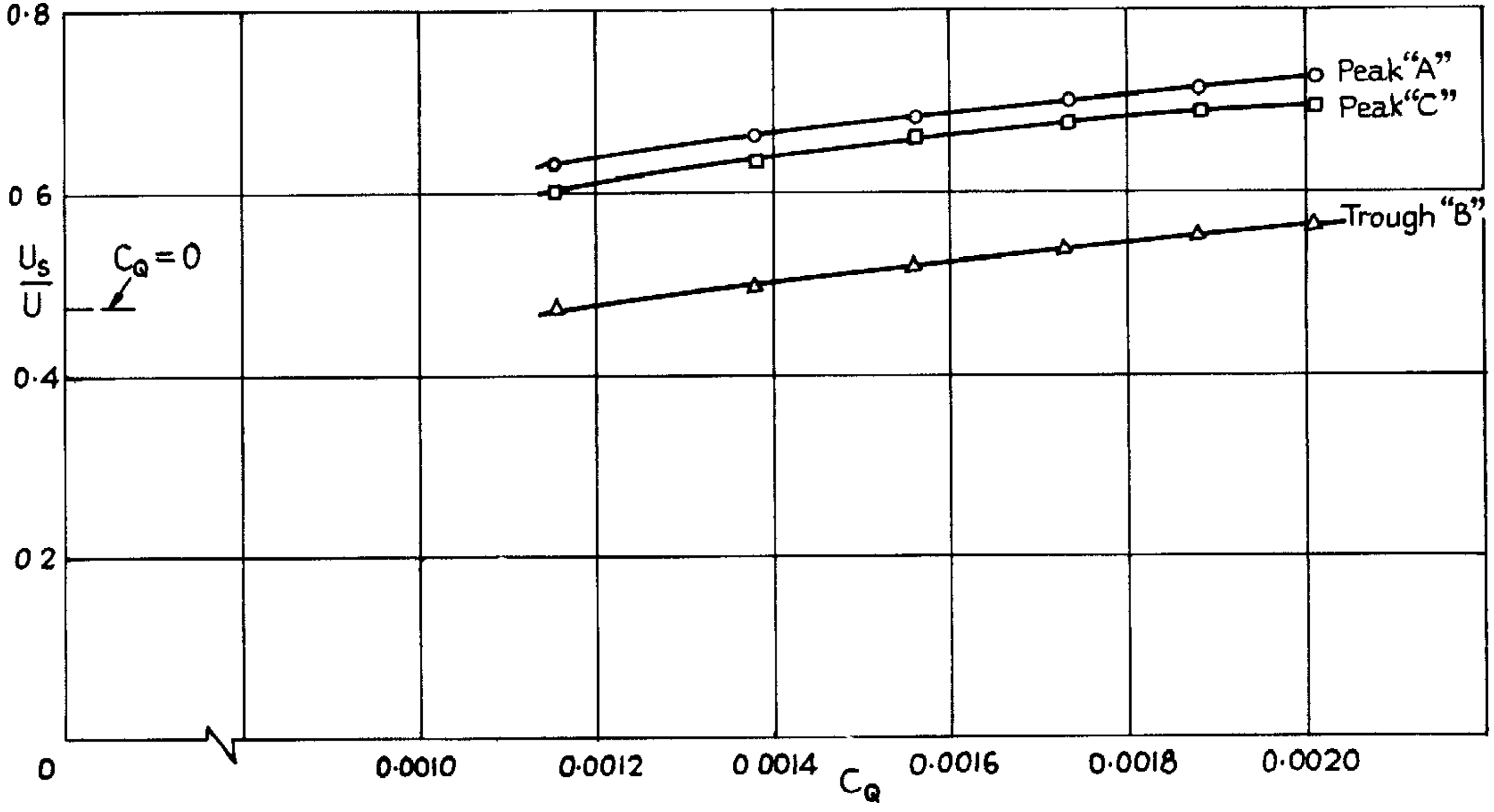


FIG. 8.

Boundary layer profiles at $x/c = 0·875$ ($\alpha = 8°$, $C_Q = 0\,00207$)



Effect of flow quantity on maxima and minimum of fig. 2
$x/c = 0{\cdot}875$, $\alpha = 5°$

FIG. 9.

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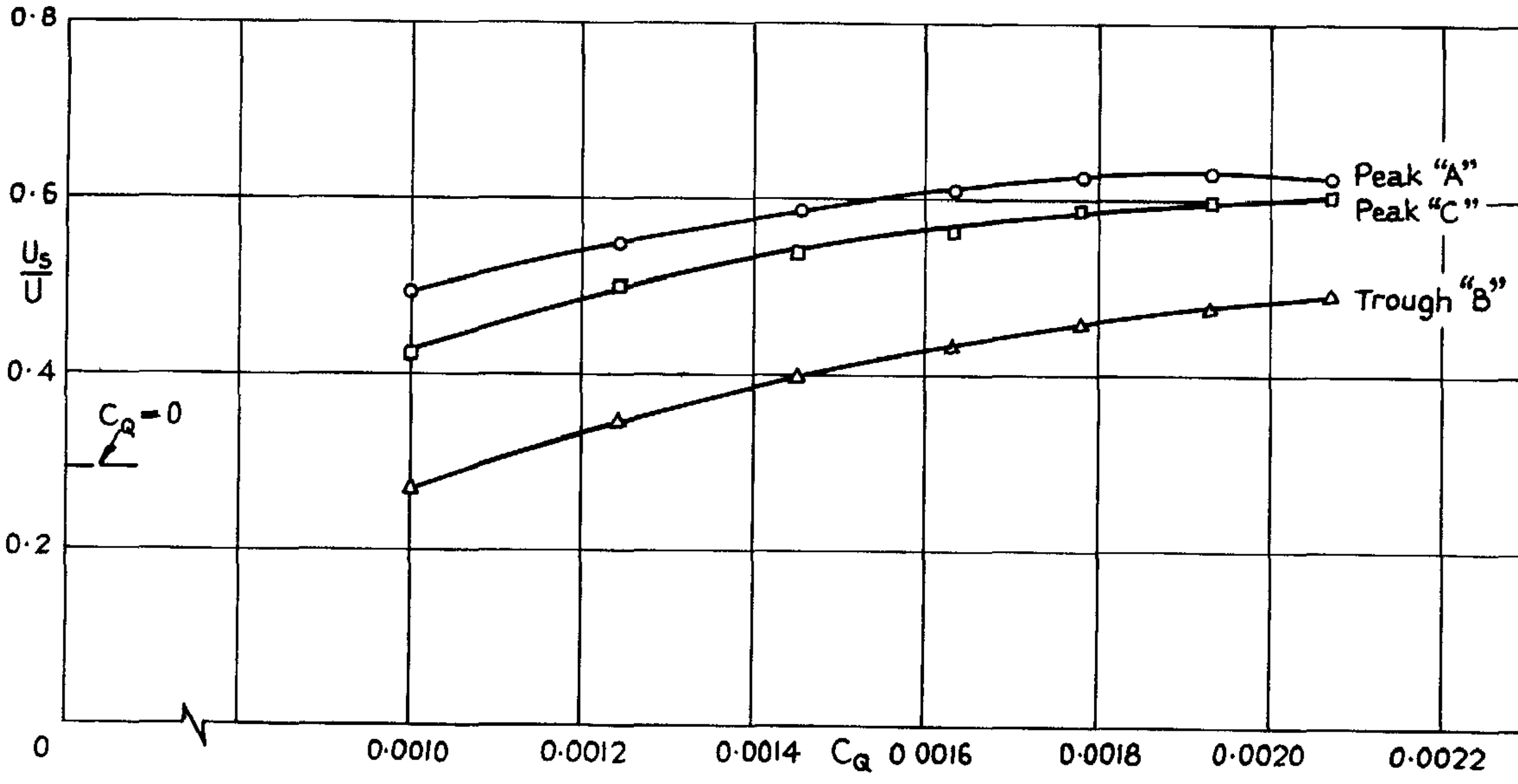
FIG. 10.



Effect of flow quantity on maxima and minimum of fig. 3.

$x/c = 0{\cdot}875$, $\alpha = 8°$

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