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By

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Two-Dimensional Normal Fences on a Flat Plate

by

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Communicated by Prof. W. A. Mair

Summary

As a first step towards understanding the mechanism of action of spoilers, two-dimensional normal fences on an effectively infinite flat plate in incompressible flow were studied experimentally. The pressure distribution on the plate upstream of a fence was found to be a function of $\frac{\delta^*}{h}$, where δ^* is the boundary layer displacement thickness measured at the fence position, in the absence of the fence, and h is the fence height.

Downstream, the pressure distribution in the separated region was a function of non-dimensional distance from the fence and the reattachment distance was proportional to h. Downstream of reattachment a dependence on $\frac{\delta^*}{h}$ was once again apparent.

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1. Introduction

As part of a wider programme of research on spoilers for lateral control of aircraft at low speeds[1] an initial investigation was conducted into two-dimensional, unswept, normal fences on an effectively infinite flat plate. The basic action of a fence (or spoiler) on the flow could then be studied without introducing the complication of modifying the circulation about an aerofoil. In particular the importance of the boundary layer on the flat plate could be investigated.

A nominally identical arrangement was studied by Nagabhushanaiah[2]. He presents pressure distributions on the front and rear faces of such fences and gives details of the geometry of the region of separated flow downstream. Pressure measurements on the plate were not made, however.

The investigation of Heyser and Maurer[3] into spoilers on a flat plate is similar to this investigation but little comparison is possible. Their Mach number range is 0.6 to 2.8 and no boundary layer measurements or reattachment distances are quoted.

2. Notation

C_p	$\frac{p - p_1}{\frac{1}{2}\rho U^2}$
C_{pf}	value of C_p at the upstream base of a fence
h	fence height
M	Mach number
p	static pressure on the plate in the presence of the fence
p_1	static pressure on the plate in the absence of the fence
$R_{\delta*}$	$\frac{\rho U \delta*}{\mu}$
U	free stream velocity
x	streamwise distance measured from the fence position
$\delta*$	boundary layer displacement thickness measured at the fence position in the absence of the fence
μ	viscosity
ρ	density.

3. Dimensional Analysis

It is instructive to consider the independent variables governing the behaviour of a normal, unswept, two-dimensional fence upon a two-dimensional flat plate. It is assumed that the length of the flat plate is large in comparison with the height h of the fence, so that the pressure field induced by the fence does not extend to the leading and trailing edges of the plate.

The flow is thus determined by the independent variables

$$h \quad \delta^* \quad \rho \quad U \quad \mu$$

where δ^* is the boundary layer displacement thickness on the plate at the fence position in the absence of the fence, ρ is air density, U is free stream velocity and μ is viscosity. The fence is assumed to be an infinitely thin plane lamina such that its geometry is fixed.

The variable δ^* is introduced since if the plate length is very large, the only relevant length scales are associated with the boundary layer.

The dimensionless groups defining the flow are then

$$\frac{\delta^*}{h} \quad \text{and} \quad R_{\delta^*}$$

where $R_{\delta^*} = \dfrac{\rho U \delta^*}{\mu}$.

4. Experimental Arrangement

All the experiments were conducted in an open return wind tunnel with a working section of mean width 28 in. and height 20 in. The walls diverged slightly in order to maintain the streamwise pressure gradient close to zero.

Experiments were carried out both on a flat plate and on the tunnel floor.

(i) Flat Plate

A light alloy flat plate 4 ft long and $\frac{5}{32}$ in. thick completely spanned the tunnel working section. Its leading edge was slightly drooped in order to suppress any tendency to leading edge separation on the surface fitted with a fence. The plate was fitted with a streamwise line of pressure tappings at 1 in. intervals along its centre line. Boundary layer transition was induced by a trip wire $1\frac{1}{2}$ in. downstream of its leading edge.

The plate was mounted 6 in. from the tunnel floor.

(ii) Tunnel Floor

In order to obtain a wider range of boundary layer thickness than was available on the plate, experiments were also conducted upon the tunnel floor.

The floor was equipped with a streamwise line of pressure tappings at $\frac{1}{2}$ in. intervals along its centre line. Boundary layer transition was induced by means of a trip wire 20 in. upstream of the start of the working section.

Preliminary investigations, using the surface oil film technique for flow visualisation, showed that the flow downstream of a nominally two-dimensional fence was far from two-dimensional, apparently due to interference from the side-wall boundary layers.

In order to minimise this interference, by reducing the side-wall boundary layer thickness at the spoiler position, false side-walls of 16 s.w.g. steel sheet were introduced along the length of the working section for both experimental arrangements. These walls reached from the floor to the roof of the tunnel in arrangement (ii) above and from the plate to the roof in arrangement (i).

In order to maintain a zero pressure gradient along the working section a slight divergence of the false walls was required. The false walls could be mounted at a variable distance from the tunnel walls but unless otherwise stated the results given refer to an effective tunnel span of 22 in.

Each of the effectively new working sections was calibrated in terms of the difference between two static pressure tappings in the wind tunnel contraction.

Provision was made for conducting pitot traverses through the boundary layer on the flat plate and tunnel floor at a number of stations and also for traverses through the separation bubble behind a fence.

4.1 The fences

The fences were constructed from 18 s.w.g. steel sheet and mounted normal to the flat plate or floor, completely spanning the false working section. The downstream face of each fence was machined at its tip to a 30° knife edge. This was the standard tip geometry. Further tip geometries tested are sketched in Fig. 1, together with the standard geometry tip.

The range of fence heights which could conveniently be used in this investigation was limited by three considerations. The maximum fence height was restricted by the need for it to be small compared with the plate length and by the estimated magnitude of the tunnel interference effects; the minimum, by the accuracy with which fences could be made. The height limits chosen were a maximum of 1 in. and a minimum of 0.25 in.

The maximum spanwise variation in fence height was ± .003 in. or ± 1.2% in height for the 0.25 in. fence.

The height of the fences used and whether they were tested on the plate or tunnel floor are noted in Table 1.

Leaks beneath the fences were prevented by a strip of adhesive tape along the downstream base of each fence.

4.2 Surface oil film technique

The mixture used was a suspension of titanium dioxide particles in "Easy Nut" penetrating oil.

5. Experimental Procedure

The wind speeds used were 92 ft/sec for experiments on the tunnel floor and 92 ft/sec and 50 ft/sec for the flat plate.

5.1 Boundary layer development

The boundary layer developments on the flat plate and tunnel floor were determined by pitot traverses at a number of stations along their centre lines. In addition, traverses were made at a number of spanwise positions to check the uniformity of the boundary layer. No detectable variations in boundary layer thickness or profile were found, except close to the side-walls.

5.2 Fence tests

Pressure distributions along the plate or tunnel floor centre line were obtained for each fence, under the conditions noted in Table 1.

The pressure distributions for fences of height 0.6 in. having the alternative geometries sketched in Fig. 1 were also determined.

The distance from a fence to the upstream separation line was determined by trailing a flattened pitot tube along the surface in a direction normal to the fence and comparing its reading with the known surface static pressure. This was carried out for each fence tested.

The position of the reattachment line downstream of a fence was determined by the surface oil film technique. These tests showed that the surface flow close to the fence was highly three-dimensional. Tests were conducted to give some indication of the effect of this three-dimensionality upon the measured pressure distributions. Additional pressure distributions and oil flow patterns were obtained with the false side-walls 16.8 and 8.9 in. apart.

In order to evaluate the effect of wind tunnel interference on the measured results the approximate geometry of the separated region was required (Section 6.1). Accordingly pitot and static tube traverses, normal to the surface, were made in order to determine the shape of the outer edge of the "bubble".

6. Results

6.1 Interference corrections

The traverses to determine the bubble height, taken in conjunction with the measured positions of separation and reattachment, revealed that in all cases the bubble could be approximated by a semi-Rankine oval of mean length 17h and mean maximum thickness 2.4h. A variable interference correction was developed to correct the measured pressure distributions. The form of this correction is similar to that of Arie and Rouse[4] and is fully described by Barnes[1].

No correction could be applied to the dimensions of the separated region but the results of Arie and Rouse suggest that any such interference effects would be small.

6.2 Pressure distributions

The corrected pressure distributions obtained are presented in Fig. 2. The pressure coefficient is defined as

$$C_p = \frac{p - p_1}{\frac{1}{2}\rho U^2}$$

where p and p_1 are the static pressures measured at a given position on the plate in the presence and absence of the fence respectively. The distributions for cases D and E in Table 1 have not been included since they were closely identical to that of case C. The significance of this is discussed in Section 7.

6.3 Separation and reattachment lines

The positions of the flow separation and reattachment lines for the fences tested are included in Fig. 2. It is seen that the separated region upstream of a fence decreases in size somewhat as the parameter $\frac{\delta^*}{h}$ decreases. The position of the reattachment line downstream, expressed non-dimensionally, varies only slightly and shows no systematic variation with $\frac{\delta^*}{h}$.

Fig. 4 illustrates the surface flow pattern behind a fence with $\frac{\delta^*}{h} = 0.52$ and $R_{\delta^*} = 3.1 \times 10^3$. The surface oil film technique was used. The reattachment line is very nearly straight and its mid-span point is approximately 15.6h from the fence. The large numerals on the scales along the edges of the figure give the distance in fence heights, $\frac{x}{h}$, measured from the rear face of the fence, this particular fence being 1 in. high.

The oil accumulation close to the fence was wiped off since it tended to spread downstream when the tunnel was stopped for photography.

6.4 Three-dimensionality

Fig. 5 shows the surface flow pattern downstream of the same fence as in Fig. 4 but with the distance between the false side-walls equal to 8.9 in. The area of three-dimensional surface flow which is present immediately downstream of a nominally two-dimensional fence, even with the false side-walls fitted is clearly seen. The presence of this type of flow was thought to be due to interference from the wall boundary layer. The reattachment distance is reduced to about 14h.

Fig. 6 illustrates the small measured dependence of the pressure distribution downstream of a fence upon the tunnel span. There is no detectable dependence upstream. In the interests of clarity no experimental points have been shown,as in most cases the points obtained at a given value of $\frac{x}{h}$, for different values of the tunnel span,coincided.

7. Discussion

On account of the fence height limitations noted in Section 4.1 it was necessary to vary δ^* in order to widen the experimental range of $\frac{\delta^*}{h}$. This implies variations in R_{δ^*}.

Consequently the range of pressure distributions in Fig. 2 includes variations of both $\frac{\delta^*}{h}$ and R_{δ^*}. A third factor is the use of both the tunnel floor and a physically finite flat plate.

Before considering the results in detail it is convenient to discuss the precautions taken to isolate the effects of varying R_{δ^*} and of employing effectively different overall experimental geometries. The latter of course is essentially concerned with the validity of the assumption that the plate length may be considered to be infinite compared with the fence height.

Cases C and D in Table 1 have equal values of $\frac{\delta^*}{h}$ but R_{δ^*} varies by a factor of approximately 1.5. Both experiments were conducted on the flat plate. The pressure distributions obtained are not reproduced here since they were closely identical after interference corrections were applied. Over the small range of R_{δ^*} obtainable, therefore, the effect of this parameter is small as might be expected for a turbulent boundary layer.

Cases C and E at constant $\frac{\delta^*}{h}$ were tested on the flat plate and tunnel floor respectively. Once again the pressure distributions obtained were closely identical.

It is considered, therefore, that the flat plate may be taken to be effectively infinite and that, over the limited experimental range, the effect of varying R_{δ^*} is small. It follows that the pressure distributions obtained are functions of $\frac{\delta^*}{h}$ only. The lack of dependence on Reynolds number of pressure distributions in subsonic separated flow is noted by Chapman, Kuehn and Larson[5] and by Tani, Iuchi and Komoda[6]. The former employed a fairly wide range of Reynolds number.

It is clear from Fig. 2 that upstream of a fence, the pressure distribution is a function of $\frac{\delta^*}{h}$. It appears that $\frac{\delta^*}{h}$ plays a less important role downstream, where the pressure distribution seems relatively insensitive to upstream conditions.

The magnitude of the pressure rise upstream of a fence increases as $\frac{\delta^*}{h}$ decreases. A small fence immersed in the boundary layer brings low total pressure air to rest but as h increases or $\frac{\delta^*}{h}$ decreases, air of greater total pressure is brought to rest and the pressure rise is correspondingly greater.

Fig. 3 suggests that the pressure coefficient, C_{pf}, at the base of the upstream face of a fence tends towards the theoretical inviscid value, $C_{pf} = 1$ as $\frac{\delta^*}{h}$ tends to zero. Also the non-dimensional distance from the fence to the upstream separation line, sketched as OS_1 in Fig. 7, decreases as $\frac{\delta^*}{h}$ decreases. The inference is that $\frac{\delta^*}{h}$ can perhaps be thought of as a measure of the departure of real fluid flow from the inviscid flow solution.[†]

This inference clearly holds only upstream of a fence, however, since the pressure distribution downstream is rather less sensitive to changes in $\frac{\delta^*}{h}$. A real fluid will, of course, always be subject to severe separation at a fence tip, as in Fig. 7, except at very low Reynolds numbers, regardless of upstream conditions. That part of the downstream pressure distribution

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[†] It is not impossible, however, that if very small values of $\frac{\delta^*}{h}$ could have been used, a limiting peak pressure coefficient between 0·6 and unity would have been found.

showing greatest dependence on $\frac{\delta^*}{h}$ is the maximum pressure attained downstream of reattachment.

It appears approximately that in the separated region the pressure distribution is dependent only upon $\frac{x}{h}$. The reattachment distance is closely proportional to h and equal to about 15.5h. In order to determine any effect of detail fence geometry the variety of tip geometries sketched in Fig. 1 were used. No variation in pressure distribution or reattachment distance could be detected.

The process of reattachment is governed largely by the entrainment of fluid from the separated region. The rate of entrainment, therefore, seems to be largely independent of the thickness of the shear layer at the fence tip within the limits of this investigation.

The lack of influence of the upstream boundary layer thickness and Reynolds number upon the distance to reattachment seems to be a feature of subsonic separations induced by rearward-facing steps etc. Tani et al.[6] obtained a constant reattachment distance of 7 step heights downstream of a series of rearward-facing steps. In an investigation nominally similar to the present one Nagabhushanaiah[2] notes a constant reattachment distance of 12 fence heights. Nash, Quincey and Callinan[7] note a dependence on Mach number, M, for values of M greater than about 0.3.

It is not clear why the distances to reattachment obtained in this investigation are greater than those of Nagabhushanaiah. It seems probable, however, that this is due to excessive interference from the wind tunnel side-wall boundary layer in the latter case, which may also be responsible for the slight scatter of reattachment distances in this investigation. The influence of such interference will be discussed shortly.

Downstream of reattachment the pressure distributions show the "overshoot" that is characteristic of subsonic reattachment[7]. It is in this region that the parameter $\frac{\delta^*}{h}$ appears to be significant once again. Its importance is probably related to the thickness of the shear layer at reattachment which is still dependent upon conditions upstream.

7.1 Three-dimensionality

It is clear from Fig. 5 that downstream of a nominally two-dimensional fence the flow pattern close to the fence is highly three-dimensional. The effect is at its worst in the case illustrated since a small effective tunnel span of only 8.9 in. is used. The area of three-dimensional flow is most marked close to the side-walls, and the middle third of the span may perhaps be considered to be reasonably two-dimensional. The reverse flow close to the surface in the separated region (see Fig. 7) reseparates from the surface close to the fence, at S_2 in Fig. 7, to form what will be called a region of secondary separation.

It appears that fluid flows from the main separated region, the region of secondary separation and from the side-wall boundary layer into a pair of vortices which stream away downstream.

Upstream of a fence, the surface oil film technique showed that there was relatively little three-dimensional flow, except in the junction between the fence and the tunnel wall.

Centre line pressure plots taken with reduced tunnel and fence spans of 16.8 in. and 8.9 in. showed no detectable difference upstream of the fence from the curves of Fig. 2. Downstream, however, a small increase in pressure was experienced with decreasing tunnel span as shown in Fig. 6. This increase tended rapidly to zero in the region of reattachment. Rough extrapolation to infinite tunnel span of the pressure coefficient versus tunnel span relationship suggested that errors in pressure coefficient were unlikely to be greater than 0.02.

Away from the centre line, static pressure measurements showed no significant spanwise pressure variations, indicating that the cross-flow velocities were small.

The reattachment distance for a given value of $\frac{\delta^*}{h}$ decreased as the side walls were moved closer together. In addition, considerable curvature of the reattachment line appeared. If, as seems possible, the linearity of the reattachment line can be taken as a measure of the approach towards genuine two-dimensional flow, then inspection of Fig. 4 is encouraging in this case.

Analysis of the measured centre line reattachment distances suggests very crudely that the departure of the measured reattachment distance from that of hypothetical, perfect, two-dimensional flow, depends upon the ratio

$$\frac{\text{wall boundary layer thickness}}{\text{tunnel span}}$$

measured at the fence position.

Since the fences were not all mounted at the same longitudinal position relative to the tunnel, there was a small variation of the above ratio in the experiments. This is consistent with the slight variation in reattachment length shown in Fig. 2.

The data of Nagabhushanaiah suggest that his values of the above ratio were relatively large. It seems likely that the discrepancy between his results and those of this investigation are due to a much higher degree of interference from the wall boundary layer in his case.

Somewhat similar wall boundary layer interference effects have been noted downstream of a rearward-facing step in supersonic flow by Sirieix[8].

8. Conclusions

The experiments show that upstream of a fence the pressure coefficient on the plate is a function of $\frac{x}{h}$ and $\frac{\delta^*}{h}$, with little effect of varying Reynolds number over a limited range. Downstream of the fence the pressure coefficient in the separated region depends mainly on $\frac{x}{h}$ but after reattachment there is again a dependence on $\frac{\delta^*}{h}$.

Although fully two-dimensional flow was not obtained, it is thought that the maximum resulting error in pressure coefficient was only about 0.02 downstream of the fence. There was no significant error upstream. The effect of three-dimensionality upon the reattachment distance is thought to be small.

Acknowledgements

The author wishes to thank Professor W. A. Mair for his generous advice and encouragement during the period of this investigation. Thanks are also due to P. P. Rouse who designed most of the apparatus and was responsible for certain experimental work.

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Case	Fence Height in inches	$\frac{\delta^*}{h}$	Test Position
A	0.25	.397	Floor
B	0.5	.164	Floor
C	0.5	.107	Plate
D	0.6	.107	Plate
E	0.875	.107	Floor
F	1.0	.052	Plate

Table 1. Fences Tested on Flat Plate and Tunnel Floor

D74062/1/Dd125875 K4 7/66 XL/CL

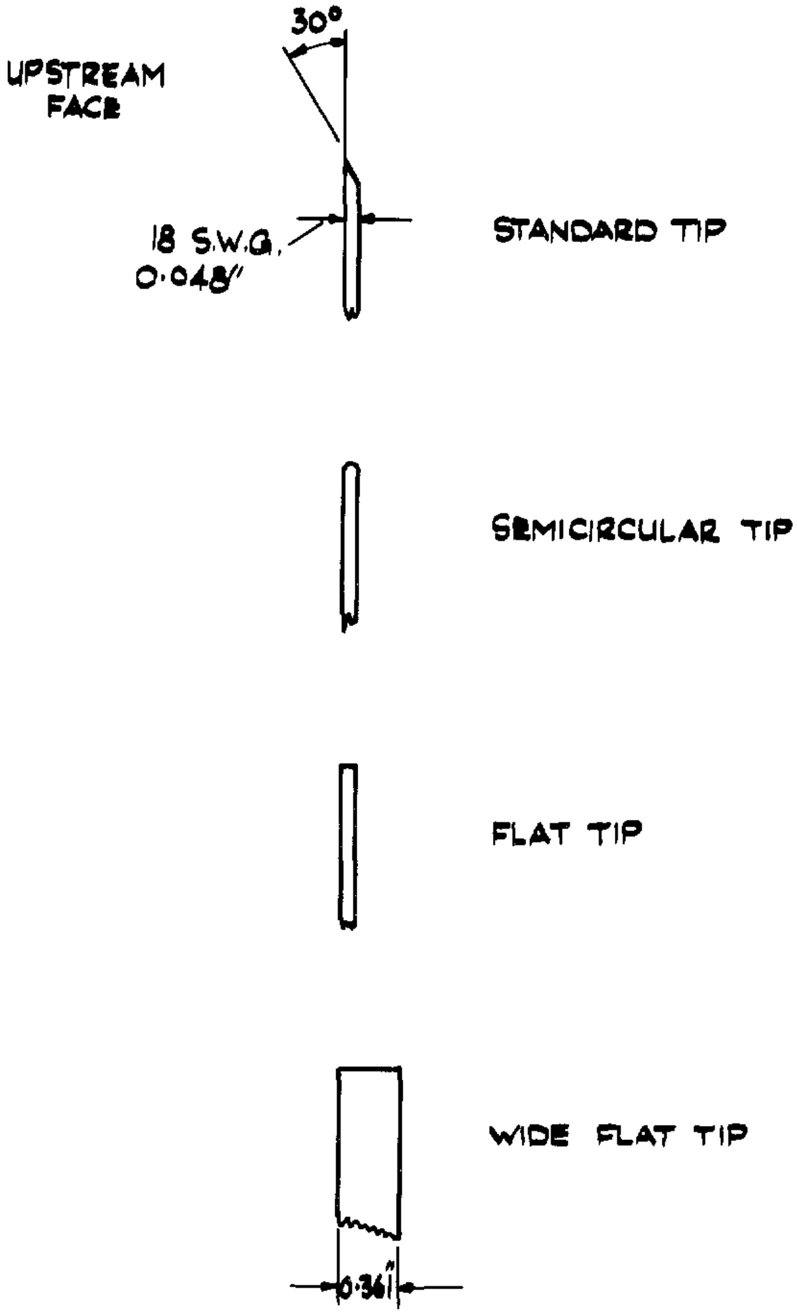

FIG. 1. SPOILER TIP GEOMETRY

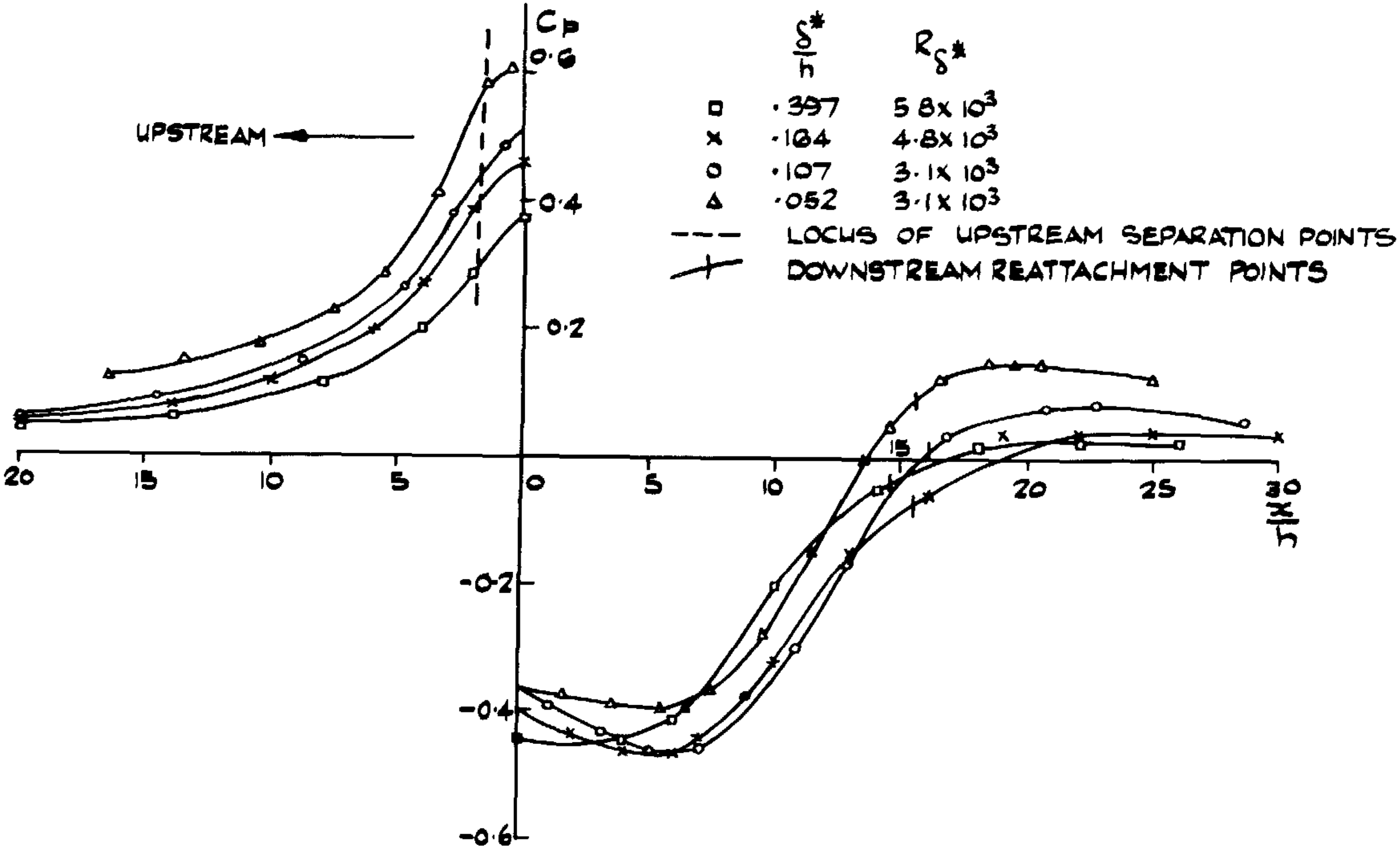

FIG. 2. PRESSURE DISTRIBUTIONS DUE TO TWO-DIMENSIONAL SPOILERS ON A FLAT PLATE

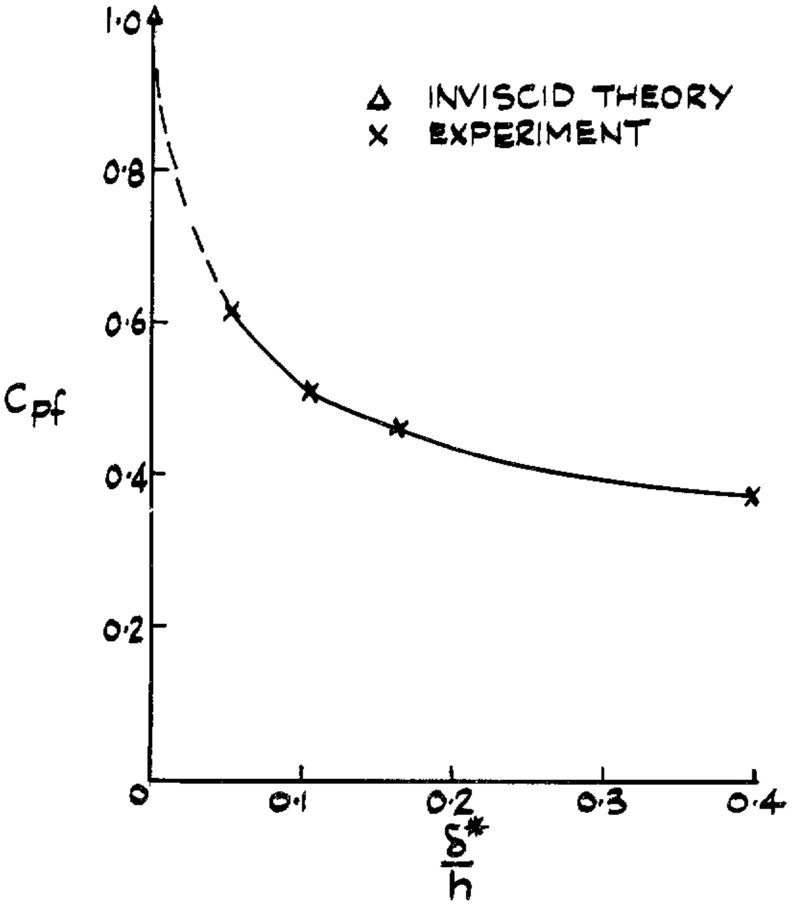

FIG. 3. VARIATION OF PRESSURE AT THE BASE OF THE UPSTREAM FACE OF A TWO-DIMENSIONAL SPOILER ON A FLAT PLATE WITH $\frac{\delta^*}{h}$

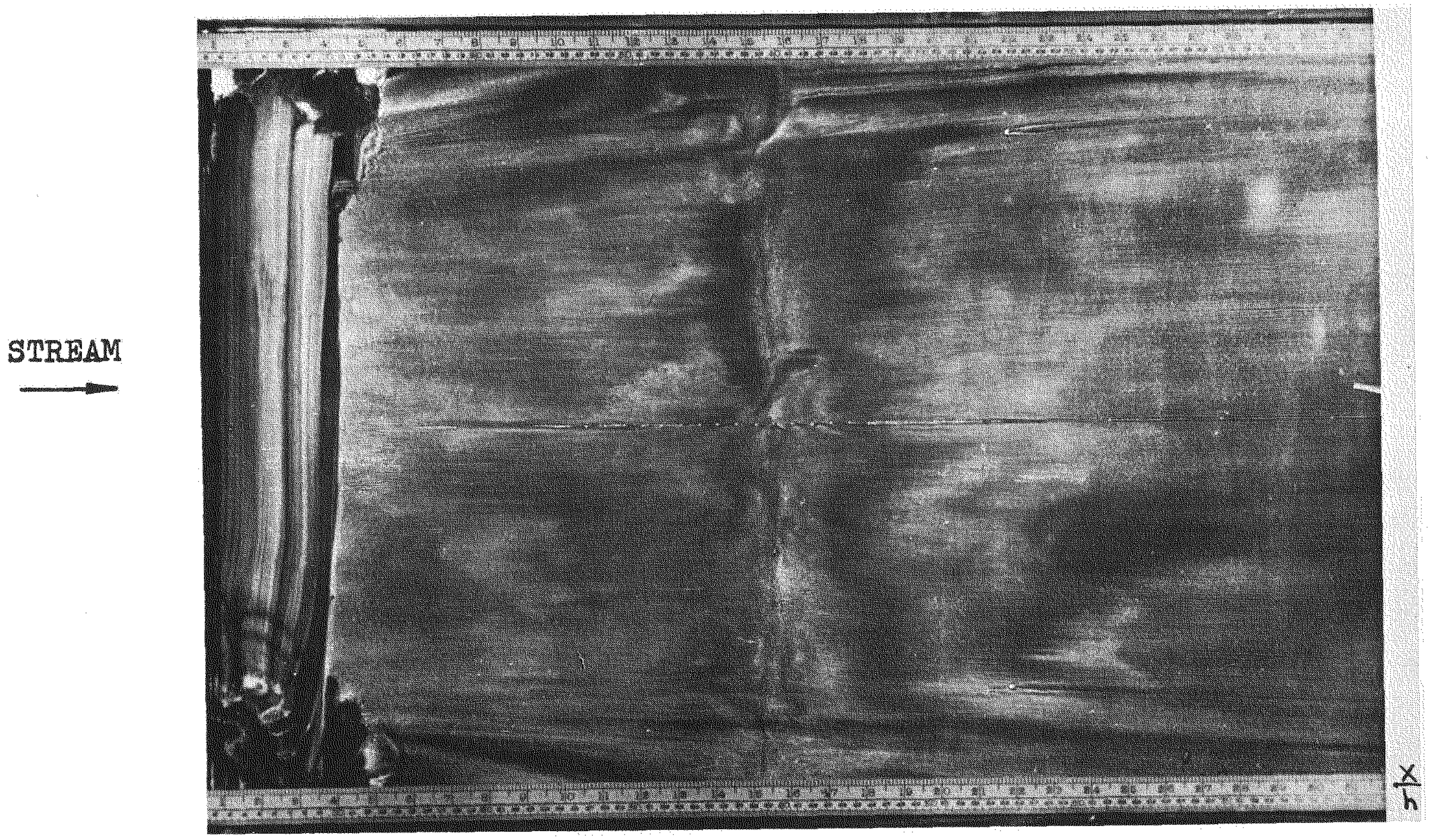

FIG. 4. SURFACE FLOW PATTERN DOWNSTREAM OF A TWO-DIMENSIONAL FENCE WITH $\frac{\delta^*}{h} = 0.052$ AND EFFECTIVE TUNNEL SPAN = 22.0 in.

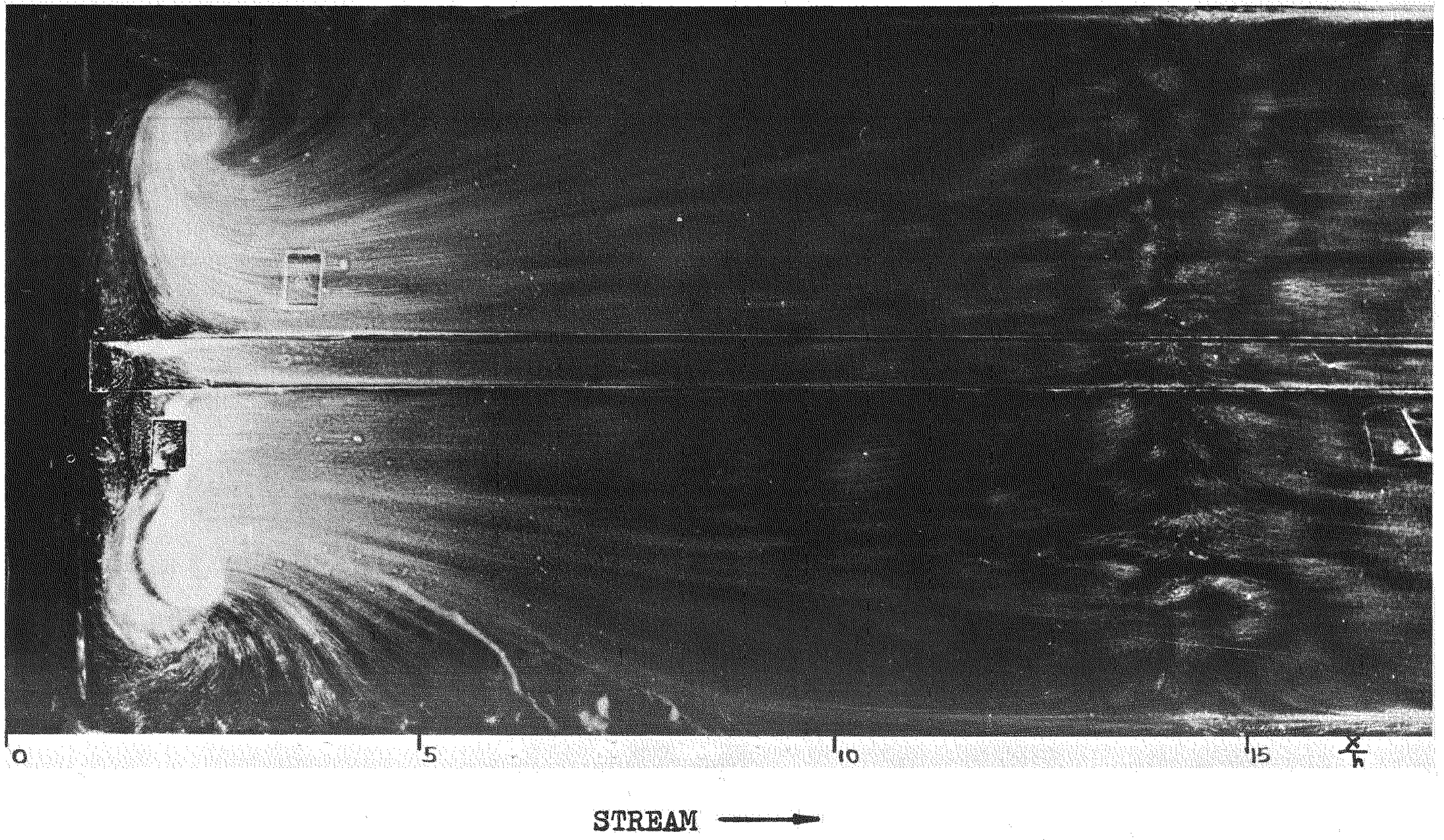

FIG. 5. SURFACE FLOW PATTERN DOWNSTREAM OF A TWO-DIMENSIONAL FENCE WITH $\frac{\delta^*}{h} = 0.052$ AND EFFECTIVE TUNNEL SPAN = 8.9 in.

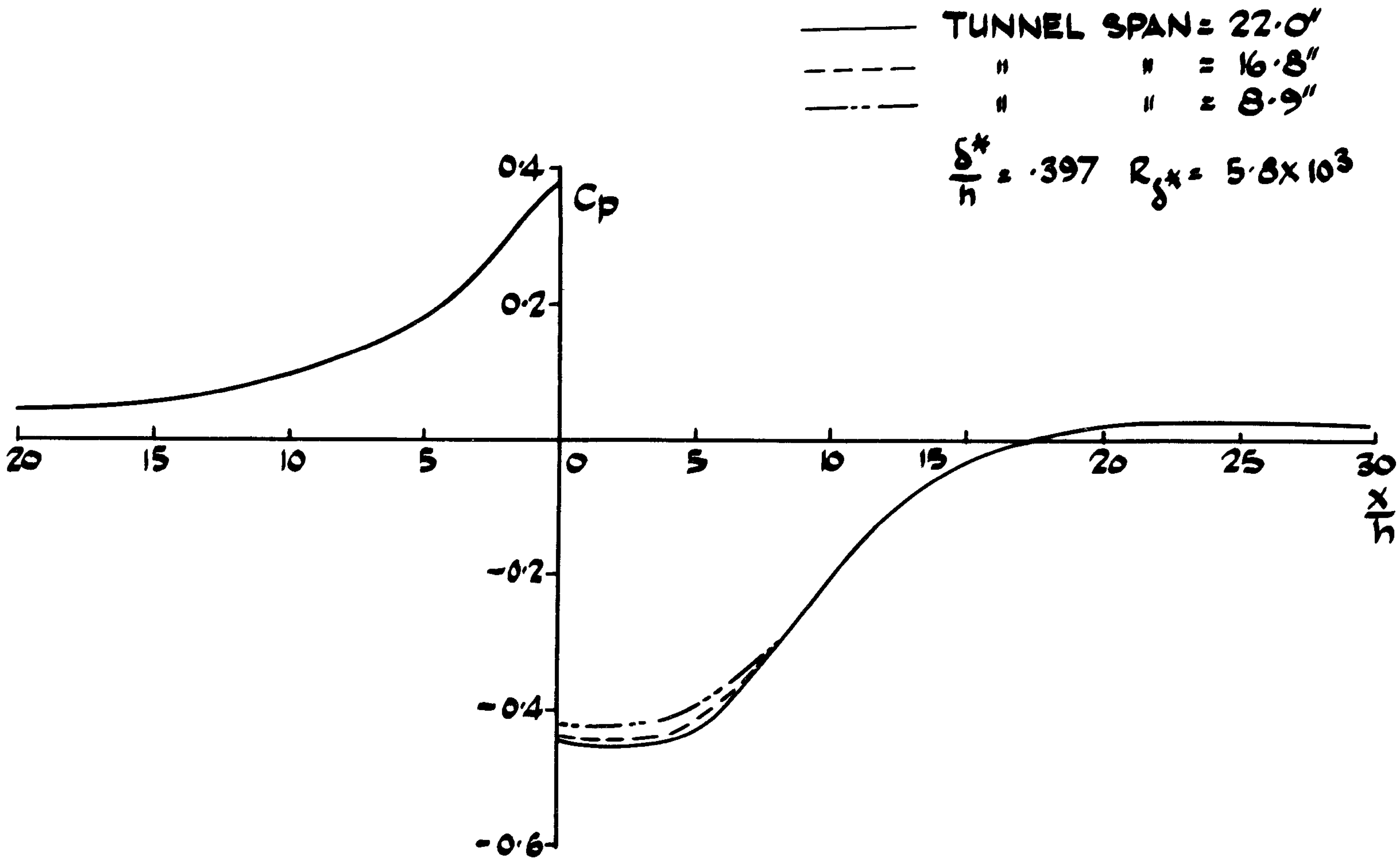

FIG. 6. DEPENDENCE OF PRESSURE DISTRIBUTIONS UPON TUNNEL SPAN

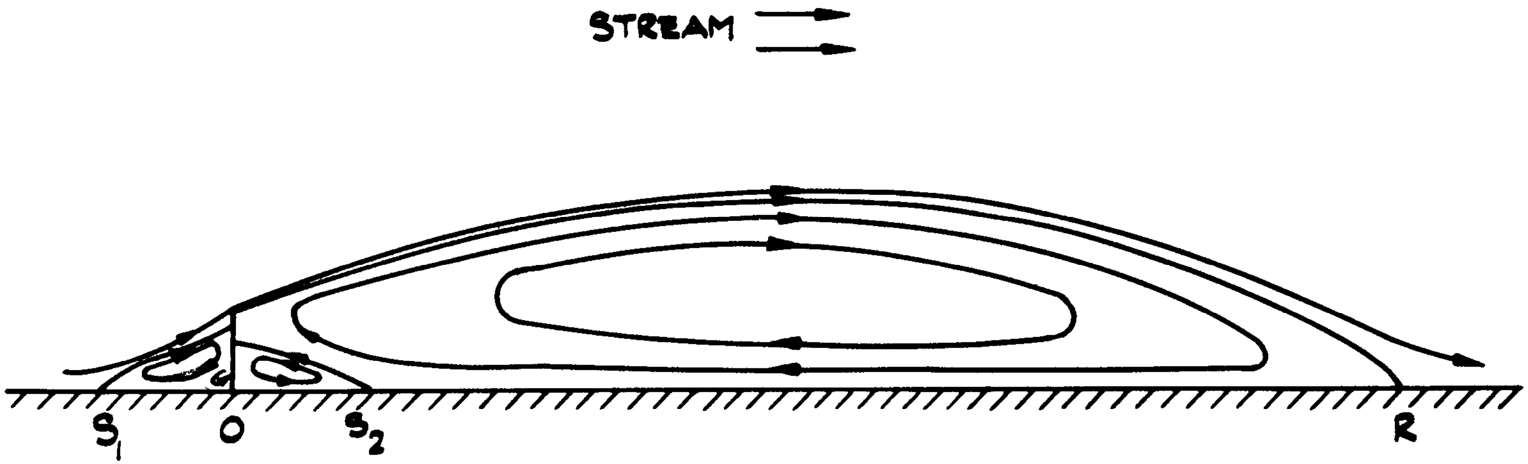

FIG. 7. APPROXIMATE FLOW PATTERN ABOUT A TWO-DIMENSIONAL SPOILER

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C. S. BARNES. FEB.1965.

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