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A Note on the Control of Secondary Flow by using Cascades of Twisted Blades

by

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A Note on the Control of Secondary Flow by using Cascades of Twisted Blades

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SUMMARY

The object of secondary flow control is to reduce one (or more) of the adverse effects which that flow introduces. The suggestion here is that by varying the blade camber in accordance with the inlet velocity distribution correction can be made for the phenomenon of overturning near the walls. It is hoped that the reduction of camber at the blade tips which this necessitates will also favourably affect the position of the separation point on the blade surfaces in the corners. Preliminary experiments demonstrating these improvements are reported here: they are of a restricted nature owing to the fact that they were designed primarily to test a first-order secondary flow theory for twisted blades. Nevertheless, the results are encouraging and it is hoped that they may lead eventually to a method of improved blade design.

Introduction

When a non-uniform air-stream flows through a cascade two main adverse effects are observed, namely the skewing of the surfaces of constant total pressure and the phenomenon of overturning near the walls. While secondary flows must arise in the cascade passage, their distribution can be controlled to some extent and in particular a first-order theory has been developed by Ehrich (1955) who sets out to minimise the spanwise velocity component. He does this by increasing the blade camber in the boundary layer; it appears from a report by Taylor, Stevenson and Dean (1954) however, that he only achieves his object at the increased risk of separation in the corners, and this effect is clearly undesirable.

The alternative approach, suggested here, is to direct attention towards the reduction of spanwise variations in outlet angles. It is felt that if this can be done without increasing secondary velocities, even if pressure losses at the blade-row in question are not appreciably altered, the greater uniformity in the inlet conditions at the succeeding blade-row should give considerable improvement there. Further, there is the hope of reducing the tendency for separation from the blade surfaces, this being an important aim in secondary flow control.

Experiments with a Cascade of Twisted Blades

For testing on the Cambridge University Engineering Department's Heat Laboratory 150 H.P. Cascade Tunnel (designed by Rhoden (1951)), a 9-blade compressor cascade was made to the following specification:-

Blade Span (2ℓ) = 18 inches

Blade Chord (c) = 5 inches

Space-chord ratio (s/c) = 1.

The blade camber was constant and equal to 10° over three-quarters of the span ($13\frac{1}{2}$") but decreased linearly to zero over the remaining quarter ($4\frac{1}{2}$"). This statement may perhaps be better expressed algebraically:-

$$\left.\begin{aligned} \theta &= 10 && \text{for} \quad -\ell \leqslant y \leqslant \ell/2 \\ \theta &= 20(1 - y/\ell) && \text{for} \quad \ell/2 \leqslant y \leqslant \ell \end{aligned}\right\} \qquad \ldots(1)$$

where θ is the camber in degrees
and y is the distance along the span measured from the centre line.

C4 compressor blade profiles were used at all sections. Each blade was made in two parts, the constant camber section in wood and the twisted section in fibre glass; these were fitted together and held firmly in place by two brass dowels 3/16" in diameter; the whole blade was then lacquered and polished smooth.

Gauzes placed in the tunnel upstream of the cascade were arranged so as to produce the inlet velocity distribution shown in Fig. 1. This approximates to the simple form:-

$$\left.\begin{aligned} U_1(y) &= \frac{U_m}{4}\left(5 + \frac{3y}{\ell}\right) && \text{for} \quad -\ell \leqslant y \leqslant -\ell/3 \\ &= U_m && \text{for} \quad -\ell/3 \leqslant y \leqslant \ell/3 \\ &= \frac{U_m}{4}\left(5 - \frac{3y}{\ell}\right) && \text{for} \quad \ell/3 \leqslant y \leqslant \ell \end{aligned}\right\} \qquad \ldots(2)$$

where $U_1(y)$ is the inlet velocity distribution used in a numerical application of the author's theory (Martin (1958)).

Experiment I.- The cascade described above was first tested at zero incidence with a nominal inlet angle of 10°. The actual variation in mean inlet angle α_1, measured across the span one chord upstream of the cascade, is shown in Fig. 2.

Total pressures and outlet angles were measured at a distance of $\frac{1}{2}$-a-chord ($2\frac{1}{2}$") downstream of the blade trailing-edges at close intervals over the width of a blade passage. Also in Fig. 2 the mean outlet angles, α_2, are given; these have been averaged over a blade passage, and are compared with those mean values predicted theoretically for a similar cascade and an inlet velocity distribution given by equation (2).

Figs. 3(a) and 3(b) show total pressure contours $\frac{1}{2}$-a-chord downstream of the cascade for the ranges $-\ell \leqslant y \leqslant 0$ (constant camber) and $0 \leqslant y \leqslant \ell$ (twisted) respectively.

The Reynolds number based on the blade chord and the mean upstream centre line velocity was approximately 2.5×10^5.

Experiment II.- While the Reynolds number and inlet velocity distribution were maintained as nearly as possible the same as for the previous test, the incidence here was increased to 20°. Total pressures both upstream and downstream of the cascade were measured and Figs 4(a) and 4(b) show the downstream total pressure contours.

Pressure Losses/

Pressure Losses

It is not easy to evaluate a mean total pressure to give a fair comparison between the constant camber and twisted halves of the cascade. The trouble arises partly because of the use here of asymmetric blades, with a consequent asymmetry in the mass flow downstream. Even if two cascades had been made, however, and tested separately, there would still have been a difficulty due to the change in contraction, and with it the static pressure rise.

Fig. 5 shows a mean total pressure H defined by the integral

$$H(y) = \frac{1}{sU_m} \int_0^s h \; V \; dx$$

where x is the distance across the blade passage and h and V are respectively the total pressure and axial velocity at the point (x, y).

Three curves in all are given showing values of H upstream and downstream of the cascade for the case where the incidence is 20°. The slightly greater mass flow on the twisted side accentuates the difference between the two downstream sections but even so, the decrease in total pressure - represented by the change in H from its upstream to its downstream value - cannot be regarded as anything but significant. Inspection of Figs. 4(a) and 4(b) might lead one to this conclusion qualitatively; the distortion of the total pressure surfaces is far more advanced downstream of the constant camber blades and separation on this side seems to be imminent. A similar inspection of Figs. 3(a) and 3(b) leads one to suppose that at low incidences the modification to the blades has little effect on pressure losses, the changes in outlet angles may however improve conditions at a second blade row.

Discussion

In discussing the experimental results there are clearly two aspects to consider. Firstly there is the problem of outlet angle variation, and secondly that of pressure losses, and separation effects.

The low deflection cascade which has been used was designed in a conservative way so as fairly to test a first-order theory for describing secondary flows in cascades of twisted blades. At low incidence it appears from Fig. 2 that some control of the spanwise variation in outlet angle may be achieved by reducing the blade camber in accordance with the velocity distribution; the agreement between theory and experiment seems satisfactory under these very restricted conditions. The theory claims no great change in perturbation velocities, but it forecasts a decrease in the value of the circulation about the blade for the uncambered tips. This latter result leads one to hope that tip-stalling may be delayed for blades modified in this way.

Reducing the camber to zero at the wall appears to have more than corrected the overturning effect due to the secondary flow. The results suggest that a wall value of 5° (half the centre-line value) might have led to greater uniformity over the whole span.

At low incidence, losses everywhere remain small and there then appears to be no appreciable difference between the value of the mean total pressure H for the constant camber and twisted halves of the cascade. With increased incidence the advantage of the uncambered tips becomes apparent, however, as is evidenced by Figs. 4 and 5. Even if the

original/

original aim of these experiments - namely the reduction of the spanwise variation of outlet angle - is no longer attained, the tendency to delay the corner separation is ample justification for controlling the secondary flow in this way.

Conclusion

In spite of the limitations of the present experiments, the results are encouraging and may lead to a method of improved blade design. The theoretical concern for inlet flows with velocity variations of considerable extent (as opposed to thin wall boundary-layers) is probably important, but the restriction to low-deflection cascades could well be relaxed. Experiments with cascades of more practical significance - 30° or 40° camber say, with the corresponding reduction of camber to 15° or 20° at the wall - should prove instructive, particularly if they can be tested over a range of incidence to show outlet angle variations, pressure losses and separation effects. It would also be useful to know whether the control of outlet angles is reflected in the pressure losses at a succeeding blade-row.

As a result of a cascade experiment with uncambered blade tips, Whitehead (1954) recommended that such a modification should be applied to a compressor. The present tests endorse this conclusion; they also give some confirmation to secondary flow theory and this may help in the future design of twisted blades.

References

No.	Author(s)	Title, etc.
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2	Moira E. Martin	Secondary flow in a cascade of twisted blades. Unpublished report. 1958.
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5	D. S. Whitehead	Unpublished report. 1954.

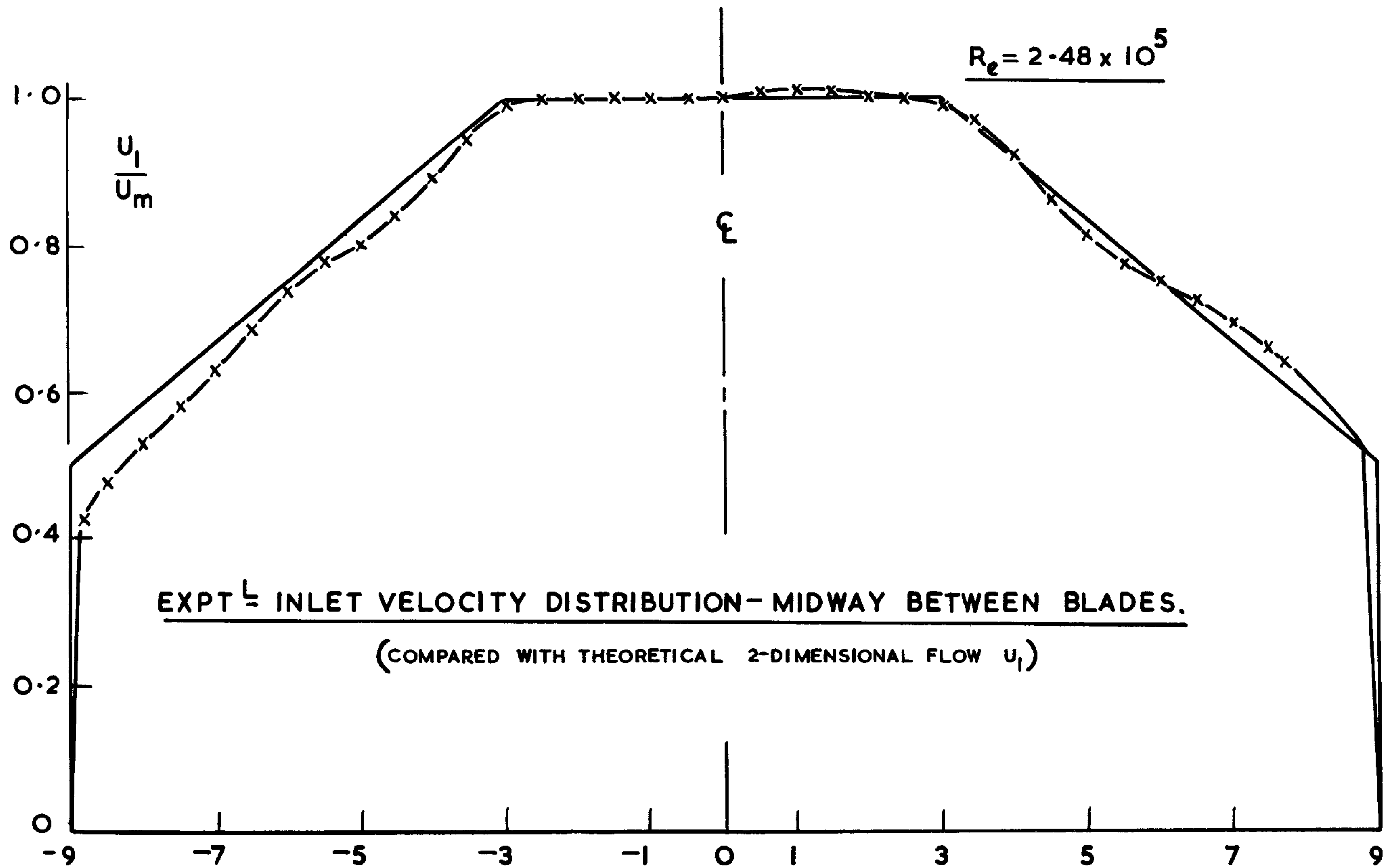
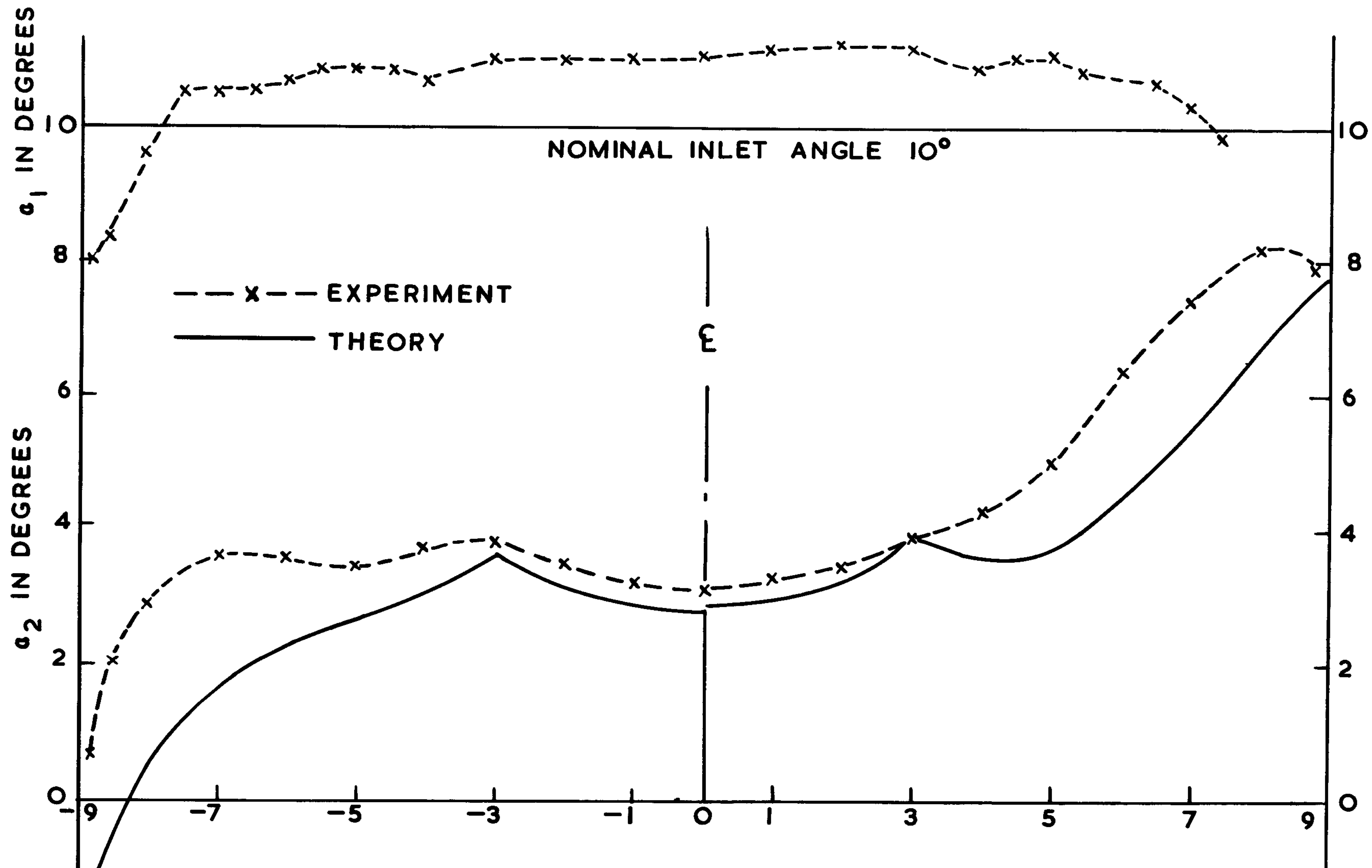

$R_e = 2 \cdot 48 \times 10^5$
1·0
0·8
0·6
0·4
0·2
0
$\frac{U_1}{U_m}$
℄
EXPT^L INLET VELOCITY DISTRIBUTION – MIDWAY BETWEEN BLADES.
(COMPARED WITH THEORETICAL 2-DIMENSIONAL FLOW U_1)
−9
−7
−5
−3
−1
0
1
3
5
7
9

FIG. 1.



MEAN OUTLET ANGLES COMPARISON BETWEEN THEORY AND EXPERIMENT.

FIG. 2.

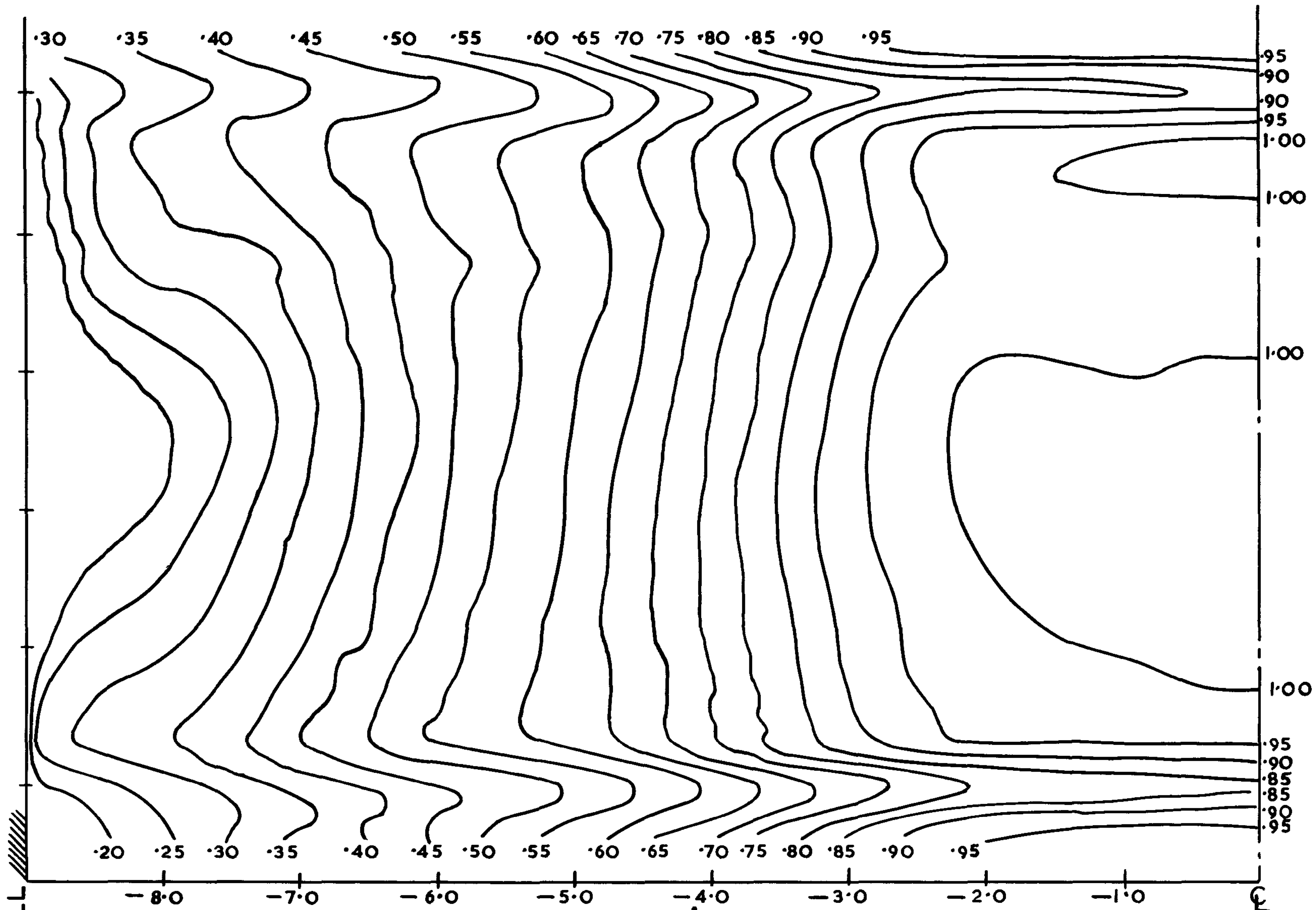


FIG. 3a. TOTAL PRESSURE CONTOURS AT HALF A CHORD'S DISTANCE DOWNSTREAM OF CONSTANT CAMBER BLADES (CASCADE AT ZERO INCIDENCE) PRESSURE AS FRACTION OF MEAN ℄ VALUE.

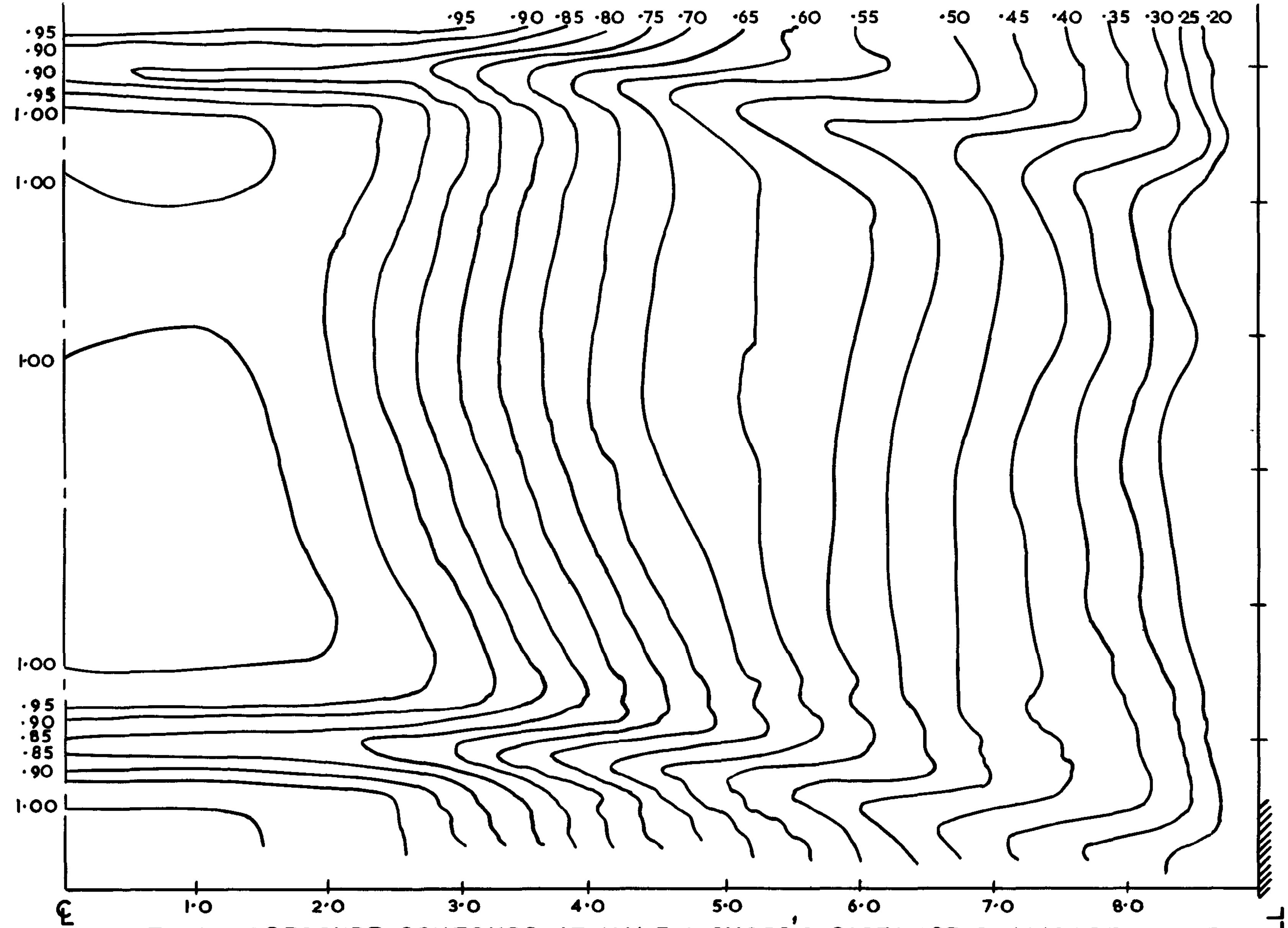
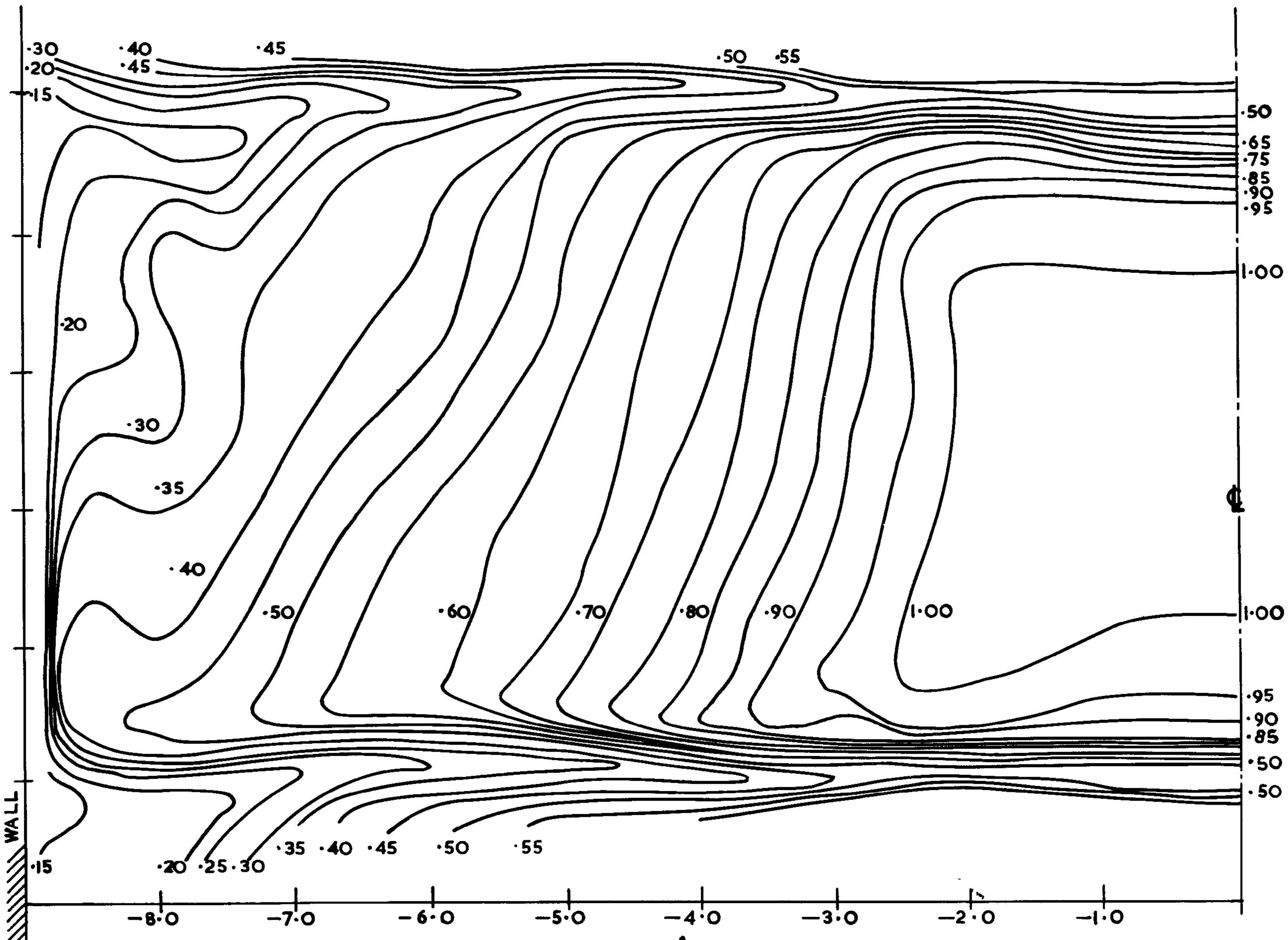
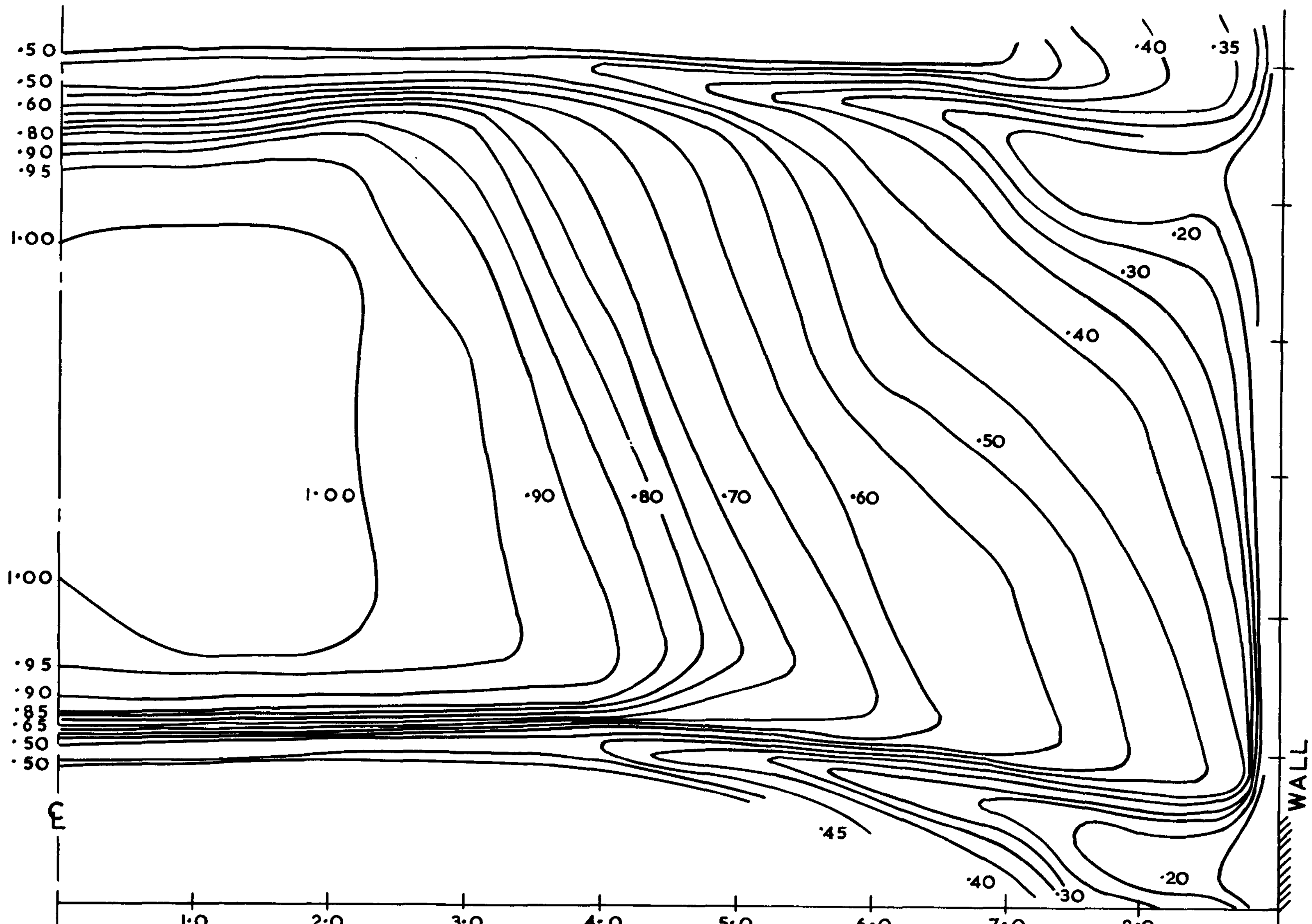


FIG.3b. TOTAL PRESSURE CONTOURS AT HALF A CHORD'S DISTANCE DOWNSTREAM OF TWISTED BLADES (CASCADE AT ZERO INCIDENCE) PRESSURE AS FRACTION OF MEAN ℄ VALUE.



TOTAL PRESSURE CONTOURS AT HALF A CHORD'S DISTANCE DOWNSTREAM OF CONSTANT CAMBER BLADES. (CASCADE INCIDENCE 20°) PRESSURE AS FRACTION OF MEAN ℄ VALUE.

FIG. 4 a.



TOTAL PRESSURE CONTOURS AT HALF A CHORD'S DISTANCE DOWNSTREAM OF

FIG. 4 b. TWISTED BLADES (CASCADE INCIDENCE 20°) PRESSURE AS FRACTION OF MEAN ℄ VALUE

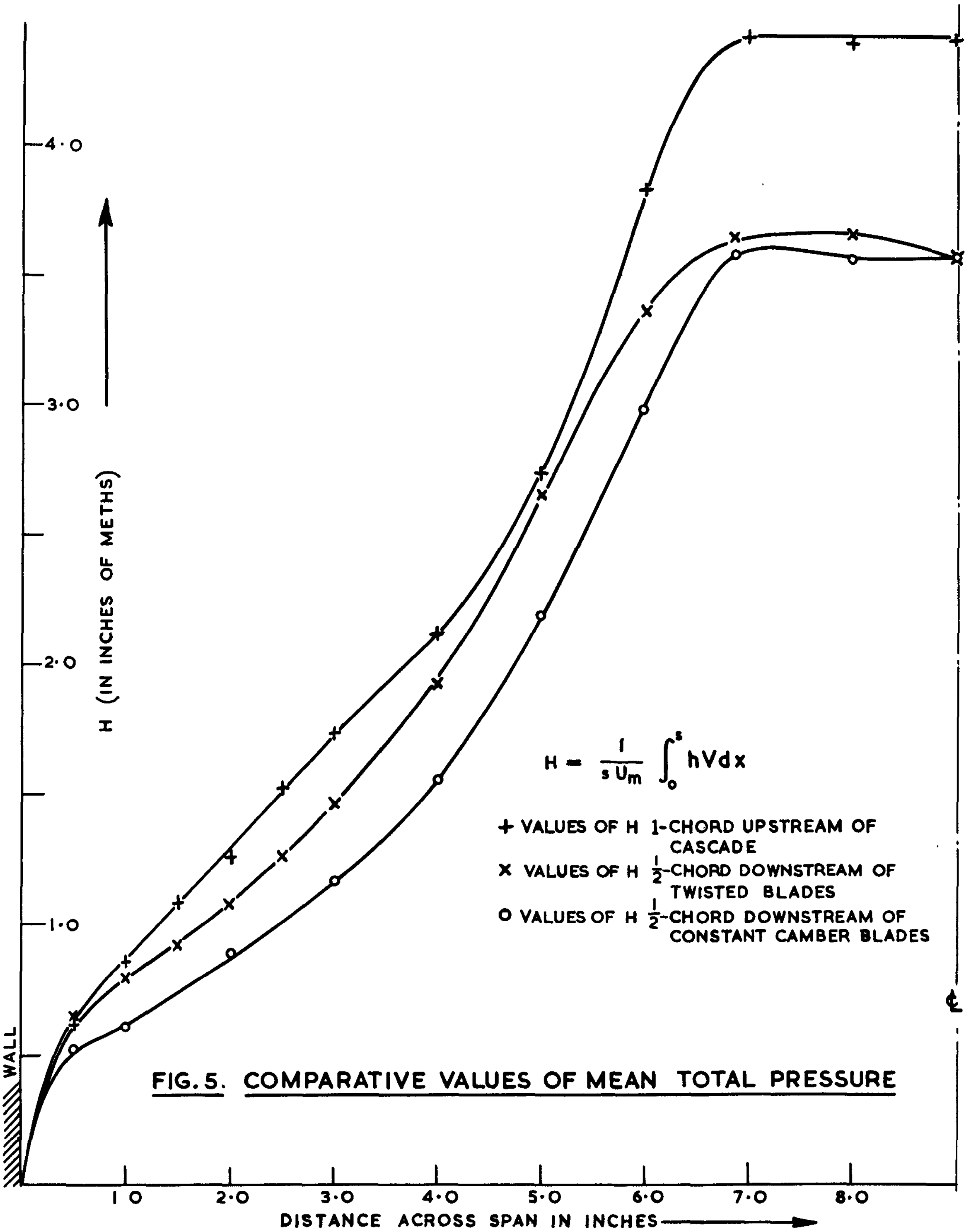


FIG. 5. COMPARATIVE VALUES OF MEAN TOTAL PRESSURE

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