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A BRIEF INVESTIGATION OF THE TWO-DIMENSIONALITY OF THE FLOW OVER AN AEROFOIL IN THE RAE 8ft × 6ft TRANSONIC WIND TUNNEL

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P. H. Cook
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SUMMARY

Oilflow on the surface and pitot pressure measurements in the wake of a 0.762m chord aerofoil in the RAE 8ft × 6ft tunnel indicate that there is no significant spanwise convergence or divergence of the flow within the boundary layer and wake of the model. The measurements were made at subsonic conditions where no regions of separated flow existed on the model, but where significant subsonic drag creep had previously been measured.

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1 INTRODUCTION

In some instances differences between turbulent boundary-layer calculations and wind-tunnel measurements have been attributed to the possibility of three-dimensionality in the wind-tunnel flow (*eg* Refs 1 and 2). One may therefore question the significance in similar comparisons of any three-dimensionality of the flow existing over the model in the 'two-dimensional test rig' of the RAE 8ft × 6ft (2.43m × 1.83m) transonic wind tunnel. In order to assess the degree of convergence or divergence of the flow, obstacles were mounted on an aerofoil, the paths of the disturbances from which could be traced by oilflow on the surface and by pitot pressure measurements in the wake of the aerofoil. The aerofoil chosen for these tests was known, from previous experiments in the RAE 8ft × 6ft wind tunnel[3], to have significant subsonic drag creep (at conditions where the flow was everywhere attached to the aerofoil) which was not predicted by calculation[4] and could not be attributed to flow separation. A similar magnitude of drag creep could be obtained either from measurements by drag rake at $x/c = 2.75$ or could be deduced from measured values of boundary-layer momentum thickness at $x/c = 0.95$.

2 TEST CONDITIONS AND METHOD

The model was an unswept, constant chord, supercritical-type aerofoil mounted vertically in the working section. The tests were made at free stream Mach numbers of 0.6 and 0.72 at a geometric angle of incidence of 1.01 degrees and a Reynolds number of 8×10^6 based on the chord of 0.762 m. The boundary layer was artificially tripped at 7% chord with 0.2mm diameter ballotini. These test conditions approximated closely to those at which the earlier measurements[3] of subsonic drag creep were shown to be substantially greater than predicted by the viscous transonic small perturbation calculation method[5]. Up to $M_\infty = 0.72$ the local flow was subsonic except in a small region $(0.05 < (x/c) < 0.10)$ on the upper surface (see Fig 2). The photographs of oilflow, shown in Figs 4a to 7a, indicate that although the flow over the model is close to separation, the flow is attached except possibly on the upper surface at $M_\infty = 0.72$ (Fig 6a) where some indication of separation is apparent at $x/c \simeq 0.98$. This is most likely to have been induced by the disturbance used to trace the flow across the aerofoil, as previous tests[3] demonstrated attached flow to the trailing edge at free stream Mach numbers up to 0.74 at otherwise identical test conditions.

Disturbances were introduced into the boundary layer at $x/c = 0.23$ by circular cylinders with their axes normal to the surface at points 0.27c above and 0.6c below the centre line of the working section on both the upper and lower surfaces of the aerofoil. The cylinders were 3.18 mm in diameter and projected 19 mm above the surface (see Fig 3).

Within the boundary layer these disturbances do not take the form usually associated with the free wake of a circular cylinder normal to an airstream. Instead, as is shown by Bradshaw (see Fig 27 of Ref 6) the interaction with the boundary layer in the junction produces a 'horseshoe' vortex ahead of the cylinder and extending downstream into the wake of the cylinder. The pattern associated with the two downstream legs of this vortex system (see Fig 3) is the most readily identified feature of the photographs of oilflow presented in Figs 4a to 7a. In Fig 6a there is an additional feature which appears to be a shock wave originating at the cylinder on the upper surface of the aerofoil at $M_\infty = 0.72$.

The effect of the cylinders on the flow over the aerofoil varied considerably with the local chordwise surface pressure distribution, but was restricted to a relatively small proportion of the span of the model (see Figs 4a to 7a). Although large local angular deflections of the flow, of the order of 10 degrees, were caused by these vortices, the surface oilflow pattern from each cylinder is reasonably symmetrical, and the mean line between each leg of the 'horseshoe' vortex is believed to delineate the direction of the undisturbed flow.

2.1 Oilflow technique used to trace the wake from the disturbances

The surface streamline patterns indicated by the mixture of titanium oxide and castor oil were photographed during the tunnel run on $2\frac{1}{4}$ inch (57 mm) square film by remote-controlled, fixed position cameras. To assist with the analysis, photographs were also taken of a reference grid with the cameras in the positions used to take the oilflow photographs. The 26.67mm square grid was produced photographically on a 'stable-base' paper as white lines on a matt-black background. The grids were attached to the surface of the aerofoil with a double-sided adhesive membrane so that they closely followed the profile of the aerofoil with the lines parallel and normal to the chord of the model. The reference grids were required to correct for the unavoidable distortion of the oilflow in the photographs due to the constraints on the positions of the cameras imposed by the construction of the wind tunnel working section. Combined prints of the grid and the oilflow (Figs 4a to 7a) were made by superimposing the images from two negatives. Considerable emphasis was put on the accurate registration of the grid and the oilflow.

2.2 Pitot measurements used to trace the disturbances in the wake of the aerofoil

To trace the disturbance downstream of the trailing edge of the aerofoil a pitot traverse was necessary. The pitot pressure measurements were made with a 1mm OD tube mounted on a 0.318m arm from the tunnel centre-line model support rig. The arm could be rotated to any position across the wake of the aerofoil and also traversed in a spanwise direction. The pitot pressure was measured on a fast response differential pressure transducer mounted in the support centre-line rig. Plenum pressure was used as a reference and a calibration was obtained by applying known pressures to the reference tube via the standard Midwood capsule manometer calibrating and leak testing system.

3 RESULTS

The aerofoil surface pressure distributions for the conditions at which the measurements were made are shown in Figs 1 and 2. The flow about the aerofoil is everywhere subsonic except between about 0.05c and 0.1c on the upper surface at $M_\infty = 0.72$, see Fig 2. Figs 4 to 7 show the oilflow and pitot pressure measurements for both the upper and lower surfaces of the aerofoil and for the two Mach numbers. The oilflow photographs have reference grids superimposed to permit readily an assessment of any departure of the flow from the chordwise direction in the surface of the model. The centre-lines of the oilflow patterns follow closely the chordwise grid lines which pass through the cylinders. Any deviation is progressively towards the tunnel floor (*ie* the bottom of the photographs) as the trailing edge is approached and is always less than a degree. This applies for all the cylinders on either aerofoil surface and both the Mach numbers tested. The downward deviation might have been attributed to a gravitational effect on the oilflow but that a similar downward deviation is observed from the pitot measurements in the wake.

The pitot pressure measurements were made in the outer half of each side of the aerofoil wake. The pressures were unsteady when the disturbances from the cylinders were encountered, but nevertheless a characteristic pattern for the spanwise variation in pressure associated with a 'horseshoe' vortex, as previously observed in preliminary trials on the wall of the RAE 2ft × 1½ft (0.61m × 0.46m) transonic wind tunnel, was recognisable. The pitot measurements have been plotted in Figs 4b to 7b, for positions in the wake at $x/c = 1.025$, 1.25 and 2.0, in the form of a change in pressure (ΔC_p) relative to the pressure in the aerofoil wake away from the influence of the cylinders. For the measurements at $x/c = 1.025$ the cylinders on both the upper and lower surfaces were present when the measurements were made. However when the measurements were made at $x/c = 1.25$ and 2.0 only the two cylinders on the side of the wake being investigated were installed in order to avoid the possibility of deflection of the disturbances due to mutual interference. For each series of streamwise positions examined, the spanwise separation of the two minima in pitot pressure associated with the 'horseshoe' vortex is approximately constant and about equal to the width of the disturbance in the oilflow at the trailing edge of the aerofoil. The centre-lines of the disturbances from the cylinders in the boundary layer at $x/c = 1.0$ are shown in Figs 4b to 7b. The magnitude of the flow deflection involved is readily appreciated by comparison with the dotted line representing a flow deflection of 1 degree from the location of the cylinders.

4 CONCLUSIONS

The tracing of disturbances induced into the turbulent boundary layer of an aerofoil in the two-dimensional working-section of the RAE 8ft × 6ft (2.43m × 1.83m) transonic wind tunnel has shown that the spanwise deflection of the flow in both the boundary layer and the wake was always less than 1 degree and normally about 0.5 degree at least for test conditions where the attached flow was sensibly sub-critical. The flow deflections measured each side of the centre-line of the tunnel have the same magnitude and sign (*ie* with the spanwise component from roof to floor) and any convergence or divergence of the flow within the boundary layer or wake is small ($\ll 1$ degree) and below the magnitude that can be measured by this technique.

Acknowledgment

The photographic techniques employed in these experiments, including the setting-up of the cameras and lighting, producing the reference grid, and the combined printing of the oilflow and grid negatives were developed with the generous assistance of Printing Department, RAE.

LIST OF SYMBOLS

c	chord length
C_p	pressure coefficient
C_p^*	critical pressure coefficient
M_∞	free stream Mach number
Re	Reynolds number based on chord length
x	chordwise distance downstream of the leading edge
y	spanwise distance, positive towards tunnel roof
α	geometric incidence (degrees)

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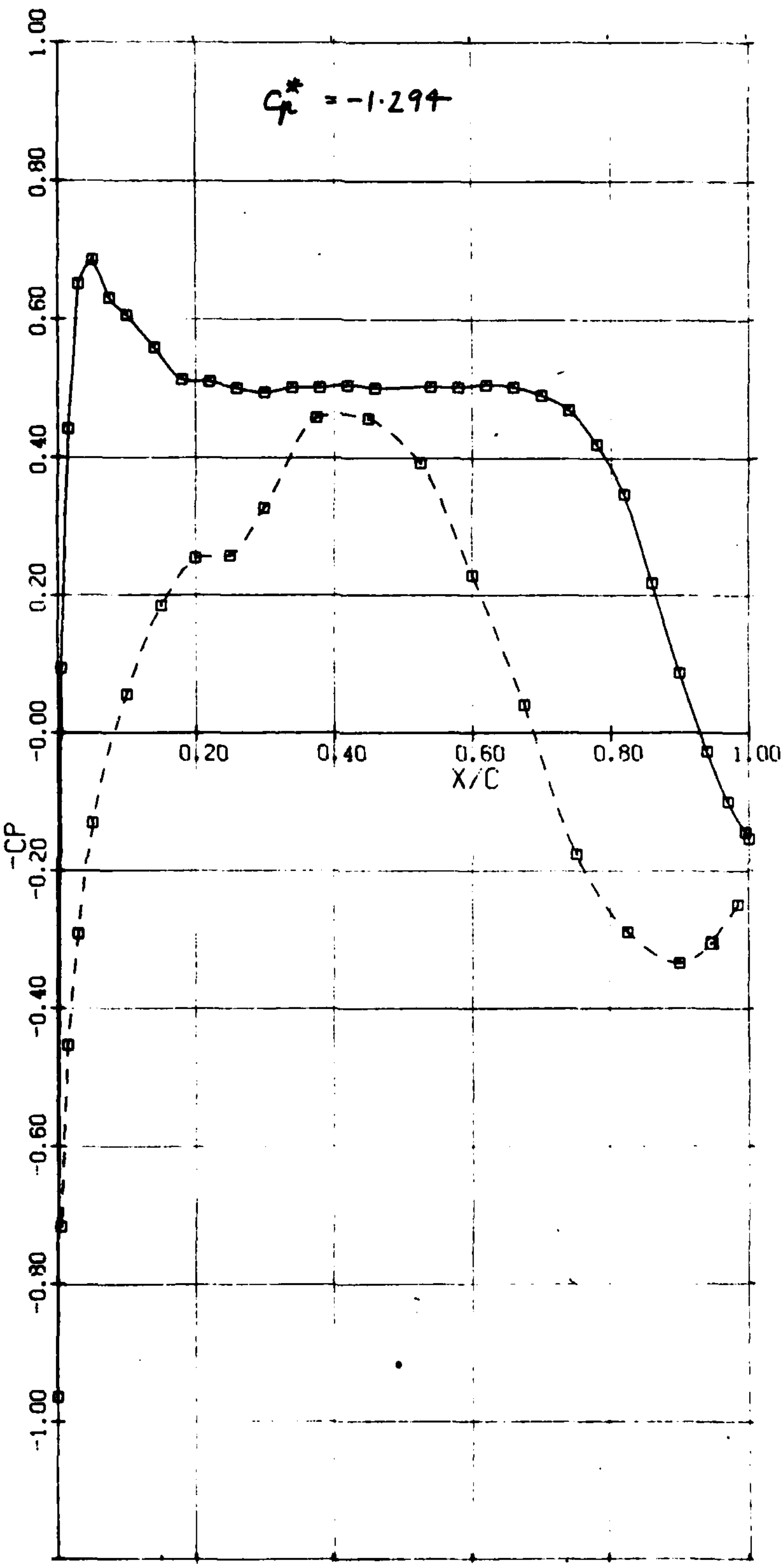

Fig 1 Surface pressure distribution at M_∞ = 0.60

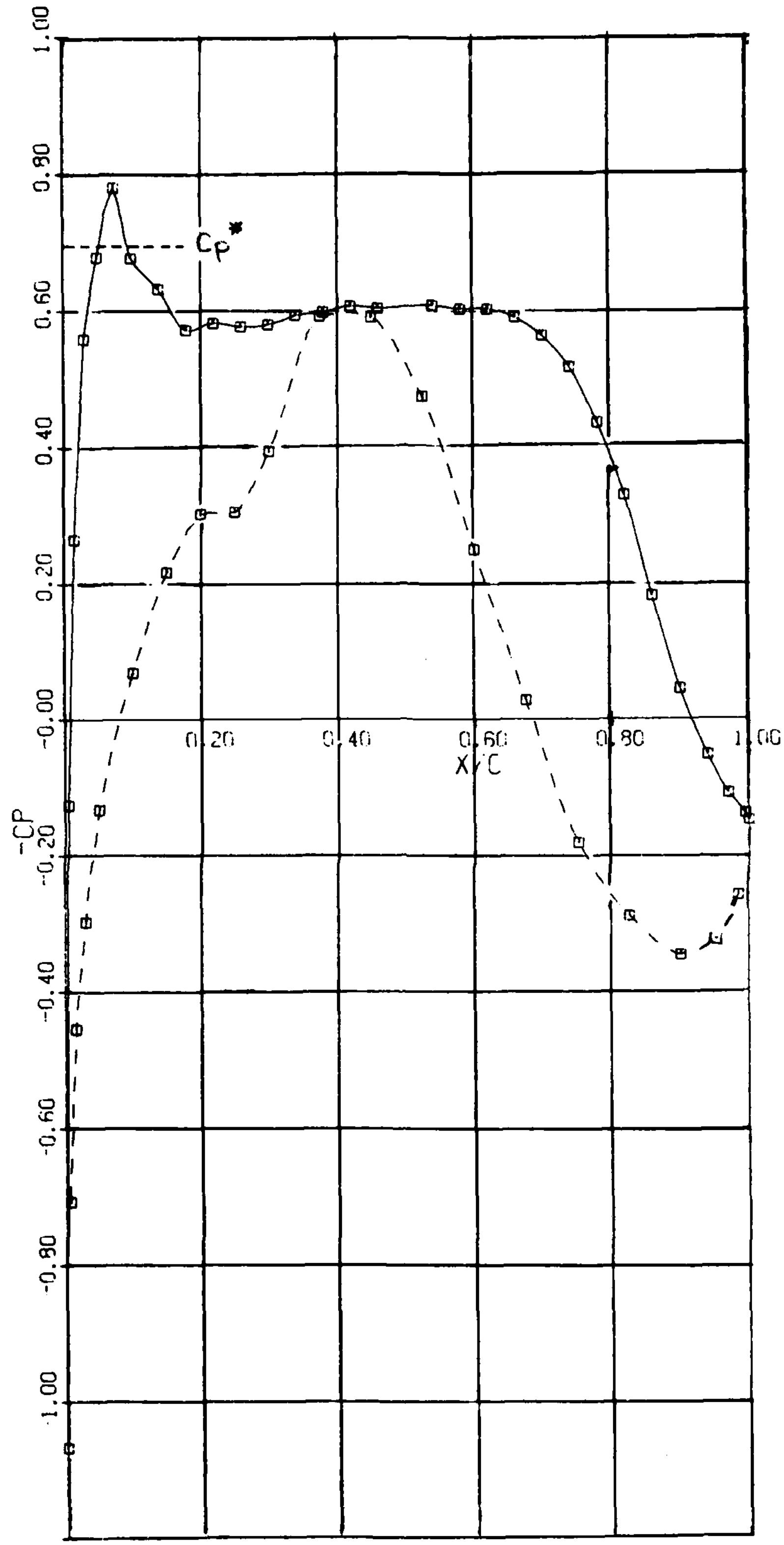

Fig 2 Surface pressure distribution at $M_\infty = 0.72$

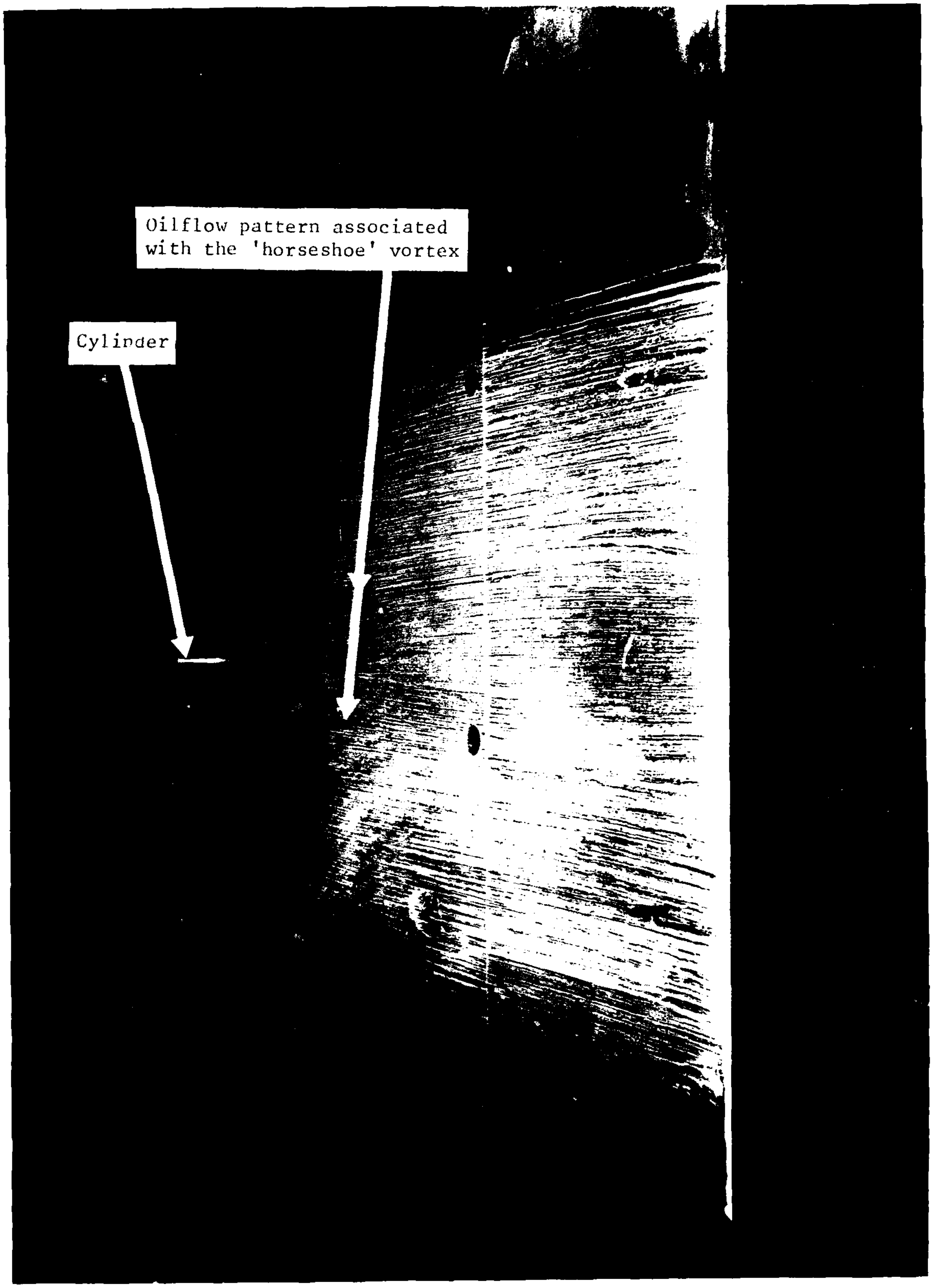

Fig 3 Typical oilflow pattern downstream of a circular cylinder at M_∞ = 0.6 on the upper surface (wind off)

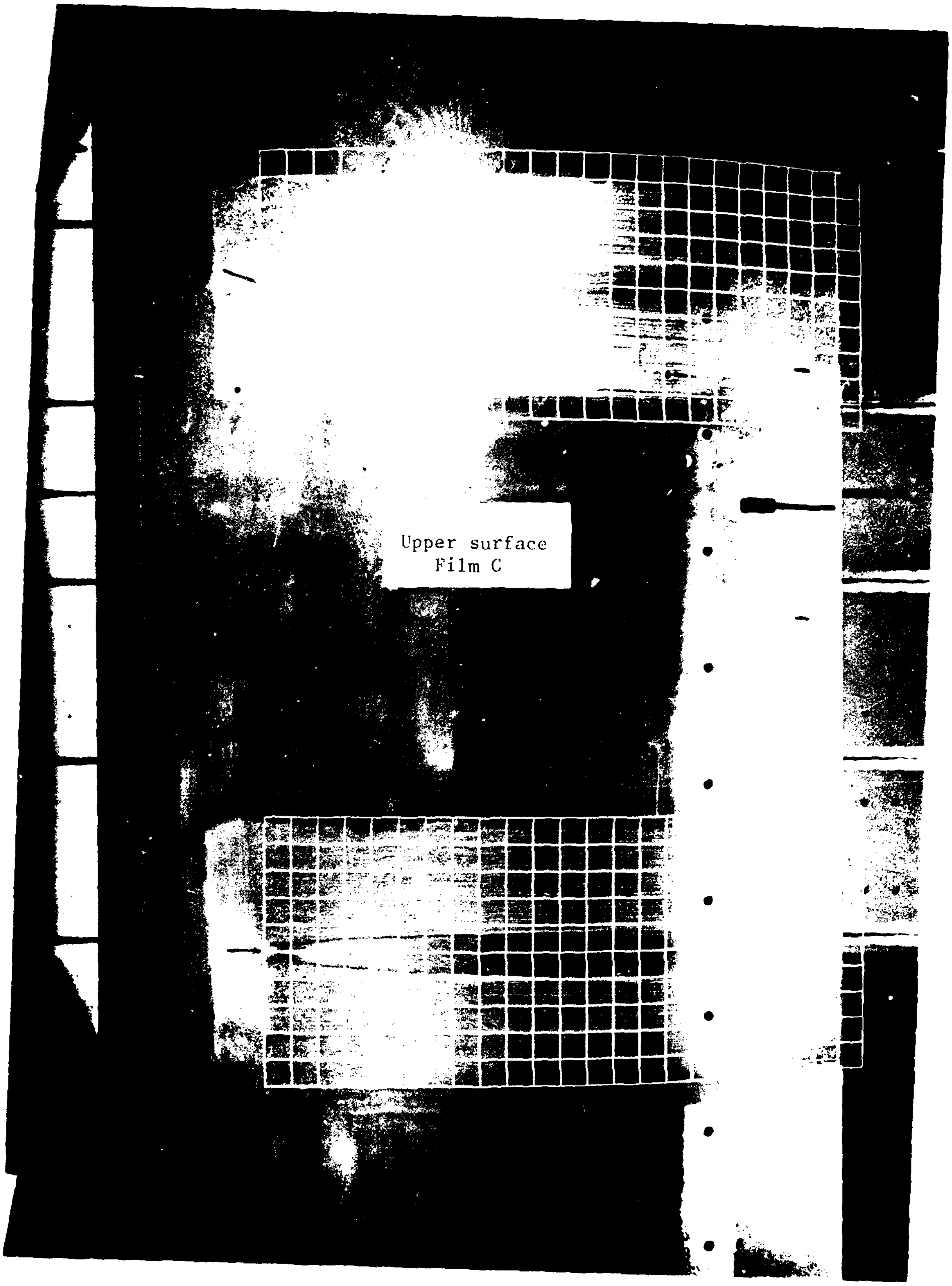

Fig 4a Oilflow on upper surface at $M_\infty = 0.6$

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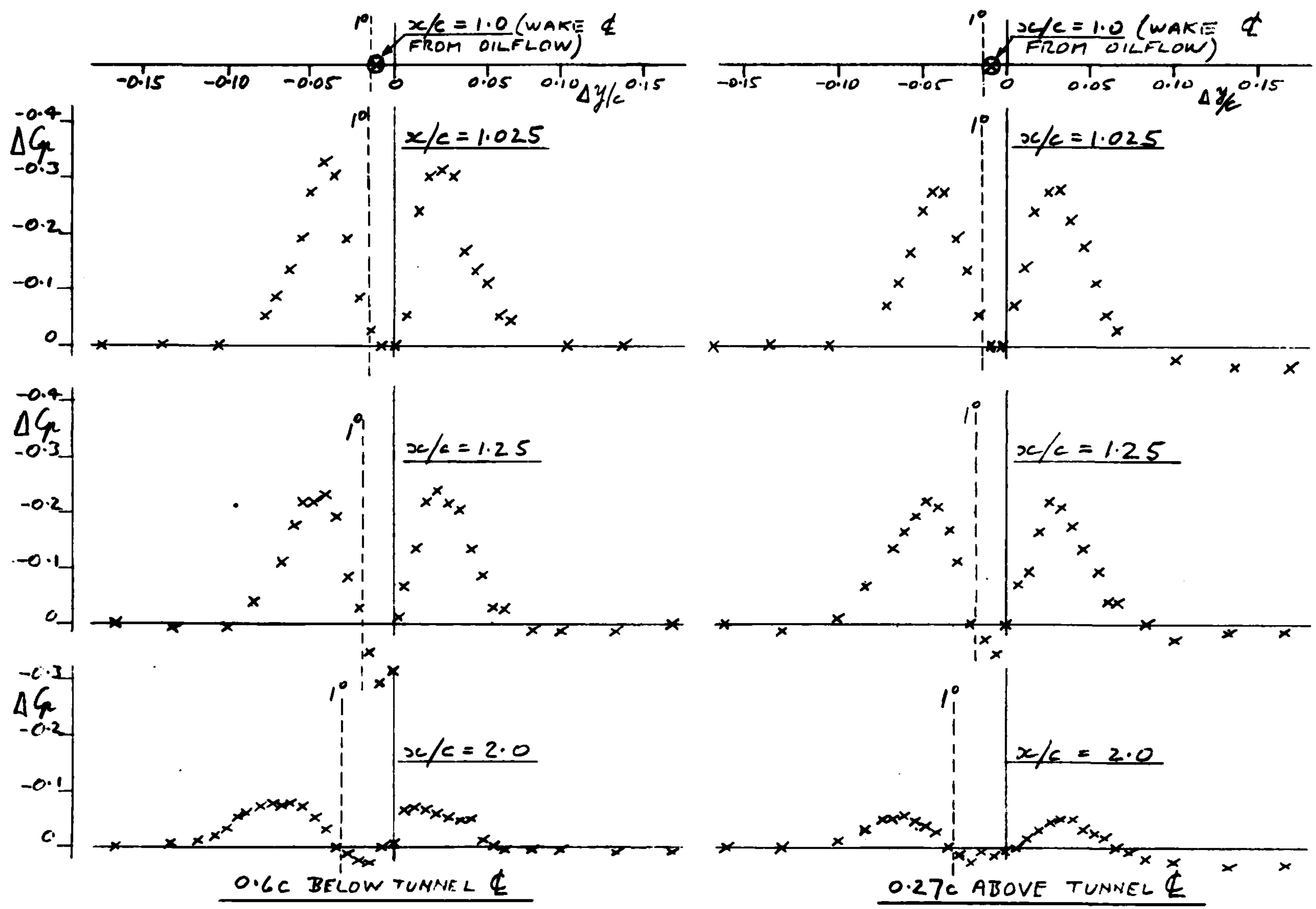

Fig 4b Pitot pressures downstream of the cylinders on the upper surface side of the wake at $M_\infty = 0.6$

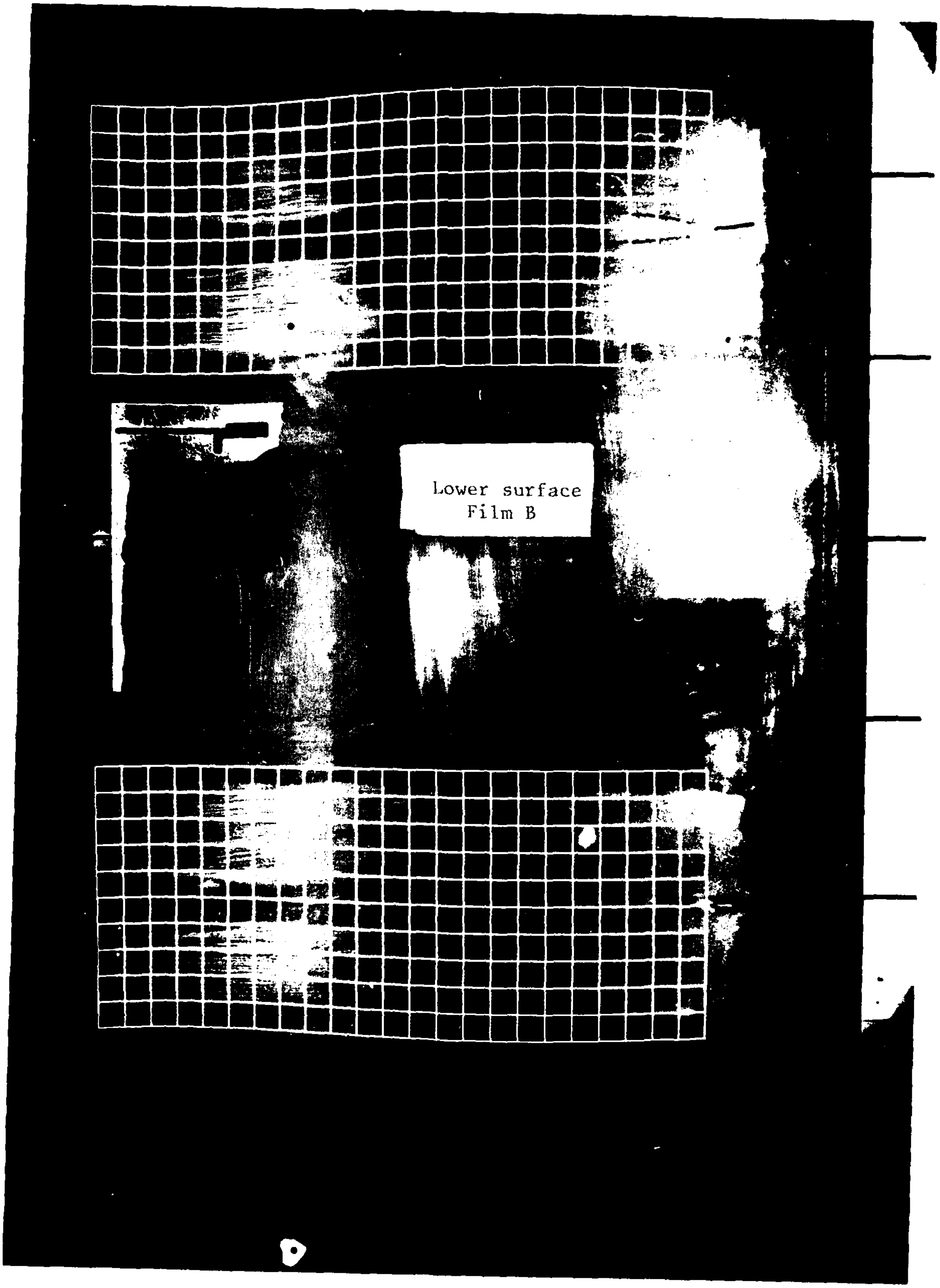

Fig 5a Oilflow on the lower surface at $M_\infty = 0.6$

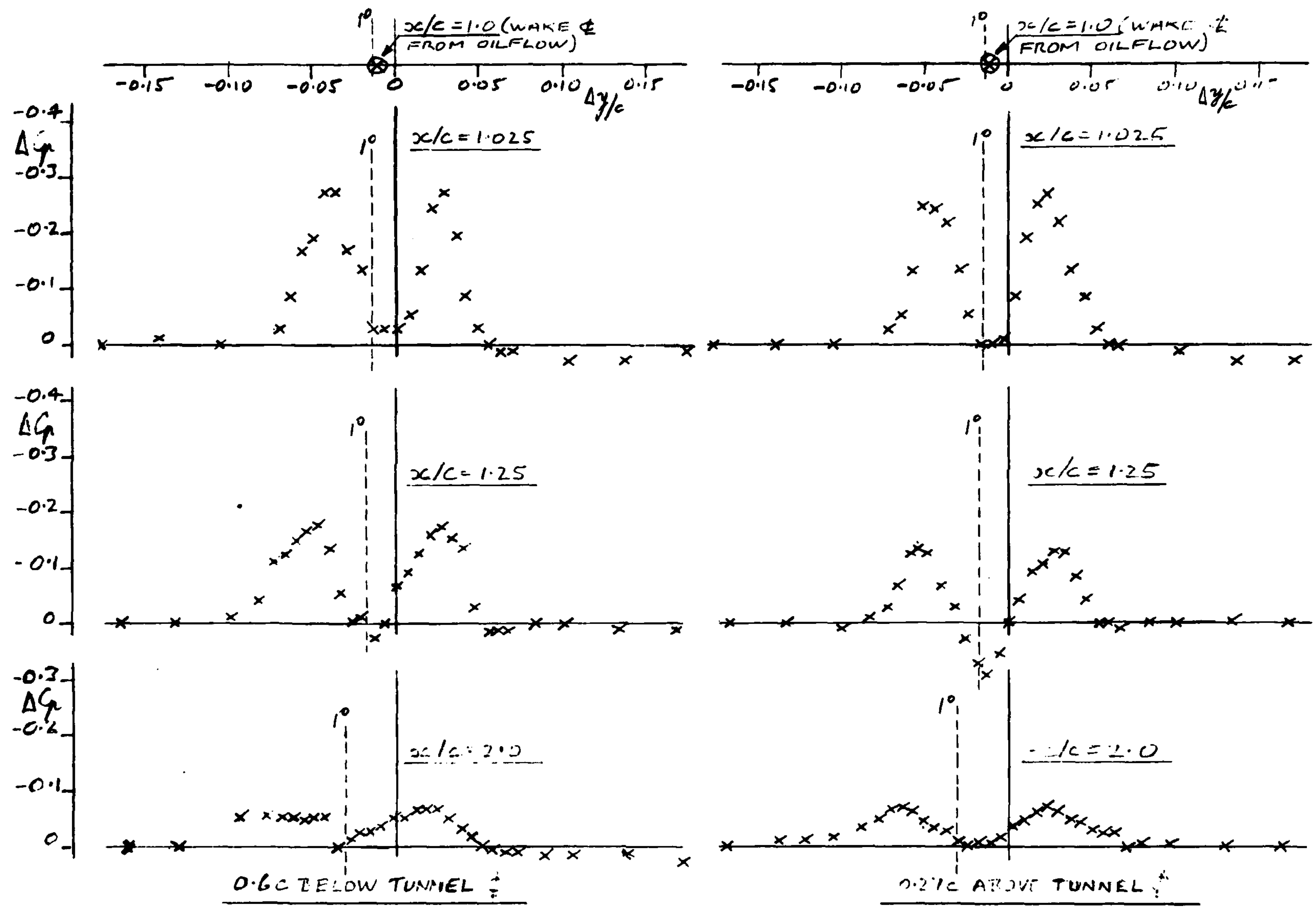

Fig 5b Pitot pressures downstream of the cylinders on the lower surface side of the wake at $M_\infty = 0.6$

Fig 6a Oilflow on the upper surface at $M_\infty = 0.72$

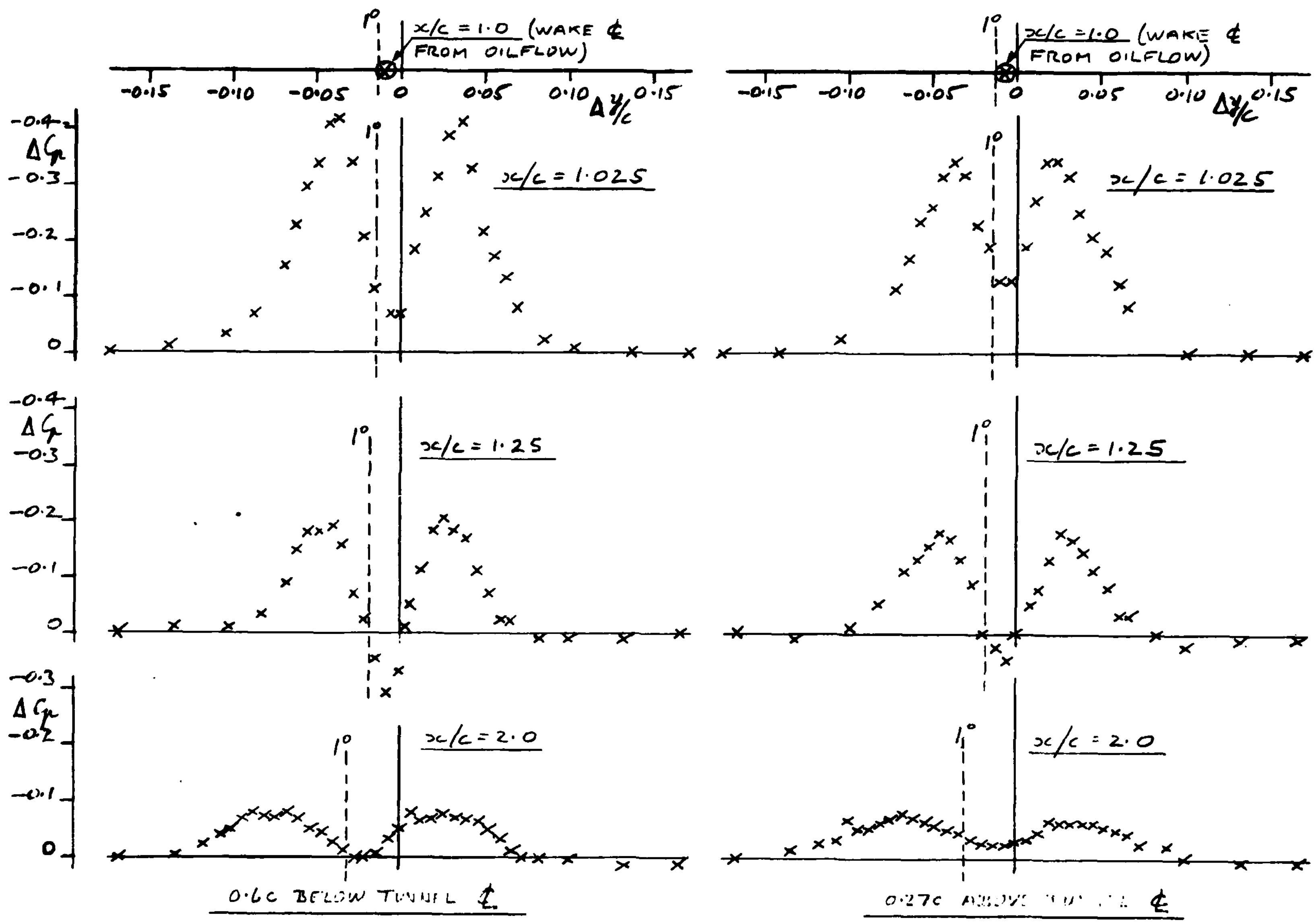

Fig 6b Pitot pressures downstream of the cylinders on the upper surface side of the wake at $M_\infty = 0.72$

Fig 7a

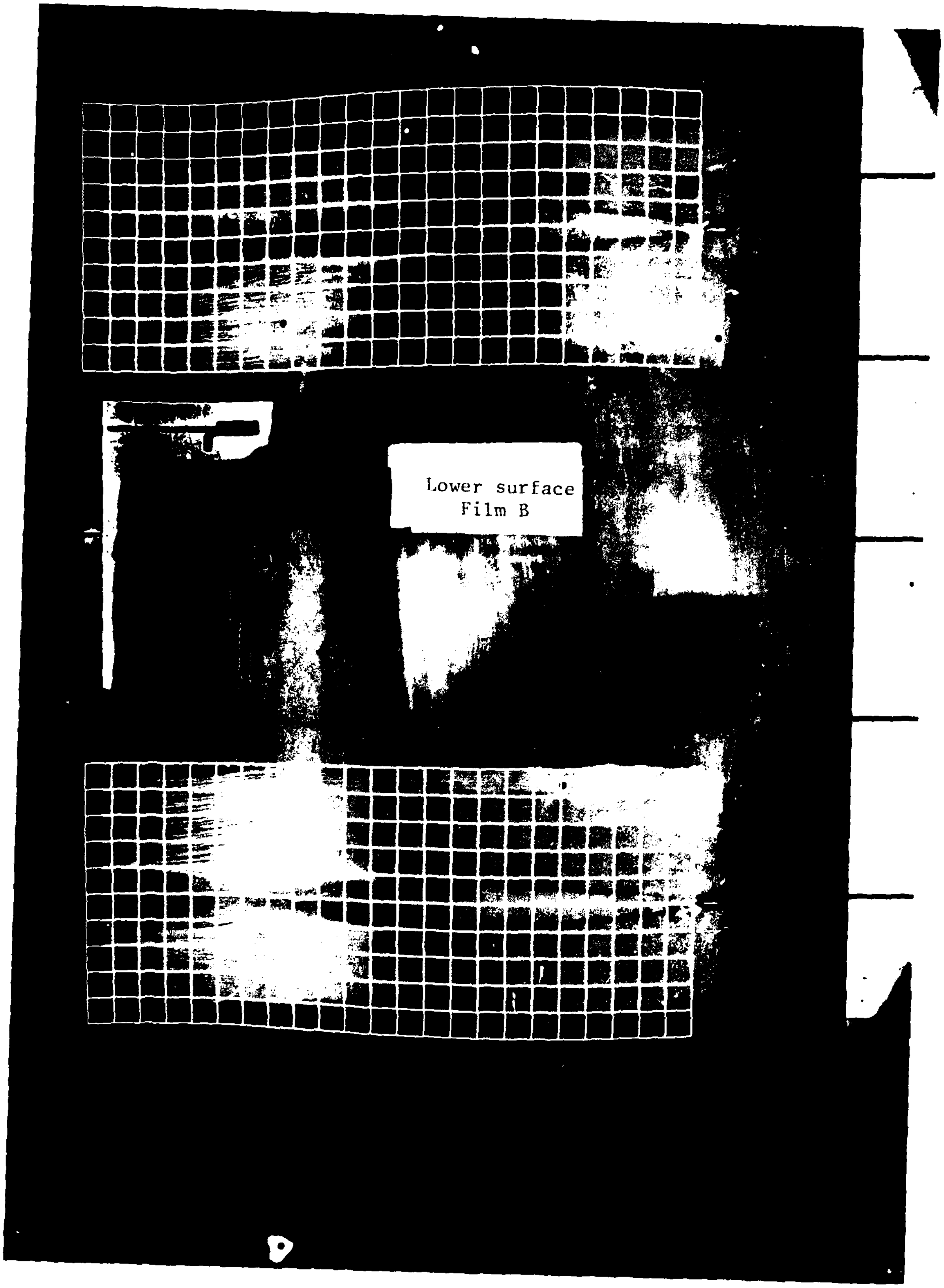

Fig 7a Oilflow on the lower surface at $M_\infty = 0.72$

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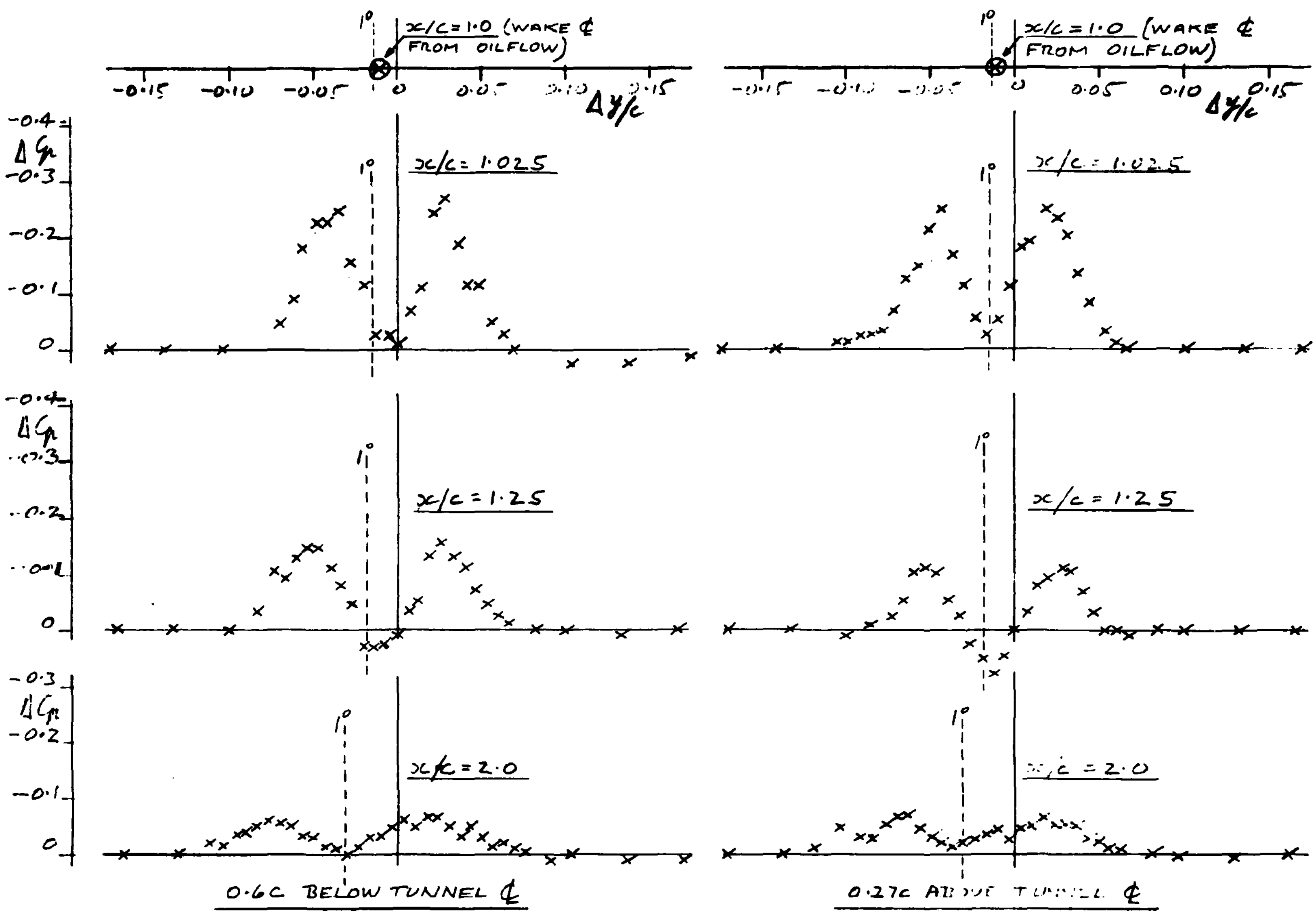

Fig 7b Pitot pressures downstream of the cylinders on the lower surface side of the wake at $M_\infty = 0.72$

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17. Abstract

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