transfer boundary-layer conditions prevailing. When compared with the dissolution data of Kramers and Kreyger [4] plotted in $\bar{S} - L^{+}$ form, the present data are less scattered and approximate more closely to the Lévêque line over the range studied.

As Fulford [5] makes clear many values of (Γ/μ) have been suggested at which turbulence may commence, the lower limit generally lying between 250 and 400. Iribarne *et al.* state that their data are well described by the laminar Lévêque solution up to $\Gamma/\mu = 700$ and in the present work no effect of turbulence is noted up to 550. Dukler [6] has criticised the concept of a film being in either purely laminar or turbulent motion and urges that a combined mechanism must always be considered. The fact that only laminar mechanisms have been observed up to $Re = 550$ and 700 does not necessarily conflict with reports of turbulence being detected as low as 250, since the ionic mass transfer is controlled by the region of flow close to the wall.

A number of further experiments were carried out with the leading edge of the electrode at varying distances from the end of the distributor and as close as 2·4 cm from it. As with the Series 2 data of the grid packing work [2] no difference was observed within the limits of experimental error between the performance of these electrodes and those placed further down the plate and this indicates development of the hydrodynamic conditions. The provision of 38·5 cm as entry length by Iribarne *et al.* was therefore over cautious, but did cause their experiments to be performed in the region where ripples had developed, whereas our work was carried out in the pre-rippling section, this fact constituting another fundamental difference between the two researches.

In conclusion we observe an essentially similar liquid–solid falling film mass-transfer behaviour to that of Iribarne *et al.*, using a flat plate system, shorter electrodes, and mass-transfer sections positioned closer to the point of liquid distribution.

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THE INFLUENCE OF STRONG ADVERSE PRESSURE GRADIENTS ON THE EFFECTIVENESS OF FILM COOLING

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NOMENCLATURE

c, mass concentration of helium in secondary air;
$c_f/2$, wall shear stress coefficient, $\tau_S/\rho u_1^2$;
c_P, surface pressure coefficient, $(p_S - p_1)/\frac{1}{2}\rho u_1^2$;
p_S, wall static pressure;
p_1, value of p_S at station 1;
Re_C, injection Reynolds number, $\rho v_S x_C/\mu$;
m, injection ratio, v_S/u_1;
u_G, free-stream velocity;
u_1, value of u_G at station 1;
v_S, average injection velocity;
x, distance measured along the plate;

x_C, length of the porous strip.

Greek symbols
- η, impervious-wall effectiveness, $(c_S - c_G)/(c_C - c_G)$;
- ρ, fluid density;
- τ_S, wall shear stress;
- μ, fluid dynamic viscosity.

Subscripts
- S, pertains to the wall;
- G, pertains to the mainstream;
- C, pertains to the slot;
- 1, pertains to the mainstream in the plane of station 1.

INTRODUCTION

IN PRACTICAL situations, the most important parameters which might influence the adiabatic-wall effectiveness of film cooling include the ratio of the injection velocity to that of the mainstream, the ratio of the density of the injected gas to that of the mainstream, the injection slot geometry and the surface pressure gradient. Previous investigations have yielded considerable information about the first of these parameters (for example, [1–5]), somewhat less about the second and third [6–9] and very little about the last. To the authors' knowledge, only two experimental investigations of the pressure-gradient effect have been reported [10, 11]; and both of these references were concerned with essentially favourable pressure-gradients.

The measurements reported in the present paper were obtained with adverse pressure gradients which were sufficiently severe to cause the boundary layer to separate from the wall. Such severe pressure gradients were employed because the earlier work of Seban and Back [10] and Hartnett *et al.* [11] had indicated that the influence of the pressure gradient was likely to be small (although these earlier experiments were for favourable pressure-gradient conditions). In the present experiments the secondary fluid was injected into the main flow through a strip of porous material placed across the test plate and flush with its surface. Most of the earlier experiments, including those reported in [1–5] and [8–11] were concerned with injection through a slot and tangential to the test plate. There is no reason to suppose that the qualitative effect of a pressure gradient on the film-cooling effectiveness for tangential injection will be different from that for normal injection.

EXPERIMENTAL APPARATUS, PROCEDURE AND CONDITIONS

A sketch of the experimental configuration, showing its layout and main dimensions, is given in Fig. 1. A side wall of the working section of a closed-circuit wind tunnel (vented to atmosphere) was employed as the test plate. The stations along the plate (in the direction of the mainstream flow) at which measurements were made are indicated in Fig. 1 by the numbers 1–10. The removal of any of the plugs, located at stations 2–10, permitted the insertion of a Preston tube [12] for the measurement of wall shear stress: the calibration of Patel [13] was employed. The working section of the wind tunnel was 12-in wide and 8-in high and had an area contraction ratio of 9:1.

An adverse pressure gradient, along the plate, was imposed by a step near the end of the plate as shown in Fig. 1: 3-in and 7-in steps were used to give the two pressure gradients used for the present experiments. The wall static-pressure distributions were recorded through taps which were located at the measuring stations.

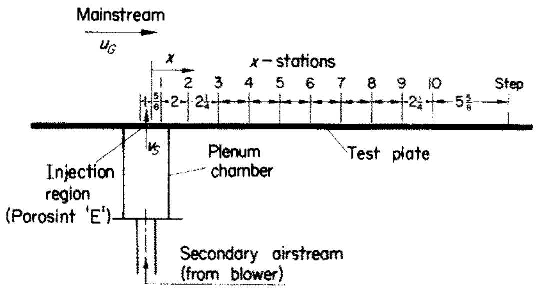

FIG. 1. Layout and main dimensions of test section (all dimensions in inches).

The secondary airstream was injected into the boundary layer on the test plate through a strip of 0·125-in thick Porosint grade E (porous sintered bronze with a porosity of approximately 37 per cent) set across the plate and flush with its surface. The flow rate of the secondary airstream was controlled with an angled seat valve and measured with a standard (BS 1042, 1951) orifice plate.

Measurements of the impervious-wall effectiveness were preferred to those of adiabatic-wall effectiveness for reasons given previously in [5]. To effect these measurements, a tracer of helium gas (about 1 per cent by volume) was injected into the secondary airstream upstream of the secondary blower. Samples of the air/helium mixture were drawn off through the static pressure taps: a sample was also taken from the plenum chamber immediately upstream of the Porosint strip. The concentration of each sample was measured with a Shandon gas chromatograph; the ratio of the helium concentration at any station to that in the plenum chamber is the impervious-wall effectiveness at that station. A detailed description of the technique employed may be found in [14]. It should be remembered, however that the impervious-wall and adiabatic-wall effectiveness are equivalent only if the effective Lewis number is unity: this point has been discussed in detail elsewhere (e.g. [14, 18]).

The mainstream velocity at station 1 (u_1) was adjusted to about 80 ft/s at the beginning of each test: the corresponding mainstream turbulence level was approximately 0·7 per cent. Three injection rates were employed, corresponding to average injection–velocity ratios (v_S/u_1) of 0·023, 0·044 and 0·070. Measurements were recorded with no step (nominally zero pressure gradient) and with both the 3-in and 7-in steps. In the absence of blowing, the boundary layer at station 1 had a momentum thickness Reynolds number of 4100 and a profile shape corresponding with that of a normal flat-plate turbulent boundary layer.

EXPERIMENTAL RESULTS

Distributions of the surface pressure-coefficient (c_P)

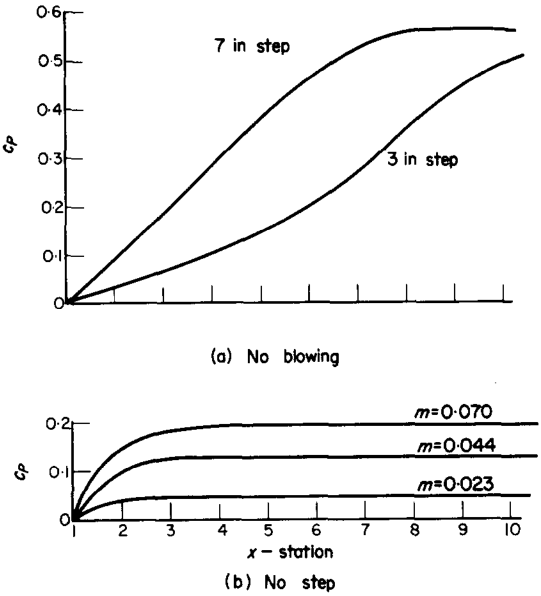

FIG. 2. Distributions of surface-pressure coefficient.

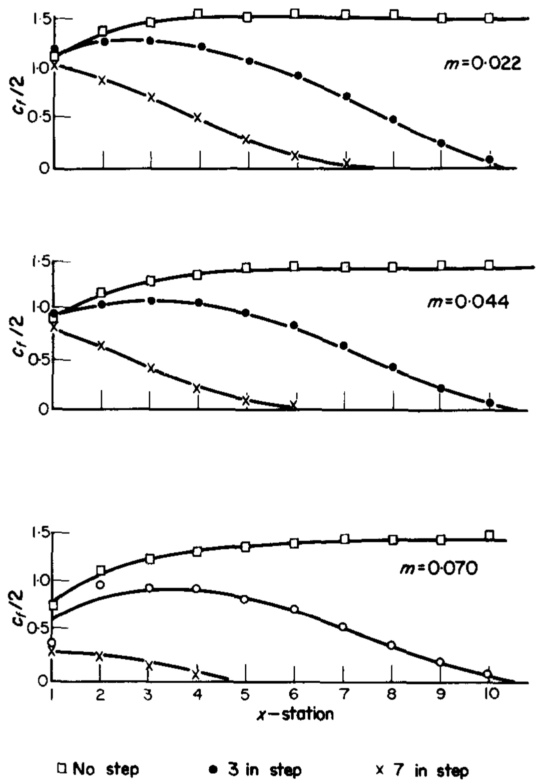

FIG. 3. Distributions of surface shear-stress coefficient.

are shown in Fig. 2. The curves in Fig. 2(a) were obtained in no-blowing conditions, with the 3-in and 7-in step in position. The influence of blowing is to lower the surface pressure (p_S) at stations 1 and 2 as shown by the curves for nominally zero pressure-gradient (no step) in Fig. 2(b).

Measurements of the wall shear stress for each of the three blowing rates and pressure distributions are shown in Fig. 3. These data show clearly the influence of the two adverse gradients. Also apparent, is the large reduction in shear stress brought about by blowing: the position of the separation point is strongly affected by the injection rate. It is important to remember, however, the limitations on the use of the Preston tube. This instrument is unlikely to record accurately the shear stress either near the injection region or near to the step. Nevertheless it is likely that the qualitative indications of Fig. 3 are correct.

The impervious-wall effectiveness (η) for zero pressure-gradient conditions are shown in Fig. 4. In addition to the three values of m ($\equiv v_S/u_1$) noted earlier, results are also presented for values of 0·036, 0·055 and 0·074. These measurements demonstrate the precision with which η can be determined: the maximum deviation from a smooth line is less than 10 per cent. Also clear from Fig. 4, is that η increases monotonically with m.

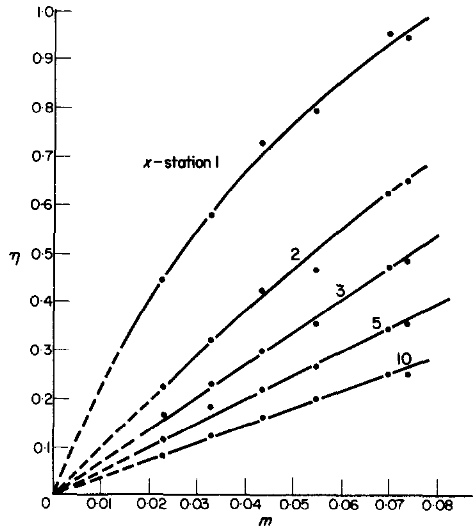

FIG. 4. Variation of effectiveness with injection rate for nominally zero pressure gradient (no step).

The data for zero pressure gradient are also shown in Fig. 5, together with those from the two pressure-gradient experiments. The curves on this figure are given as datum lines from which to view the plotted data: they represent the correlation equation recommended by Goldstein *et al.* [6], i.e.

$$\eta = \{0{\cdot}325\,(4{\cdot}08 + X)^{0{\cdot}8}\}^{-1}$$

where

$$X = (x/mx_C)\,(Re_C)^{-0{\cdot}25}.$$

This equation applies to zero pressure-gradient conditions and was based on data obtained for values of m less than 0·05. The curves do not fit the present zero pressure-gradient data particularly well; the deviations may be attributed to the differences in geometry and porosity of the injection regions. Similar differences may be found between the data contained in [6, 15, 16] and obtained using porous injection regions. The effectiveness measurements of Scesa [17] and of Sivasegaram [18], obtained for vertical injection through an open slot agree with one another but tend to be lower than the measurements obtained with a porous injection-region.

The most significant feature of the data shown on Fig. 5

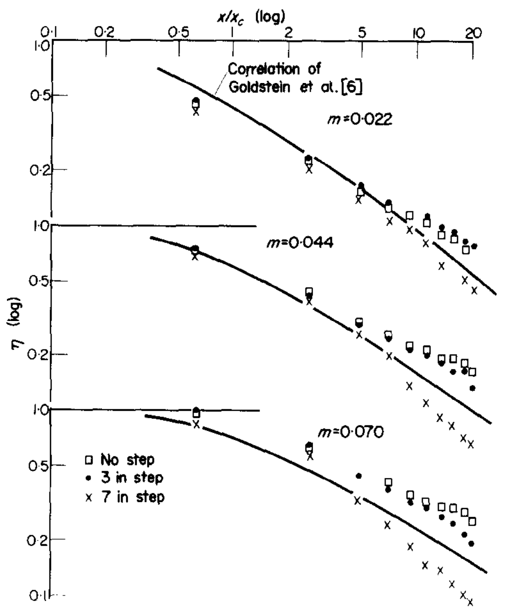

FIG. 5. Distributions of effectiveness.

is the relatively small influence of the pressure gradients. Not until separation is reached, does the effect become of major significance: this conclusion is in agreement with the measurements of [10, 11] where the influence of a favourable pressure gradient is also shown to be very small. It may also be seen from Fig. 5 that there is a tendency for the pressure gradient to have its greatest effect at the highest blowing rate.

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