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THE EFFECTIVENESS OF THREE-DIMENSIONAL FILM-COOLING SLOTS—I. MEASUREMENTS

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Abstract—Measurements of impervious wall effectiveness are reported downstream of three-dimensional film-cooling slots. The slots were made up of discrete holes which discharged the coolant parallel to the plane surface to be cooled. The results are relevant to gas turbine combustion-chamber design and were obtained with two purposes in mind: first to quantitatively assess the influence of velocity ratio, density ratio and geometrical parameters such as open area ratio and open area on the effectiveness and secondly to provide data against which the three-dimensional prediction procedure described in Part 2 could be tested.

NOMENCLATURE

A_0, open area;
A, total area;
C, concentration;
D, hole diameter;
D_m, mean diameter corresponding to a single row;
E, constant in the law of the wall;
J, diffusion flux;
l, Prandtl mixing length;
L, length of the lip;
L_D, depth of the hole;
N, number of rows of holes;
P, pressure in the cross-stream equations;
$\bar{P}$, pressure in the U-momentum equation;
P_i, pitch
S_ϕ, source terms;
t, lip thickness;
U, longitudinal velocity;
U_w, $(U_G + U_C)/2 - U_{min}$;
V, normal velocity;
W, lateral velocity;
x, longitudinal distance;
y, normal distance;
y_c, two-dimensional slot height;
y_H, total slot height;
δ, boundary layer thickness;
η, impervious wall effectiveness $\equiv \dfrac{C_W - C_G}{C_C - C_G}$;
ϕ, additional dependent variables—concentration in the present work;
ρ, density;
μ_{eff}, effective viscosity;
σ_{eff}, effective Prandtl number;
$\varkappa$, constant in the law of the wall;
τ, shear stress.

Subscripts

C, slot conditions, i.e. the secondary flow at $x = 0$;
G, free stream;
W, wall;
ϕ, concentration equation;
C_m, secondary maximum;
min, minimum.

1. INTRODUCTION TO EXPERIMENTAL INVESTIGATION

THE GREAT majority of papers describing investigations of film cooling have been concerned with two-dimensional slot configurations. The authors' own efforts have, until recently, also been devoted to two-dimensional film cooling [1–3] although many applications are concerned entirely with three-dimensional film cooling. This part of the paper is concerned with three-dimensional slots and has been stimulated by the need for experimental information on the cooling performance of such slots together with the knowledge that the two-dimensional situation is well understood and that methods are now available for solving the equations appropriate to three-dimensional flows [4].

The particular slot configurations considered here are appropriate to gas-turbine combustion-chamber practice and are made up of discrete holes which discharge the coolant parallel to the plane surface to be cooled.

Previous relevant measurements are described in [5] and [6]. [5] describes a preliminary experimental study of practical slot configurations and provides an indication of the influence of several parameters on the adiabatic-wall effectiveness. [6] reports measurements made downstream of slots with a single hole and was intended to provide a basis for the present work. The purpose of this paper is to present measurements of impervious-wall effectiveness which facilitate an understanding of the influence of the various parameters. The measurements allow the detailed evaluation of the three-dimensional prediction procedure presented in Part II and their understanding permits related slot configurations to be scaled with confidence.

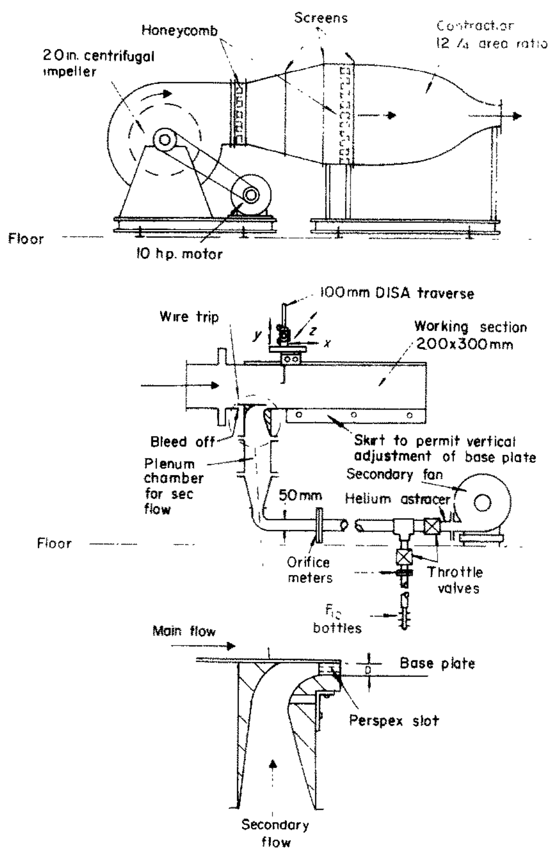

FIG. 1. Geometrical arrangement of wind tunnel and slots.

2. EQUIPMENT AND EXPERIMENTAL TECHNIQUE

The results described in the next section were obtained in a wind tunnel of working section 300 mm wide by 200 mm high. A line diagram of the tunnel and details of the slot arrangements considered are shown on Fig. 1. The slot pieces were easily changed and the ducting to the slot permitted the injection of air plus a tracer of helium gas; alternatively mixtures of air and Arcton 12 could be injected.

A round impact probe of inside diameter 0·75 mm was used to measure mean total-head pressure and a flattened probe of external dimensions 0·4 mm × 0·25 mm was used to obtain isokinetic samples for concentration measurements away from the wall. The total-head pressure was measured using a calibrated pressure transducer and the concentration using a katharometer and bridge circuit; the katharometer was maintained in a constant temperature atmosphere and was calibrated for trace concentrations of helium in air and for high concentrations of Arcton 12 in air. The helium–air calibration proved to be linear but the

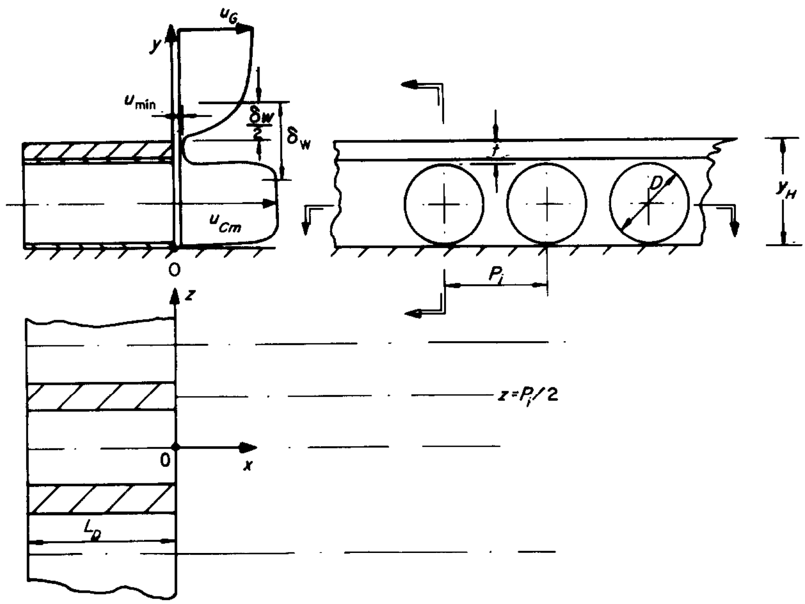

FIG. 2. Slot configuration and coordinate system.

Arcton 12–air calibration was not. The helium–air calibration was performed in the manner described in [7]. The Arcton 12–air calibration was performed by preparing mixtures of known concentration over water, assuming Dalton's law of partial pressure and assuming that Arcton 12, air and mixtures of both obeyed the perfect gas law. Values of impervious-wall effectiveness were obtained by drawing samples of gas through suitably located 0·5 mm dia holes in the base plate of the wind tunnel and measuring their concentrations with the katharometer.

The two-dimensionality of the wind tunnel had previously been confirmed by measuring mean velocity profiles at 10 stations over a length of one meter and without the backward-facing step. Values of shear stress, calculated from momentum deficit, agreed with Clauser chart values ($K = 0{\cdot}4187$, $E = 9{\cdot}793$) to within 4 per cent. The longitudinal pressure-gradient for these check measurements and for the jet measurements was negligible. The free-stream velocity used for all measurements was approximately 20 m/s. The average velocity at the slot exit was measured with an orifice meter (B.S. 1042) in the secondary pipe line.

The slot configurations shown generally on Fig. 2 had the following specific dimensions:

	Y_H	D	P_i	t	L_D	N	A_0	A_0/A
Slot 1	15·25	12·5	25	2·25	25	1	$15{\cdot}3 \times 10^2$	0·328
Slot 2	23·25	12·5	25	10·25	25	1	$15{\cdot}3 \times 10^2$	0·215
Slot 3	10·95	9	12·5	1·60	18	1	$15{\cdot}3 \times 10^2$	0·457
Slot 4	3·72	2	4	1·64	4	1	$2{\cdot}45 \times 10^2$	0·215
Slot 5	15·25	3·18	4·77	2·25	6·36	3	$15{\cdot}3 \times 10^2$	0·328

All length dimensions in mm.

The dimensions of Slot 1 were chosen to approximate a scaled up version of a practical combustor-cooling device. After the measurements with this slot, the dimensions of slot 2 and 3 were selected to allow the influence of t and P_i/D to be determined for constant values of other parameters including the open area. These results, together with those of [5] allowed an understanding of the influence of various parameters. Slot 4 was designed to provide an exactly scaled version of Slot 2 but with practical dimensions. Slot 5 represents an alternative means of injecting the coolant and its dimensions were chosen to provide an open area similar to that of Slots 1, 2 and 3 and open area ratio (A_0/A) similar to Slot 1: its three rows of holes were staggered.

3. RESULTS

Measured values of effectiveness corresponding to slots 1, 2, 3, 4 and 5 are shown on Figs. 3–7 respectively. The measurements are for uniform density and a density ratio of 2·1 and, in all cases, were obtained from sampling holes located in line with an injection-hole centre line. Measurements between the hole centres indicated that the impervious-wall effectiveness did not attain two-dimensionality as rapidly as had been suggested by measurements of adiabatic-wall effectiveness [5]; for velocity ratios greater than unity, the region of three dimensionality extended up to 30 diameters.

The results show trends which are, in general, similar to those previously observed for two-dimensional slots. As was expected the present results are significantly lower than those obtained with two-dimensional slots and the effectiveness curves reveal a maximum for uniform density: for non-uniform density this maximum is generally absent. The effectiveness at a particular value of x/D is always greater for the higher density ratio provided the comparison is made at the same velocity ratio; this is not so if the comparison is made at equal mass velocity ratios.

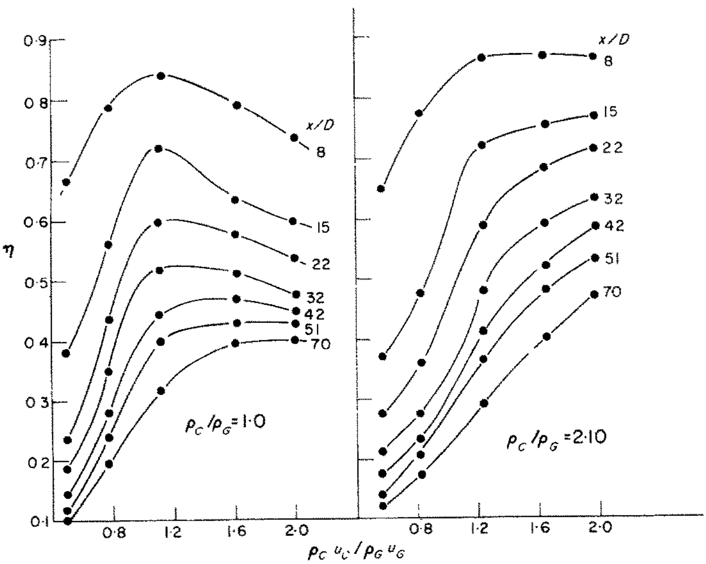

FIG. 3. Measured values of impervious-wall effectiveness corresponding to slot 1.

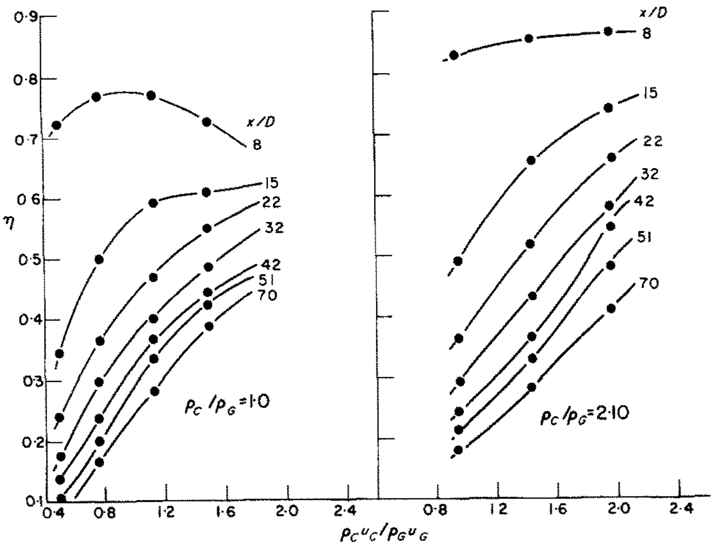

FIG. 4. Measured values of impervious-wall effectiveness corresponding to slot 2.

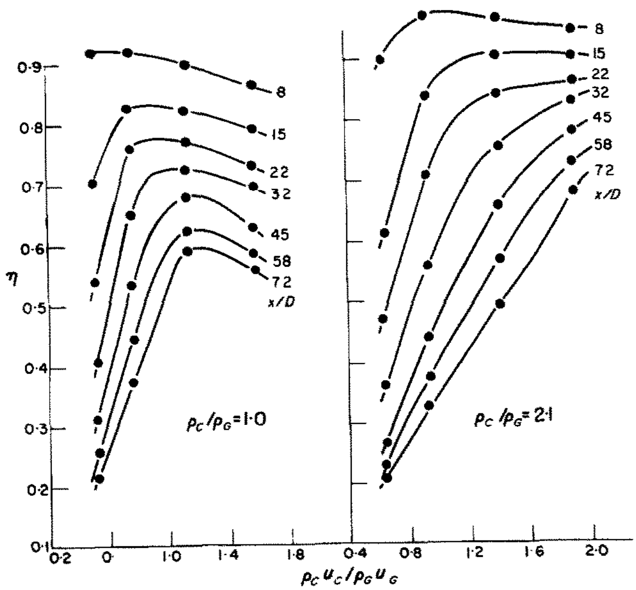

FIG. 5. Measured values of impervious-wall effectiveness corresponding to slot 3.

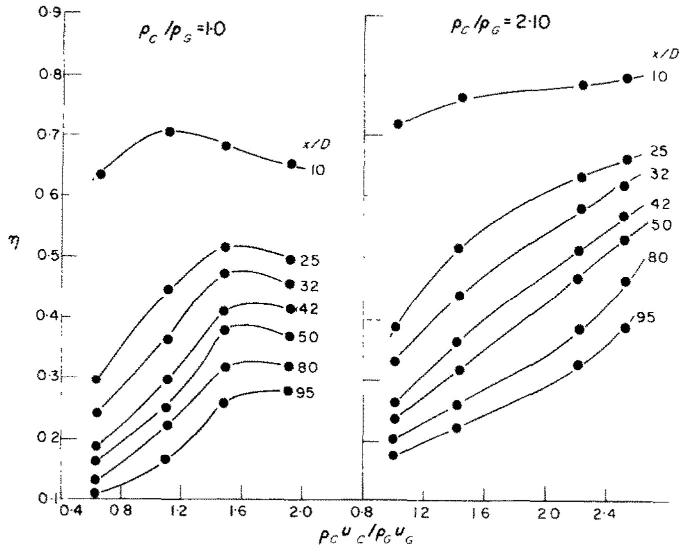

FIG. 6. Measured values of impervious-wall effectiveness corresponding to slot 4.

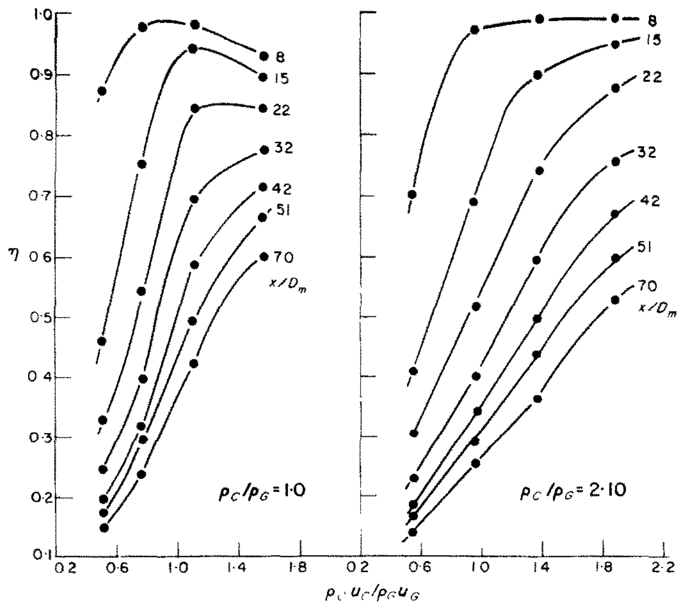

FIG. 7. Measured values of impervious-wall effectiveness corresponding to slot 5.

4. DISCUSSION

In gas turbine practice the heat conduction through the combustion-chamber wall will result in a tendency for the three-dimensional distribution of effectiveness to become two-dimensional more rapidly than the present impervious-wall effectiveness values or the adiabatic-wall effectiveness measurement of [5]. Thus, the present investigation of geometrical parameters will result in trends which are directly related to gas-turbine practice but the absolute values of wall temperature computed from the present measurements can be expected to be conservative.

A comparison between Figs. 3 and 4 shows that an increase in t leads to a decrease in effectiveness. This is in accord with the findings of [5] where a slot lip extended beyond the slot exit. It is also in accord with the findings of [9] for the two-dimensional geometry although the magnitude of the influence is less if the comparison is made on the basis of a value of t/y_c with y_c based on the open area.

From Figs. 3 and 5 it can be deduced that effectiveness increases as the ratio of pitch to diameter decreases. This statement assumes that other parameters, and in particular the open area, remain constant. This implies that in the limit where P_i/D is zero the effectiveness will obtain a maximum and, as previously indicated, the two-dimensional results of [1] and [8] are correspondingly higher than those measured here.

Slot 4 was designed as a scaled down version of Slot 2 and the ratios y_H/D, P_i/D, t/D and L_D/D were maintained constant. As can be seen from Figs. 4 and 6, the results obtained from the two slots are sensibly identical. For both slots the holes were located tangential to the base plate. In some cases, practical considerations render tangential holes impossible and a further parameter is required. Non-tangential injection will reduce the effectiveness but, on the basis of the two-dimensional measurements of [7], the reduction can be assumed negligible for small deviations from tangential. The upper lip boundary-layer thickness was not scaled (approx. 12 mm in both cases) and this resulted in the slight differences in effectiveness measured for values of x/D greater than 30.

Slot 5, at first sight, appears to provide a simple means of causing a three-dimensional slot to have a two-dimensional effectiveness with practical structure. In practice the jets emerging from the various holes mix rapidly and, in so doing, create a region of relatively high turbulence. Comparison with the performance of a two-dimensional slot which has the same open area and a thin lip shows that the two are similar for uniform density and values of velocity ratio above approximately 1·4; for lower values of velocity ratio the two-dimensional slot is more effective. This result stems from the effectiveness maximum, obtained with two-dimensional, thin lipped slots at velocity ratios around unity and its absence from Fig. 7. Of course, for a given mass flow rate and uniform density, the two-dimensional slot height and hence the velocity ratio can always be adjusted to result in maximum effectiveness. This does not apply to flows where the slot fluid has a higher density than the free stream; available data does not permit exact comparison but the data of [1] suggests that the performance of the multi-row slot is similar to that for a two-dimensional slot over a much wider range of velocity ratios provided the open area, mass flow rate and density ratio are the same. The performance of the multi-hole slot 5 was, in all cases, better than that of slot 1 which had the same open area and open area ratio. Slot 3 with its greater open area ratio (i.e. smaller P_i/D) is to be preferred for values of x/D greater than 30.

5. CONCLUSIONS

The following conclusions may be deduced from the results presented and discussed in previous sections:

1. The impervious-wall effectiveness is significantly three-dimensional at least up to 30

diameters from the slot exit. This confirms the need for three-dimensional prediction procedures to correctly predict the present results.

2. The influence of velocity ratio, density ratio and geometrical parameters is shown to be *complex* but the results show significant similarities to previously obtained two-dimensional results. The measurements are suitable for testing the ability of three-dimensional prediction methods to predict these influences.

3. A larger value of open area ratio results in higher effectiveness. Similarly, for the same open area a smaller value of pitch to diameter ratio (i.e. smaller hole diameter) results in an improved effectiveness.

4. The understanding of the scaling parameters obtained from the present measurements has been tested by effectiveness measurements with two slots scaled by a factor of 6·25. The results are identical in the near slot region, i.e. the region of practical interest and show that the important parameters have been correctly identified.

5. Multi-row slots are shown to be preferable on an open area and open area ratio basis to slots with a single row. On the same basis, they also compare well with two-dimensional slots except for uniform-density flows where the velocity ratio is less than approximately unity.

EFFICACITE DES FENTES DE REFROIDISSEMENT PAR FILM TRIDIMENSIONNEL I: MESURES

Résumé—Des mesures d'efficacité en paroi imperméable sont effectuées en aval des fentes de refroidissement par film tridimensionnel. Ces fentes sont constituées de trous discrets qui déchargent le réfrigérant parallèlement à la surface plane à refroidir. Les résultats sont applicables à la conception des chambres de combustion de turbine à gaz et sont guidés par deux objectifs: premièrement, l'évaluation quantitative de l'influence sur l'efficacité, du rapport de vitesse, du rapport de densité, de paramètres géométriques tels que le rapport d'aire ouverte et l'aire ouverte; deuxièmement l'obtention de résultats à comparer avec ceux calculés dans la deuxième partie.

DIE WIRKSAMKEIT VON KÜHLSCHLITZEN FÜR DREI-DIMENSIONALE FILMKÜHLING—I. MESSUNGEN

Zusammenfassung—Messungen zur Kühlwirkung von Kühlschlitzen bei drei-dimensionaler Filmkühlung im Abstrom werden beschrieben.

Die Schlitze bestanden aus Einzellöchern, aus denen das Kühlfluid parallel zu der zu kühlenden ebenen Oberfläche ausströmte. Die Ergebnisse sind für den Entwurf der Brennkammern von Gasturbinen von Bedeutung.

Sie wurden aus zwei Gründen ermittelt: erstens, zur quantitativen Abschätzung der Einflüsse von Geschwindigkeitsverhältnis, Dichteverhältnis und geometrischer Parameter wie Öffnungsverhältnis und Öffnungsflächen und zweitens um Daten zur Überprüfung des in Teil II beschriebenen Berechnungsverfahrens zu erhalten.

ЭФФЕКТИВНОСТЬ ТРЕХМЕРНЫХ ОТВЕРСТИЙ ДЛЯ ПЛЕНОЧНОГО ОХЛАЖДЕНИЯ. 1. ИЗМЕРЕНИЯ

Аннотация—Проводились измерения эффективности непроницаемой стенки ниже по течению от трехмерных щелей для пленочного охлаждения. Щели представляли собой дискретные отверстия, через которые параллельно охлаждаемой поверхности пропускался хладагент. Результаты могут быть применены при проектировании газотурбинных камер сгорания и получены, во-первых, для количественной оценки влияния отношения скоростей, отношения плотностей и геометрических параметров и, во-вторых, как данные, на основе которых можно проверить трехмерную схему расчета, описываемую во 2-ой части.