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FILM COOLING WITH HELIUM INJECTION INTO AN INCOMPRESSIBLE AIR FLOW

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Abstract—An experimental study of film cooling effects produced by injection of a helium secondary flow into a low speed air mainstream is presented. The helium was injected through a porous section into a turbulent boundary layer flowing over a flat plate. For comparison, measurements were also made using air as the secondary fluid.

The adiabatic wall temperature, presented in a dimensionless group known as the film cooling effectiveness, was measured for both helium and air secondary flows. The experimental data are compared with predictions. It is found that helium injection produces higher film cooling effectiveness than anticipated. The measured helium concentration along the wall is in relatively good agreement with predictions.

Temperature and helium concentration profiles are also presented. The concentration and temperature profiles are very similar and in good agreement with profiles measured with air injection.

NOMENCLATURE

C_{p_0},	specific heat at constant pressure for mainstream gas;
C_{p_c},	specific heat at constant pressure for coolant gas;
h,	length of porous wall in flow direction or slot height;
M,	$(\rho_c U_c/\rho_0 U_0)$ = mass flow parameter;
m,	mass flow rate of gas in the boundary layer per unit space;
N,	mole fraction of helium;
Pr,	Prandtl number of mainstream;
Re_h,	$(U_c h/\nu_c)$ = Reynolds number based on h;
Re_x,	$(U_0 x/\nu_0)$ = Reynolds number based on x;
T,	temperature;
ΔT,	$T_c - T_0$;
U,	velocity, $\left(u_c = \dfrac{M_c}{\rho_c h}\right)$;
W,	molecular weight;
x,	distance downstream from trailing edge of porous wall;
X,	$(x/Mh)(Re_h)^{-\frac{1}{4}}$;
$Y = y$,	distance away from adiabatic wall;
$\delta_N = \int_0^\infty \dfrac{N}{N_w}\,dy$,	helium concentration boundary-layer thickness;
$\delta_T = \int_0^\infty \dfrac{T - T_0}{T_{aw} - T_0}\,dy$,	temperature boundary-layer thickness;
$\eta = \dfrac{T_{aw} - T_0}{T_c - T_0}$,	film cooling effectiveness;
μ,	dynamic viscosity;
ν,	kinematic viscosity;
ρ,	mass density.

Subscripts

0,	mainstream;
aw,	adiabatic wall;
c,	coolant;
w,	wall.

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INTRODUCTION

INTEREST in film cooling as a method for protecting solid surfaces from high temperature gas streams flowing over them continues. With film cooling a secondary fluid is injected, usually through a slot or small porous section, into the gas boundary layer on a surface. The injected fluid is swept downstream by the main flow (or by its own momentum) and serves as an insulating layer between the surface and the free stream. This model also approximates the effects of ablation downstream of the ablating material. In the ensuing discussion we shall restrict ourselves to the case when a gas is injected into an incompressible two-dimensional turbulent boundary layer of air flowing over a flat plate.

Experiments by Scesa [1] and Hartnett *et al.* [2] indicate that the heat transfer with film cooling can be closely approximated using the heat-transfer coefficient indicated for a similar mainstream flow, without secondary injection, and the temperature difference between the actual wall temperature and the adiabatic wall temperature (with secondary flow). Thus, interest has centered on measuring or predicting the adiabatic wall temperature distribution usually in the form of a dimensionless temperature ratio, the film cooling effectiveness. For convenience, many of the experiments have been performed with the secondary gas at a higher temperature than the mainstream. These results, however, may often be directly applied to the more common applications where the free stream gas would be at the higher temperature (cf. discussion of reference [2]).

Hartnett *et al.* [2], Wieghardt [3], Chin *et al.* [4], Seban [5], and Eckert and Birkebak [6] have studied film cooling with air as the secondary gas. In these studies the secondary fluid entered the boundary layer through a slot in the wall so that the initial velocity of the injected fluid was almost parallel to the mainstream. Nishiwaki *et al.* [7] and Goldstein *et al.* [8] measured the film cooling effectiveness with secondary air injected through a narrow porous section placed in the surface to be studied. The measurements of the film cooling effectiveness from the above studies can be correlated fairly successfully (see Spalding [9] and Stollery and El-Ehwany [10]) with some relatively simple predictions which will be discussed below.

There have been few measurements of film cooling effectiveness on a flat plate using gases other than air as the secondary fluid. Hatch and Papell [11] injected helium through a tangential slot into a high temperature boundary layer but their film cooling results are somewhat inconclusive. Transpiration cooling experiments have been performed with helium injected through a porous wall (along the whole length of the test surface as contrasted to film cooling studies) into a turbulent boundary layer of air by Tewfik *et al.* [12] and Scott *et al.* [13]. It is interesting to note here that these transpiration cooling results were influenced strongly by diffusion-thermo effects.

In the present work helium, and in some runs air, is injected through a porous section into a low speed two-dimensional turbulent layer on an adiabatic flat plate. Interest is centered on the film cooling effectiveness, but measurements of the wall concentration of helium as well as the temperature and helium concentration distributions in the boundary layer are also presented.

ANALYTICAL CONSIDERATIONS

The turbulent film cooling correlations that have been theoretically derived to date are usually based on the concept of the secondary fluid as a heat source (or sink) entering the boundary layer and assume that the boundary layer, downstream of the injection point, grows in a manner similar to a turbulent boundary layer with no injection. Somewhat different assumptions have been made, in deriving the different correlations, as to the mixing process in the boundary layer and the effective origin of the boundary layer.

Tribus and Klein [14], acting upon a suggestion of Eckert, considered the secondary fluid as a line heat source at the wall. The magnitude of the source depended on the mass flow, temperature, specific heat, etc., of the injected fluid. Using Duhamel's theorem they predicted the film cooling effectiveness to be

$$\eta = \frac{5 \cdot 77\, Pr^{\frac{2}{3}}}{(C_{p0}/C_{pc})(\mu_0/\mu_c)^{0 \cdot 2}} X^{0 \cdot 8} \qquad (1)$$

where

$$X = \frac{x}{Mh} Re_h^{-\frac{1}{4}} = \frac{x}{Mh}\left(\frac{U_c h}{\nu_c}\right)^{-\frac{1}{4}}$$

and

$$\eta = \frac{T_{aw} - T_0}{T_c - T_0}.$$

Later predictions by Librizzi and Cresci [15] and Kutateladze and Leont'ev [16] also considered the secondary fluid as a heat source, but were simpler in that they assumed the mainstream and coolant fluids in the boundary layer to be completely mixed and at the wall temperature (T_{aw}). In both of these analyses the actual mass of secondary gas is assumed to be added to the boundary layer which then grows as a normal turbulent layer on a flat plate. They are thus able to write a heat balance to get the mean boundary-layer temperature (which in these analyses is also the adiabatic wall temperature).*

$$m_0 C_{p0} T_0 + m_c C_{pc} T_c = (m_0 C_{p0} + m_c C_{pc})\, T_{aw} \qquad (2)$$

or

$$\eta = \frac{1}{1 + (m_0 C_{p0}/m_c C_{pc})}. \qquad (3)$$

Since m_c is measured and C_{p0} and C_{pc} are known, the problem reduces to a prediction of the mass flow in the boundary layer which comes from the mainstream, m_0. Both predictions are derived assuming the boundary layer to develop as a normal turbulent boundary layer on a flat plate. Librizzi and Cresci assume that the free stream mass is added to the boundary layer as if it starts at the point of injection. Using this assumption (and adding the effect of a secondary gas different from that in the mainstream), one obtains*

$$\eta = \frac{1}{1 + 0 \cdot 325\,[(C_{p0}/C_{pc})(\mu_0/\mu_c)^{0 \cdot 2}\, X^{0 \cdot 8}]}. \qquad (4)$$

Kutateladze and Leont'ev assume the boundary-layer flow to have begun at such a distance upstream of the injection point that there would be a mass m_c in the boundary layer at the point of injection. Using this assumption, one finds

$$\eta = \frac{1}{1 + (C_{p0}/C_{pc})\{0 \cdot 325\,[4 \cdot 08 + (\mu_0/\mu_c)^{\frac{1}{4}} X]^{0 \cdot 8} - 1 \cdot 0\}}. \qquad (5)$$

Far downstream of the injection, equations (4) and (5) predict very similar values of the effectiveness. Spalding [9], Stollery and El-Ehwany [10] and Goldstein, Shavit, and Chen [8] have shown that expressions similar to equations (4) and (5) give an excellent prediction of the film cooling effectiveness when air is used as both the mainstream and the secondary fluids. It should be borne in mind, however, that the two key assumptions of a completely mixed boundary layer (i.e. uniform temperature) and boundary-layer growth unaffected by the injected fluid are known to be untrue. Apparently these two incorrect assumptions fortuitously come close to cancelling each other out (c.f. discussion of reference [8]).

If the secondary gas is different from the free stream gas, a prediction of gas concentration at the wall would also be desirable. Assuming complete mixing in the boundary layer and mass addition from the free stream, m_0; one

* These two studies mainly consider air injection. The extension to different injection gases is quite straightforward (c.f. Stollery and El-Ehwany [10] and Rask [17]).

* The constant (0·325) in equations (4) and (5) depends on the boundary layer growth rate and is slightly different from the values found in the original studies. Here we have assumed a one-seventh power velocity profile and $\delta/x = 0 \cdot 371\, Re_x^{-\frac{1}{5}}$.

has, equivalent to equation (3), the mass fraction of injected gas in a boundary layer $[m_c/(m_0 + m_c)]$ and the mole fraction,

$$N_w = \frac{m_c/W_c}{(m_0/W_0) + (m_c/W_c)}$$

or

$$N_w = \frac{1}{1 + (m_0/m_c)(W_c/W_0)}. \quad (6)$$

where W_c and W_0 are the molecular weights of the two gases.

Using the expression for m_0 similar to that used in deriving equation (4), we find

$$N_w = \frac{1}{1 + 0{\cdot}325\,(W_c/W_0)(\mu_0/\mu_c)^{0{\cdot}2}\,X^{0{\cdot}8}}. \quad (7)$$

Similar to equation (5), we can obtain,

$$N_w = \frac{1}{1 + (W_c/W_0)\{0{\cdot}325[4{\cdot}08 + (\mu_0/\mu_c)^{0{\cdot}25}X]^{0{\cdot}8} - 1{\cdot}0\}}. \quad (8)$$

A more detailed derivation of these equations is contained in reference [17].

APPARATUS AND EXPERIMENTAL RESULTS

The wind tunnel, Fig. 1, used in this study has a $10 \times 5\frac{1}{4}$-in cross-section with a test section length of 45 in. The mainstream air is drawn through the tunnel by a blower capable of producing air speeds up to 190 ft/s. Secondary air or helium can be injected through a 1×10-in piece of sintered stainless steel. The 10-in wide tunnel floor is well insulated and there is a developed two-dimensional turbulent boundary layer on this wall. The coolant temperature is recorded by thermocouples affixed to the lower side of the porous material, and the adiabatic wall temperature is measured by thermocouples embedded in the surface of the insulated wall. Probes are also available to measure the velocity, temperature and helium concentration distributions in the boundary layer. A calibrated thermal-conductivity cell is used to measure the helium concentration of samples drawn through a probe in the boundary layer

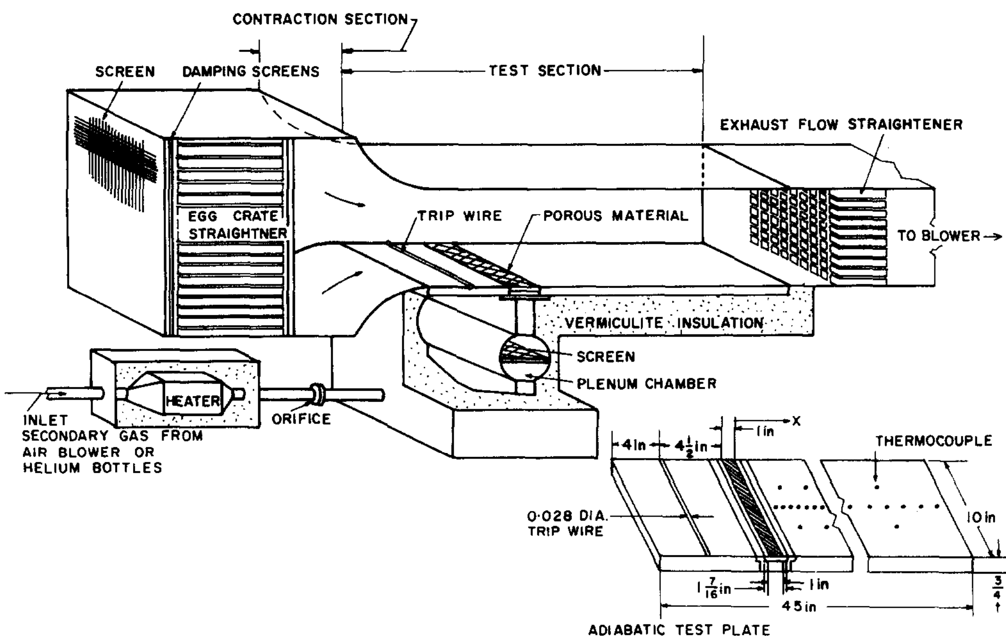

FIG. 1. Apparatus for film cooling study.

or from wall pressure taps. Details of the apparatus and instrumentation can be found in references [8] and [17] respectively. The range of variables for the air injection tests (A-1 to A-5) and the helium injection tests (H-1 to H-5) is shown in Table 1.

Table 1

Run No.	U_0 (ft/s)	M	m (lb_m/s)	ΔT (degF)
H-1	176·7	0·00222	0·00189	80·72
H-2	117·7	0·00330	0·00191	82·18
H-3	175·5	0·00442	0·00372	105·66
H-4	113·7	0·00683	0·00376	100·73
H-5	109·4	0·00763	0·00418	4·11
A-1	158·2	0·0127	0·0100	83·64
A-2	107·6	0·0155	0·00831	99·27
A-3	122·3	0·0470	0·0279	77·18
A-4	153·3	0·0360	0·0273	73·75
A-5	183·7	0·0517	0·0460	68·22

The film cooling effectiveness with air as the injected gas is shown in Fig. 2. The distance x is measured from the downstream edge of the porous region and h is the actual spacing (1 in) through which the secondary gas is injected. Re_h is calculated using properties evaluated at the temperature of the porous section. Equations (4) and (5) (with $C_{p_0} = C_{p_c}$ and $\mu_0 = \mu_c$) are plotted for comparison and as expected (c.f. references [8, 9, 15]) there is close agreement between the experimental points and the predictions. The disagreement at large values of the parameter X may be due to the small values of effectiveness and the resulting small temperature differences in this region. Thus, a small error in temperature measurement could cause a significant deviation in effectiveness.

The film cooling effectiveness with helium injection is presented in Fig. 3. The data for the four runs (see Table 1) are representative of a large number of tests taken over the same range of flow conditions. Re_h and μ_c are evaluated at the injection temperature and μ_0 is evaluated at the mainstream temperature. For comparison, equations (1), (4) and (5) are also presented on the figure. In these equations C_{p_0}/C_{p_c} is taken to be 0·1934. It is observed

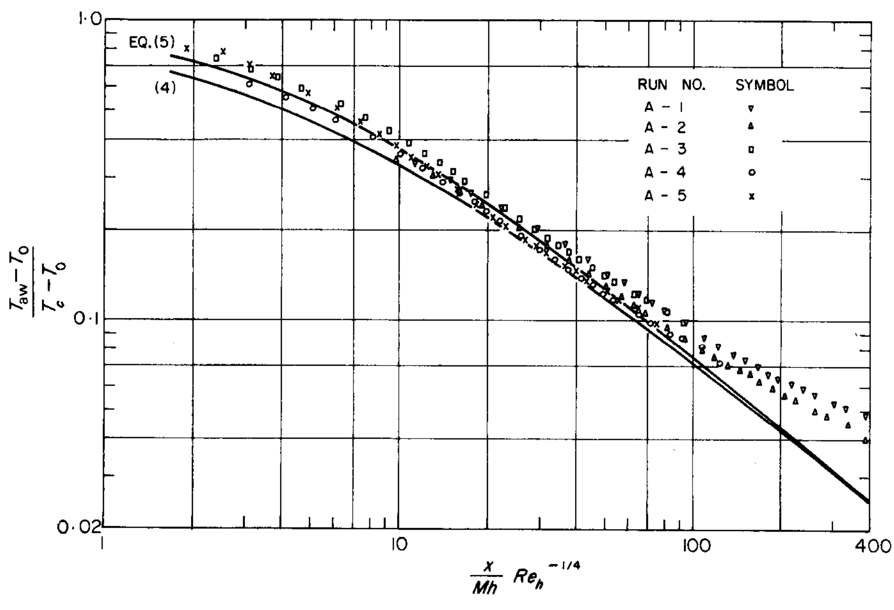

FIG. 2. Film cooling effectiveness with air injection.

that equations (4) and (5), which predict the film cooling data with air injection quite well, fail to give adequate prediction of the film cooling effectiveness when the secondary gas is helium. This is apparently due to an inherent weakness in the theoretical models used. A similar qualitative effect may be observed in reference [10] where the film cooling effectiveness has been recalculated from the helium injection data of reference [11]. To see whether thermal diffusion or diffusion-thermo effects were the cause of this deviation, a test run was made with the injection temperature of the helium (T_c) equal to the mainstream air temperature (T_0). Although a slight variation in temperature along the test plate resulted, the effects were small and a few inches downstream of the porous section the wall temperature was almost identical to the free stream temperature.

To correlate the helium film cooling data, an empirical equation was obtained. It is apparent from Fig. 3 that the parameter $(\mu_c/\mu_0)^{-\frac{1}{4}}\ X$ or $(C_{p_0}/C_{p_c}\ (\mu_0/\mu_c)^{0\cdot 2}\ X^{0\cdot 8}$ would bring the data close to a single curve. In addition the slope of the effectiveness far downstream is closely proportional to $[(\mu_c/\mu_0)^{-\frac{1}{4}}\ X]^{-0\cdot 8}$. Thus, an equation of a form similar to equation (4), but with two adjustable constants, was fitted to the data. The resulting equation is

$$\eta = \frac{3\cdot 725}{1\cdot 664 + (C_{p_0}/C_{p_c})(\mu_0/\mu_c)^{0\cdot 2}\ X^{0\cdot 8}}$$

or

$$\eta = \frac{19\cdot 26}{8\cdot 606 + (\mu_0/\mu_c)^{0\cdot 2}\ X^{0\cdot 8}} \qquad (9)$$

taking

$$\frac{C_{p_0}}{C_{p_c}} = 0\cdot 1934.$$

This equation is plotted in Fig. 3. The normalized standard deviation of the experimental data from equation (9) is 0·075. It should be noted here that equation (9) does not indicate an effectiveness of unity as x approaches zero. Some other empirical equations are described in the Appendix.

The wall concentration of helium is presented

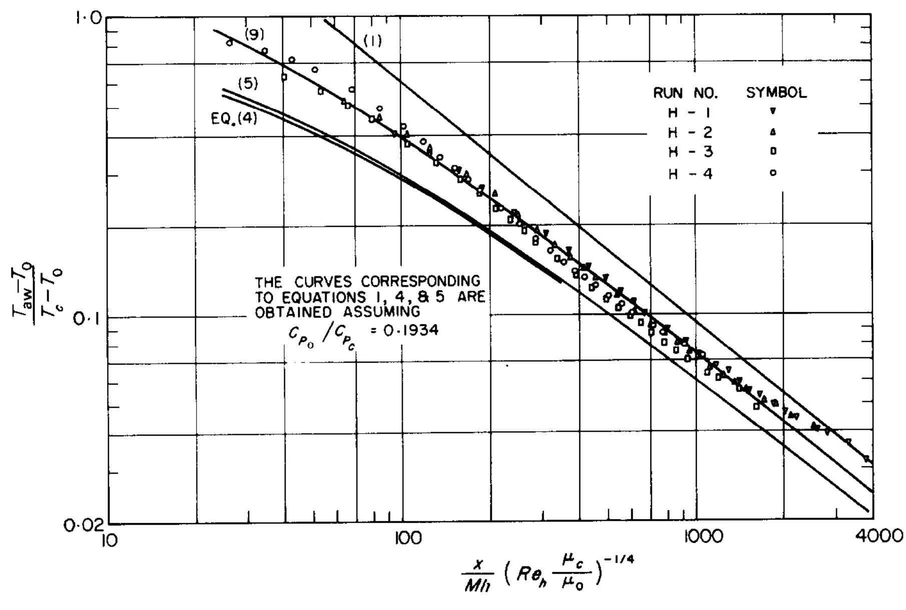

FIG. 3. Film cooling effectiveness with helium injection.

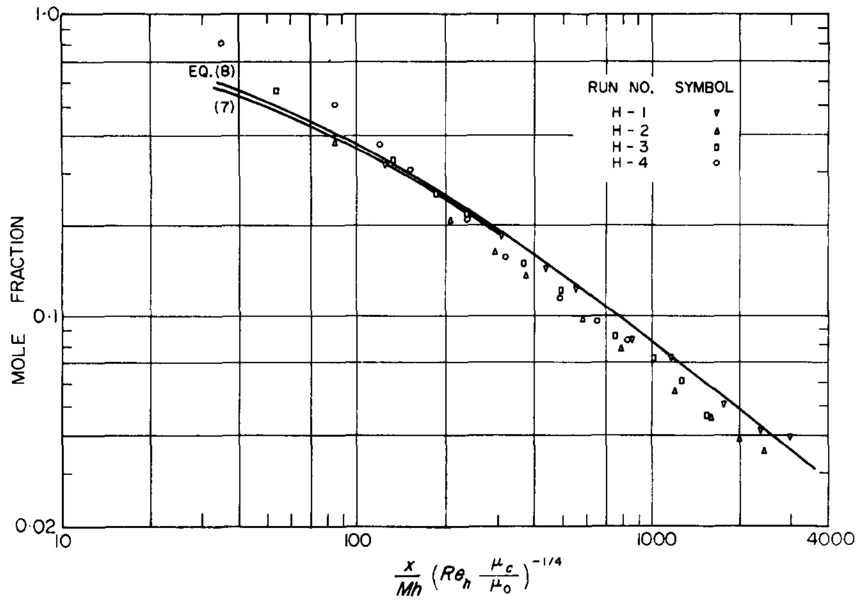

FIG. 4. Helium concentration at the wall.

as a function of $(\mu_0/\mu_c)^{\frac{1}{4}} X$ in Fig. 4. The parameters are evaluated as described above. Equations (7) and (8) are also presented in Fig. 4, and it may be seen that the data is in fairly good agreement with the two predictions. This agreement is much better than is the case for the film cooling predictions of equations (4) and (5) for helium injection. In fact, a comparison of Figs. 3 and 4 indicates that the helium wall concentration is very nearly equal to the film cooling effectiveness for equal values of $(\mu_0/\mu_c)^{\frac{1}{4}} X$. This suggests that equations (7) or (8) can be used to calculate effectiveness values with good accuracy.

Figure 5 presents the dimensionless temperature profile obtained with helium injection. The Y-distance is normalized by use of the boundary layer thickness

$$\delta_T = \int_0^\infty \frac{T - T_0}{T_{aw} - T_0}\,dy.$$

The temperature is presented as the dimensionless group

$$\frac{T - T_0}{T_{aw} - T_0}.$$

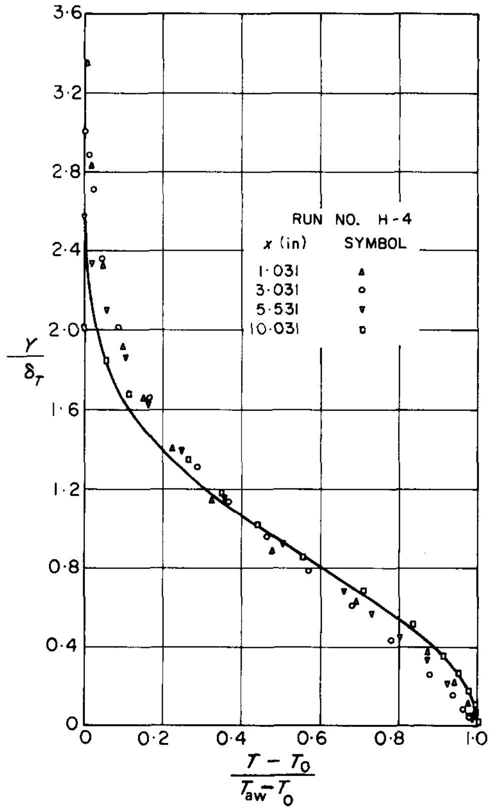

FIG. 5. Temperature profiles with helium injection.

Also shown in Fig. 5 is Wieghardt's [3] profile,

$$\frac{T - T_0}{T_{aw} - T_0} = \exp\left[-0{\cdot}768\left(\frac{y}{\delta_T}\right)^{\frac{13}{6}}\right].$$

It is seen that the temperature profiles are somewhat less curved than the "S-shape" proposed by Wieghardt. Considering that Wieghardt developed his correlation for secondary air injected through a slot, the experimental results are in surprisingly good agreement with the prediction. Profiles were also measured with air as the secondary gas and are in agreement with the profiles presented in Fig. 5.

Figure 6 presents the dimensionless helium concentration profiles for three locations downstream of the injection slot. The Y-distance is normalized using

$$\delta_N = \int_0^\infty \frac{N}{N_w}\,\mathrm{d}y$$

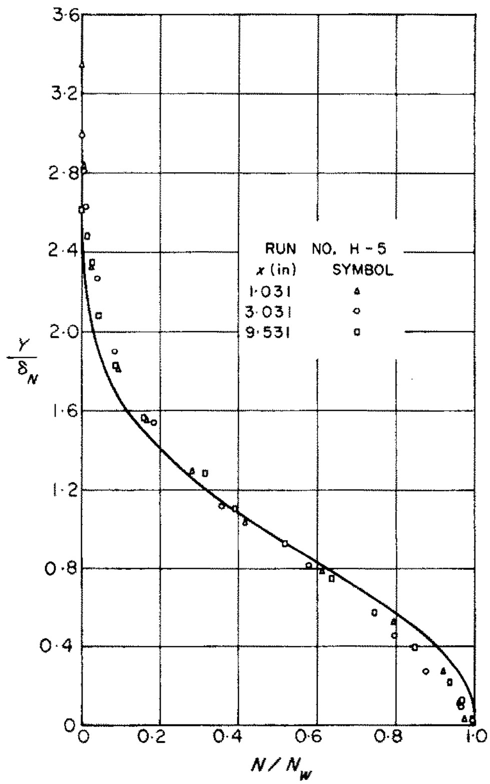

FIG. 6. Helium concentration profiles.

and the concentration is normalized using the helium wall concentration. Also shown is Wieghardt's temperature profile modified for helium concentration. This correlation is

$$\frac{N}{N_w} = \exp\left[-0{\cdot}768\left(\frac{y}{\delta_N}\right)^{\frac{13}{6}}\right].$$

The helium concentration profile is in good agreement with this correlation, being only slightly straighter than the "S-shape."

Both the helium concentration boundary-layer thickness, δ_N, and the temperature boundary layer thickness, δ_T, were found to be approximately equal to each other and to increase slightly with M at any given value of x. On an average, they can be approximated by the equation

$$\delta_T = \delta_N = [0{\cdot}02\,(x + 1{\cdot}1)]^{\frac{4}{5}}$$

where δ and x are in inches.

SUMMARY AND DISCUSSION OF RESULTS

The film cooling effectiveness with air injection agrees quite well with the predicted correlations [equations (4) and (5)] while the data with helium injection is considerably above these predictions. An empirical correlation can be obtained to fit the effectiveness data with helium injection [equation (9)—c.f. Appendix].

The helium concentration at the wall is in quite good agreement with the predictions of equations (7) and (8). It is of considerable interest to note that the helium wall concentration and the film cooling effectiveness are nearly identical at equal values of

$$\frac{x}{Mh}\left(Re_h\frac{\mu_c}{\mu_0}\right)^{-\frac{1}{4}}$$

This last statement forces us again to question the validity of the assumptions leading to equation (2). Thus, when we only consider the injected fluid as carrying along a given amount of energy (or enthalpy), we neglect the volume flow entering the boundary layer. This increase in volume of the boundary layer could strongly affect the insulating of the wall from the free stream. If one only considered the volume addition, the equation for effectiveness would reduce to that of mole fraction of added gas in the boundary layer [equations (7) and (8)]. These equations predict a film cooling effectiveness with helium injection relatively close to the measured values reported above. In the case of air injection, the predictions would, of course, reduce to equations (4) and (5).

The temperature and helium-concentration profiles are found to be nearly identical when presented on dimensionless coordinates. Both profiles are in good agreement with the correlation of Wieghardt.

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APPENDIX

Equations (1), (4), (5) and (9) possess a general form

$$\eta = \frac{A}{B + \{C + (x/Mh)[Re_h\,(\mu_c/\mu_0)]^{-\frac{1}{4}}\}^{0.8}}$$

where the corresponding constants A, B and C are calculated and listed in Table 2 (for

Table 2

Equation	A	B	C
(1)	23·7	0·0	0·0
(4)	15·93	15·93	0·0
(5)	15·93	12·85	4·08
(9)	19·26	8·606	0·0
(10)	19·74	0·0	41·61
(11)	21·33	21·33	0·0
(12)	20·92	17·84	4·08

helium injection $C_{p_0}/C_{p_c} = 0{\cdot}1934$). Three more equations can be obtained by deleting B or C, or retaining all the coefficients. Hence equations (10–12) are fitted to the experimental data by using a least squares technique. Unlike equation (9), these later equations have the property that $\eta = 1$ as

$$\frac{x}{Mh}\left(Re_h \frac{\mu_c}{\mu_0}\right)^{-\frac{1}{4}} \rightarrow 0.$$

The constants for the equations (10–12) are also listed in Table 2.

Résumé—On présente une étude expérimentale des effets de refroidissement par film produits par injection d'un écoulement secondaire d'hélium dans un écoulement général d'air à faible vitesse. Des mesures ont été faites également, dans un but de comparaison, en employant de l'air comme fluide secondaire.

La température pariétale adiabatique, présentée sous la forme d'un groupe sans dimensions connu sous le nom d'efficacité de refroidissement par film, a été mesurée pour des écoulements secondaires d'hélium et d'air. Les données expérimentales sont comparées avec les prévisions. On trouve que l'injection d'hélium produit des efficacités de refroidissement par film plus élevées que prévu. La concentration en hélium mesurée le long de la paroi est en accord relativement bon avec les prévisions.

Les profils de température et de concentration en hélium sont également présentés. Les profils de concentration et de température sont très semblables et en bon accord avec les profils mesurés avec injection d'air.

Zusammenfassung—Eine experimentelle Untersuchung des Filmkühleffekts beim Einblasen eines Heliumzweitstroms in einen Lufthauptstrom geringer Geschwindigkeit ist beschrieben. Das Helium wurde in die turbulente Grenzschicht an einer ebenen Platte durch einen porösen Abschnitt eingebracht. Vergleichsmessungen mit Luft als Zweitstrom wurden ebenfalls gemacht.

Die adiabate Wandtemperatur, die als dimensionslose, Filmkühlungswirkungsgrad genannte Gruppe angegeben ist, wurde sowohl für Helium—als auch für Luftzweitströme gemessen. Experimentelle Daten werden mit Voraussagen verglichen. Es zeigt sich, dass Heliumeinblasung höhere Filmkühlungswirkungsgrade hervorruft als erwartet. Die gemessene Heliumkonzentration entlang der Wand stimmt relativ gut mit Vorhersagen überein.

Profile für die Temperatur und die Heliumkonzentration werden ebenfalls angegeben. Die Konzentrations- und Temperaturprofile sind sehr ähnlich und stimmen gut mit den gemessenen Profilen für Lufteinblasung überein.

Аннотация—Представлено экспериментальное исследование пленочного охлаждения при подаче гелия в низкоскоростной поток воздуха. Гелий инжектировался через пористый участок в турбулентный пограничный слой плоской пластины. Для сравнения проведены измерения, когда вторичной жидкостью служил воздух.

Как для вторичного потока гелия, так и для вторичного потока воздуха измерена адиабатическая температура стенки, представленная безразмерным комплексом, обычно называемым «эффективностью пленочного охлаждения».

Найдено, что подача гелия увеличивает эффективность пленочного охлаждения в большей мере, нежели предсказывают расчеты. Измеренная концентрация гелия вдоль стенки довольно хорошо согласуется с расчетными значениями.

Представлены также распределения температуры и концентрации гелия в пограничном слое. Профили концентрации и температуры весьма подобны и вполне согласуются с профилями, измеренными при подаче воздуха.