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EFFECT OF MASS ADDITION ON THE HEAT TRANSFER TO A CAVITY IN SUPERSONIC FLOW

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Abstract—An experimental investigation of the heat transfer to the floor of a rectangular cavity of square planform with secondary injection into the cavity is described. The flow over the cavity was supersonic (Mach number 2·8) and the upstream boundary layer was turbulent. Several configurations of multiple, discrete secondary injection orifices blowing subsonically and supersonically upstream from the recompression step and/or downstream from the separation step are studied; a range of blowing rates, secondary air stagnation temperatures, and cavity floor temperatures were tested and a semi-empirical generalization of the data is developed. As long as the secondary air is colder than the stagnation temperature of the free stream, the heat transfer to the cavity is reduced, often substantially; when it is colder than the wall temperature, the direction of the heat flux can be reversed with moderate amounts of blowing. The most efficient injector configuration calls for blowing upstream from near the floor on the recompression step. Measurements of the cavity bulk temperature with and without blowing and studies of the steady and transient penetration into the cavity of fine graphite particles carried by the oncoming boundary are also presented.

NOMENCLATURE

B,	blowing parameter defined by equation (11);
h,	heat-transfer coefficient based on the natural adiabatic recovery temperature;
H,	depth of the cavity;
i,	relative change in intensity of illumination;
L,	length of the cavity in the streamwise direction;
$\dot{m}$,	secondary mass injection rate per unit span of the cavity;
M,	Mach number;
P,	static pressure;
q,	heat flux to the wall per unit area;
r,	adiabatic recovery factor $(Taw - T)/(To - T)$;
Re,	Reynolds number per unit length;
St,	Stanton number;
T,	static temperature;
To,	stagnation temperature;
Taw,	adiabatic recovery temperature;
Tm,	mean bulk temperature of the gas in the cavity;
W,	spanwise width of the cavity;
x,	streamwise distance along the floor of the cavity, origin at the separation step.

Greek symbols

α,	cavity time constant associated with transient injection in upstream boundary layer;
β,	secondary injection temperature parameter defined by equation (9);
η,	recovery temperature ratio Taw/To;
τ,	dimensionless temperature parameter defined by equations (5) and (10);
ϵ,	characteristic recovery temperature parameter for the wall layer defined by equation (16);
ρ,	mass density;
δ,	thickness of the boundary layer upstream of separation;
δ^*,	displacement thickness of the boundary layer upstream of separation;

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θ, momentum thickness of the boundary layer upstream of separation;
γ, ratio of specific heats;
$\Gamma_{(B)}$, the resistance ratio for the cavity wall layer defined by equation (14);
$\Theta_{(B)}$, characteristic transfer function for the shear layer defined by equation (15).

Subscripts
B, pertaining to secondary injection;
c, pertaining to the cavity as a whole;
0, pertaining to conditions without secondary injection;
s, pertaining to the shear layer;
w, wall conditions;
∞, the free stream.

Superscript
$\bar{}$, denotes average value over the cavity floor.

INTRODUCTION

INVESTIGATIONS of the heat transfer to notches in the boundary of supersonic [1, 2] and subsonic [3, 4] flows showed that when the region at and downstream of the recompression corner is included, the total flux to the boundaries is usually somewhat increased. The possibility of thermally "shielding" the wall by generating separated-flow regions suggested by early considerations of semi-analytical models of cavity flow [5–7] is not realized, particularly where the recompression of the free shear layer occurs against a boundary (as contrasted with base wakes). The present experiments extend the study of heat transfer to separated flow regions to include the effect of injection of a gaseous coolant into the cavity.

Bleeding into separated regions was studied previously [7, 8] but only for base-wakes and small rates of blowing with negligible blowing velocity (wall-transpiration). Cavity flows are quite different from base wakes because of the importance of the recompression mechanism on the structure of the internal flow, so that neither experimental data nor results of the available analytical models are transferable from one geometry to the other. Moreover, transpiration of the secondary gas through the boundaries into the cavity at the temperature of the wall is not practical and, therefore, secondary injection through discrete multiple orifices at arbitrary stagnation temperature is also of interest.

The present experiments are limited to a specific cavity having a rectangular cross-section with a depth to length ratio of 0·5 and a square planform (span to length ratio of unity). The free stream Mach number and the Reynolds number at separation are held constant and the boundary layer is turbulent. The principal variables are: the wall temperature, the stagnation temperature and the mass rate of injection. Secondary variables are the distribution and geometry of the injection orifices. Only air was used as the secondary injectant.

New data pertaining to the thermal equilibrium established in the cavity without blowing is also presented. It includes measurements of the average temperature in the "bulk" of the recirculating region and estimates of the effective average adiabatic recovery factors for the shear layer, the boundary layer forming on the cavity floor, and the cavity as a whole. These studies parallel some recent measurements obtained in base wakes [8–10] and show that the thermal resistance of the wall layer is large relative to that of the shear layer (and not negligible [5–7]) but that their ratio is very different in base-wakes and cavities.

EXPERIMENTAL EQUIPMENT AND TECHNIQUES

The experiment was conducted at a free stream Mach number of 2·8 with a stagnation temperature between 800 and 1000°R and atmospheric stagnation pressure. The free stream conditions, their uniformity as well as reference data such as P_∞, h_∞ and boundary-layer profiles were measured at a station 0·500 in ahead of the model which consisted of a rectangular cavity in the test-section wall. The model geometry is shown on Fig. 1, which also defines the termino-

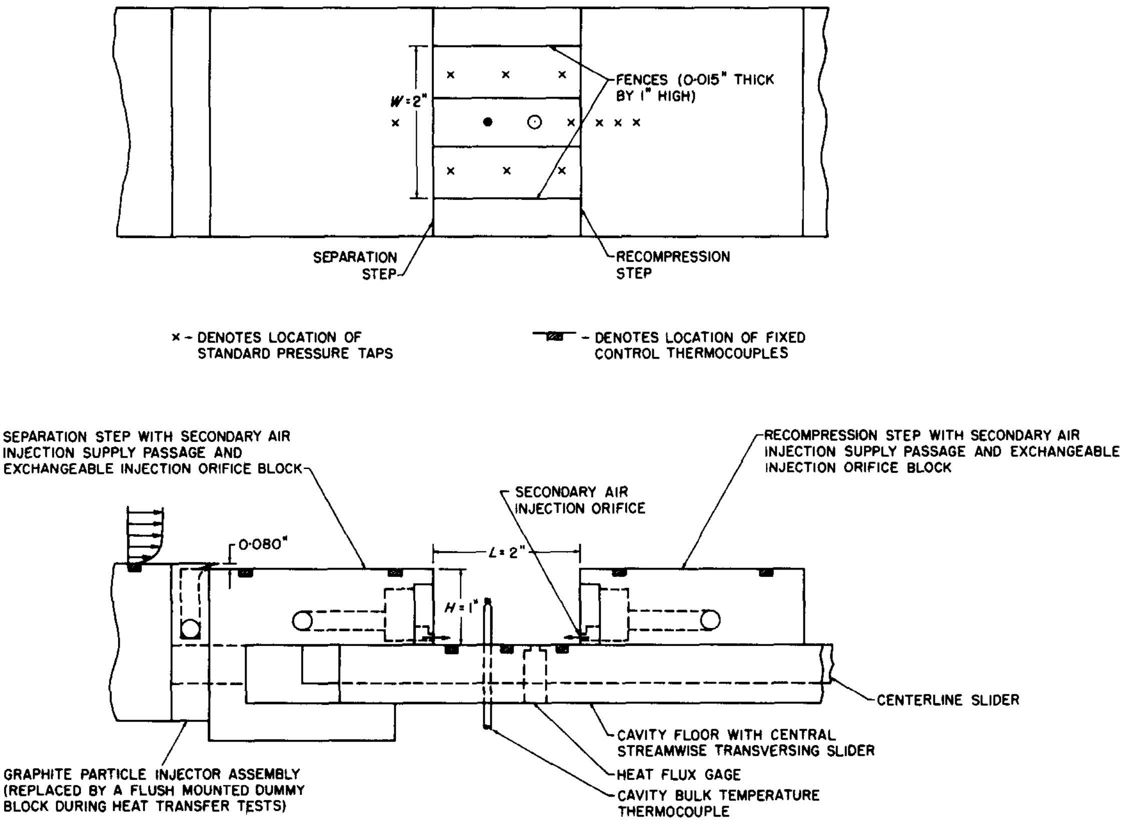

FIG. 1. Schematic of the model assembly.

logy used in the following discussion. Note the fences which isolated the rectangular 2 × 2 in central portion of the cavity from the tunnel side-wall boundary layers; the depth of the cavity was 1 in.

The effective Reynolds number ahead of the cavity was determined from boundary-layer traverses at the reference station for the measured upstream wall temperature ratio. The integral moments of the profile and the comparison between the measured heat-transfer coefficient and the turbulent boundary-layer theory of Van Driest [11] are given in Table 1. The data indicate that the boundary layer can be considered to be a full developed equilibrium turbulent flat plate boundary layer to a satisfactory degree of precision.

The floor of the cavity was fitted with a slider carrying a flush-mounted heat flux gauge ($\frac{1}{8}$ in dia.), thermocouples and pressure taps. This instrumentation traversed the streamwise centreline of the model; cross-section pressure measurements and flow visualization indicated that the structure of the flow in the cavity was essentially two-dimensional, but no heat-transfer data were obtained off the centerline. The slider also carried a thermocouple which protruded into the center of the cavity (see Fig. 1) and traversed it streamwise. The average temperature of the internal fluid measured by this thermocouple is denoted in the following as the cavity bulk temperature Tm.

The separation and the recompression steps contained the stagnation reservoirs for the

Table 1

Free stream Mach number	M_∞	$= 2{\cdot}8\ (\pm 1\%)$
Reynolds number per unit length	Re	$= 1{\cdot}23 \times 10^6 \text{ft}^{-1}$
Wall to free stream temperature ratio	T_w/T_∞	$= 2(\pm 4\%)$
Boundary-layer thickness	δ	$\simeq 0{\cdot}230$ in
Boundary-layer displacement thickness	δ^*	$= 0{\cdot}062$ in
Boundary-layer momentum thickness	θ	$= 0{\cdot}0143$ in
Measured Stanton number	St_∞	$= 1{\cdot}4 \times 10^{-3} (\pm 10\%)$
Calculated Stanton number	St_∞	$= 1{\cdot}35 \times 10^{-3}$

secondary air. The actual stagnation conditions of the secondary air were measured immediately upstream of the injection orifices. The flow rate was determined by an independent venturimeter installed in the flow system outside the tunnel.

Several injector geometries were tested. The injector configurations included upstream blowing from the recompression step and downstream blowing from the separation step, parallel to and at an angle to the free-stream direction. The secondary jets were produced either by a row of orifices (48 orifices, 0·028-in dia.) or by a slot spanning the cavity (0·032-in wide). There was no detectable difference between their behavior. The velocity of the secondary jets varied with the mass injection rate and included subsonic and supersonic blowing.

The floor of the cavity and (separately) the separation and recompression steps were provided with internal cooling passages which permitted some control over the level and distribution of the temperature of the model surfaces. The average cavity floor temperature was uniform within at most 10 per cent of the overall driving temperature potential ($To_\infty - T_w$). The measurements of the temperature on the recompression step are considered to be qualitative only because of the large gradients which exist in the region of reattachment; they were used primarily to monitor the uniformity of the conditions from test to test.

RESULTS WITHOUT SECONDARY INJECTION

The usual definition of the heat-transfer coefficient is

$$q = h(Taw - T_w) \qquad (1)$$

where the local adiabatic wall recovery temperature Taw contains information regarding the structure of the flow field and its diffusive properties. This quantity must be properly defined, viz. $T_w = Taw$ at $q = 0$ if h is to be even approximately universal.

The overall adiabatic recovery temperature of the cavity (Taw_c) need not be the same as that of the upstream boundary layer. It is extremely difficult to acquire direct information leading to a clear definition of this parameter in a flow as complex as that in the cavity. Measurements in cavities with non-conductive walls [12] show, as may be expected, that Taw_c is not constant over the surface. It is practically possible to define it only in an average sense.

The fact that the flow in a separated region involves two separate resistances to the transfer of heat has been recently emphasized in the literature [8]. These resistances which are in series are that of the shear layer and that of the (subsonic) boundary layer forming over the internal surfaces of the model. The recirculating fluid in the cavity is then at an average temperature Tm which is intermediate between the temperature of the wall and the free-stream stagnation temperature. Measurements of Tm are reported [8] for a blunt base wake. These measurements (which are indicated on Fig. 2; see, for instance [8]) show that the conductance of the wall boundary layer is less than that of the shear layer: the cavity bulk temperature is always quite close (typically 90 per cent) to the wall temperature. It follows that the base surface temperature under adiabatic conditions nearly equals the shear layer adiabatic recovery temperature and one can use the correlation of adiabatic data [10, 12, 13] to calculate Taw_s, the adiabatic recovery temperature of the shear layer alone:

$$\eta \equiv \frac{Taw_s}{To_\infty} = \frac{\left(1 + r_s \dfrac{\gamma - 1}{2} M_\infty^2\right)}{\left(1 + \dfrac{\gamma - 1}{2} M_\infty^2\right)} \tag{2}$$

$$r_s \equiv \frac{Taw_s - T_\infty}{To - T_\infty} = 0{\cdot}85.$$

We propose to assume that Taw_s is the same for base-wakes and cavities in the same free stream.

Figure 2 shows measurements of the average cavity bulk temperature Tm_0 presented as a ratio to Taw_s calculated from equation (2). The data includes tests with both a variable wall temperature and a variable stagnation temperature. The domain of variation of the ratio Tm_0/Taw_s is between unity, corresponding to the case in which the resistance of the wall boundary layer dominates, and the line defined by $Tm_0 = T_w$, corresponding to an infinite conductance of the wall boundary layer. Note that Chapman's analytical treatment of the cavity heat-transfer problem [5] assumes the latter to be true.

The shear layer and the wall layer coefficients

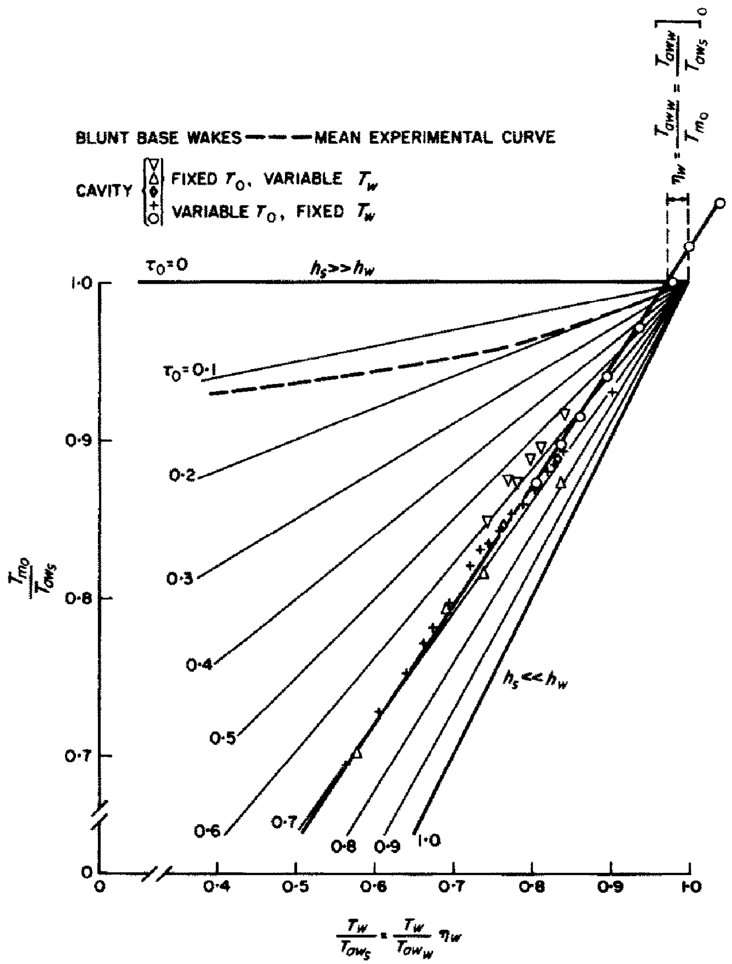

FIG. 2. The wall-bulk temperature equilibrium of wakes and cavities without secondary injection.

are defined with reference to their individual adiabatic recovery temperatures, that is,

$$q_0 = h_s(Taw_s - Tm_0) = h_w(Taw_w - T_w). \qquad (3)$$

These are the only definitions which preserve the conceptual character of these coefficients as properties of the flow field.

It is clear that the line $Tm_0/Taw_s = 1$ describes an adiabatic cavity. Simultaneously, T_w/Taw_w must be unity for the adiabatic case. Therefore, the value of Tm_0/Taw_s at $T_w/Taw_w = 1$ defines the recovery ratio of the wall layer

$$\eta_{w_0} = \frac{Taw_w}{Tm_0} = 0{\cdot}97. \qquad (4)$$

Tm_0 plays the role of a stagnation reservoir temperature with respect to the wall layer. It will be convenient to define a function τ_0:

$$\tau_0 = \frac{Taw_s - Tm_0}{Taw_s - T_w}. \qquad (5)$$

With the aid of equation (3), τ_0 can be expressed as

$$\begin{aligned} \tau_0 &= \frac{h_w}{h_s}\left[1 - \frac{Taw_s - Taw_w}{Taw_s - T_w}\right] \\ &\simeq \frac{h_w}{h_s} \quad \text{for} \quad \frac{Taw_s}{T_w} \gg 1. \end{aligned} \qquad (6)$$

Thus, τ_0 represents grossly the ratio of the conductances of the wall layer to the shear layer. In a cavity this ratio is about 70 per cent and considerably larger than in the base wake in which it is more nearly 10 per cent. In view of the much more violent recompression process leading to a stronger internal vortex in the former case (see, for instance [2], which discusses the structure of the flow in the cavity), these findings seem reasonable. It follows from this interpretation, however, that cavities having different shapes of the recompression step (ramp, fillet, etc.) may have different "characteristic curves" than the rectangular one studied in the present case.

There is a question as to whether the "characteristic" curve of Fig. 2 is invariant with respect to the free stream Mach and Reynolds number (where the Reynolds number should be thought of as describing the character of the oncoming boundary layer). It seems reasonable to suppose that a change in heat-transfer properties of the shear layer due to changes in the external flow is associated with a proportional change in its momentum transfer properties (Reynolds analogy). Since this drives the internal vortex in the cavity, the "effective" free stream velocity over the floor of the cavity, and, therefore, the transfer properties of the wall boundary layer, would change proportionally. It follows that at least over a reasonable range of Mach and Reynolds numbers and with turbulent oncoming boundary layers, the ratio of resistances of the shear layer and the wall layer can be assumed to remain fixed, which means that the τ_0 curve is a "characteristic" of the cavity.

The recovery ratio η_w of the wall layer can be related to a recovery factor r_w which introduces a mean internal cavity velocity. It is reasonable to assume that r_w is a fixed property of the layer by analogy with boundary-layer theory. As long as the effective mean internal cavity velocity is low-subsonic, $\eta_w \simeq r_w$ (from their respective definitions). η_w can be assumed independent of the free stream in this domain. The assumptions that τ_0 and η_w are constants are approximations of the same order.

One can now define an overall average adiabatic wall recovery factor of the cavity

$$r_c = \frac{Taw_c - T_\infty}{To - T_\infty} = \frac{\eta_w \eta_s \dfrac{To}{T_\infty} - 1}{\dfrac{To}{T_\infty} - 1} \qquad (7)$$

and reduce the measured heat flux to a coefficient using the definition

$$q_0 = h_0(Taw_c - T_w). \qquad (8)$$

An analysis of our data proves that indeed this coefficient h is more nearly independent of q (that is of T_w/T_0) than a coefficient defined using the thermal driving potential ($Taw_\infty - T_w$) which applies to the upstream boundary layer. As it is, Taw_c is a mean quantity for the entire cavity so that only $\bar{h}_0$ can be expected to remain constant as $\bar{q}_0$ tends to zero. Local values of h are expected to exhibit scatter, particularly near the adiabatic condition at which the present approximate framework is certainly invalid.

Data represented on Fig. 3 in the form of ratios of h_0 to the heat-transfer coefficient in the boundary layer ahead of separation. The character of the distribution corresponds closely to that found previously for supersonic flow over rectangular cavities with thin oncoming boundary layers (thin relative to the depth of the cavity) [1, 2]. The scatter bars indicated on Fig. 3 include tests for ratios of the cavity wall temperature to free stream stagnation temperature ranging from 0·6 to 0·9.

RESULTS WITH INJECTION

Three independent parameters describe the secondary injection: the mass flow rate, the relative enthalpy level of the secondary gas and the geometry of the injection.

The relative thermal level of the added mass is represented by the dimensionless parameter β:

$$\beta = \frac{Taw_s - To_B}{Taw_s - T_w}. \tag{9}$$

A value $\beta = 1$ means that the stagnation temperature of the secondary injectant equals the average temperature of the cavity wall; $\beta > 1$ and $\beta < 1$ represent blowing colder and hotter than the walls, respectively. The condition

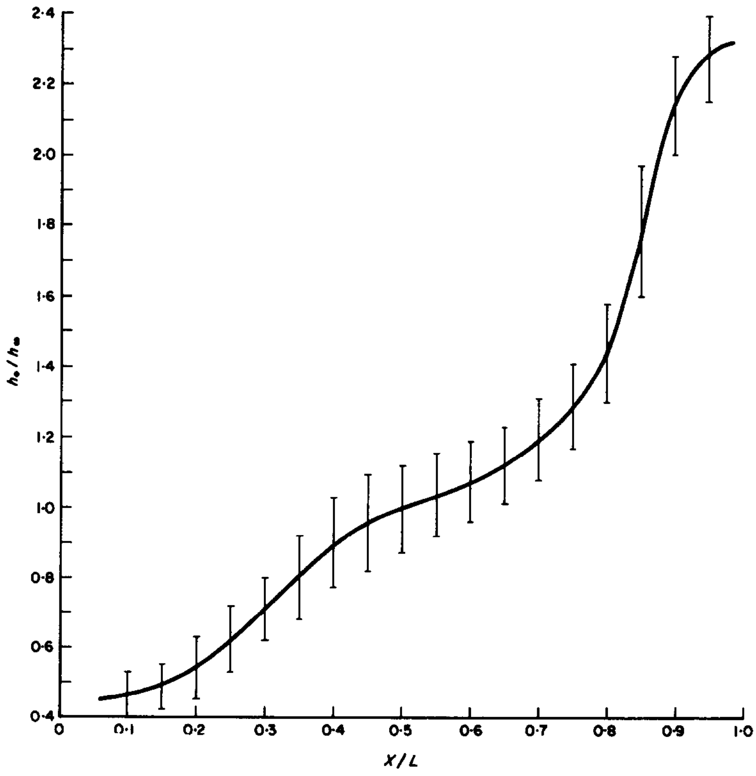

FIG. 3. Heat-transfer distribution on the cavity floor without secondary injection.

$\beta = \tau$, where τ is defined in analogy to the no-blowing case [see equation (5)]

$$\tau = \frac{Taw_s - Tm}{Taw_s - T_w} \tag{10}$$

(with Tm a variable dependent on the injection) represents the addition of mass at exactly the average enthalpy prevalent in the bulk of the cavity. Grossly one would expect that changes in the overall transfer properties of the cavity when $\beta = \tau$ are due to dynamic modification of the structure of the internal flow without the simultaneous participation of the additional mass as a heat sink.

The secondary mass flow rate is given in terms of the dimensionless blowing parameter

$$B = \frac{\dot{m}}{\rho_\infty U_\infty H St_0}. \tag{11}$$

The definition suggests that the effect of mass addition is felt over a projected area H (per unit span) where H is numerically equal to the depth of the cavity. The choice of H as reference length is based on considerations of the basic structure of the internal flow in the cavity. It is characterized by a strong recompression vortex occupying a volume of magnitude H^2W immediately upstream of the recompression step. The remainder of the cavity (downstream of the separation step) is nearly "dead air"; detailed investigations of this flow (with no injection) are recorded, for example, in [2]. In the case of upstream injection from near the floor on the recompression step, that is, injection tangential to the "rim" of the recompression vortex, this structure is preserved and the added gas circulates with the vortex; that is, in the length characterized by the dimension H.

The measurements of heat transfer to the floor of the cavity with blowing are presented in the form of the local heat-transfer coefficient h to the coefficient h_0 at the same location in the cavity but without injection. This ratio emphasizes the local effect of blowing. Both h and h_0 are defined on the basis of the temperature difference $(Taw_c - T_w)$ implying that the mean adiabatic recovery factor of the cavity does not change with blowing. From equation (7), Taw_c depends on η_w and η_s. The factor η_w was evaluated with blowing by noting that, if h_w is indeed a property of the flow, the singularity $\bar{q}_w = 0$ must be associated with $(Taw_w - T_w) = 0$ which defines Taw_w. The ratio T_w/Tm was measured and plotted against $\bar{q}_w$. At $\bar{q}_w = 0$ (obtained by interpolation) this ratio is exactly $Taw_w/Tm = \eta_w$. The results for all tests with blowing yielded $0{\cdot}96 < \eta_w < 0{\cdot}99$ so that within the accuracy of this analysis

$$\eta_w = \eta_{w_0} = 0{\cdot}97 = \text{const.}$$

independent of B. An equivalent study of η_s as a function of B is not so simple because even though $\bar{q}_w$ (heat flux to the wall) is set to zero, $\bar{q}$ (heat flux to the cavity) may not be zero, the difference being absorbed by the thermal capacity of the secondary injectant.

Figure 4 shows a typical series of heat-transfer traverses. In each series β and the wall to stagnation temperature ratio are held (nearly) constant and the blowing parameter B is varied. The injector geometry is fixed; it is shown by a sketch on the figure. The major effect of blowing is to reduce, and in this case in which the secondary gas is added at a stagnation temperature lower than T_w, to reverse the sign of the peak heat transfer in the neighborhood of the recompression step. The "dead air" zone near separation is affected little.†

Several injector geometries were tested. Typical data (nearly equal values of β, and T_w/To) are shown on Fig. 5 along with the schematics of the injector configuration. It is clear that blowing from the separation step in the downstream direction, or from both steps simultaneously, results in a smaller reduction in heat flux to the cavity floor than the case studied

† This portion of the curves is dotted in following the average of the data obtained in several tests. Specific points are not shown because, since h is low in that region, the experimental error and the scatter is much higher than in the remainder of the model.

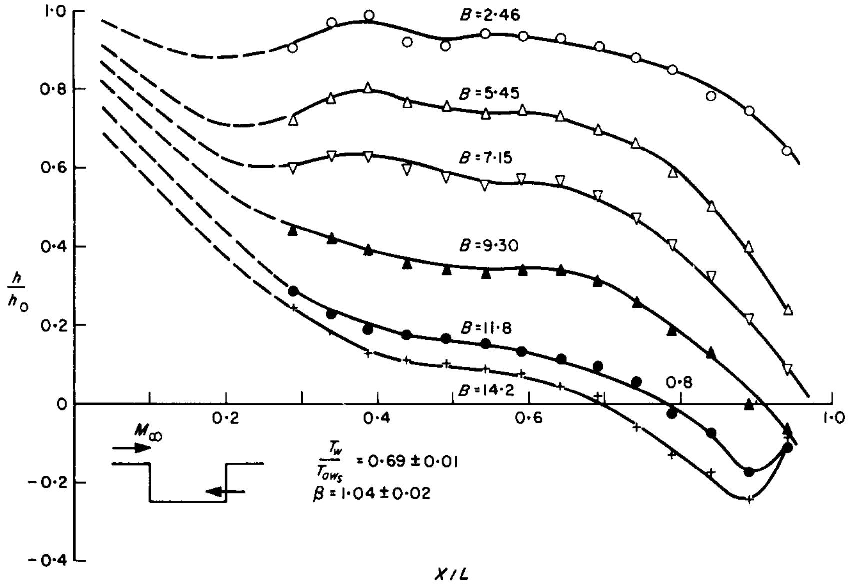

FIG. 4. Influence of secondary injection on the cavity floor heat-transfer distribution.

previously and causes several peaks in the distribution of heat flux to the floor. This is compatible with the model suggested previously: injection opposing the sense of the recompression vortex disturbs the basic structure of the flow in the cavity and "churns" up the nearly dead-air pocket near separation, increasing its thermal conductance. Figure 6 shows some comparative flow visualization pictures obtained by coating the cavity with a suspension of lamp-black-in-kerosene which dries during the test. These pictures are taken with one of the "fences" removed. The example showing injection from both steps exhibits clearly a two-vortex structure (corresponding to the double peak and the distribution of h typical of these tests) while the well-defined single vortex is preserved even with extreme blowing upstream from the recompression step.

Downstream directed injection may be preferable when the objective is to mix the secondary injectant with the gas in the cavity (such as when a cavity is to be used as a flameholder in supersonic combustion). However, since the primary concern here is the reduction of heat transfer to the cavity, the tests with downstream injection (which are so irregular that they all but escape generalization) will not be discussed in the following.

Figure 7 presents the average heat-transfer coefficient over the floor of the cavity as a function of blowing for upstream injection. It must be remembered that the blowing and the wall temperatures are two additional parameters which enter the problem. These are not quite constant from point to point so that the correlation curves drawn through the experimental points on Fig. 7 are only approximate.

GENERALIZED CORRELATION OF RESULTS

The objective of the following analysis is to provide a conceptual framework for generalizing the experimental measurements. We postulate a model whereby the secondary mass added to the cavity at a stagnation temperature To_B is first brought to thermal equilibrium with the gas contained in the cavity; that is, it absorbs or releases $[HC_p\dot{m}(To_B - Tm)]$ units of energy

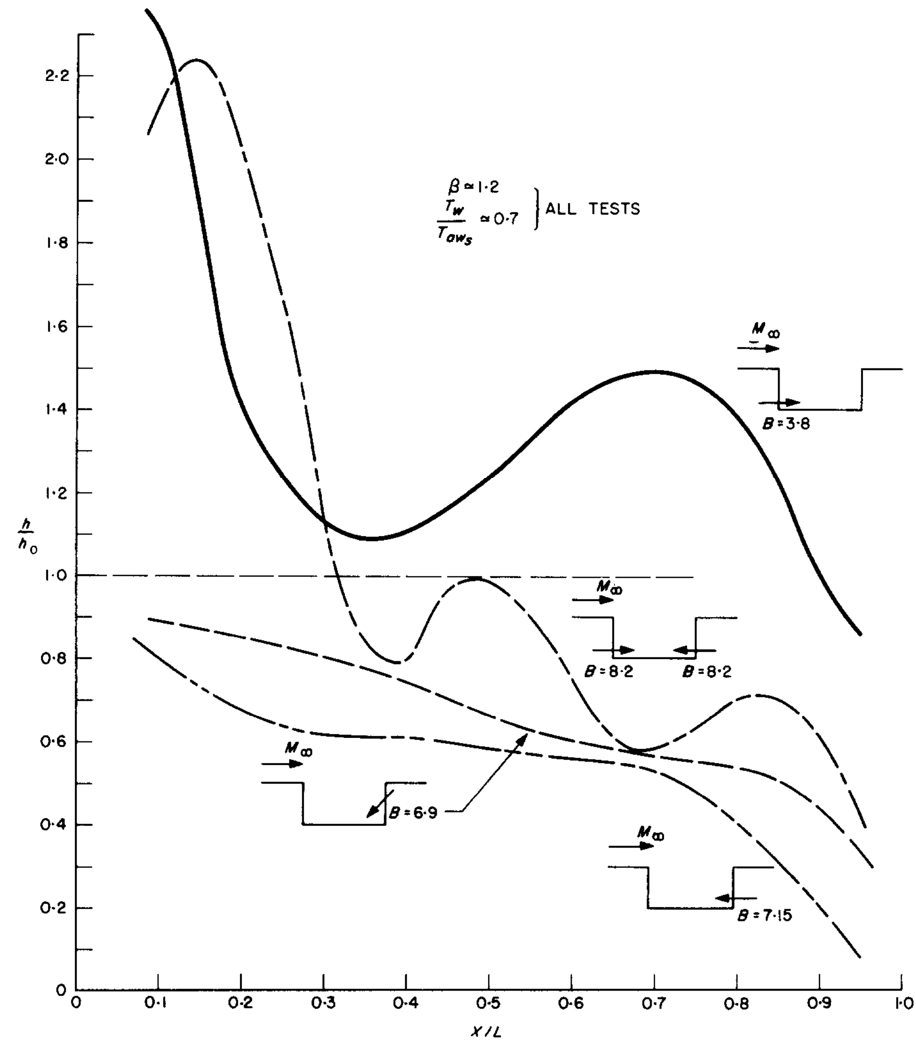

FIG. 5. Typical heat-transfer distributions for various injector configurations.

per unit time. No energy is transferred to the cavity walls directly from the injected gas.

Under this assumption the thermal properties of the cavity can be represented by the equivalent electrical network shown on Fig. 8. R_s and R_w are the thermal resistances of the shear and wall layers, respectively, defined as follows:

$$R_s \equiv \frac{1}{h_s} = \frac{Taw_s - Tm}{q} \tag{12}$$

$$R_w \equiv \frac{1}{h_w} = \frac{Taw_w - Tm}{q_w} \tag{13}$$

where R_s and R_w (or h_s and h_w) are properties of the dynamic structure of the flow. They depend, therefore, on the intensity of blowing and on the geometry of the injector, but not on the thermal properties of the secondary air or the thermal boundary conditions at the wall of the cavity (β and T_w/To).

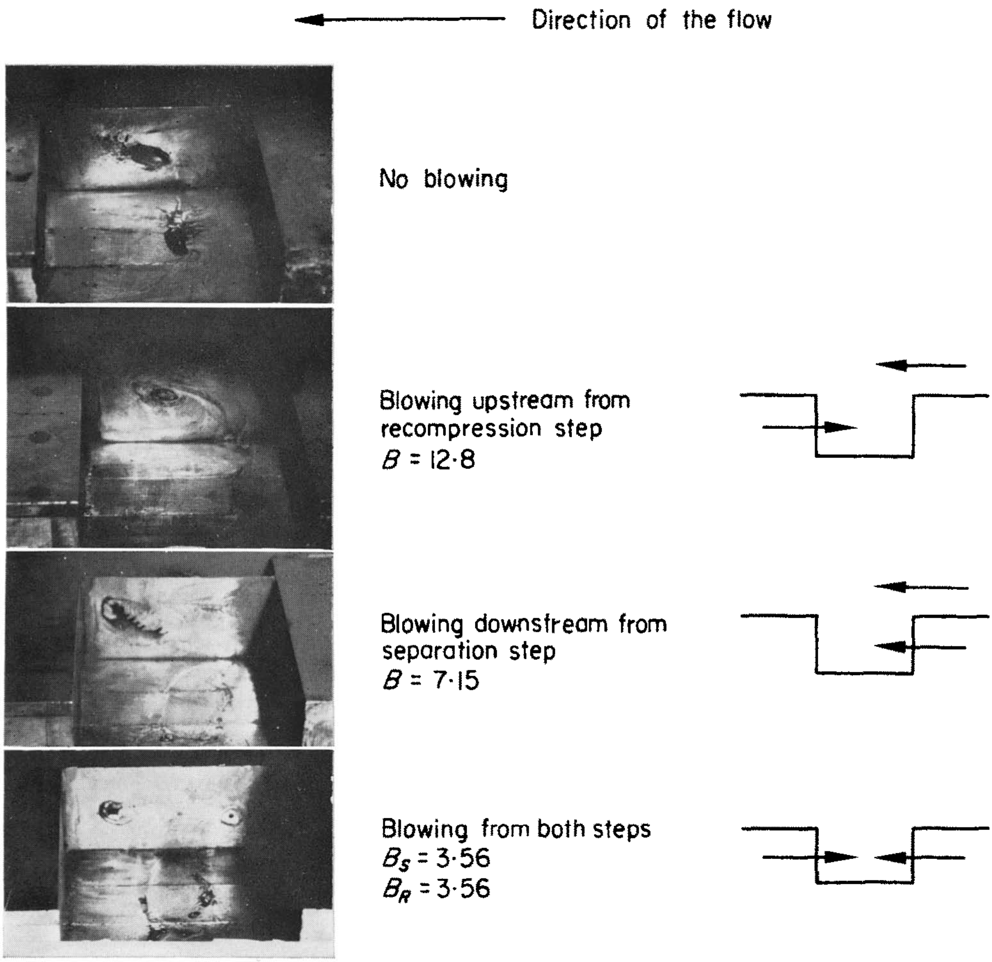

FIG. 6. Typical lampblack visualization of the cavity flow structure.

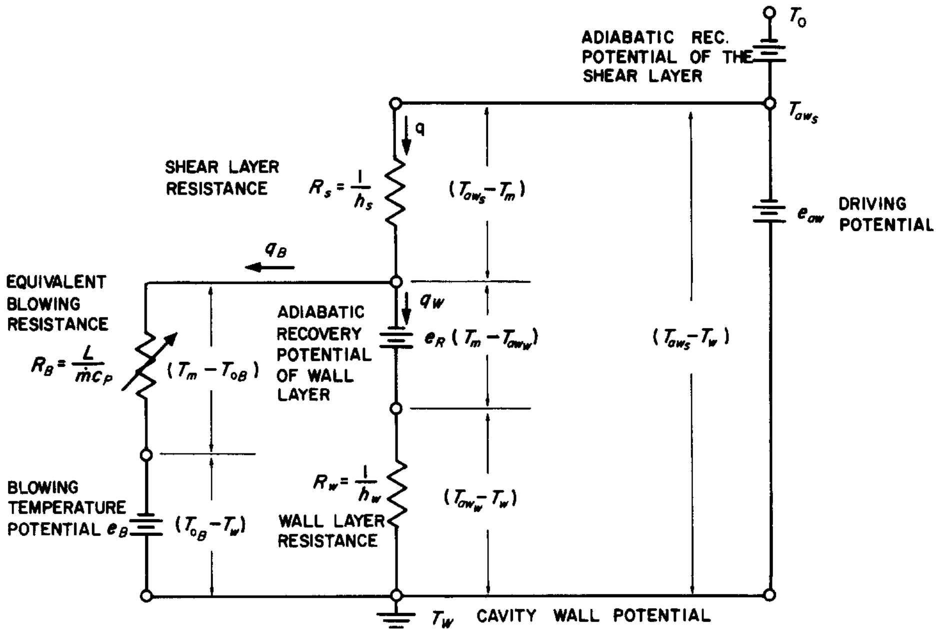

FIG. 8. The equivalent electrical network representation of the cavity heat balance.

results can probably be used to estimate the properties of cavities with $1 < L/H < 3$, but we would not recommend using these data for $L/H > 3$, for different planforms, for shallow cavities relative to the boundary layer ($\delta/H > 1$) and cavities with rounded or ramped recompression surfaces.

(b) Only upstream injection from the recompression step is considered. The secondary jet axis must lie at a small distance above the wall because otherwise the assumption that no energy is transferred directly from the secondary gas to the wall would fail.

(c) The "cavity characteristic" τ_0 vs. T_w/Taw_s, which was assumed to be invariant with respect to the free stream Mach number and the Reynolds number, limits the validity of the present results to the case of turbulent flow in the oncoming boundary layer and probably restricts it to supersonic (as contrasted with hypersonic) flow.

(d) The functions Γ and Θ were assumed to depend on B only, for which we have no experimental justification. This is compatible with the theory of transpiration,† but the existence of the recompression process may well invalidate this analogy In that case, Γ and Θ would also be functions of St_0.

(e) In the same sense, the effect of the velocity (or Mach number) of the secondary jet is not resolved. In the present experiments the jets become sonic at values of B between 2·5 and 7·5 depending on the specific injector plate. However, the location and angle of the jet axis (for upstream blowing) had no noticeable effect on the function Γ. Also the subsonic–supersonic transition in the jet flow regime could be held responsible for the drop in the Γ curve but not for the simultaneous drop in the Θ curve. These curves seem, therefore, to be a function of the mass addition-rate and not the jet velocity.

Note that the parameter β has an upper limit which corresponds to the maximum cooling

† The linear "heat blockage" equation, $St/St_0 = 1 + KB$, can be considered as the first term of an expansion of the Θ function in B.

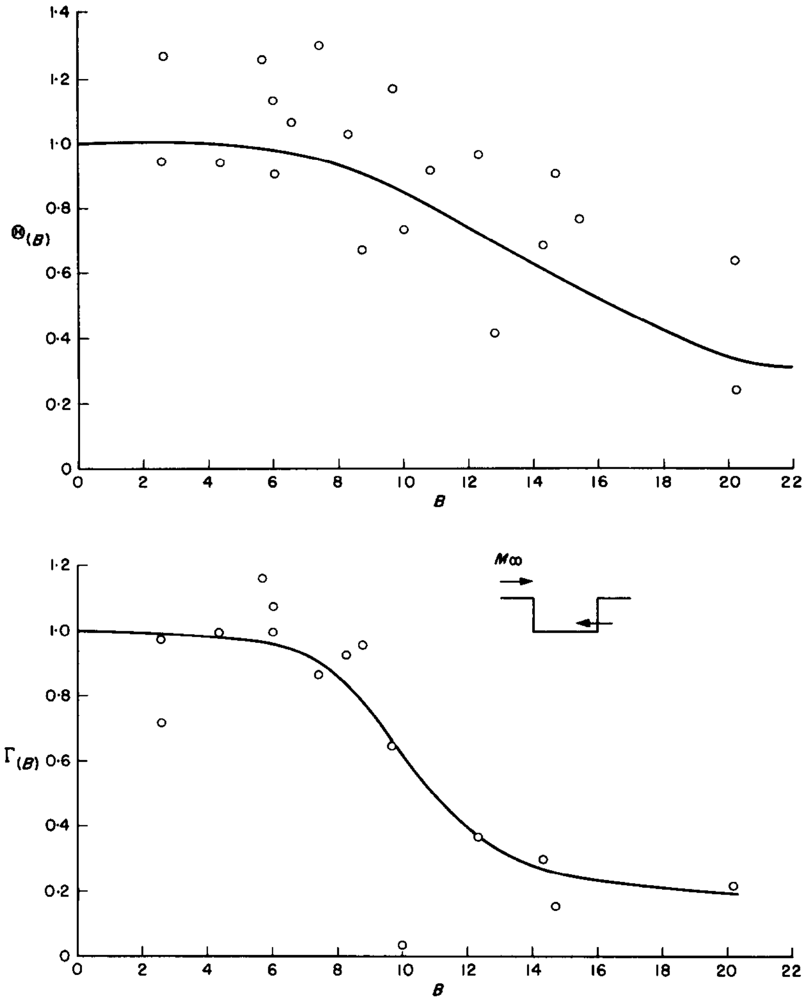

FIG. 9. The $\Gamma_{(B)}$ and $\Theta_{(B)}$ functions for blowing upstream from the recompression step ($H/L = 0{\cdot}5$).

potential of the secondary injectant; that is, to the lowest possible blowing temperature $To_B = 0$.

$$\beta = \beta_{\text{lim}} = \frac{1}{1 - \dfrac{T_w}{Taw_s}}. \tag{17}$$

Therefore, to obtain a prescribed heat transfer ratio $\bar{h}/\bar{h}_0$ there exists a minimum blowing rate $B_{\min}$ which is only a function of the wall-to-stagnation temperature ratio.

Another useful result derivable from the generalized correlation is the value of the blowing parameter B_{crit} at which the heat transfer to the cavity is zero. From the equations of the thermal circuit one finds that at $\bar{q} = 0$

$$\frac{H}{L}\tau_0(\beta - 1) = F_{(B_{\text{crit}})} = \frac{\Theta_{(B)}}{B} \tag{18}$$

Θ/B can be plotted using Fig. 9. The curve tends to an asymptotic value $B_{\text{crit}} \simeq 25$ as $\beta \to 1$ which, from the definition of β, represents blowing at a temperature equal to shear layer adiabatic recovery temperature. Obviously, the

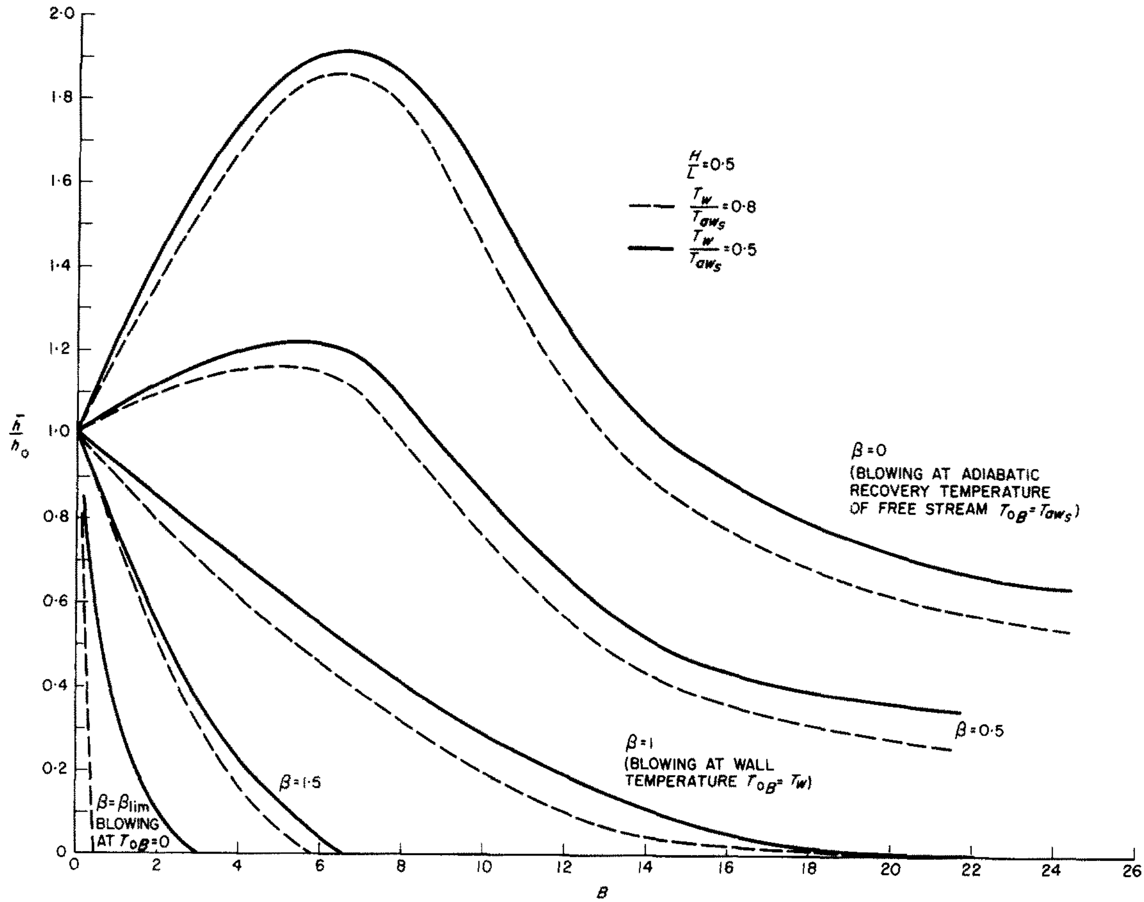

FIG. 10. Generalization of the heat-transfer results for $H/L = 0{\cdot}5$.

condition $q = 0$ cannot be reached with blowing at a temperature higher than this limit.

EXPLORATORY STUDY MASS EXCHANGE

The transfer characteristic of the shear layer (the Θ function) is a purely empirical correlation, which could also be derived, in principle, from an analysis supplemented by appropriate statements regarding the nature of the shear-layer flow and the inner boundary conditions. Eckert and Scott [8] do this (for the base-wake) using an integral solution of a steady, two-dimensional boundary-layer approximation with a transpiration boundary condition and an assumed form of the velocity profile through the region. It is questionable though whether such a model is at all realistic in the present case.

Some insight into this question can be derived from an exploratory study of the penetration of particles from the free-stream into the cavity, which is also interesting in its own right. Graphite dust (3–10 μ dia.) was injected tangentially through the wall into the boundary-layer upstream of the cavity (at a station approximately fifteen boundary-layer thicknesses ahead of separation). The attenuation of two collimated beams of visible light traversing the tunnel upstream (1·5 in ahead of separation) and through the center of the planform of the cavity was measured by photocells and used to indicate the integrated density of particles suspended in the flow.

A typical record for a particular injection pulse is shown on Fig. 11. The results show that a steady state exists and obeys the relation

$$\left[\frac{i_c}{i_b}\right]_{\text{eqn}} = 1{\cdot}8 \pm (0{\cdot}5) \qquad (19)$$

which is independent of blowing. This condition can be seen towards the end of the (approximately) exponential decay portion of one can solve for α by a numerical integration of the data. The result is plotted on Fig. 12. It is found that the time constant does depend on the blowing rate.

The fact that the equilibrium distribution is independent of blowing while the time constant is not suggests an unsteady periodic mass exchange, the dynamic character of which (frequency and amplitude) is affected by blowing. In any case, one can conclude from these tests that it is unlikely that realistic estimates of the transfer properties of the shear layer over the cavity as a whole can be based on analytical models such as that discussed in the introductory paragraph of this section.

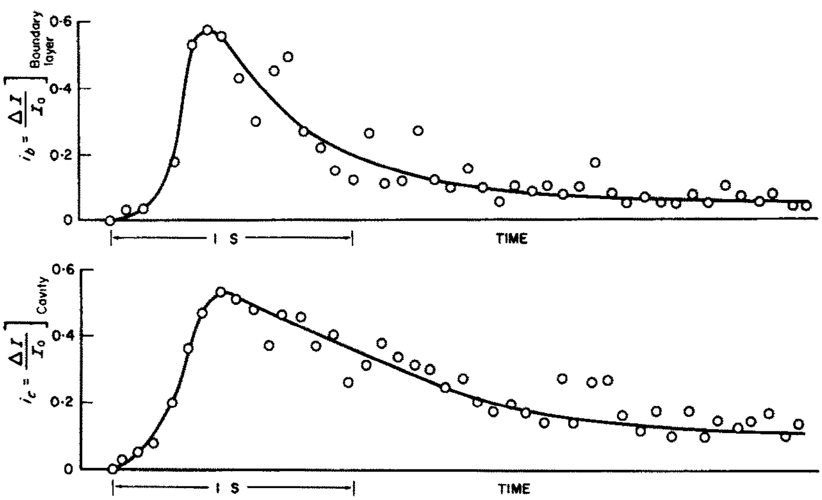

FIG. 11. Typical record of the fractional change in light density for the cavity and the upstream boundary layer due to graphite particles carried by the oncoming boundary layer ($B = 3{\cdot}75$, $H/L = 0{\cdot}5$).

the pulse shown in Fig. 11.† Conversely, there is a definite time constant associated with the transient initial period during which the rate of change of the injection is large. Describing the process by a linear approximation

$$\frac{di_c}{dt} = \frac{1}{\alpha}(i_{c_{\text{eqn}}} - i_c) = \frac{1}{\alpha}(1{\cdot}8 i_B - i_c) \qquad (20)$$

† During all the tests under discussion no deposition of graphite on the walls of the cavity occurred, which was verified by steady injection over long periods. To preserve this condition the walls must be meticulously clean (with alcohol) and devoid of any oil-film; otherwise graphite powder sticks immediately to the floor. Since the wind tunnel is vertical, gravity has no influence on the penetration of particles into the cavity.

CONCLUSIONS

The results show that it is possible to control the heat transfer to the floor of a cavity with relatively modest rates of injection of secondary gas. The most efficient injector configuration consists of jets directed upstream from the recompression step near the floor of the cavity. This configuration results in the most uniform distribution of the local heat-transfer coefficients at the lowest level for a given mass addition rate.

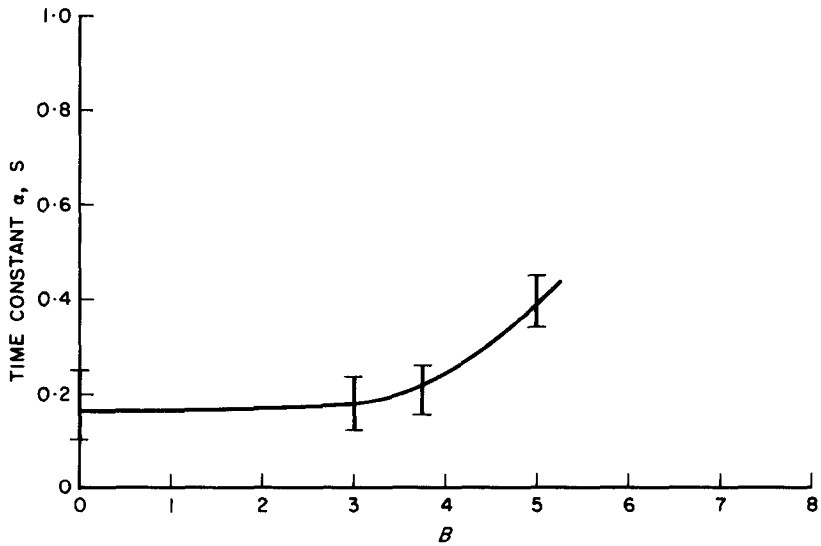

FIG. 12. The influence of blowing on the time constant associated with transient injection in the upstream boundary layer.

The average heat flux can be reduced to zero when the temperature of the secondary injectant is lower than the temperature of the wall.

A generalized correlation of the data in terms of two empirical functions of the blowing parameter is presented. These functions are determined only for the specific geometry and the free-stream conditions tested. However, the model of the structure of the flow on which the generalization is based provides a conceptual framework for suggesting that the present results (in terms of the dimensionless parameters defined in the text) are approximately valid in a reasonable range of supersonic Mach numbers and for turbulent oncoming boundary layers. Similarly, scaling over a reasonable range of sizes for geometrically similar cavities seems permissible, but the present results cannot be applied but as a qualitative guide to different planforms or length-to-depth ratios of the cavity, especially if the shape of the recompression step is different than that tested.

Measurements of the average temperature in the cavity with no blowing show that the largest resistance to heat flux (in an average sense) lies in the shear layer, but that both the shear layer resistance and the resistance of the boundary layers on the internal walls are of the same order of magnitude.

Exploratory studies of the flow with solid particles injected into the free stream boundary layer indicate that there is a definite and important interchange of mass between the free stream and the cavity. The steady-state density of particles suspended in the cavity is not affected by mass injection into it; however, the transient filling time in response to a burst of particles in the external flow is a function of blowing and increases with increasing mass injection.

REFERENCES

1. H. K. LARSON, Heat transfer in separated flows, *J. Aero/Space Sic.* **26**(11), 731–737 (1959).
2. A. F. CHARWAT, C. F. DEWEY, JR, J. N. ROOS and J. A. HITZ, An investigation of separated flows—part II: flow in the cavity and heat transfer, *J. Aerospace Sci.* **28**(7), 513–527 (1961).
3. J. FOX, Heat transfer and air flow in a transverse rectangular notch, *Int. J. Heat Mass Transfer* **8**, 269–279 (1965).
4. R. A. SEBAN and J. FOX, Heat transfer to the air flow in a surface cavity, *International Developments in Heat Transfer*. Am. Inst. Chem. Engrs, New York (1963).
5. D. R. CHAPMAN, A theoretical analysis of heat transfer in regions of separated flow, NACA TN 3792 (1956).

6. D. R. CHAPMAN, D. M. KUEHN and H. K. LARSON, Investigation of separated flows in supersonic and subsonic streams with emphasis on the effect of transition, NACA Report No. 1356 (1958).
7. H. H. KORST, A theory for base pressure in transonic and supersonic flow, *J. Appl. Mech.* **23**, 583–593 (1956).
8. E. R. G. ECKERT and C. J. SCOTT, Heat and mass exchange in the supersonic base region, AGARD CP No. 4, Separated Flows, Part I, pp. 429–478. Proceedings of the AGARD Specialists Meeting on Separated Flows, Brussels, Belgium (May 1966).
9. P. M. CHUNG and J. R. VIEGAS, Heat transfer in the reattachment zone of separated laminar boundary layers, NASA TN D 1072 (September 1961).
10. H. THOMANN, Measurement of the recovery temperature in the wake of a cylinder and wedge at Mach numbers between 0·5 and 3, Report 84, The Aeronautical Research Institute of Sweden (1959).
11. E. R. VAN DRIEST, Turbulent boundary layer in compressible fluids, *J. Appl. Sci.* **18**(3), 145–160 (1951).
12. H. THOMANN, Measurements of heat transfer and recovery temperature in regions of separated flow at a Mach number of 1·8, Report 82, The Aeronautical Research Institute of Sweden (1959).
13. R. E. LARSEN, C. J. SCOTT, D. R. ELGIN and R. E. SEIVER, Turbulent base flow investigations at Mach number 3, University of Minnesota Rosemount Aero Labs., R.R. No. 183 (July 1962).

Résumé—On décrit une étude expérimentale du transport de chaleur au plancher d'une cavité rectangulaire de forme carrée avec injection secondaire dans la cavité. L'écoulement au-dessus de la cavité était supersonique (nombre de Mach 2,8) et la couche limite était turbulente. On étudie plusieurs configurations d'orifices d'injection secondaire multiples et séparés par lesquels on souffle avec une vitesse subsonique ou supersonique en amont du décrochement de recompression et/ou en aval du décrochement de décollement. On a essayé une gamme de vitesses de soufflage, de températures d'arrêt de l'air secondaire et de températures du plancher de la cavité et l'on a établi une généralisation semi-empirique des données. Aussi longtemps que l'air secondaire est plus froid que la température d'arrêt de l'écoulement libre, le transport de chaleur vers la cavité est réduit, souvent d'une façon substantielle; lorsqu'il est plus froid que la température pariétale, la direction du flux de chaleur peut être renversée avec des valeurs modérées de soufflage. La configuration la plus efficace des injecteurs nécessite un soufflage en amont au voisinage du plancher sur le décrochement de recompression. On présente également des mesures de la température globale de la cavité avec et sans soufflage et des études de la pénétration dans la cavité d'une façon permanente ou transitoire de fines particules de graphite apportée par la frontière en mouvement.

Zusammenfassung—Es wird eine experimentelle Untersuchung des Wärmeübergangs an der Basis einer rechtwinkligen Vertiefung von quadratischer Form mit Sekundärlufteinblasung in die Vertiefung beschrieben. Über die Vertiefung strömte die Luft mit Überschall (Mach 2.8), und die Grenzschicht stromaufwärts war turbulent. Verschiedene Anordnungen einer Vielzahl von einzelnen Sekundärluftöffnungen wurden untersucht, wobei Luft mit Unter- und Überschall, stromaufwärts von der Wiederverdichtungsstelle und/oder stromabwärts von der Separationsstelle eingeblasen wurde. Eine Reihe von Einblasverhältnissen, Stautemperaturen der Sekundärluft und Temperaturen der Basis der Vertiefung wurden überprüft, und es wurde eine halbempirische Verallgemeinerung der Versuchsdaten entwickelt. Solange die Sekundärluft kälter als die Stautemperatur der freien Strömung ist, verringert sich der Wärmeübergang an die Vertiefung, vielfach sogar erheblich; wenn die Sekundärluft kälter als die Wandtemperatur ist, lässt sich die Richtung des Wärmestromes bei mässigem Ausblasen umkehren. Um eine möglichst wirkungsvolle Anordnung der Lufteinblasung zu erhalten, muss man gegen die Strömungsrichtung von einer Stelle nahe an der Basis der Vertiefung auf der Seite der Wiederverdichtung einblasen. Es werden Messungen der Temperatur des Gases in der Vertiefung mit und ohne Ausblasen und Untersuchungen darüber mitgeteilt, inwieweit feine Graphitteilchen, die von der ankommenden Grenzschicht mitgeführt werden, stetig, bzw. vorübergehend in die Vertiefung eindringen.

Аннотация—Дается описание теплообмена потока прямоугольной полости квадратного сечения, в которую вдувается воздух. Поток в полости сверхзвуковой (число Маха 2,8), а пограничный слой вверх по течению — турбулентный. Изучены несколько конфигураций насадок с дискретным вторичным дозвуковым и сверхзвуковым вдувом. Вдув вверх по потоку производится при повторном сжатии, а вниз — при отрыве потока. Исследуется диапазон скоростей вдува, температур заторможенного потока вторичного воздуха, а также температур поддона полости и дается обобщение полученных полуэмпирических данных. Пока температура вторичного воздуха ниже температуры торможения свободного течения, теплообмен к полости уменьшается, и часто довольно значительно, когда же она ниже температуры стенки, можно изменить направление теплового потока при слабом вдуве.

При повторном сжатии с помощью наиболее эффективных насадок производится вдув от поддона. В статье, кроме того, приводятся измерения объемной температуры полости с вдувом и без него, а также исследуется стационарное и нестационарное попадания мелих графитовых частиц, вносимых набегающим потоком в полость.