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Laminar Film Cooling Experiments in Hypersonic Flow

B.E. Richards*
von Karman Institute for Fluid Dynamics, Rhode St Genèse, Belgium
and
J.L. Stollery†
Cranfield Institute of Technology, Bedford, U.K.

The paper describes an experimental study of the thermal protection of a surface, in hypersonic flow, by tangential injection of a coolant through a slot with laminar flow prevailing throughout. Heat-transfer measurements were taken on a flat plate in a gun tunnel under isothermal wall conditions and the effect of slot height, streamwise position of slot, flow conditions, and differing coolant gases were examined. A simple discrete layer theory was found to give fair agreement with the experiments. Optimizations of cooling effectiveness using this theory showed that hydrogen was likely to be the most efficient gas for constant mass injection rate.

I. Introduction

THE study concerns the film cooling of a surface exposed to a high heat-transfer rate from a hypersonic stream by tangential injection of a gas coolant through a discrete slot. This method of cooling has already found applications in gas turbines and rocket nozzles, and in future it may be considered as a means of cooling exterior and ramjet intake surfaces of hypersonic vehicles.

Immediately downstream of the slot there is a region where the coolant remains a discrete layer. Further downstream there exists a boundary-layer-like flow which is governed near the wall by the local wall friction, and in the outer flow by the mixing between the film and the existing preslot boundary layer. This latter influence disappears with increasing distance from the slot until eventually the velocity profiles become similar and fully boundary-layer-like.

Most studies of film cooling have involved turbulent, rather than laminar flow to suit the application, and since such a flowfield is easy to set up in an experiment. Goldstein's[1] significant review of the subject concerns only the turbulent case. In future hypersonic vehicles, there are likely to be situations where laminar flow is dominant but heating rates and/or recovery temperatures are high such that cooling is needed, and furthermore, in high Mach number facilities it is relatively easy to set up an all-laminar flow situation.

In most applications, the thermal boundary conditions are difficult to define, since the wall temperature is unlikely to be constant and there is likely to be heat transfer to the wall. Research, rather than developmental, experiments are usually carried out under adiabatic wall conditions with the wall temperature measured. Less frequently, experiments are carried out under isothermal wall conditions with the wall heat transfer measured. The latter technique is more appropriate in practice, since in most applications designers wish to cool surfaces exposed to hot flows (e.g., turbine flows, rocket exhausts, hypersonic flows) to a constant temperature level that is thermally acceptable for the material used. This is possible using a combination of film cooling with an internal convection or heat sink cooling system.

The choice of a short duration tunnel (in this case the Imperial College hypersonic Gun Tunnel) to carry out this study is particularly appropriate, since at Mach 10, laminar flows over fairly long flat plates can be generated, and measurements of heat-transfer rates under isothermal wall conditions are made easily and accurately. Problems posed in studying laminar film cooling involve: the establishment of a film within milliseconds; the choice of conditions such that laminar flow prevails throughout; then finally because of lack of earlier such studies the determination of the physical mechanisms controlling the flow behavior in order to correlate the data and guide the work on predicting real flow situations. This paper describes the experimental techniques required to obtain laminar film cooling data at hypersonic speeds, presents examples of the results, and provides a simple but effective empirical description of the overall results taken at different flow conditions, coolant injection rates, slot heights, and coolant gas constituents.

II. Experimental Techniques

The Imperial College No. 1 Gun Tunnel was used for this study. Briefly it is a blowdown tunnel with a shock compression heater. The shock is generated by compressed air driving a free light piston down a 20-ft long barrel filled with the test gas (air). An 8-in. exit diameter conical nozzle gave a source flow at $M = 10$. An open jet section was used. The useful running time was approximately 40 ms.

The film-cooled flat-plate model shown in Fig. 1, has a plenum chamber, fed from two pipes from the rear, which led to a rearward facing slot through a 180-deg bend. This enabled the coolant to be injected tangentially along the model away from the leading edge. The splitter plate which divided the coolant flow from the mainstream tapered down to a thickness of approximately 0.002 in. The distance from the leading edge of the model to the trailing edge of the splitter plate was 1.3 in. The span of the model and the slot were 5 in. and 4.5 in., respectively. The slot height could be varied to 0.033, 0.048, and 0.063 in.

The model was instrumented with thin film platinum resistance gages, painted on pyrex inserts, 2.25-in. wide and 0.05-in. thick, which were mounted flush with the model surface downstream of the slot. An insert could be added in which 14 static pressure holes of 1/16-in. diam were drilled on the centerline. These model configurations were mounted at

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*Professor. Member AIAA.

†Professor and Head, College of Aeronautics. Associate Fellow AIAA.

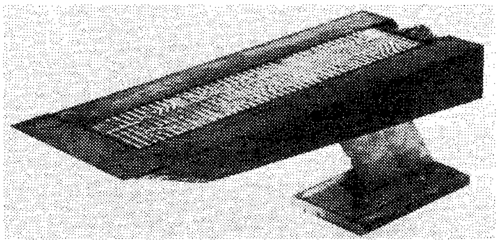

Fig. 1 Flat plate film-cooled model.

zero incidence in the tunnel on a pedestal mount 0.5 in. below the centerline with the slot positioned at the exit plane of the nozzle.

Gas from a high-pressure cylinder was fed through a standard pressure control valve, giving a preset delivery to a floating ball flowmeter which could measure air flows up to 0.125 lb/min at atmospheric pressure and 70°F. The flow was controlled by a 0.125-in.-diam needle valve and was initiated by a 0.5-in.-diam solenoid valve, which was remotely operated at the gun-tunnel control panel a fraction of a second before a test. For air injection, the air was fed directly into the flowmeter from atmosphere. The whole feed system and models were designed such that the coolant gas would choke at the slot exit providing the pressure ratio was high enough. This enabled two dimensionality to within 5% to be achieved across the slot, as checked by pitot pressures measured at the slot exit.

The transient technique based on the surface measurement of a "semi-infinite" conducting material was used to obtain values of heat-transfer rate. The resistance change of any five of the platinum thin film resistance thermometers could be measured during each test. The transient signals were fed to analog networks to provide outputs directly proportional to heat-transfer rate which were recorded on Tektronix 502 oscilloscopes fitted with Polaroid cameras. Pressure measurements were made using C.E.C. 4-326 0-10 psi absolute pressure strain gage transducers.

The following three test conditions were used in the study: $M=10$, $Re/\text{in.}=1.6\times10^5$, $T_0=1290$ K (main test condition), $M=10$, $Re/\text{in.}=1.35\times10^5$, $T_0=1170$K; $M=10$, $Re/\text{in.}=1.05\times10^5$, $T_0=1030$K. The wall and coolant temperature were at the laboratory level of 290K. The coolant flow rate was varied from 0.039 to 0.097 lb/min for air, 0.076 to 0.143 lb/min for freon, and 0.033 to 0.054 lb/min for helium. Argon was injected in one test at 0.101 lb/min.

III. Results and Discussion

Experimental Results

The heat-transfer rate on the flat plate with zero slot height and without injection for the three test conditions used is presented in Fig. 2. The results were compatible with laminar reference temperature theory. The mean line drawn through each set of data was used for nondimensionalizing the film cooling data.

An indication of how much disturbance the injection makes to the outside stream was made by measuring the static pressure on the plate surface at three injection rates including no injection (Fig. 3). The results with injection show slightly higher pressures fairly close to, but not in the immediate vicinity of the slot compared with the no injection case. The low reading at the lowest value of x for the 0.112 lb/min case suggests that there is a large centrifugal effect of the coolant mass due to its being turned rapidly through 180-deg before the slot. The disturbance to the outside stream is considered to be small for the configurations used in these tests.

Examples of the heat-transfer measurements at $M=10$ made in this study with injection are presented in Fig. 4.

Measurements of heat-transfer rate were also made at 0.75 in. from the centerline along the whole model in some tests. Close agreement with the values obtained from the centerline

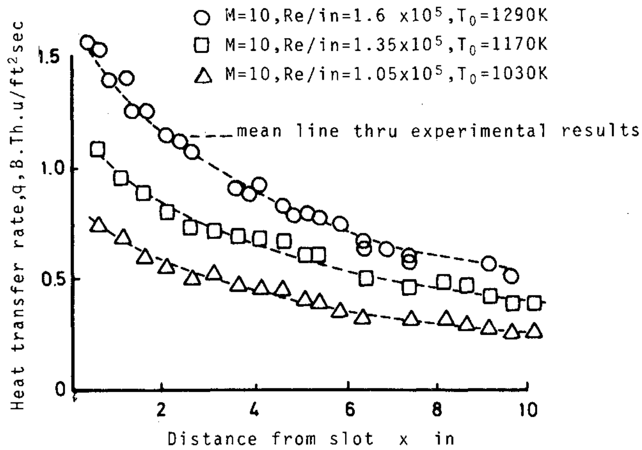

Fig. 2 Heat transfer on flat plate. No injection.

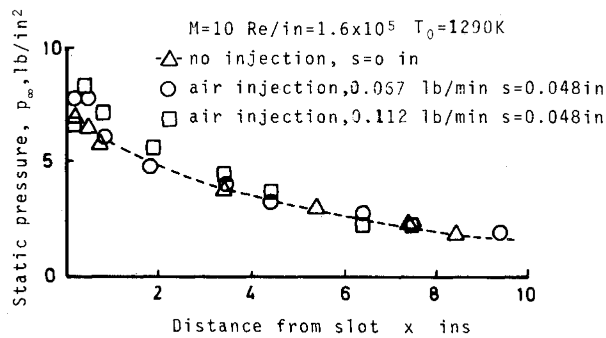

Fig. 3 Measurement of static pressure on flat plate with and without injection.

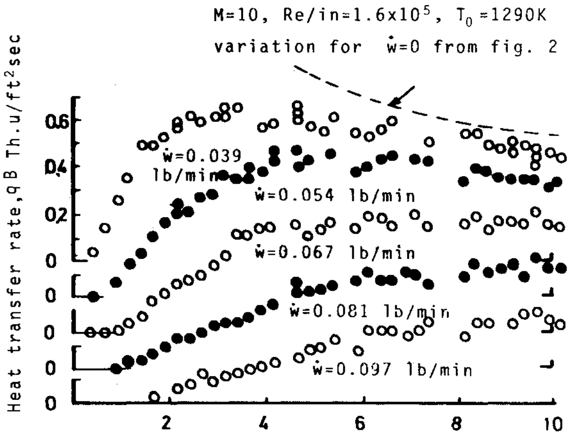

Fig. 4 Heat transfer on flat plate with film cooling. Examples showing effect of varying mass flow rate.

gages was obtained illustrating that two dimensionality was achieved over the length of the plate. Typical schlieren photographs are shown in Fig. 5. (Small side shields placed on the surface of the model just downstream of the slot were used to prevent lateral outflow of the coolant. The slot position is indicated by the zero mark on the photographs.) These results and the steadiness of the heat-transfer traces justify the use of the short duration flow in the gun tunnel to study the problem of film cooling under solely laminar flow conditions.

Analysis and Discussion

The most striking result illustrated in Fig. 4 is the effectiveness with which a laminar film can protect a surface. For example at 100 slot heights downstream of injection, the heat-transfer rate is reduced by 25% and 75% at injection

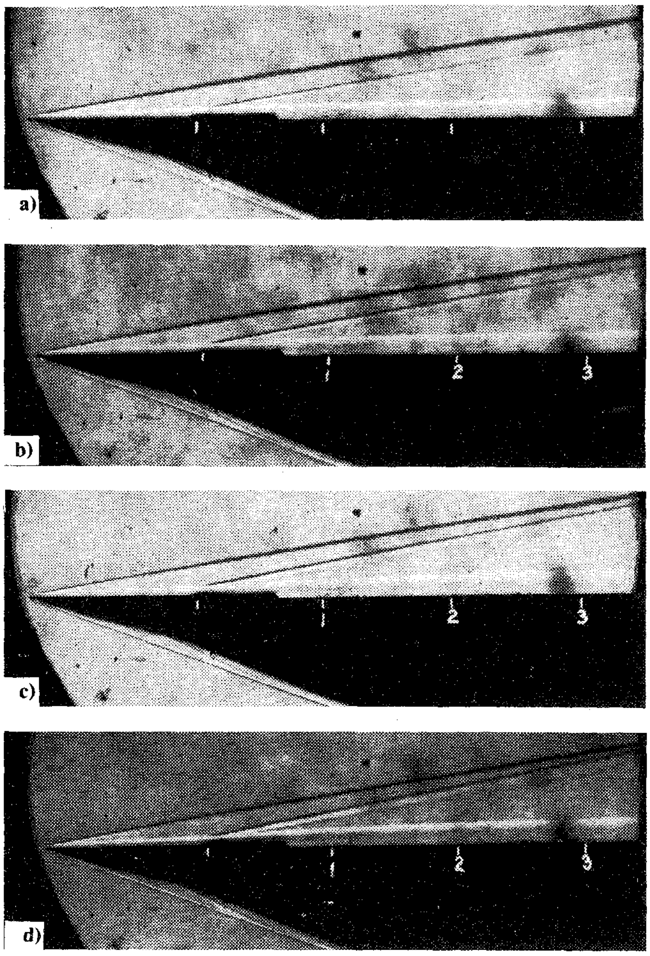

Fig. 5 Schlieren photographs of laminar film cooling $M=10$, Re/in. $=1.6\times10^5$, $T_0=1290$K: a) $\dot{w}=0.039$ lb/min, $s=0.048$ in., b) $\dot{w}=0.067$ lb/min, $s=0.048$ in., c) $\dot{w}=0.081$ lb/min, $s=0.048$ in., d) $\dot{w}=0.097$ lb/min, $s=0.048$ in.

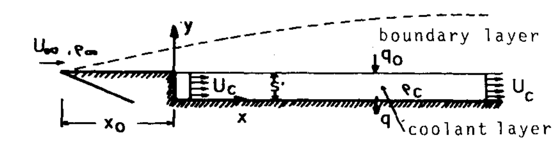

Fig. 6 Discrete layer theory.

rates of 0.039 lb/min and 0.097 lb/min for a slot height of 0.048 in. In turbulent film cooling, since mixing of the two streams is predominant, theories based on heat sink or boundary-layer models are successful in not only correlating film effectiveness data far from the slot (for which they were developed) but also fairly close to the slot as well.[1] This approach would not be expected to work so well for the laminar situation, since it is evident that mixing is slow as shown by the heat-transfer measurements, and the persistence of the film illustrated by the dark line in the schlieren photographs delineating the boundary between the two fluids. A discrete layer theory, of the type used by Hatch and Papell[2] may be expected to be applicable. The effectiveness of the film is best illustrated in these experiments by the ratio of heat-transfer rate with injection to that without injection, q/q_0.

The following assumptions are used in the choice of a function to correlate the data (Fig. 6).

1) The coolant exists as a discrete layer (no mixing) of thickness, s'.

2) The velocity across the profile of this layer remains constant at the injection velocity, v_c. This "rectangular" profile is assumed to remain constant at all stations downstream.

3) The heat transfer through the boundary layer is diffused by one-dimensional heat conduction.

4) The heat transferred from the "outside laminar boundary layer" to the discrete coolant layer, q_i is the same as that to a flat plat surface whose wall temperature is equal to the initial total temperature of the coolant, T_{0c}.

5) The coolant travels a distance x' from the slot before the heat diffuses through the layer.

The full equation for one-dimensional unsteady heat conduction through a slab is

$$\frac{\partial T}{\partial \tau}=\frac{k}{\rho_c C_p}\cdot\frac{\partial^2 T}{\partial y^2} \tag{1}$$

where

T = temperature
y = distance
τ = time
k = thermal conductivity
C_p = specific heat at constant pressure
ρ_c = density

The solution for the ratio of heat transfer at depth d in the slab q to that at the surface q_0 is given in Carslaw and Jaeger[3] as

$$\frac{q}{q_0}=f\left(\frac{2k\tau}{\rho C_p d^2}\right) \tag{2}$$

More exactly, the function is a complementary error function of the bracketed quantity. Applying this equation to the discrete layer assumptions given earlier and putting $\tau=x/u_c$, $d=s'$, and the coolant flow rate $\dot{w}=\rho_c u_c sL$, where ρ_c is the density of the coolant and L is the width of the slot, Eq. (2) then becomes

$$\frac{q}{q_0}=f\left(\frac{2kLx}{\dot{w}s'C_p}\right) \tag{3}$$

Equation (3) was modified to the following equation to account for the time in which the heat diffuses to the lower side of the film:

$$\frac{q}{q_0}\sim\left(\frac{2kLx}{\dot{w}s'C_p}-\kappa\right)\left(1+\frac{x'}{x_0}\right)^{0.5} \tag{4}$$

where κ is a constant defining the starting length, x', and x_0 is the distance of the slot from the leading edge. The second bracketed term was added to account for the complicated heat-transfer function applied to the "rectangular profiled" conducting layer in the model which approximately varies as $x^{-1/2}$ (see Fig. 2). The local film-cooled heat-transfer data was nondimensionalized with the heat transfer rate that was measured without the film, whereas in the flow model it was influenced by the heat-transfer rate at x' upstream of it.

Correlations based on Eq. (4) met with encouraging success for $\kappa=0.12$ for all cases except for the situation of dissimilar gases. (In this correlation, the value s', and that of u_c to be introduced, are determined by assuming the coolant gas to expand from its sonic condition at the slot to a supersonic stream appropriate to the pressure ratio across the slot.) It appeared that there was a consistent trend throughout the results that higher coolant layer velocity caused more efficient cooling and, hence, Eq. (4) was appropriately modified to

$$\frac{q}{q_0}\sim\left[\frac{2kLx}{\dot{w}s'C_p}\left(\frac{u_c}{u_{c0}}\right)^{0.5}-0.12\right]\left(1+\frac{x'}{x_0}\right)^{0.5} \tag{5}$$

in order to correlate the data. Here u_c is the assessed coolant velocity just after the slot and u_{c0} is an arbitrary coolant

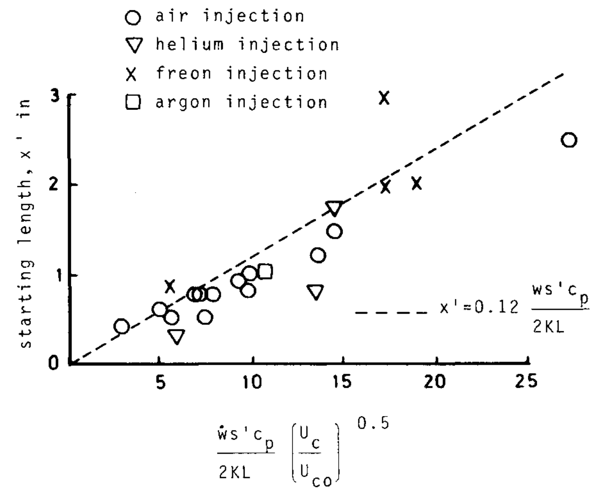

Fig. 7 Correlation of starting length data with modified heat conduction parameter.

velocity chosen as the sonic velocity of the coolant gas of the same constituent as the mainstream (i.e., air). The value of x' in Eq. (5) is given by the empirical formula

$$x' = 0.12\frac{\dot{w}s'C_p}{2kL}\left\{\frac{u_c}{u_{c0}}\right\}^{0.5} \tag{6}$$

The success with which the data are correlated by Eqs. (5) and (6) is illustrated in Figs. 7 and 8. It can be seen that good correlation of the data is obtained with the following formulas

$$q/q_0 = 0.8F \tag{7}$$

where

$$F = \left[\frac{2kLx}{\dot{w}s'C_p}\left(\frac{u_c}{u_{c0}}\right)^{0.5} - 0.12\right]\left(1+\frac{x'}{x_0}\right)^{0.5}$$

and x' given by Eq. (6) for values of F up to 0.8 (when $q/q_0 \simeq 0.64$). The main deviation from the correlation appears to arise from the difficulty in correlating the starting length x'. The range of the correlation could be slightly improved by using a more complicated function of F. From the reasonable success of the correlating parameters, it can be seen that the physical process involved in laminar film cooling is heat conduction within a discrete layer. Further improvement of analysis might be expected to arise from an assumption of couette flow within the discrete layer, rather than "rectangular flow," with no streamwise change in velocity.

Optimization of Laminar Film Cooling Effectiveness

The discrete layer theory, modified empirically is found to describe the laminar experimental results fairly well. It is now possible to assess the optimum configuration of laminar film cooling for the case of slot being choked. For maximum cooling effect, $(\dot{w}s'C_p/kL)(u_c/u_{c0})^{1/2}$ must be a maximum. Hence, we require $\dot{w}/L$ high, C_p high, and $(k/s')(u_c/u_{c0})^{-1/2}$ low.

Considering first the optimum slot geometry for laminar film cooling effectiveness, the $(k/s')(u_c/u_{c0})^{-1/2}$ term is dependent on the degree of expansion from the plenum chamber conditions for a particular coolant. Using gas tables to predict the coolant conditions, it is found that the term is minimized, for constant $\dot{w}$, by choosing a slot size such that the flow is just choked. For a particular mass flow rate it can also be shown that the slot height for just choked conditions is approximately proportional to $(MW)^{-1/2}$, where MW is the molecular weight of the coolant gas.

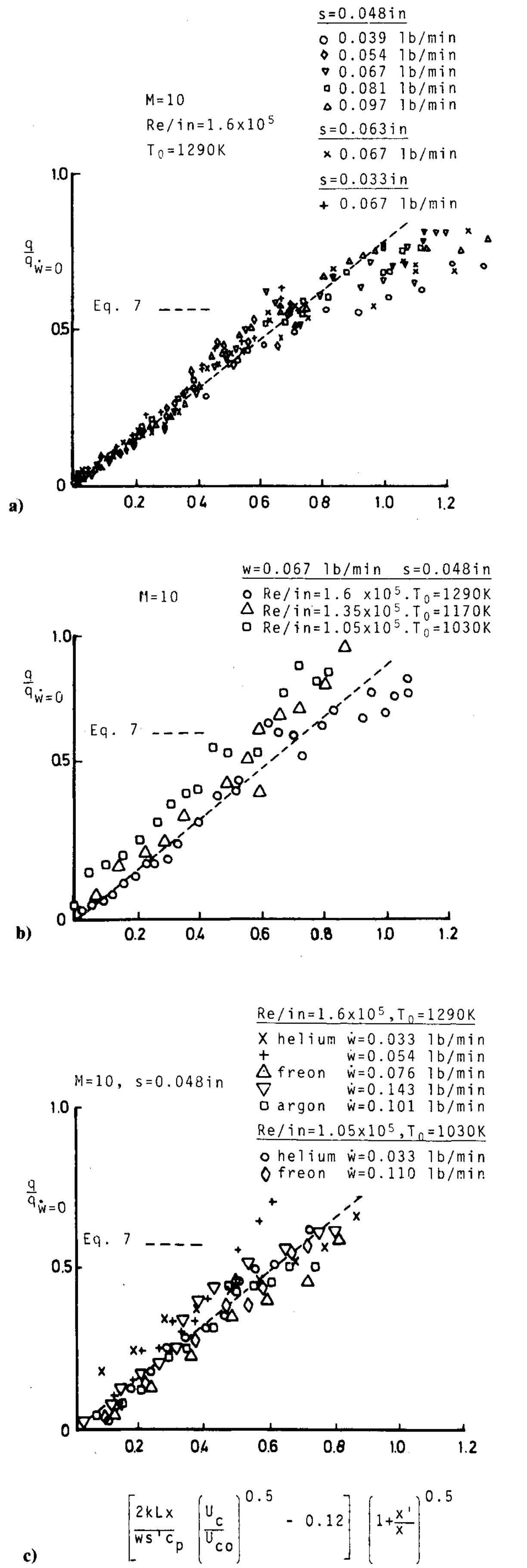

Fig. 8 Correlation of heat-transfer results of laminar film cooling using modified heat conduction parameter. a) Effect of varying mass injection rate and slot height. b) Effect of changing outside flow condition. c) Effect of foreign gas injection.

The most efficient gas can now be found by considering the parameter

$$\frac{\dot{w}s'C_p}{kL}\left(\frac{u_c}{u_{c0}}\right)^{1/2} \sim \frac{C_p}{K}(MW)^{-1/2}(\gamma R)^{1/2}$$

for just choked conditions. Using the values of physical quantities from the *American Handbook of Physics* we find that hydrogen is 28 times, helium 7 times, methane 3 times, ethane 2 times more effective than air which is itself 3 times more effective than freon for the same mass injection rate.

IV. Conclusions

An experimental investigation of the heat-transfer rate due to laminar film cooling using various gas coolants and model geometries was made in hypersonic flow with cold isothermal wall conditions in a gun tunnel. The injection, through a choked slot, was found to cause little disturbance to the outside flow and the layer remained discrete and laminar providing a very effective means of cooling a surface even at hundreds of slot heights downstream. Good comparison of the measurements, involving variations of mass flow rate, slot height, coolant composition, and external flow conditions was found with a discrete layer theory with heat diffused by one-dimensional conduction. An empirical correction, based on coolant injection velocity was required to obtain agreement. Using the correlation, for a particular mass flow rate, the slot size just to cause choking at the slot was found to be most efficient. Hydrogen was assessed to be far more effective than helium, which is itself far more effective than air for the same injected mass flow rate.

Acknowledgments

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