9th AUSTRALASIAN
FLUID MECHANICS CONFERENCE
AUCKLAND, 8-12 DECEMBER 1986

High Reynolds Number Heat Transfer to the Cold Walls of a Model Scramjet

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ABSTRACT

The results of simultaneous heat transfer and pressure measurements at the walls of three different configurations of a model scramjet are presented. The heat transfer results are compared with results empirically predicted from the pressure measurements. It is shown that the measured heat transfer rate is comparable with, or lower than that predicted for a laminar boundary layer.

A mathematical model is proposed for the film cooling effect observed when a hydrogen fuel is injected along a wall of the scramjet. In this mathematical model the heat transfer rate is shown to be insensitive to the velocity profile in the insulating layer of fuel. The model suggests that the cooling layer is turbulent and that 90% of the fuel is mixed with the air.

INTRODUCTION

The scramjet (supersonic combustion ramjet) potentially represents the most attractive form of propulsion in the upper atmosphere at Mach number greater than four, (Jones, 1978). If prolonged flight is to be sustained considerations must be given to heating of the aircraft and more critically to the heating of the inside of the combustion chamber of the scramjet. As a preliminary study of this engine, simultaneous measurements of the heat transfer rate and the pressures at the walls were taken for three different configurations of the combustion chamber when there was no injection of fuel. Different configurations of the chambers were; a parallel (or constant area) duct, a parallel duct with an injector step, and a diverging duct. The freestream flow was at Mach number 3.5 with the unit Reynolds Number ranging between 6.6×10^6 m^{-1} and 23×10^6 m^{-1}. The freestream total enthalpy was varied between 2.5 MJ/kg and 8.6 MJ/kg and the walls were initially at room temperature. Predictions of the heat transfer rate for both a turbulent and laminar boundary layer were made from the pressure measurements using empirical formulae developed for flat plates (Stollery 1975 and Hayes 1959). Although there is no theoretical reason for those predictions to apply to all these geometries, they have been shown to be useful in other than flat plate configurations, (Morgan 1985).

One means of cooling the surface of the combustion chamber is to form an insulating layer of fuel along the wall by injecting from a step in the wall, more fuel than can be burnt. Wall injection would also seem to be one of the most feasible means of injection, (Morgan 1985).

To gain an initial understanding of the mechanisms which govern the heat transfer rate to the wall, a simple mathematical model has been proposed. In this model the fuel is assumed to be in two layers. (See Figure 2). In the upper layer fuel is mixed with air and the layer closest to the wall consists only of fuel. A diffusion-convection heat equation which ignores diffusion in the direction of the convection and which allows for different mass flux profiles is used to describe the unmixed layer.

A similar model which uses a uniform flow approximation has been successfully applied by Richards (1979) to describe the film cooling effect when the injected gas is the same as the freestream gas. Stollery (1967) used a "no mix" layer theory similar to that proposed by Hatch (1959) to obtain good correlation between predicted and measured heat transfer rates when air is used as the coolant and freestream gas. Stollery (1967) also gives heat transfer measurements for the injection of helium into air at the rate of .0012 kg/s. In the experiments recorded here, hydrogen is injected at the much larger rate of .08 kg/s.

The heating effects of combustion have been separated from those of the freestream by recording the heat transfer rates for injection into a test gas of nitrogen, as well as for air. The two parameters; the mass flow rate and the diffusivity are adjusted to fit the data for injection into a nitrogen test gas. The diffusivity is not known because the degree to which the insulating layer is turbulent is not known. A third parameter $\dot{q}_o$, which is the heat transfer rate to the wall far downstream of the injector, is determined from the fuel-off experiments. The values of the first two parameters are then used to predict the maximum added heat flux which might be observed when burning occurs. This is done by determining a new value of $\dot{q}_o$ which fits the heat transfer rates measured when fuel is injected into air.

Experimental Apparatus

A schematic of the two dimensional model which was used is shown in Figure 1. When required, hydrogen fuel was injected at supersonic speeds out of the .005 m step. The injector has a .0009 m throat and extends across the entire width of the model (.05 m.). The injector could be removed if required. The intake is .08 m long and there is a .025 m combustion chamber immediately downstream of the injector. The thrust surface either diverges at 15^o or a constant area duct can be made by setting the divergence to 0^o.

Different test conditions were obtained by using a free piston shock tube with a Mach 3.5 nozzle. From measurements of the shock velocity and stagnation pressure at the end of the shock tube, the intake conditions are calculated using a numerical program for the non-equilibrium expansion of a reacting gas down the nozzle (Lordi et al (1966)).

Pressure and heat transfer measurements were calculated from instrumentation on the thrust surface. The instrumentation did not allow for the evaluation of negative heat transfer rates. The experimental apparatus and procedures are described more fully in Morgan (1985).

Empirical Predictions; No Fuel Injected.

Predictions of heat transfer rates to a wall from either a turbulent or a laminar boundary layer are made from the pressures on the wall and the freestream conditions. The predictions for a turbulent boundary layer are made using the same formulae as Morgan (1985). Their treatment follows that presented by Stollery (1975) which is based on the empirical method of Eckert (1955).

If a Lewis number of 1 is assumed then the empirical predicted heat transfer rate to wall from a turbulent boundary layer is

$$\dot{q}_w = \frac{0.0296}{P_r^{2/3}} \rho^* u_e (H_r - H_w) \left[\frac{\rho^* u_e X}{\mu^*} \right]^{-1/5} \quad (1)$$

The superscript * quantities are evaluated at the reference temperature T* where

$$T^* = \frac{T_e}{2} \left[\left[1 + \frac{T_w}{T_o} \right] + \frac{\gamma-1}{2} M_e^2 \left[0.44r + \frac{T_w}{T_o} \right] \right] \quad (2)$$

The recovery enthalpy is

$$H_r = h_e + \frac{1}{2} r u_e^2 \quad (3)$$

The conditions at the edge of the boundary layer are calculated from the inlet conditions assuming an isentropic expansion to the local static pressure. A specific heat ratio of 1.4 and a Prandtl number of 0.72 are assumed. The recovery factor is taken as $\sqrt{Pr}$. From empirical correlations presented by Hayes (1959), the predicted heat transfer rate to the wall from a laminar boundary layer for a Lewis number of 1 is

$$\dot{q}_w = \frac{0.332}{P_r^{2/3}} \rho^* u_e (H_r - H_w) \left[\frac{\rho^* u_e X}{\mu^*} \right]^{-1/2} \quad (4)$$

where the superscript * quantities are evaluated at the reference enthalpy

$$h^* = 0.5(h_e + h_w) + 0.22 (H_r - h_e) \quad (5)$$

Theoretical Predictions For Fuel Insulating Layer.

It is assumed that downstream from the injector there are two distinct regions which contain fuel; (I) a region in which the fuel and air are mixed, and (II) a region in which no mixing occurs. (See Figure 2.) For simplicity the boundary between these two regions is taken to be parallel to the wall. The unmixed region represents the layer which insulates the thrust surface from the heat produced by combustion in the mixed region, and the heating from the freestream. This layer is modelled by assuming that the mass flux of fuel has the profile.

$$\rho u = \rho_o u_o \left[\frac{y}{y_o} \right]^{\lambda} \quad (6)$$

where $\lambda > 0$, $\rho_o U_o$ is the mass flux of the injector and y_o is the thickness that the unmixed layer would be if there was no mixing layer. It is also assumed that diffusion in the direction of convention is negligible compared with the convection. Hence for constant diffusivity the temperature inside the unmixed region satisfies

$$k \frac{\partial^2 T}{\partial y^2} - \rho_o u_o \left[\frac{y}{y_o} \right]^{\lambda} Cp \frac{\partial T}{\partial x} = 0 \quad (7)$$

The boundary conditions are given in Figure 2. To be consistent with the boundary layer profile used for the mass flux, there should also be an upstream temperature profile of the fuel. For simplicity this is assumed to be linear. It is also assumed that the walls remain at room temperature and that the flux of heat from the mixed region is constant. Under these assumptions the heat flow into the wall is

$$\dot{q}_w = \dot{q}_o - \left[\dot{q}_o + \Delta T \frac{k}{y_o} \alpha^{\frac{-1}{\lambda+1}} \frac{2^{2-v}}{\Gamma(v)} \right] \sum_{n=1}^{\infty} \frac{Z_n^{v-2}}{J_v(Z_n)} e^{-A_n x} \quad (8)$$

where

$$A_n = \frac{Z_n^2}{4v^2} \left[C_p \alpha \rho u_o y_o \right]^{-1} \left[\frac{k}{y_o} \alpha^{\frac{-1}{\lambda+1}} \right] \quad (9)$$

and α is the proportion of the total mass flow of fuel in the insulating layer.

The upstream temperature of the fuel at the boundary of regions (I) and (II) is assumed to be equal to the temperature that the fuel would be after an isentropic expansion from the fuel reservoir conditions to the pressure measured immediately downstream of the injector. The total mass flow is similarly determined.

RESULTS

Heat Transfer Measurements; No Fuel Injected.

For each model configuration the heat transfer rates were measured for three different enthalpies of the freestream. The measured heat transfer rates for a constant area duct without and with an injector step, and for a 15° divergent thrust surface downstream of an injector step, are displayed in Figures 3a,b,c, 4a,b,c and 5a,b,c respectively. Also displayed on these diagrams are the empirically predicted heat transfer rates for a laminar boundary layer, (Equation (2)). The heat transfer rates predicted by Equation (1) for a turbulent boundary layer are of order ten times those measured. Thus it is concluded that in all configurations the boundary layer is laminar.

From Figures 3a and 3b it is seen for the constant area duct without a step, that good correlation exists between the predicted and measured values at the two lower enthalpies, of 2.5 MJ/kg and 4 MJ/kg. For the higher enthalpy, 5.5 MJ/kg, (Figure 3c), the upstream measurements are approximately 75% of those predicted. However, downstream there is good correlation between the predicted and measured values. It is not clear why low measurements were observed in the upstream region.

The heat transfer measurements to the wall of a constant area duct with an injector are displayed in Figures 4a, 4b and 4c for the enthalpies 4.3 MJ/kg, 6.2 MJ/kg and 8.2 MJ/kg respectively. From Figure 4a it is seen, that at the lower enthalpy, the expansion past the step does not effect the correlation between the predicted and measured values. However, at the higher enthalpies the measured values are approximately half the predicted values. A similar order reduction in the measured heat transfer rates was observed by Stollery (1983) for higher enthalpies. They showed that their reduction could be accounted for if non-equilibrium chemical reactions occurred in the boundary layer. It may be possible that the discrepancies at the higher enthalpies may be explained by similar reactions which result from the decrease in pressure which occurs when passing the step.

Similar arguments might also be used to explain the low measured heat transfer rates to the 15° divergent thrust surface, displayed in Figures 5a, 5b and 5c. It is seen that even at the lowest enthalpy of 4 MJ/kg that the measured value is approximately half the predicted value. The greater reduction in heating rates may be the result of initially lowering the pressure at the step, followed by a further pressure reduction at the start of the divergent surface.

These results do not correspond to those obtained by Morgan (1985), where the measured heat transfer results were higher than those predicted for a laminar flow. The discrepancies between these two sets of data is not understood. However, it may be possible that the twin 7.5° thrust surface configuration used in their model is a significantly different environment to the single 15° thrust surface used here.

Heat Transfer Measurements With A Fuel Insulating Layer.

TABLE 1.

λ	X_z (m)	α	k(W/mK)
0.14	0.2	0.08	2.5
0.14	0.19	0.07	1.7
1.0	0.2	0.13	3.0
1.0	0.19	0.11	2.1

The insulating layer created by the injection of the hydrogen fuel out of the step can be seen in Figure

6. In this figure the heat transfer rates to the walls of a constant area duct, when fuel is injected into a nitrogen and air test gas, are compared with those when fuel is not injected. The nitrogen test gas was used to separate the heating effects of the combustion and the freestream.

The total enthalpy of the test gas is approximately 8.6 MJ/kg. The reservoir pressure of the fuel is 2900 kPa and is at 300 K. The pressure measured immediately downstream of the injector when injecting into the nitrogen test gas was 114 kPa. Thus ΔT = 180 K and the fuel flow rate is 0.08 kg/s. This is approximately six times the rate required for a stoichiometric mixture with the oxygen available in the air test gas.

From Equations (8) and (9) it can been seen that for any value of λ there are three unknown quantities $\dot{q}_o$, α and k. These three parameters are adjusted so as to fit the data measured when injecting into the nitrogen test gas. From Equation (8) it is seen that $\dot{q}_o$ represents the heat transfer rate at large distances down the wall. This is taken to be equal to the average of the heat transfer rate in the absence of fuel. Hence from Figure 6, $\dot{q}_o = 80\times10^4$ W/m². The remaining two parameters are determined by insisting that the theoretical curve and the measured values are zero at the same point and have the same value at the furthest distance measured.

In Table 1, the different values of α and k are listed for a shear flow, $\lambda = 1$, and a turbulent flow, $\lambda = 1/7$. (The density is assumed constant (Hayes, 1959)). It can be seen that the value of k is sensitive to the position of zero heat transfer. It is worthy to note that, in all cases, the predicted values of k are always in excess of the recorded value of k for hydrogen at 300 K; 0.19 W/mK. Thus this model would suggest that the cooling layer is turbulent. This is in contrast to the results obtained for a boundary layer without fuel. However, turbulence may be created in the fuel by the injector before injection.

Morgan (1986) has observed that at high equivalent ratios all the available oxygen in the duct would appear to be consumed, which suggests that significant mixing does occur. This is also suggested by this mathematical model, for it can be seen from Table 1 that for a turbulent velocity profile, only 8% of the injected fuel goes into the unmixed layer.

The values of α and k recorded in rows 1 and 3 of Table 1 are used to determine new values of $\dot{q}_o$ which will fit the heat transfer rates measured when the fuel is burnt in the air test gas. These values were 45.2×10^4 MJ/kg and 42.7×10^4 MJ/kg respectively. Insufficient data is available to obtain an accurate indication of the heat released by combustion into the cooling layer predictions.

It can be seen from Table 1 that the value of k is sensitive to the value of λ. However, from Figure 6 it can be seen that the predicted heat transfer rates are insensitive to this profile. This may be one reason why the uniform flow profile used by Richards (1979) is successful.

CONCLUSIONS

Flat plate empirical predictions give an order of magnitude estimate of the heat transfer rates for a laminar boundary layer for the scramjet configuration. Deviations from the predicted values is greater at the higher enthalpies and more pronounced as more expansions to the flow are introduced.

The mathematical model proposed for the insulating layer of fuel displays three of the parameters which affect the heat transfer rate. It suggests that the mass flux profile of fuel is not important in determining the heat transfer rate. The model is incapable of accurately predicting the diffusivity constant of the insulating layer.

ACKNOWLEDGEMENTS

This work was performed under NASA contract No. NAGW-674 and with the support of the Australian Research Grants Scheme.

The help of the Physics Department of the Australian National University in providing and operating the shock tunnel was fundamental to all the experimental work.

NOTATION

Cp	specific heat at constant pressure
h	static enthalpy
H	total enthalpy
J_v	Bessel function of order v
k	thermal diffusivity constant
M	Mach number
P	pressure
Pr	Prandtl number
$\dot{q}$	heat transfer rate (heat flux)
r	recovery factor
Re	Reynolds number
T	temperature
u	velocity
x	wetted length from injector
x_z	wetted length from injector to zero flux point. (Nitrogen test gas)
X	wetted length from intake
y	distance above thrust surface
Z_n	nth zero of J_{v-1}
α	proportion of fuel in insulating layer
γ	specific heat ratio
Γ	the Gamma function
ΔT	temperature difference
λ	insulating layer mass flux power law coefficient
μ	viscosity
v	$\frac{1}{\lambda+2}$
ρ	density

Subscripts and Superscripts

e	edge of the boundary layer
I	intake
o	total
r	recovery
w	wall
*	reference

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TABLE 2

Figure	H_0 Mj/kg	P_I kPa	T_I K	u_I m/s	T_0 K
3a	2.5	101	614	2432	2194
3b	4.0	97	986	2350	3191
3c	5.5	108	1454	2747	4031
4a	4.3	91	1104	2465	3418
4b	6.2	113	1633	2867	4295
4c	8.2	105	2213	3204	5052
5a	4.0	63	976	2337	3180
5b	5.4	72	1425	2698	3907
5c	7.8	86	2082	3131	4858

Fig. 1

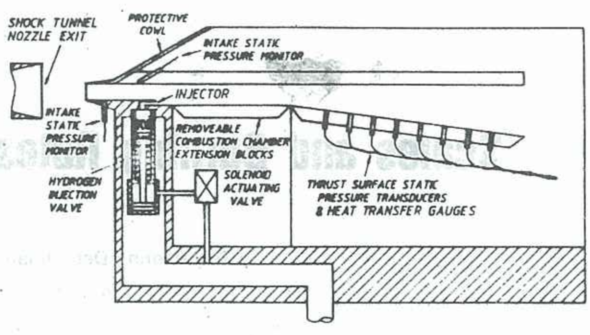

Fig. 2

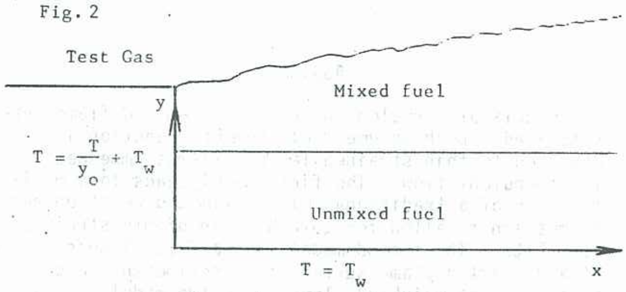

Fig. 6