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AN EXPERIMENTAL AND NUMERICAL STUDY OF HYPERSONIC FLAT PLATE FLOW

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ABSTRACT

The problem of hypersonic laminar flat plate boundary layer flow is examined experimentally and numerically. Experimental presure and heat transfer data have been obtained in a free-piston shock tunnel operating at a total enthalpy of 2.8 MJ kg^{-1}, giving a perfect gas free-stream flow. The numerical method compares quite well with the experimental data in terms of both the pressure and heat transfer distributions. The results also compare reasonably well with established perfect gas theories.

INTRODUCTION

Renewed interest in hypersonics has been generated by the desire to design and construct the next generation of hypersonic vehicles (eg. Hope in Japan, Sänger in Germany, NASP in USA). These vehicles will encounter a wide range of flow situations, not all of which may be completely simulated in the laboratory environment. It is therefore important to develop computational fluid dynamics (CFD) codes in order to determine the flows over the vehicles for those parts of the trajectories that cannot be completely simulated.

One of the important issues to remember when dealing with CFD is that the code must be able to perform well at predicting the flow data obtained from wind tunnel experiments. The present study has, as its ultimate aim, the calculation of three-dimensional, turbulent flows with account of real gas effects (eg. vibration, dissociation, ionization). Such flight conditions will be encountered for a large portion of any re-entry trajectory and are therefore of considerable importance. To begin with, however, it was decided to determine the effectiveness of the code in predicting a rather straighforward problem - hypersonic flow over a sharp leading edge flat plate - in which turbulence and real gas effects may be ignored.

The problem of flat plate flow is one of the most fundamental problems in fluid mechanics. For hypersonic flat plate flows in general, the viscous / inviscid interaction between the boundary layer and the leading edge shock is quite strong near the leading edge of the plate while the interaction free classical boundary layer growth occurs far downstream of the leading edge. This may be described in terms of the hypersonic viscous interaction parameter,

$$\bar{\chi} = M_\infty^3 \, (C^* / Re_x)^{1/2} \qquad (1)$$

where $C = (\mu / \mu_\infty)\,(T_\infty / T)$ and the superscript '*' refers to values evaluated at the Eckert (1955) reference temperature. All other symbols in Eqn. (1) are defined in Table 1. For similarity to hold, $\bar{\chi} \rightarrow 0$ (weak interaction) and when $\bar{\chi} >> 1$ (strong interaction) similarity breaks down. Similarity may also break down when there is chemical and vibrational nonequilibrium in the boundary layer.

In this paper, we will compare experimental data, obtained in a low enthalpy flow produced by a free-piston shock tunnel, with predictions from the present CFD code and also with well-established theories for perfect gas flows.

EXPERIMENTAL DETAILS

The experiments were conducted in the free-piston shock tunnel, T3, which is located at the Australian National University. The details of its operation have been presented elsewhere (Stalker, 1972). The time from shock reflection until a steady flow is established over the flat plate was approximately 1 ms, which is well before helium driver gas contamination becomes a problem (Crane & Stalker, 1977).

The total enthalpy of the flow was 2.8 MJ kg^{-1}, which is sufficiently low for the flow to be treated as a prefect gas. Also, the Reynolds number based on plate chord is approximately 6 x 10^5, meaning that flow transition to turbulence is unlikely (He, 1991). The procedure used to determine the reservoir and free-stream conditions,

h_0 MJ kg^{-1}	p_0 MPa	T_0 K	p_∞ kPa	T_∞ K	ρ_∞ g m^{-3}	u_∞ km s^{-1}	M_∞	Re_∞ x10^{-5} m^{-1}	γ_∞
2.80	22.0	2400	0.69	155	15.5	2.30	9.2	32.2	1.40

Table 1. Reservoir and free-stream conditions. h = enthalpy, p = pressure, T = temperature, ρ = density, u = velocity, M = Mach number, Re = unit Reynolds number, γ = ratio of specific heats; subscripts '0' and '∞' denote reservoir and free-stream conditions, respectively. The wall temperature was taken as T_w = 300 K (ambient)

presented in Table 1, has been discussed elsewhere (Mallinson et al., 1995). The uncertainty in the conditions are small (of the order 5%) which is similar to the shot-to-shot repeatability of the facility.

A flat plate model machined from mild steel has been used in the present instance. The leading edge was sharp (Re_d < 100), so that bluntness effects may be ignored. The plate chord and span were both 180 mm. Calculations have been performed for only the first 85 mm of the plate chord. Side plates were employed to prevent flow from underneath the model affecting the measurements. A conical nozzle was employed in the present experiment. It is therefore important to examine whether a significant pressure gradient is induced by the nozzle flow divergence. The value of the Falkner-Skan pressure gradient parameter, m, was calculated according to the method of Cohen and Reshotko (1956) and found to be less than 0.01. Also, a pitot survery of the nozzle revealed a flow divergence of less than 1° near the model edges. Thus, the pressure gradient due to the nozzle conicity may be neglected.

The surface static pressure and surface heat flux distributions were measured using PCB 113M165 pressure transducers and 'in-house' manufactured co-axial chromel-alumel (type 'K') surface junction thermocouples, respectively. Details of their calibration have been presented elsewhere (Mallinson, 1994). Both on- and off-axis measurements were made to assess any three-dimensional effects. It was found that any such effects were negligible. The uncertainties due to flow divergence, shot-to-shot repeatability, signal fluctuation and gauge calibration uncertainty are approximately ±10% for the normalized pressure, p/p_∞ (see Mallinson, 1994) and ±15% for the Stanton number, St, (see Gai and Joe, 1992) where

$$St = \frac{q_w}{\rho_\infty u_\infty (h_r - h_w)} \qquad (2)$$

Here, q_w is the measured heat transfer, h_r is the recovery enthalpy where

$$h_r = h_0 + \frac{(Pr^{1/2} - 1)}{2} u_\infty^2 \qquad (3)$$

h_w is the enthalpy correpsonding to the wall temperature and Pr is the Prandtl number, taken as 0.72 (see Mallinson, 1994).

NUMERICAL METHOD

The present numerical method has been described in detail elsewhere (Milthorpe, 1992) and only a brief outline will be presented here. The domain (see Fig. 1) is divided into a number of rectangular cells. The

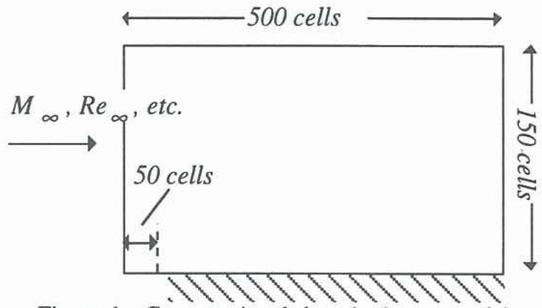

Figure 1. Computational domain (not to scale).

upstream boundary is initialized with the free-stream conditions. The outflow boundaries are set by projecting the contours of flow variables across the boundaries. The contour direction at the boundary is obtained by selecting the direction which provides the minimum average deviation from the contour value itself. Outside the boundary, the contour vallue is taken as the mean value along the inner direction for a small distance (typically 10 cells) in this region outside of the domain. This produces a straight projection of the contours over the boundary. The wall boundary is prescribed by enforcing a zero mass-transfer condition.

The conservation algorithm may be explained with reference to Fig. 2. Each cell has a certain mass, momentum and energy. In a time-step, δt, the mass, momentum and energy are convected by a small amount in the transverse, x, and normal, y, directions. Also, diffusion and pressure gradients may reduce the mass, momentum and energy in a given cell. After each time step, the resulting distributions are used to calculate the new values of the mass, momentum and energy in each cell. Partial upwinding is employed to prevent instabilities due to pressure gradient effects on momentum and energy. The procedure is repeated interatively until a converged solution is obtained. For the present 500 x 150 grid, the calculation took approximately 400 hours of CPU time on a single-processor Sparcstation.

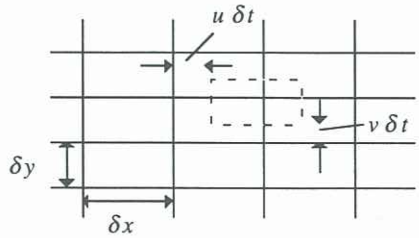

Figure 2. Convection of cell with velocity $U = (u, v)$ during time δt.

RESULTS

The experimental pressure and heat transfer distributions are presented in Figs. 3 and 4. Also shown are the numerical prediction and the well known weak interaction theory (Anderson, 1989) for pressure and the reference temperature theory (Eckert, 1955) for heat transfer. The typical error bars represent ±10% and ±15%, for the pressure and heat transfer respectively. The small discontinuities evident in the curves for the numerical prediction are an artefact of the plotting program and do not reflect any physical process inherent in the flow.

The experimental pressure data and the weak interaction theory are in fair agreement. It seems from these measurements that the pressure gradient effects are indeed small. The CFD prediction seems to compare well with the experimental data. The small differences which exist particularly near the front of the plate are thought to be due to uncertainties in the gauge calibration.

The experimental heat transfer data seem to compare well with the reference temperature theory, but the scatter is the data is somewhat greater than that observed with the pressure. This is due to much greater signal-to-noise ratio experienced when measuring the heat transfer. The comparison between the numerical prediction and both the experimental data and the reference temperature theory appears to be quite reasonable.

Figure 5 shows a contour plot of the velocity field. From this, the velocity profile across the boundary layer may be extracted (see Fig. 6). Also shown in Figure 6 is the compressible Blasius result (Stewartson, 1964). The comparison between the numerical prediction and the Blasius result can be said to be fair at best. The reason for the difference is unkown, but may be due to the downstream influence of the viscous / inviscid interaction near the leading edge of the flat plate which is not accounted for in the simple Blasius theory.

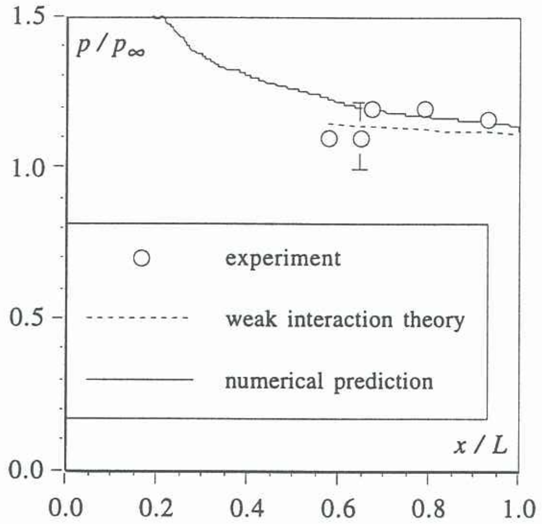

Figure 3. Flat plate pressure distribution.

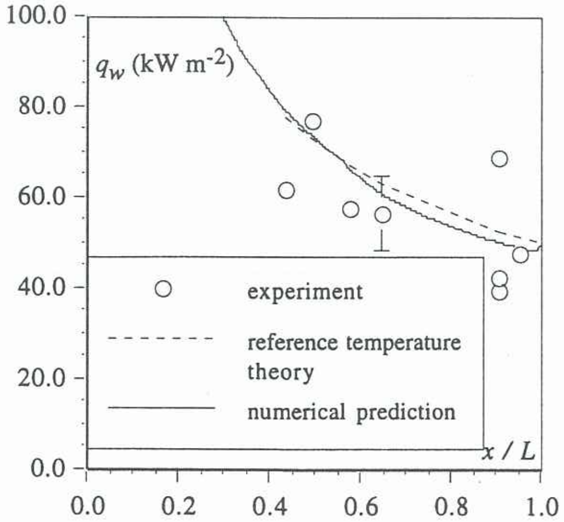

Figure 3. Flat plate heat transfer distribution.

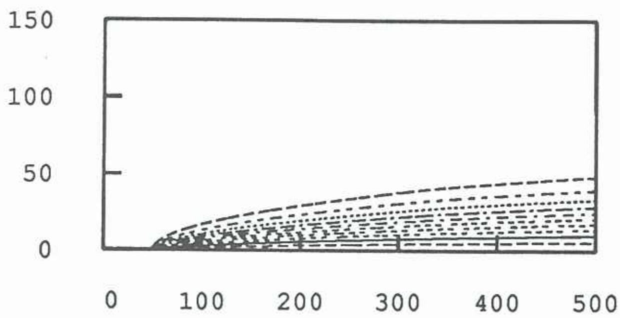

Figure 6. Contour plot of the velocity field (not to scale).

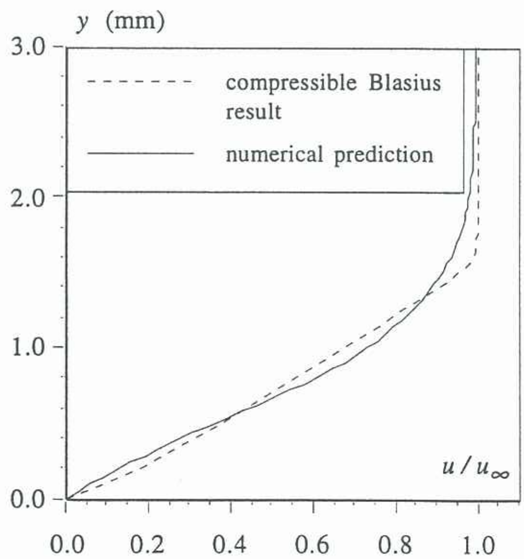

Figure 6. Velocity profile across the boundary layer.

Further studies are in progress to examine the effects of grid spacing. Prelimary results would seem to suggest that most of the flow physics are captured using the present grid.

CONCLUSIONS

The hypersonic laminar flat plate boundary layer flow has been examined experimentally and numerically. The experimental data is shown to compare well with perfect gas theories and the numerical prediction. If anything, the numerical values lie somewhat above the experimental data, but well within the experimental uncertainty due to flow divergence, shot-to-shot repeatability, signal fluctuations and gauge calibration uncertainty.

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