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TRANSITION OF COMPRESSIBLE HIGH ENTHALPY BOUNDARY LAYER FLOW OVER A FLAT PLATE

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Abstract

This paper presents the results of an experimental investigation of boundary layer transition to turbulence in hypervelocity flows. A preliminary series of experiments was conducted using a flat plate model equipped with static pressure and thin film heat transfer transducers in a free piston shock tunnel. In the laminar regions of the flow, the heat transfer was found to agree well with empirical predictions. A reduction in transition Reynolds number was observed as the enthalpy increases.

Introduction

The prediction of boundary layer transition is a general problem relating to high Reynolds number flows. Transition has been closely investigated for many flow situations, but there is a lack of knowledge of transition phenomena relating to hypersonic, high enthalpy flight. The boundary layer has a significant influence on the external flow fields of re-entry bodies, such as the space shuttle, and is likely to have a critical influence on hypersonic duct flows such as would be created in scramjet engines. In the case of subsonic and supersonic flow of low enthalpy, it has been well established that the boundary-layer instability and transition are closely related to the unit Reynolds number, Mach number and cooling of the wall. The existence of unsteady waves in the boundary layer has been predicted by linear stability theory and proven by vast number of experiments (Reshotko, 1976). The onset of transition is often considered as the point in the shear flow where nonlinearity become dominant (Kendall, 1975) and the corresponding Reynolds number is, in many cases, of order of 10^6. Owen (1970) discovered that the onset transition Reynolds number falls into a narrow region in the plot of transition Reynolds number against unit Reynolds number. It was not found to have a strong Mach number dependency, although the peak transition Reynolds number and the end transition Reynolds number increase with increasing Mach number and unit Reynolds number. However, no evidence is available to show the validity of this conclusion for hypersonic and high enthalpy boundary-layer flows.

One of the features of hypervelocity and high enthalpy flow is that high temperature and high heat transfer rate are generated when the flow is bounded by a solid wall. Linear stability theory (Mack, 1984) indicates that boundary layer cooling, as determined from stagnation enthalpy and wall temperature, and free stream Reynolds numbers, will be the dominant factors in locating the onset of transition. In the present study an attempt was made to investigate the influence of enthalpy, free stream unit Reynolds number, pressure, as well as wall cooling, on the transition. The methodology of the experiments was to produce a range of test conditions so that stagnation enthalpy and free stream unit Reynolds number could be varied independently.

Equipment and Experimental Conditions

Experiments were conducted in T4 shock tunnel (Stalker *et al.* 1988). A contoured nozzle with a fixed area ratio was used. A flat plate model was placed in the test section. 13 transducer mountings were arranged in the plate in a direction of 14 degrees (slightly greater than Mach angle) to the flow direction. The purpose of this arrangement was to reduce the influence of disturbances from upstream transducers and the corner of the leading edge. For the same reason, a fin was attached to each side edge of the plate. The total length of the plate was 600 mm. The first transducer was 50 mm from the leading edge. The second 74 and the third 100. After that, the distance between each two consecutive transducers was 35 mm and the last transducer was 450 mm from leading edge.

The stagnation enthalpy of the flow varied in the range 2.4 to 26 MJ/kg, but Reynolds number limitations of our model meant that transition effects were only detectable in the range 2.4 - 14 MJ/kg. The nominal conditions were T_r = 2130 to 9130 K, P = 4.8 to 35 kPa and M = 5.2 to 6.6, where T_r is the recovery temperature.

Thin film gauges were used to measure surface temperatures during the tests. Temperature traces were then integrated to obtain heat transfer rates along the plate. At least one pressure transducer was used in each test, in order to obtain a reference static pressure and to determine the steady flow conditions.

The test conditions were selected with the help of the T4 tunnel performance characteristic chart (Fig.1). At a fixed value of enthalpy, several unit Reynolds number are available by changing the shock tunnel diaphragm rupture pressure. Similarly, at a fixed value of unit Reynolds number, different enthalpies can be selected. The tunnel operating conditions were then determined by the size of the diaphragm and the stagnation enthalpy required.

Detection of Transition

Many physical quantities are sensitive to variations in the state of the boundary-layer , and any of these properties may be used as a criterion for determining transition. Owen *et al* (1975) defined the onset of transition as the

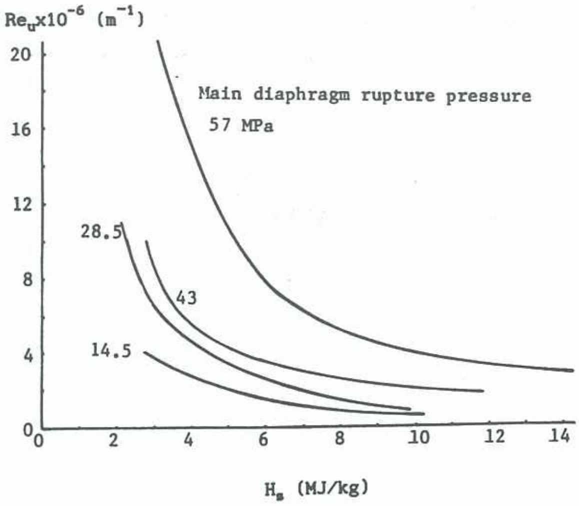

Fig. 1. Performance characteristic chart of T4 tunnel.

point where the Stanton numbers first consistently exceed the laminar value. However, even within the laminar boundary layer, the measured Stanton number may not always be consistent with the value predicted by laminar theory. Based on the fact that for a flat plate with uniform pressure, the heat transfer rate decreases with the distance from leading edge unless the laminar nature of the flow is disturbed, the transition point is defined, for the present work, as the point where the Stanton number has a minimum value.

Local Stanton number St_x is linearly related to heat transfer rate q_x by definition, i.e.

$$St_x = \frac{q_x}{\rho u(H_r - H_w)}, \qquad (1)$$

where ρ and u are density and velocity of the gas, x is the distance from leading edge, H_r and H_w are the recovery enthalpy and the enthalpy at wall temperature respectively. Dividing Eq.(1) by reference values at $x = x_*$, gives

$$\frac{St_x}{St_*} = \frac{q_x}{q_*} = St_n = q_n , \qquad (2)$$

where St_n and q_n are normalized Stanton number and heat flux respectively. In other words, the normalized Stanton number is equivalent to the normalized heat flux. For processing the data, it was more convenient to deal with the normalized quantities such as q_n.

Analysis of Experimental data

Shock tubes by nature create a flow which is fundamentally unsteady, and care must be taken when applying steady state analysis to the results of such experiments. During the period when uncontaminated test gas is passing over the model, the stagnation and static pressure levels are not constant, but decay with time by an amount which is a function of the tunnel operating conditions. However, a region of flow exists where the ratio of pressures across the expansion nozzle is steady, and the Mach number of the flow may considered constant. The ratio of stagnation pressure to dynamic pressure will also be constant, and for the flow field around any body shape to be steady, then the locally measured static pressures must be steady when normalized with respect to stagnation pressure. Provided these pressure ratios are constant, then a small change in the overall pressure level will not cause substantial change to the overall flow field or the shape of the stream lines, and a steady state analysis may be used. The situation for heat transfer is slightly different. For the flow to be considered steady, the Stanton number must be constant, and this implies from Eq(1) that the heat transfer must decrease in proportion to the product of the mass flow rate with the recovery enthalpy. If the test flow conditions are computed on the assumption that an isentropic expansion follows shock reflection in the stagnation region, then it can be shown that, for constant Stanton number, heat transfer must have the following relationship with stagnation pressure P_s:

$$q \sim P_s^{(3\gamma-1)/2\gamma}$$

where γ is an effective ratio of specific heats for the nozzle expansion. For a γ of 1.4, this leaves heat transfer dependent on stagnation pressure to the power of 1.14. For the purposes of determining the duration of the steady flow period, this power of 1.14 was ignored for numerical expediency, and the heat transfer rates were normalized by stagnation pressure directly. For a decay in stagnation pressure of 30% this would lead to an error of 5% in Stanton number, and does not substantially effect the conclusions drawn from the data, and reasonably steady normalized traces were obtained in the laminar flow regions.

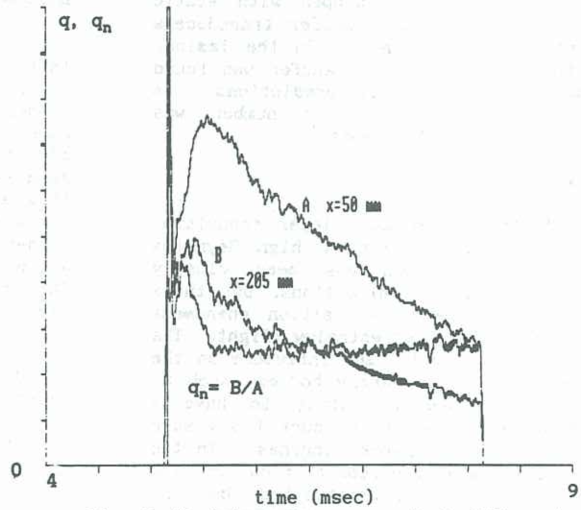

Fig. 2 Heat transfer measured at different position.
Max. scale: 3 MW/m^2 for q, 1 for q_n.

Fig.2 shows the heat transfer rates at two distances from leading edge. It is seen that the ratio of these heat transfer rates, which is equivalent to normalized Stanton number, remains constant during test time. Fig.3 displays the heat transfer rate at x = 50 mm, the static pressure at x = 275 mm and the ratio of heat transfer rate to reservoir stagnation pressure. The ratio of static pressure to reservoir stagnation pressure is also shown on Fig.3 to indicate the steady period of the test flow.

The unsteadiness of the test flow made the comparison of measured and calculated heat transfer rates difficult. The test conditions determined by the plot of pressure ratio (See Fig.3) were used in the calculation. Correspondingly, the measured heat transfer rate was taken at the moment when pressure ratio first reaches the steady state. Fig.4 shows the relative error between measured reference (x_*= 50 mm) heat transfer rates and calculated values. It is seen that most relative errors are less than 20%.

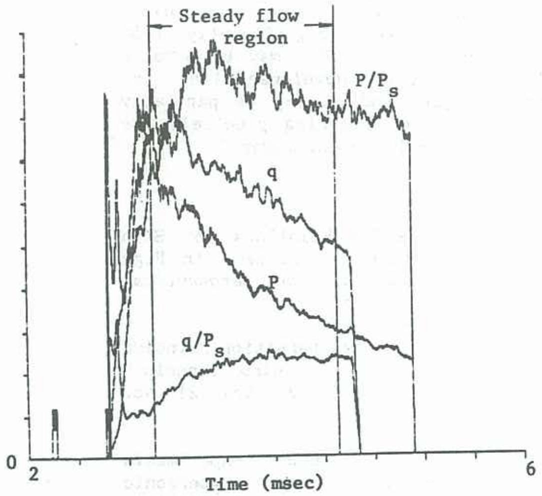

Fig. 3 Typical normalized heat transfer and static pressure traces. H_s=14 MJ/kg, Max. scale: 40 kPa for P, 2.5 MW/m^2 for q, 7×10^{-4} for P/P$_s$, 0.3 m/s for q/P$_s$.

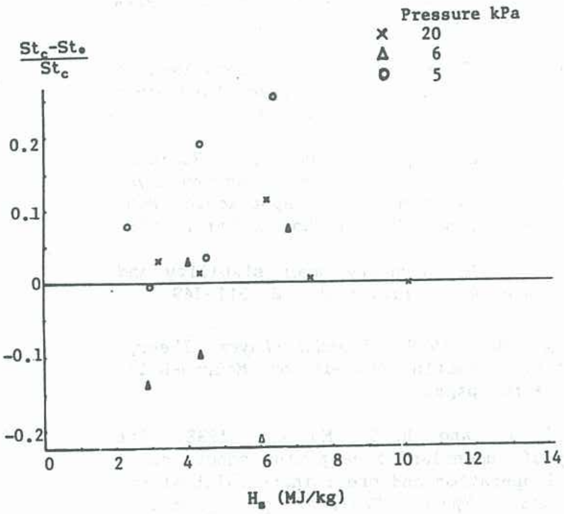

Fig. 4. Deviation of measured Stanton number from laminar predictions at x=50 mm.

As an example, the normalized heat transfer rate, or Stanton number, along the plate in a particular test is plotted in Fig.5 and compared with analytical calculations. The predicted turbulent heat transfer rates were obtained from Stollery's (1975) treatment of an empirical correlation (Eckert 1955). When applying this correlation, one has to choose a reference origin for turbulent boundary layer. The solid curve in Fig.5 represents the calculated value when turbulence reference origin is set at the leading edge of the plate; the dotted curve was obtained with origin set at the point of transition-onset. It is seen from Fig.5 that within the laminar boundary layer, the normalized Stanton number distribution closely follows the theory (Schlichting, 1979). After passing though a minimum point, the Stanton number increases rapidly, then it falls again. The rise of Stanton number indicates the onset of transition. The establishment of a turbulent boundary layer is marked by a consistent falling of Stanton number after the maximum value, although the shape of the experimental Stanton number profile does not follow the curve calculated from turbulent boundary-layer theory.

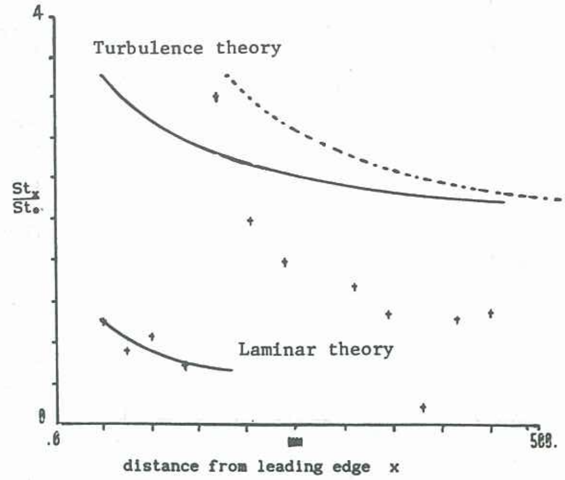

Fig. 5. Normalised Stanton number distribution.

(a), H_s= 4.36 MJ/kg, Re_u= 1.37×10^7 m^{-1}.

Another feature observed in data analysis is that the position of the transition onset point is not fixed during the test, but fluctuates over a reasonably wide region. This is not surprising since transition by its nature is unsteady, and the unit reynolds number is not completely constant throughout the test. In our case, the uncertainty of the onset position is constrained by half of the distance between two consecutive transducers.

From the plot of transition Reynolds number against reservoir stagnation enthalpy (Fig.6), it is clear that the transition Reynolds number is pressure, as well as enthalpy, dependent. But in the plot of Ret *vs* unit Reynolds number (Fig.7), the measured points collapse closely on to a straight line. Data from other workers are also shown for comparison. In both Fig.6 and Fig.7, the effect of Mach number is not eliminated, i.e. all the data are plotted into the diagrams regardless the Mach numbers involved in test flows.

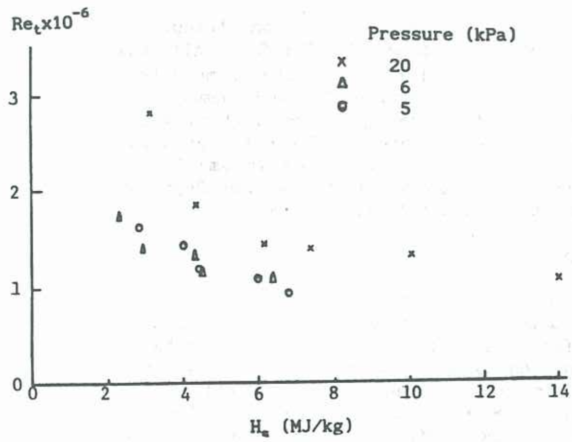

Fig.6 Enthalpy and pressure dependency of transition onset.

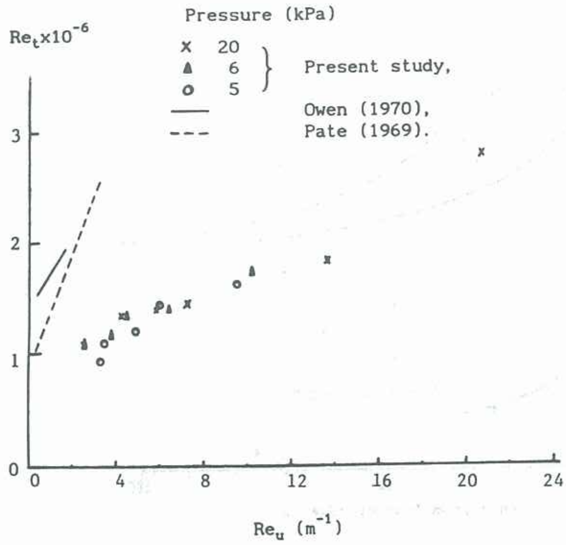

Fig.7 Variation of transition-onset Reynolds number with unit Reynolds number.

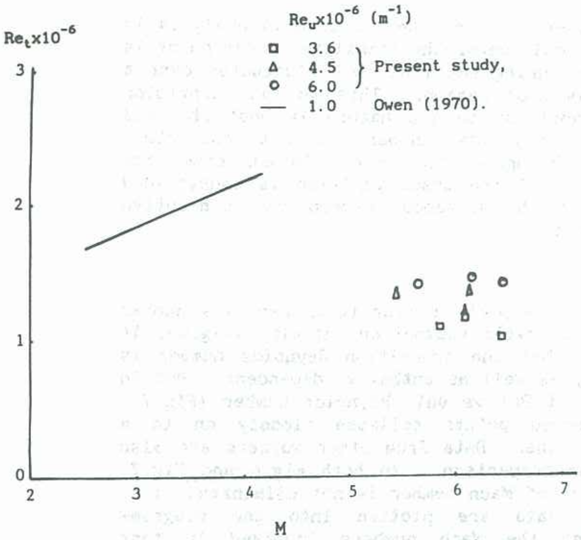

Fig.8 Plot of transition Reynolds number *vs* Mach number.

The effect of Mach number on transition Reynolds number is shown in Fig.8. All the experiments were performed on the same fixed geometry nozzle, and changes in mach number are due to the the different gas compositions which the tunnel creates under different operating conditions. The mach number range is small, and no systematic dependence of transition Reynolds number was observed within that range.

Conclusion

The relation between the onset transition Reynolds number and unit Reynolds number in high enthalpy flows is similar to that in low enthalpy flows. The conclusion drown by Laufer (1954) that the free stream disturbance does not affect the transition for M > 2.5 has not been verified on the T4 shock tunnel. More experiments are planned to provide measurements of the free stream noise levels to help assess this effect.

The measured heat transfer rates from laminar boundary layers gave good agreement with analytical predictions, whereas from turbulent boundary layer, it differs significantly from available turbulent models. This may be because fully turbulent flow is not developed within the available model length, and it may be partially due to the difficulty of defining precisely the effective origin of the turbulent layer.

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