Heat Transfer and Transition Mechanism on a Shock-Tube Wall

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An investigation was conducted in a 10 cm (4 in.) diam shock tube over incident shock Mach numbers of 1.16-3.0 to study the local heat-transfer rate to the shock-tube wall and to observe the transition mechanisms in the shock-induced flow. Fast-response thin-film heat gages were used to measure the local heat-transfer rates and to record the time of transition of the wall boundary layer. The local heat-transfer rate of the laminar boundary layer was computed and compared with Mirels' flate-plate theory for the laminar boundary layer and with empirical formulas for the turbulent boundary layer. The agreement between the theoretical and experimental value for the local heat-transfer rate was good for both the laminar and turbulent boundary layers. The transition Reynolds number showed a strong dependence upon the unit Reynolds number over the range of experiments studied. The phenomenon of "transition reversal" and the existence of turbulent spots were observed in this study.

Introduction

THIS work was undertaken to accomplish three objectives: 1) study the boundary-layer transition mechanism on the shock-tube wall, 2) verify Mirels' 1955 theoretical work[1] predicting the laminar heat-transfer rate to a wall from a moving shock wave, and 3) observe the occurrences of turbulent "spots" in the laminar boundary layer near the onset of transition. The ultimate aim of obtaining high-temperature, high-pressure heat-transfer data in a shock tube by the method of partial reflection motivated this investigation of the transition effects generated on the shock-tube wall. There have been a number of experimental and theoretical studies[1-30] that partially addressed the objectives of this work.

For heat-transfer studies in shock tubes, Ref. 2 presents experimental data that agree with laminar[3-5] and turbulent[3,6] boundary-layer theories, but does not address the q vs t relationship presented by Mirels in Ref. 1. This relationship of the local heat rate vs time after the shock passage was the primary interest in this study. Other experimental investigations[8-14] addressed various theories on laminar and turbulent heat transfer in shock tubes, but did not present experimental data in comparison with Ref. 1 in the form of q vs t.

The shock-tube wall transition mechanism has also been studied in the past, both analytically and experimentally. Experimental work has confirmed theoretical predictions for the gross features of the laminar boundary layer.[9,11,14,15] Early theoretical work[6,16] for the turbulent boundary layer indicated that it was less well understood. Predictions of boundary-layer thickness, density profiles, and heat transfer had, to some degree, been justified by experiment.[10,12,15,17] The occurrence of the phenomenon of what is called "transition reversal" has not been so well reported. This phenomenon has sometimes been seen to occur in flow conditions where the transition Reynolds number shows a strong dependence on the unit Reynolds number (Re/cm). This dependence was observed in some flow conditions in Ref. 2, but the phenomenon of transition reversal was not observed. Although Ref. 31 presented a review of experimental observations of the transition in shock tubes, there were only hints that a phenomenon such as "transition reversal" may have been observed. One must be careful, however, to focus on precisely which parameters, if any, can cause a "reversal" of the transition Reynolds number (Re_{tr}) trends. Reference 2 looked at a much larger range of shock Mach numbers than this study and found that, for conditions of low wall cooling, Re_{tr} showed a strong dependence on Re/cm. Reference 2 further found that an increase in Re/cm caused an increase in Re_{tr}. The present study found this to be true only for a portion of the Re/cm range studied. This will be explained later. Additionally, Ref. 2 presents data showing that the laminar boundary layer can persist much longer than had been seen in other studies. Reference 7 found laminar flow persisting for as much as five times longer than previous investigations.

In studies of steady flows[18-23] and unsteady flows,[24,25] the boundary-layer transition was observed to begin with the appearance and growth of turbulent spots in the laminar boundary layer. Reference 7 studied the growth of both naturally and artificially occurring turbulent spots utilizing thin-film heat gages. Turbulent spots were also observed in this study. The behavior of the turbulent spots observed in the present study corresponded to that described by other investigators.[7,18-25]

Conduct of Experiments

Experimental Setup

The experiments were conducted in a 22 m long shock tube with an inside diameter of 10.16 cm over a Mach number range of 1.16-3.0. The instruments used for obtaining the heat-transfer data and detecting the boundary-layer details were fast-response thin-film platinum surface heat-transfer gages. Pressure measurements were made with Kistler pressure transducers. All experiments were conducted in the region bounded by the incident shock wave and the contact surface. The rapid response of the thin-film heat gages enabled them to detect even small features in the boundary layer. For further information on the experimental setup and calibration of the heat gages, see Ref. 32.

Reduction of Data

For the purpose of predicting the heat transfer to the shock-tube wall, the wall was assumed to behave like a semi-infinite

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flat plate. With this assumption, the theory of Mirels[1] could be utilized to predict the experimental local heat-transfer rate to the tube wall for laminar flow. Such a prediction derived in Ref. 1 is

$$q(t) = -k_w \left(\frac{1}{2} \frac{u_2}{u_l} \frac{1}{t} \frac{1}{\nu_w} \right)^{1/2} (T_w - T_{wi}) S'(O) \qquad (1)$$

where k_w is the thermal conductivity at the wall, T_w the wall temperature, T_{wi} the insulated wall temperature, ν_w the kinematic viscosity at the wall, u_2 the velocity behind the normal stationary shock, u_l the freestream velocity, and $S'(O)$ a coefficient tabulated in Ref. 1.

For the turbulent boundary layers, empirical relations were used to predict the turbulent heat-transfer coefficient. First, it was necessary to define a characteristic length to compute the local Reynolds number at the heat gage. For this purpose the product of the relative flow velocity $(u_s - u_2)$ and the time t was selected as the characteristic length. This length is simply the distance a fluid particle has moved in a shock-fixed coordinate system in a given time t after passage of the shock. Thus, we define the local Reynolds number as

$$Re_x = \rho_2 u_2 (u_s - u_2) t / \mu_2 \qquad (2)$$

where subscript *2* denotes the conditions in region 2 (outside the boundary layer) after the incident shock wave.

The theoretical estimate for the skin-friction coefficient C_F due to the turbulent boundary layer used in this present study is given by White (Ref. 33, Eq. 6-134, p. 498). The local heat rates were then computed by von Kármán's theory for incompressible boundary layers.[34]

The experimental heat-transfer rate is reduced from the temperature-time oscilloscope traces by use of the following equation from Ref. 27:

$$q(t) = \frac{(\pi)^{1/2}}{2} \frac{[(\rho c_p k)_b]^{1/2}}{\alpha I_0 R_0} \left(\frac{\Delta E(t)}{t^{1/2}} + \frac{1}{\pi} \int_0^t \frac{(\lambda/t)^{1/2} \Delta E(t) - \Delta E(\lambda)}{(t-\lambda)^{3/2}} \mathrm{d}\lambda \right) \qquad (3)$$

where $(\rho c_p k)_b$ are the density, specific heat, and thermal conductivity of the gage backing material, respectively, α the thermal resistivity of the platinum strip, I_0 and R_0 the initial current and resistance, respectively, of the platinum gage, and ΔE the voltage change measured from the heat gage trace. This equation was integrated numerically to yield the heat-transfer data. The heat gages were calibrated according to the method described in Refs. 26 and 32.

Transition Study

The transition Reynolds number was computed by recording the time of transition for each case. This time of transition enabled a characteristic length to be defined since there is no leading edge in these experiments. The characteristic length is simply the distance a fluid particle moves after being shocked into motion before it encounters the turbulent flow. This length was then used to calculate the transition Reynolds number,

$$Re_{tr} = \rho_2 u_2 (u_s - u_2) t_t / \mu_2 \qquad (4)$$

This transition Reynolds number was plotted against various other parameters (Re/cm, M_2, T_2/T_w, T_{O2}/T_w) to detect any trends; the unit Reynolds number is given by

$$Re/\mathrm{cm} = \rho_2 u_2 / \mu_2 \qquad (5)$$

Discussion of Results

Wall Heat Transfer

The experimental results for the laminar boundary-layer heat transfer to the shock-tube wall consistently showed very good agreement with Mirels' prediction [Eq. (1)]. Figures 1, 3, and 5 show sample traces with a laminar boundary layer. The corresponding local heat rate for these traces is shown in Figs. 2, 4, and 6, respectively. The solid lines represent the theoretical predictions and the experimental points are indicated for comparison. In all cases where a laminar bound-

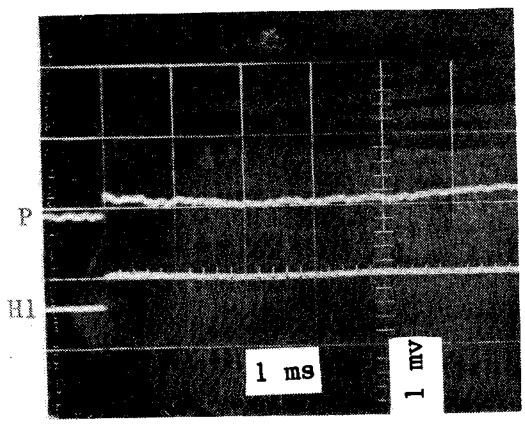

Fig. 1 Oscilloscope trace of laminar boundary layer, shot 124.

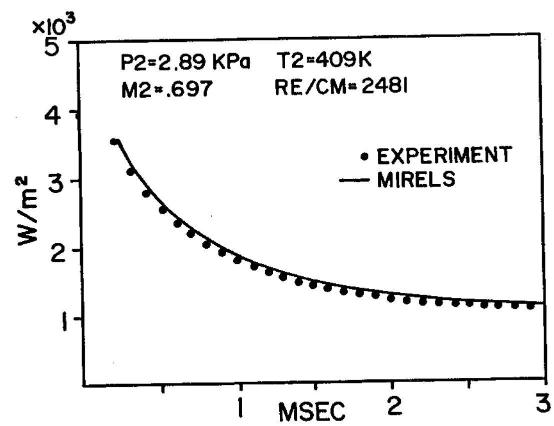

Fig. 2 Heat flux density, shot 124.

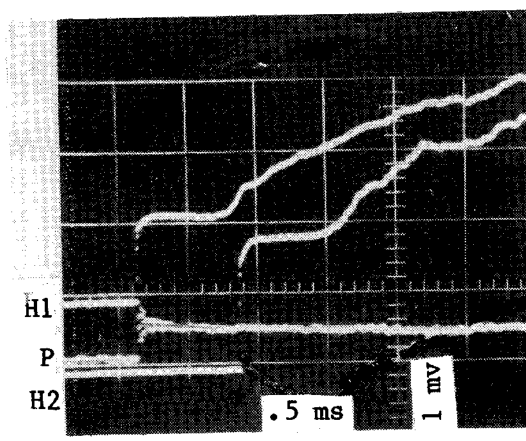

Fig. 3 Oscilloscope trace of laminar boundary layer with transition, shot 139.

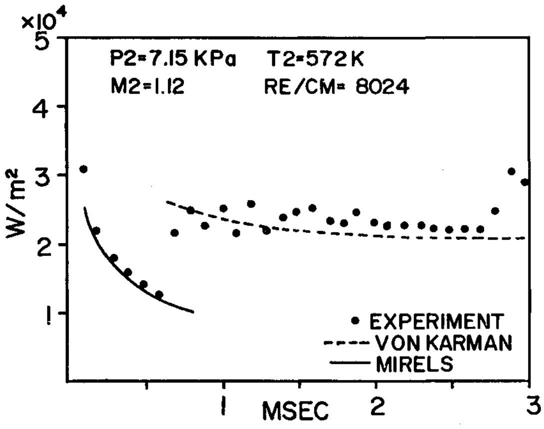

Fig. 4 Heat flux density, shot 139.

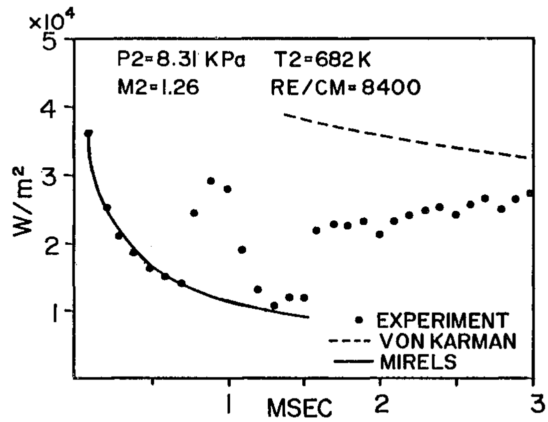

Fig. 6 Heat flux density, shot 129.

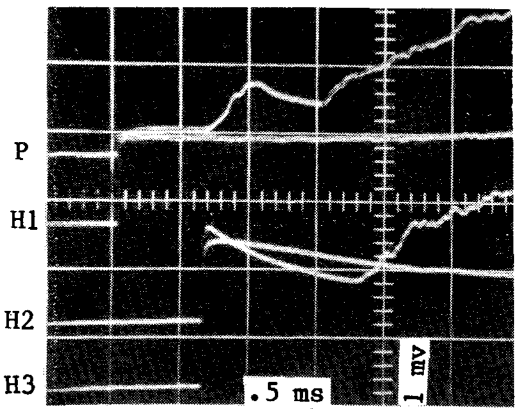

Fig. 5 Oscilloscope trace of turbulent burst, shot 129.

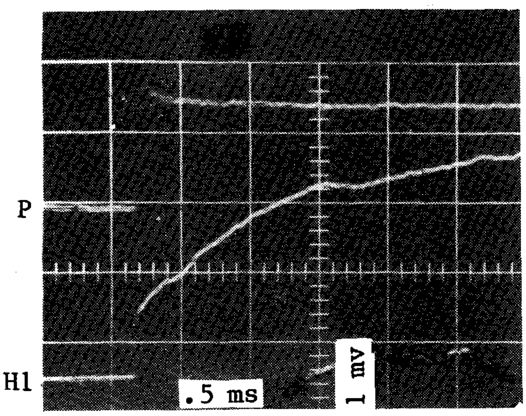

Fig. 7 Oscilloscope trace of turbulent boundary layer, shot 113.

ary layer was observed, a close agreement between the experimental data and Mirels' theory resulted.

Some theoreticians have expressed a concern that the test times in this study could have shortened due to the contact surface overtaking the incident shock wave. Such a process is described fully in Ref. 35. As a check, the test times for some of the low-pressure traces were calculated by the method presented in Ref. 35. For the worst case, trace 124 with its low-pressure, low-incident shock Mach number, the test time available at the heat gage location was found to be 13 ms. This is much longer than the oscilloscope trace duration seen in Fig. 1.

Good agreement was also obtained in those cases where the laminar boundary layer was followed by transition to turbulence. One such example is shown in Fig. 3. The output from heat gage 1 indicates laminar flow for approximately 600 μs, after which the turbulent front passes over the gage. Figure 4 shows the corresponding local heat-transfer rate. As always, the laminar experimental results matched very closely with Mirels' prediction. However, as soon as transition occurred, the experimental heat-transfer rate very closely matched von Kármán's prediction for the incompressible turbulent boundary layer.

Figure 6 shows the heat-transfer rates produced by the time/voltage traces shown in Fig. 5. Again, the laminar boundary-layer results agree very well with Mirels' prediction. At about 700 μs the arrival of the turbulent burst over the gage is indicated by the rapid rise in the local heat-transfer rate. The decay to the laminar value is shown as is the subsequent rise to the turbulent value of the heat-transfer rate. In this case, it is interesting to note that there is poor agreement with von Kármán. This is beieved to be due to the boundary layer stabilizing after the passage of the turbulent burst. When the boundary layer finally shifts with the arrival of the main turbulent front, the flow is not believed to be fully developed, resulting in the lower than expected heat flux density seen in Fig. 6.

For the case of fully developed turbulent boundary layer following the shock wave shown on the oscilloscope trace in Fig. 7, the parabolic temperature rise commences immediately following the shock wave passage over the heat gage. Figure 8 shows the corresponding values of the local heat-transfer rate for the turbulent case. Again, the experimental values are within 11% of those predicted by von Kármán.[34]

Boundary-Layer Transition

The transition Reynolds number was determined for every trace by the method described earlier. For the range of shock Mach numbers studied (1.16-3.0), the behavior of Re_{tr} showed the strongest dependence on Re/cm. The spread of Re_{tr} that occurred when it was plotted against other parameters such as Tw/Te, Uw/Ue, and M_2 was similar to that found in Ref. 2 and in other studies over the same range of Mach numbers.

As mentioned earlier, Hartunian et al.[2] saw a linear dependence of Re_{tr} on Re/cm over the range of Mach numbers described here. However, the results found in this study were different. Figure 9 shows the Re_{tr} as a function of Re/cm. The data and trend lines are shown for the cases of subsonic and supersonic flow velocities. The existence of what this study calls "transition reversal" is shown at either end of the Re/cm spread.

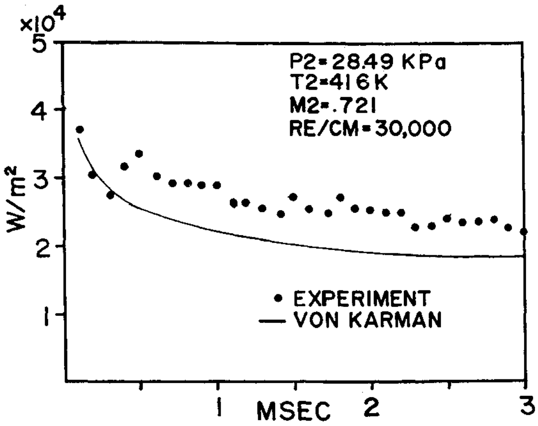

Fig. 8 Heat flux density, shot 113.

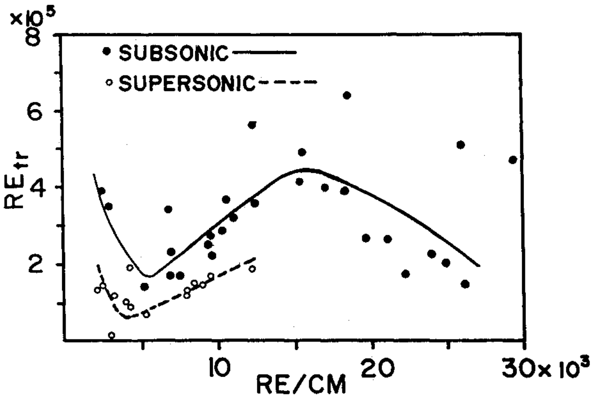

Fig. 9 Transition Reynolds number trend.

This "transition reversal" can be explained fairly easily. As one decreases Re/cm in the midregion, the Re_{tr} also decreases. At some point, however, the flow becomes so stable that the laminar boundary layer persists much longer. So long in fact that the characteristic length becomes dominant enough to drive the Re_{tr} to very high values. The persistence of this laminar region in some cases lasted for as long as 5 ms. For those flow conditions with Re/cm less than 2400, the laminar boundary layer did not change during the entire test time.

The "reversed" trend also developed as the Re/cm was increased. When Re/cm was increased, the Re_{tr} also followed until the flow conditions became so unstable as to cause the turbulent front to move closer to the incident shock wave. This reduction of the characteristic length became dominant and caused the Re_{tr} to fall as the Re/cm was raised to about 11,800. In the limiting case when Re/cm was above 28,000, the turbulent front was immediately behind the shock wave and no laminar boundary layer could be detected. The presence of the fully turbulent front can be seen in the heat gage trace in Fig. 7.

Thompson and Emrich[7] found that observed transition times were much shorter in some of the earlier studies and further recorded finding transition times to be as much as five times longer than previous investigations. Where Ref. 7 found transition times ~500 μs, this study found laminar flow to persist as long as a few milliseconds. Like other ground test facilities, however, this occurrence most likely depends heavily on the facility itself rather than on any particular flow characteristic.

Turbulent Bursts

As had been observed in other studies,[7,25,26] turbulent bursts were observed in some of the traces. The very fast response time of the thin-film platinum heat gages enabled the passage of the bursts to be detected easily. The bursts appeared as a rapid rise in temperature and then decayed back to the laminar value (Fig. 5). Later, with the arrival of the fully turbulent front, the trace is characteristic of the nearly parabolic rise associated with the turbulent boundary layer. The burst leading-edge arrival is marked by the first deviation from the laminar temperature "plateau." The trailing edge passes at the peak of the wall temperature jump. The subsequent decay of the heat-transfer rate is the result of the boundary layer becoming laminar. As noted in Refs. 7, 25, and 26, this study confirmed that turbulent bursts moved with a speed corresponding to 0.8 or 0.9 of the freestream velocity.

The appearance of turbulent bursts was very elusive. Efforts to duplicate the appearance of the bursts were largely unsuccessful. It was found that by conducting a routine set of experiments the turbulent bursts were detected in about 20% of the shots. In all cases, the bursts were observed as being highly localized on the shock-tube wall.

Conclusion

Experimental results for heat-transfer rate of the laminar boundary layer showed excellent agreement with the theory of Mirels. For the case of turbulent boundary layers, the experimental results agreed well with the empirical theory of von Kármán for incompressible turbulent boundary layers.

The boundary-layer transition showed a dependence on Re/cm over the midrange Re/cm values. At the high and low ends of Re/cm the Re_{tr} showed opposite trends. The boundary-layer transition for subsonic and supersonic flow conditions followed similar trends. The supersonic flow conditions produced a slightly less stable boundary layer.

Turbulent bursts were easily detected by the thin-film heat gages and were observed in about 20% of the traces. The turbulent bursts were a highly localized occurrence and the burst trailing edge was quickly overtaken by the turbulent front. The bursts moved with a mean velocity of about 0.8 of the freestream velocity.

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