Observations of Hypersonic Boundary-Layer Transition Using Hot Wire Anemometry

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The primary objective of the experiments described here was to investigate in some detail the source and nature of the disturbances originating within a hypersonic transitional boundary layer and to compare these observations with surface heat-transfer measurements on an identical model. The tests were made on sharp leading edge flat plates in a Mach 7 gun tunnel operating at a total temperature of 720°K and total pressure of 50 atm. Constant temperature, hot wire anemometer probes were developed to operate in the high enthalpy, hypersonic flow environment. Electronic instrumentation was developed for the analysis of the hot wire fluctuation levels during the short running time of the gun tunnel tests. The anemometer probes indicated the existence of high fluctuation levels within the boundary layer upstream of the point where mean surface heat-transfer measurements indicated the beginning of transition. These fluctuations were observed to be initially confined to a very narrow region of the boundary layer but gradually spread normal to the surface with increasing distance downstream to cover the entire layer near the surface-observed beginning of transition. A detailed examination of the fluctuation wave forms revealed a discrete pattern which suggested the existence of turbulent spot breakdown at least a factor of 2.5 in Reynolds number before the surface-observed beginning of transitional behavior.

Nomenclature

c	= specific heat
e	= voltage
$\Delta e_m, \Delta e_T$	= wire sensitivity coefficients
k	= thermal conductivity
L/D	= wire length/diameter ratio
M	= Mach number
Re	= Reynolds number
R	= resistance
T	= temperature
T_w	= wall temperature
u	= velocity
x	= distance from model leading edge
y	= distance from model surface
α	= thermal coefficient of resistivity
δ	= boundary-layer (velocity) thickness
ρ	= density
$(\ )'$	= instantaneous fluctuation from mean
$\langle\ \rangle$	= mean property

Subscripts

e	= conditions at boundary-layer edge
0	= room (ambient) conditions
r	= recovery conditions
t	= total (stagnation) conditions
w	= wire property
∞	= freestream conditions

1. Introduction

EXPERIMENTAL investigations of supersonic/hypersonic laminar boundary-layer transition have emphasized the importance of defining a transition region and not merely a transition "point." This transition region was usually defined as bounded by the beginning and end of the region of rapid increase in mean surface properties such as recovery temperature, heat-transfer or surface Pitot pressure. This ambiguity was increased still further when hot wire measurements within the boundary layer[1] revealed "transitional" behavior originating upstream of the point where surface changes were first observed.

In the course of an earlier study[2] of boundary-layer transition using the mean surface heat-transfer method, it was observed that certain transient phenomena became apparent on the surface instrumentation before mean changes were measured. These transient "spikes" in the heat-transfer records were attributed to the presence of turbulent eddies generated within the unstable upper regions of the upstream laminar boundary layer. By implication it was suggested that since the surface-observed events were possibly the late stages of the turbulent spot growth history, measurements at y/δ greater than zero may indicate transitional behavior upstream of the surface beginning-of-transition point.

In order to investigate in more detail the existing ambiguity in defining the beginning of transitional breakdown in hypersonic boundary layers a program was initiated to probe the boundary layer upstream of the surface transition region on a flat plate model. A hot wire anemometer probe was judged most likely to meet the requirements. Although very little hypersonic experience with hot wires has been reported in the literature (see Sec. 3), the potential usefulness of such a probe made an extensive effort to develop some hot wire instrumentation capability a worthwhile endeavor.

This paper describes some of the experience which has been gained in the construction and use of fine wire probes in the gun tunnel including the development of electronic instrumentation for the analysis of hot wire signals in the short running times available. A discussion of some extensive boundary layer surveys with fine wires operated at constant temperature is then presented and compared with the transition results presented in Ref. 2.

2. Experimental Apparatus

Gun Tunnel

The hypersonic gun tunnel is basically a shock-tube-driven hypersonic nozzle. It differs from a conventional shock tunnel only in the presence of a free sliding piston in the gun tunnel.

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The basic advantage of a gun tunnel compared with shock tunnels is a great increase in running time brought on in part by the physical separation of the driver and driven gases. The gun tunnel is used to greatest advantage as a low-enthalpy shock tunnel with high Reynolds number simulation capabilities and relatively long running times.

An extensive description of the Oxford University gun tunnel calibration has been presented in another report by the author.[3] The tests described in this paper were conducted in the open jet test section of a Mach 7 contoured nozzle. The exit plane Mach number was $M = 7.0 \pm 0.05$ with an axial Mach number gradient of 0.25% per inch at the Reynolds number of the tests described here ($Re/\text{cm} = 1.75 \times 10^5$; $Re/\text{in.} = 4.45 \times 10^5$). This condition corresponded to a total temperature of $720°\text{K} \pm 10°\text{K}$ and a total pressure of about 50 atm. The repeatability of conditions was improved by the use of a double diaphragm driver assembly.[3]

Models

A flat plate mean heat-transfer model was constructed with an over-all length of 13.7 in. and a width of 3.37 in. The material was ground to a surface finish of the order of 10 μin. The leading edge had a 15° bevel angle on the underside and was ground and honed to a "sharp" edge after heat treatment and oil quenching. A precision travelling microscope measured the leading edge diameter as less than 0.0006 in.

Platinum thin film heat-transfer gages fabricated according to the procedures outlined in Ref. 3 were painted on fused quartz substrates using Hanovia 05-X platinum alloy suspension, and were mounted along the model top surface centerline at $\frac{1}{4}$-in. intervals starting at $1\frac{3}{4}$ in. from the leading edge. The two-dimensionality of the mean flow for this model-test section configuration was verified in separate experiments by Batham[4] using a row of gages placed down one side of the model between the centerline gages and the model edge in conjunction with carbon black-oil drop markings. (Sharp edged side plates were designed to prevent "spillage" of the high pressure flow on the underside of the model to the test surface.) Details of the model and gage construction and calibration are given in Ref. 3. The roughness between the gage substrate and model was estimated to be no greater than 0.001–0.002 in. High-speed observations of the effect of roughness on transition[5] indicated that roughness of this order of magnitude would have no effect on transition except perhaps very near the leading edge where the laminar layer is thinnest. Since the first nonmachined joint on the model surface was $1\frac{1}{2}$ in. from the leading edge, this roughness was not expected to influence the experiments.

A second flat plate model was constructed with similar over-all dimensions to the heat-transfer model described previously to provide a direct comparison between the hot wire probe surveys and the surface heat-transfer information. Instrumentation ports were located along the model surface centerline at 1-in. intervals starting $2\frac{1}{2}$ in. from the model leading edge. A micrometer driven traversing mechanism was designed to be mounted on the underside of the plate. A detail drawing of the traversing mechanism in position on the model is shown in Fig. 1. The probe height above the model surface was set at a reference position using a 10X cathetometer aligned with the plate and a scribed surface set near the probe tip. Movement from this reference position was read from the micrometer scale (and checked by the cathetometer). The reference position was checked at both flow and no-flow conditions with a direct shadowgraph picture. Microdensitometer analysis of the probe position in the shadowgraph indicated that the probe was within ± 0.001 in. of its expected position.

Hot Wire Probes

The combined effects of the high total temperature and high total pressure hypersonic flow environment of the present gun tunnel tests precluded the use of standard commercial hot wire probes. An extensive program, therefore, was undertaken to develop probes which were physically small, mechanically robust, and electrically sensitive over an adequate bandwidth. Details of the probe construction techniques and operational development efforts are described in Ref. 2.

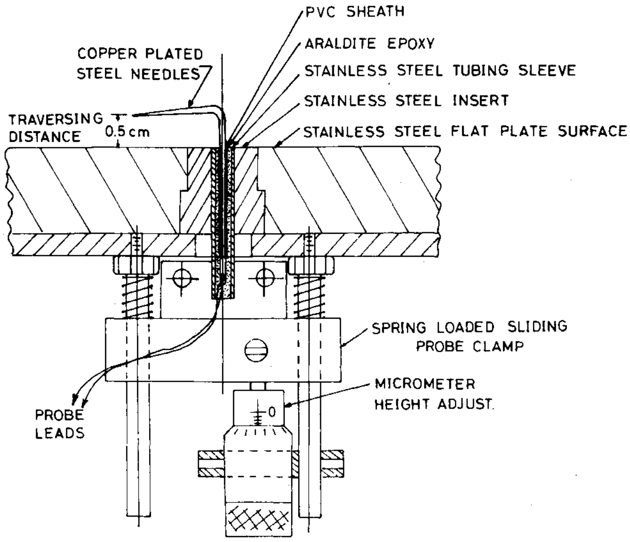


Fig. 1 Flat plate hot wire and traversing mechanism arrangement.

The final probe configuration is shown in place in a model instrumentation port in Fig. 1. The probe supports were made from 0.024-in. diam copper plated steel sewing needles. The wire used for all the experimental results was 0.00025 in. (6μ) diameter platinum—20% iridium alloy wire.

Details of the electrical connections to the probe and the supporting electronics equipment are discussed below. Basically, the wire was placed in a bridge circuit with the bridge kept in balance for any set value of probe resistance by a high-gain feedback amplifier. The wire "cold" resistance (R_0) was measured and then a value of hot resistance (R_w) was set and maintained by the bridge. The ratio R_w/R_0 is a measure of the mean wire operating temperature $\langle T_w \rangle$ and can be expressed for a linear temperature-resistance relation as

$$R_w = R_0[1 + \alpha(\langle T_w \rangle - T_0)] \tag{1}$$

Knowledge of the wire α was required to estimate the $\langle T_w \rangle$ from the resistance ratio. It should be emphasized, however, that the actual distribution of temperature levels along the wire will deviate considerably from the mean value obtained from Eq. (1). This is due to the relatively massive needle supports which remain near room temperature during the run time.

All the probes tested in the gun tunnel were run in the constant temperature mode in a DISA 55D01 universal anemometer. With careful adjustments of bridge balance, the feedback amplifier gain could be taken to its maximum setting allowing a maximum system upper frequency limit of 100–135 kHz (for the 1:20 bridge arm ratio used in the tests). In practice, the over-all frequency response of the system depended on both the amplifier and the probe. Theoretically, for a given probe, the bandwidth increased with flow velocity and probe temperature.

Ideally, the system bandwidth should be measured by applying a step change in velocity to the probe. In practice this is difficult but can be approached indirectly by applying a sudden step change of electrical power to the probe and observing the system response. This procedure was followed for each of the probes used in the gun tunnel tests with the probes in place in the working section. The resulting system bandwidth probably represented a lower limit as the tests were necessarily run with zero flow velocity. The maximum frequency response of the system was defined by $f = 1/2\pi\tau$, where τ was the square wave response rise time ($1/e$). The 0.00025-in. platinum alloy probes produced a system bandwidth of between 50–65 kHz for wire lengths in the range between 0.010–0.020 in. The freestream velocity of all the tests was about 3775 fps and thus this bandwidth corresponded to a spatial resolution of at least 0.9 in. in the freestream.

Electronic Instrumentation

The fluctuating wire signal component is of primary interest in most hot wire applications in turbulent flow. In order to quantify a fluctuating signal that is usually random in frequency and amplitude, most theoretical analysis and experimental measurements of hot wire signals deal with the signal rms values. Although the measurement of rms values is routine in continuous wind-tunnel facilities, their measurement in short duration facilities is a more formidable problem and has not been reported in the literature to date.

A slightly different approach was adopted in the present tests to provide a quantitative measure of wire fluctuation levels. The total voltage fluctuation signal was half-wave rectified and the resultant signal was then integrated by an active integrator circuit. This system thus provided an accurate value for the integrated signal level (half-wave) during any time interval during the gun tunnel running time. Quantitative comparisons of fluctuation levels at different probe locations were then possible. To prevent integration of the hot wire noise level immediately before the test run, the integrator was shorted until the gun tunnel diaphragms were burst. In addition, the integrator input bias current was adjusted so that output drift due to wire noise was not measurable in several seconds.

A low pass filter enabled the d.c. component of the signal to be accurately measured. A high pass filter allowed the a.c. component of the signal to be monitored. The signal was monitored after it had passed the rectification stage and before integration. This part of the signal was displayed in a time sweep that covered the whole test run and also on an extended sweep that covered 1 msec of the test starting near the 30 msec point after flow establishment. This extended sweep provided great detail of the flow fluctuation structure within the boundary layer. These detailed observations of fluctuations would normally be lost by the conventional approach of rms averaging in continuous tunnels. Although either positive or negative fluctuations could be integrated, the fluctuation measurements described in this paper all involved negative fluctuations from the mean wire output as discussed below.

3. Hot Wires in Compressible Flows

The sensitivity of hot wire anemometers in supersonic flow has been extensively discussed in papers by Kovasznay[6] and Morkovin.[7] The single piece of statistical information available from hot wire measurements is the fluctuating voltage level $(e)'$. This fluctuating voltage is produced by instantaneous changes in wire heat transfer produced by fluctuations in the flow properties, ρ, u, and T_t. In supersonic flows the effects of ρ and u are usually combined into mass flow fluctuations (ρu). The wire sensitivity is then given as

$$(e)' = -\Delta e_m (\rho u)'/\langle \rho u \rangle + \Delta e_T (T_t)'/\langle T_t \rangle \tag{2}$$

The sensitivity coefficients Δe_m and Δe_T have been derived by Morkovin[7] and depend on several empirically determined relationships including 1) wire resistance-temperature relation, 2) wire overheat parameter $(R_w - R_r)/R_r$, and 3) wire Nusselt number (corrected for end loss effects) and recovery factor variation with flow Mach number and Reynolds number. It is also assumed in Eq. (2) that the measured value of $(e)'$ has been corrected for probe time constant effects (thermal lag).

The extension of hot wire anemometry to hypersonic conditions would require extensive additional wire calibration procedures if quantitative fluctuation information is to be extracted. As a result, very little published information on wire performance exists for hypersonic conditions. Demetriades[8] used hot wires at $M = 5.8$ to measure the amplification of natural and artificial disturbances in a laminar boundary layer. Relative $(e)'$ measurements only were required for his tests. Potter and Whitfield[1] made comparative $(e)'$ (rms) measurements in a flat plate boundary layer up to $M = 8$ with no sensitivity corrections attempted. Staylor and Morrisette[9] presented a calibration procedure for finite length wire end loss corrections at $M = 6$. This allowed $(e)'$ and mean mass flow profiles to be determined in a flat plate laminar boundary layer although no attempt to separate the $(e)'$ components was made.

The problems in wire calibration procedures at the high total temperature conditions of hypersonic wind tunnels was avoided in some very recent wire measurements made in a $M = 20$ helium tunnel by Wagner et al.[10] In their important work, a unique calibration of each separate wire's Nusselt number, recovery factor and time constant variation with Reynolds number was obtained (at constant M). With accurate calibration data, Wagner et al., were able to separate the mass flow and total temperature fluctuations in the tunnel freestream by the standard technique.[11]

The calibration of hot wires for the gun tunnel flow conditions is further complicated by several factors. The short running times (40 msec) make a direct in situ calibration of wire heat transfer, recovery factor and time constant variation with Re quite difficult. The use of a universal wire calibration procedure[12] would (even if one existed) also lead to uncertainties in the end loss corrections. Unlike the continuous facility experiments described in the previous two paragraphs, the probe supports will remain at room temperature during the tests in the gun tunnel. Since the wire mean temperature must operate above the wire recovery temperature to obtain reasonable sensitivity, the end loss correction term[12] would become of the order of 50% for typical operating conditions for the wire in the gun tunnel (at $T_t = 720°K$). At such high operating temperatures, even the normally straightforward measurement of the wire resistance-temperature relationship also becomes nontrivial.

No attempt to calibrate the wire was made because of the aforementioned difficulties mentioned. Only factors which were likely to affect probe sensitivity were controlled within reasonable limits. All tests described in this paper were with probes of the same material, diameter, L/D (approximately), and mean temperature (R_w/R_0). Relative fluctuation level comparisons may then be meaningful at different x positions if y/δ is constant and then only before the boundary-layer mean flow property profiles begin to change. The actual fluctuation y profiles are probably somewhat distorted by changes in wire sensitivity with flow properties. The location of a maximum in the fluctuation profiles should be less affected by this sensitivity distortion. These basic sensitivity limitations and uncertainties along with the bandwidth limitations discussed earlier underline the qualitative nature of the measurements discussed below.

4. Experimental Results and Discussion

Mean Surface Heat Transfer

Richards has shown that the variation of mean surface heat-transfer rates on a model provides a sensitive indication of the location of the "transition region" in hypersonic boundary layers. This region was defined as bounded by the beginning and end of the rapid increase in the steady state heat-transfer rate to the wall. This region was also found to correspond approximately to the transition region defined by surface pitot pressure measurements.[5]

The "transition region" based on the steady heat-transfer results of this test are shown in Fig. 2. It is this region which is referred to in the following pages as the surface-observed-transition region. It is near the beginning of this region where "transient events" are first observed with surface instrumentation.[5,13]

The results of additional tests[2] on the same model are also shown in Fig. 2 where total pressure only (unit Reynolds number) was varied. It should be emphasized that all tests described here (and in Fig. 2) were conducted at $T_w/T_t = 0.41$, i.e., cold wall conditions. The results show the often-observed supersonic "unit Reynolds number effect."

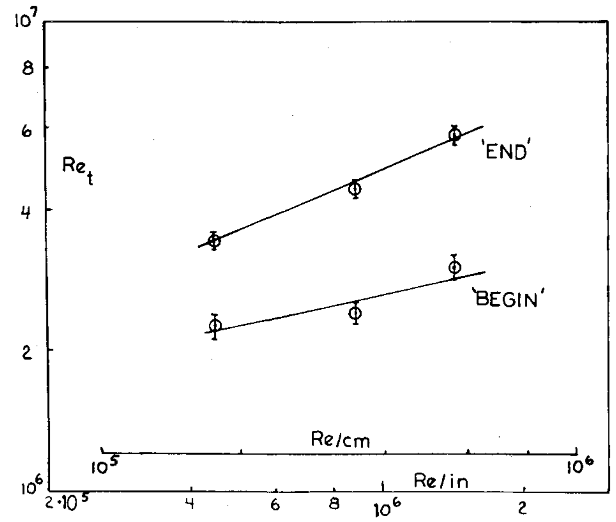


Fig. 2 Flat plate transition Reynolds number based on surface heat-transfer variation vs unit Reynolds number.

Fluctuation Profiles

Boundary-layer fluctuation level surveys were made along the flat plate model described in Sec. 2. The wire probes were operated at L/D between 50 and 100, approximately. The probes were all operated in a DISA type 55D01 constant temperature bridge at $R_w/R_0 = 1.5$–1.6.

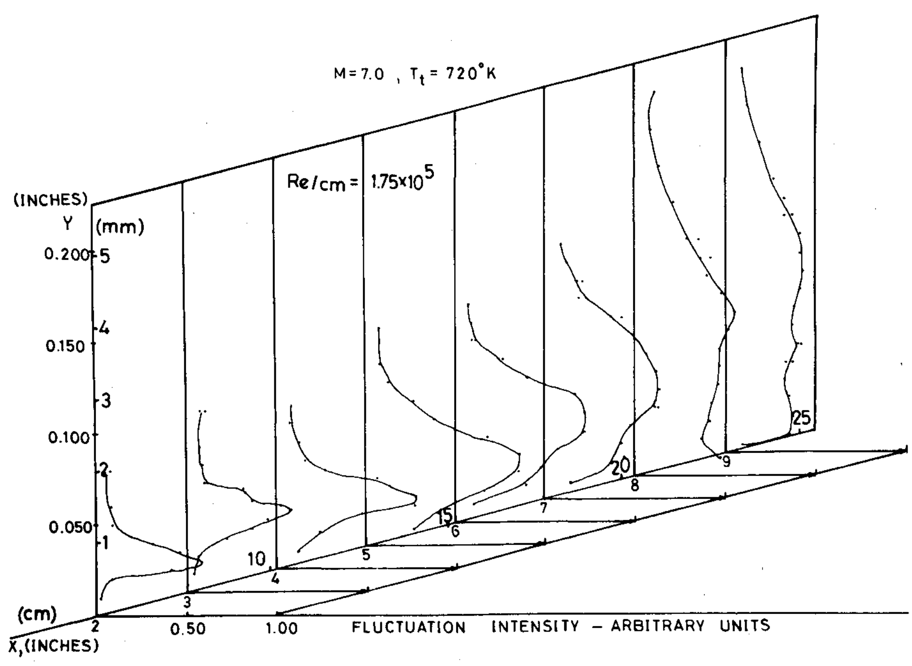
Typical anemometer amplifier fluctuation outputs showed a strong increase in fluctuation levels in the central regions of the boundary layer even when the Reynolds number was over a factor of two less than the beginning of transition defined by the surface $\dot{q}$ experiments. The distribution of fluctuation levels is illustrated more clearly in the integrated profiles presented in Fig. 3. In these figures the fluctuation intensity is given in arbitrary units obtained from the integrator output measured over a fixed time interval during each run.

Examining the profiles in succession, it is seen that even the lowest Re case ($x = 2$ in.) contains very strong fluctuations within the boundary layer which start to increase from the freestream level near the outer edge of the boundary layer then rise to a very sharply defined peak before falling off very rapidly below the peak. At the $x = 3$ in. position, the profile had broadened with the level falling off from the peak less rapidly. The next profile ($x = 4$ in.) remained similar in shape although the peak level had increased substantially and the profile has continued to broaden. Substantial changes in the profile shape first become apparent at $x = 5$ in. where rapid broadening of the profile toward the freestream began. The profile broadening toward the wall continued and the level at the $y = 0.010$ in. position increased further. The observations at this x position take on special significance when it is remembered that the transition region defined by the surface heat-transfer results on the flat plate is located approximately between $x = 5$ and $x = 8$ in. It thus appears that surface heat transfer measurements do not detect a change in laminar conditions until the laminar breakdown which begins in the outer regions of the boundary layer has spread to the proximity of the wall. This conclusion has also been observed at adiabatic supersonic conditions by Potter and Whitfield[1] and at hypersonic adiabatic conditions in a helium tunnel by Maddalon and Henderson.[14] The nature of the breakdown process will be discussed further below.

Beyond the $x = 5$ in. point, the profiles continue to broaden substantially with the peak level decreasing and becoming less well defined. The profile at the surface-defined end of transition ($x = 8$ in.) indicates a greatly increased boundary layer thickness and a much flatter fluctuation level distribution extending over the inner half of the boundary layer. There is some further slight readjustment in the profile at the $x = 9$ in. position. The flat distribution profile in the inner portion of the boundary layer is characteristic of the inner core of a turbulent shear layer. In fact, the entire fluctuation profile shape for the fully developed turbulent case ($x = 9$ in.) is remarkably similar to the intermittency factor distribution measured by Klebanoff[15] for a flat plate incompressible turbulent boundary layer. Detailed examination of the probe output signal (before integration) in the present tests revealed that the drop-off in integrated output was apparently due to the intermittent nature of the outer edge of the turbulent boundary layer when viewed by a fixed probe. This phenomenon has much larger dimensions than the turbulence itself and is thus easily observed as "spikes" on the signal.

The mean (d.c.) probe output was also measured during each run. With radiation losses, free convection, and heat conduction to the probes balanced by the bridge before the run, the

Fig. 3 Hot wire integrated fluctuation profiles through flat plate boundary layer for various (x) positions along model.



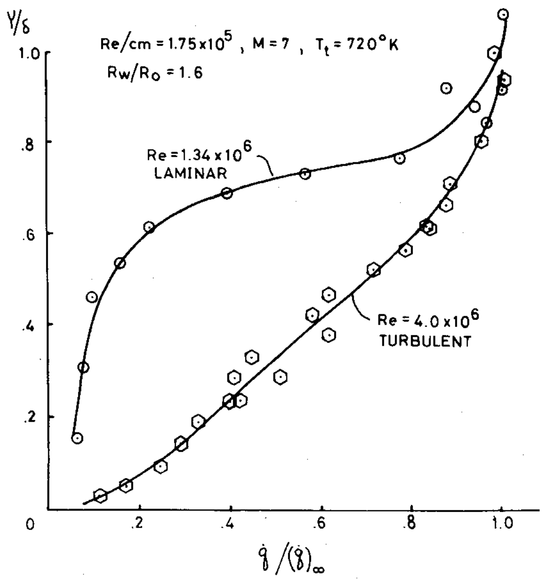


Fig. 4 Mean convected heat transfer from hot wire probe across boundary layer.

increase in bridge voltage (squared) required to maintain bridge balance during the run was proportional to the forced convection heat transfer from the wire due to the flow. The variation of wire mean convected heat transfer through the boundary layer is shown in Fig. 4 for two x positions (3 and 9 in.) corresponding to "laminar" and turbulent conditions respectively. The present heat-transfer data could not be converted directly to mass flow profiles without knowledge of the wire's Nusselt number dependence on Re and M, and ρu profiles could not be reduced to u without a separate temperature measurement. It is interesting to observe the point of inflection in the laminar profile of Fig. 4 near $y/\delta = 0.75$. This sharp gradient appears to be a real effect since the wire sensitivity is not likely to change so rapidly. The peak fluctuation location for this station is at nearly the same y/δ as the inflection. The existence of such sharp gradients in the presence of strong fluctuation activity remain a puzzle especially if the fluctuations are associated with turbulent eddies.

Measurements of the streamwise velocity fluctuation distribution through a flat plate laminar boundary layer in low speed flow by Schubauer and Klebanoff[16] showed a very well defined region of maximum activity similar to the sharply defined peaks found in the present hypersonic tests (see Fig. 3). The main readily apparent difference between the two sets of profiles was that for the incompressible results the fluctuation peak location was very

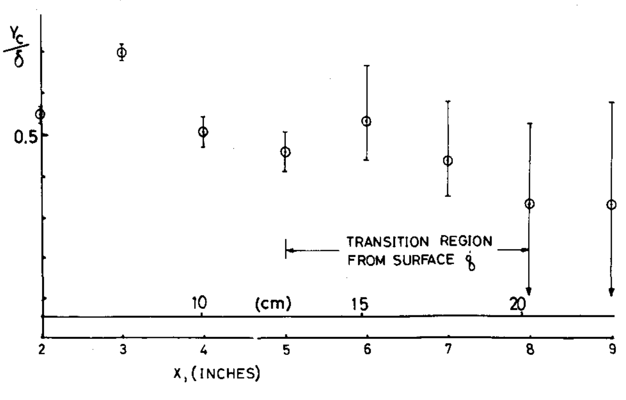


Fig. 5 Peak integrated fluctuation intensity location (y/δ) along flat plate model (x). $M = 7.0$, Re/cm $= 1.75 \times 10^5$, $T_t = 820°$K.

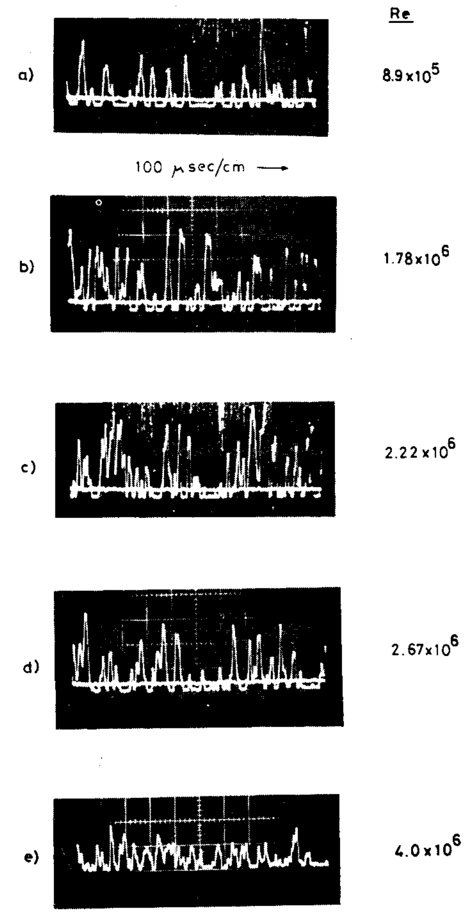


Fig. 6 Typical hot wire signal details near peak y/δ for various positions along flat plate model (Re). $M = 7.0$, Re/cm $= 1.75 \times 10^5$, $T_t = 720°$K.

near the wall whereas in the hypersonic results the peak had moved out a considerable distance from the wall. The location of the peak (y_c) in the present tests is shown in Fig. 5 for all the x positions measured. As mentioned earlier, the sharpness of the peaks tended to decrease as the Re increased and thus the definition of the peak location became more ambiguous as transition progressed until, at the fully turbulent condition, the "peak" extended over most of the lower half of the boundary layer.

The outward displacement of the peak fluctuation point at supersonic conditions was first observed by Laufer and Vrebalovich[17] at $M = 1.6$ and 2.2 and by Demetriades[8] at $M = 5.8$ on an adiabatic flat plate. Demetriades[8] found a peak fluctuation height of $y/\delta = 0.9$. Potter and Whitfield[1] measured peak fluctuation location on an insulated flat plate between $M = 3$ and 8 and found that it increased monotonically with M and agreed with the measurements of Refs. 8 and 17. Owen[18] recently confirmed these earlier measurements at $M = 2.4$–4.5 on an insulated flat plate. The only other adiabatic measurements reported were on cones by Maddalon and Henderson[14] in a helium tunnel between $M_e = 7.5$ and 15.6. They found the peak fluctuation height approximately constant over the M range tested although there was some downward movement of the peak when the boundary layer became transitional (from surface measurements). The only cold wall measurements in the literature was reported by Nagamatsu et al.[19] ($M = 14$, $y/\delta = 0.8$) and Softley et al.[20] ($M = 10$, $y/\delta = 0.75$). The data from Refs. 19 and 20 were measured on 10° total angle cones in shock tunnels. Both measurements were admitted by the authors to be very tentative, preliminary estimates of peak fluctuation location.

Probe Output Details

The method of anemometer output analysis permitted a fast sweep oscillogram of the signal to be obtained for each run. This sweep was usually made at 100 μsec/cm starting at 30 msec after the start of the run. Typical oscillograms at five different x positions (all taken at values of y/δ near the peak in the profiles of Fig. 3) are shown in Fig. 6. The first trace (a), corresponding to $x = 2$ in., contains very well defined, randomly distributed "spikes" in the output. The amplitude of some of the spikes represent a 30% fluctuation in mean wire output during the run. If these disturbances are attributed to embryo turbulent eddies, the amplitude variation is probably dependent on the size of the eddy swept past the wire and bandwidth limitations of the wire system. The low amplitude narrow spikes could be due to disturbances which have either formed later than the others (and thus are smaller when reaching the wire) or have originated at spanwise positions away from the wire and only partially intersect the probe. The pulse width of some of the larger spikes would indicate eddies of appreciable size (of the order of 1 in. even assuming a propagation velocity of only one half the freestream value).[21] This in turn would indicate that the disturbance origin is much further upstream than the first test port ($x = 2$ in.) for the present test conditions.

Another interesting aspect of the character of the sharp fluctuations in the probe output is their preferred direction (sign). Analysis of the complete a.c. bridge amplifier output signal indicated that all of the dominant fluctuations are negative, i.e., the fluctuations represent an instantaneous decrease in heat transfer from the wire. This is similar to Klebanoff and Tidstrom's[22] observations of turbulent eddy production in low speed laminar boundary layers. Although comparisons at such grossly different test conditions are dangerous, the wire outputs of Ref. 22 are remarkably similar to the observed spike pattern in the present tests. The decrease in wire heat transfer during spot passage can be conceptually explained by visualizing the newly formed spot as a region of fluid moving at a velocity somewhat less than the local mean velocity for a purely laminar flow. This concept is consistent with the optical supersonic findings of Spangenberg and Rowland[21] where the eddies were seen as erupting with a low mean velocity before accelerating to a velocity of about 0.7 freestream speed at $M_e = 2$.

An examination of the changes in the detailed probe output oscillograms with increasing x in Fig. 6a–e reveals a pattern consistent in many ways to Emmons'[18] turbulent spot model of boundary-layer transition. The spike amplitude and frequency increased with x until many of the individual peaks had merged with adjoining peaks at the beginning of surface transition (Fig. 6). The amplitude of strong fluctuations then began to decrease possibly because of the rearrangement of the large scale merged turbulent eddies into the smaller scale turbulence associated with turbulent boundary layers. The frequency of this turbulence rapidly exceeds the bandwidth of the system with a reslting drop in probe output. The final oscillogram (Fig. 6e) is in the fully turbulent region and has lost all trace of large scale discrete turbulent spots.

A plot of the integrated probe output level at a constant y position over the length of the model supports this general picture of spot growth. This is shown in Fig. 7 with the location of transition determined from the surface heat transfer experiments included. The nearly linear increase in integrated fluctuation intensity from the first upstream probe position until the surface beginning of transition would correspond to the region of linear growth of individual turbulent spots. At this point ($x = 5$ in.) the turbulence has reached the wall and much of the region consists of merged groups of spots (Fig. 6c). The fluctuation intensity is then at a peak and begins a linear decrease in a new region of reorganization of the large groups of merged spots into smaller scale turbulent eddies. This continues until the breakdown is completed at or near the end of surface transition at which point the fluctuation intensity levels

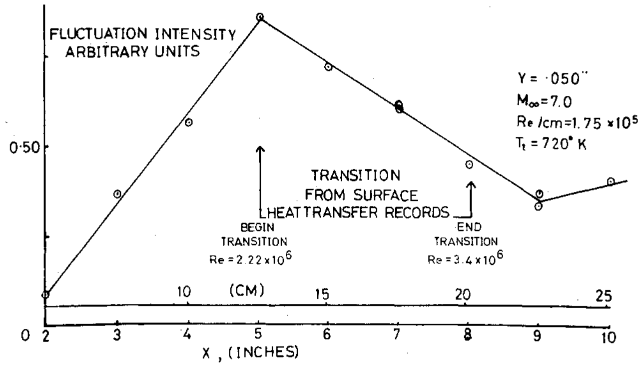


Fig. 7 Flat plate hot wire integrated fluctuation output traverse along model at constant height (y).

off in the fully turbulent boundary layer. It is the merger and breaking down of these large massed groupings of spots which are observed by the slower swept traces of surface film heat-transfer outputs.

Comparisons with Other Experiments

In the discussion of the integrated wire output fluctuations for the present tests, details of the nature of the individual fluctuations initially were not examined. This is also true of the references cited in the preceding section in which supersonic laminar boundary-layer fluctuations were measured. In all cases, fluctuation details were lost in some average measurement such as rms voltage. Schubauer and Klebanoff[23] in their study of low-speed laminar boundary-layer transition, concluded that "while certain mean quantities, such as the rms value of the fluctuations, were useful, records of the actual wave form of the fluctuations turned out to be by far the more meaningful." The results of their detailed analysis led to a picture of the transition region as being composed of discrete "spots" of turbulence which grew in size while travelling downstream to finally merge into fully turbulent flow and thus substantiating Emmons'[24] turbulent spot model. Schubauer and Klebanoff's wire output signals indicated low-level periodic oscillations in the laminar layer followed by a sudden burst of turbulence which was in turn followed by laminar oscillations. Following this important contribution, many increasingly more sophisticated studies were reported by various workers which added important details to the understanding of at least the low-speed transition phenomenon. It is important to emphasize again that it is not necessarily a direct analogy between the incompressible and compressible mechanisms which is being presented here. It is meant merely to emphasize an analogy of experimental methods. The incompressible transition picture was conceptually advanced by the wire waveform analysis of Schubauer and Klebanoff.[23] It is therefore suggested that actual fluctuation waveforms for the compressible case may be of similar value conceptually.

Only the laminar instability region of transition has received both theoretical and experimental attention at supersonic speeds and then with only limited success due to the strong influence of freestream disturbances in most tunnels.[25,2] A notable exception is the unpublished work of Kendall reported by Morkovin[26] in which partial verification of Mack's[27] numerical stability predictions were made in a supersonic tunnel with laminar sidewall boundary layers.

The only other region of the transition regime to receive attention at supersonic speeds is the final turbulent spot growth region and here only experimentally. Although the existence of supersonic turbulent spots is well established,[21,28] most experimental information about their behavior has been obtained from optical observations and these are, necessarily, somewhat limited. Wide bandwidth surface heat-transfer instrumentation is capable of detecting the passage of turbulent spots, as was mentioned above and in Refs. 19 and 13, but the detection is only after the spot has extended its influence to near the wall. The question of whether turbulent spots originate at or near the model leading edge[28] or further downstream[21] is by no means settled. The question of the y location of spot origin and subsequent growth rate perpendicular to the model surface is equally uncertain.

The detailed anemometer measurements of the supersonic adiabatic laminar boundary layer leading up to transition, which were discussed above, generally (where several x positions were probed) presented a picture of a gradual spreading of fluctuations from a very narrow region within the boundary layer toward the wall with increasing Re. A similar picture was presented for the cold wall measurements of the present study shown in Fig. 3. Yet, as mentioned in the opening paragraphs of this section, previous "microscopic" measurements of supersonic laminar boundary layer transitional breakdown did not include detailed observations of the nature of the fluctuations. In fact, it was generally assumed by the various authors[1,8,9,14,17,18] that the fluctuations observed were synonymous with the laminar self-excited instability oscillations associated with the early stages of transition. This assumption may have been justified in some cases, although not conclusively substantiated.

Analysis of the data from those references where the growth of the fluctuations with Re was observed,[1,9,14] however, indicated a continuous growth in intensity up to the surface-observed beginning of transition starting from the lowest Re position (very near the leading edge in the case Ref. 1). This observation contrasts sharply with the subsonic measurements of Schubauer and Klebanoff[23] in which a very strong increase in fluctuation level was found between the purely laminar oscillation disturbances and that region where turbulent spots began to appear. This in turn suggests that the fluctuation measurements of Refs. 1, 9 and 14 were, in fact, observations of turbulent spot growth within the boundary layer. If this assumption is true, then it would seem that embryo turbulent spots are generated very early within the supersonic laminar boundary layer indeed, verifying James'[28] observation that in supersonic/hypersonic boundary layers, turbulent spots originate very near the leading edge. It is possible that this shortened region of instability and three dimensional development is the region which is dominated by the strong freestream disturbance (primarily sound modes) shown to control the transition process in supersonic wind tunnels.[25]

Although the preceding discussion emphasizes many similarities of the present tests (and other cited references) with the incompressible Emmons' transition model, the discussion is not meant to preclude the possibility of entirely different compressible mechanisms which are also consistent with the observations. In fact, the fundamental difference between the two cases must be emphasized, viz., the outward movement of the fluctuation profile maxima from the low-speed to the high-speed case. In addition, the possibility of an alternate high-speed transition mechanism has recently been brought to the authors' attention. This is the work of Kendall[29] at J.P.L. currently in progress. Kendall's hot wire analysis of the flat plate "laminar" layer upstream of transition suggested that the large amplitude fluctuations observed were not associated with turbulent spots in the range $M_\infty = 3.0$ to 5.6 although his experiments at $M_\infty = 1.6$ and 2.2 found that turbulent spots were an important part of the transition process. Evidence linking the strong boundary-layer fluctuation activity with the freestream sound field radiated from the tunnel walls was also presented by Kendall. These interesting results offer an alternative qualitatively consistent with a wide range of previous data. It remains for future experiments to extend the range of application of this mechanism to earlier data and hopefully eventually bridge the wide gulf between high-speed wind-tunnel data and free flight results.

5. Conclusions

The significant results and conclusions of the present experimental study of hypersonic flat plate boundary-layer transition follow: 1) Hot wire anemometer probes and instrumentation have been developed which are capable of limited bandwidth operation in the environment and time scale of the Mach 7 gun tunnel ($T_t = 720°$K, Re/cm $= 1.75 \times 10^5$). 2) The use of these probes revealed strong fluctuations within the boundary layer upstream of the point where transitional effects are first observed on the model surface. These fluctuations were observed to be initially confined to a very narrow region of the boundary layer before gradually spreading normal to the surface with increasing distance downstream to cover the entire layer at the surface-observed beginning of transition. These observations emphasized the ambiguity of attempting to define a transition point in high speed flows quite independent of the uncertainty created by the freestream disturbances in various tunnels.[2] 3) A detailed extended sweep examination of the fluctuating wave forms during the runs revealed a discrete pattern which suggested the possible existence of turbulent spot breakdown at the lowest Re position tested on the model (8.9×10^5). Although the turbulent spot model was consistent in many ways to the observed data, there were important unanswered inconsistencies between this model and the data which precluded a definitive conclusion. Further experimental and theoretical work on the details of the complex mechanism of high-speed boundary-layer transition is clearly needed.

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Hypersonic Transitional Boundary Layers

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Surface thin film gages have been used to determine the extent of the transition region, intermittency distribution, and disturbance convection velocities in the boundary layer on a sharp 5° half angle cone at $M_\infty = 7.4$ in the Ames 3.5-ft Hypersonic Wind Tunnel. In addition, extensive hot wire space-time correlation measurements have been obtained in the wind-tunnel freestream and in the transitional hypersonic boundary layer on a cone-ogive-cylinder in the same facility. Disturbance convection velocities have been obtained from the longitudinal cross correlation measurements as a function of fluctuation scale and distance from the wall. The results of normal cross correlation measurements are also discussed.

Nomenclature

f = frequency
M = Mach number
p = pressure
Re = Reynolds number
t = time
T = temperature
U = velocity
V' = rms voltage fluctuations
x = distance from model cone apex, along model centerline
Δx = separation distance in x direction
y = distance normal to model surface
z = lateral distance around model
α = disturbance inclination angle
γ = intermittency
δ = boundary-layer thickness determined from Pitot pressure profiles
λ = turbulence scale, $U/2\pi f$

Subscripts

c = convection
e = boundary-layer edge
l = local
o = total
w = wall
∞ = freestream

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Introduction

IN spite of the extensive experimental and analytical work which has been conducted in supersonic and hypersonic transitional boundary layers in recent years, there is still much speculation regarding the detailed structure of and mechanisms influencing boundary-layer transition.

Morkovin[1] and Laufer[2] have pointed out that, at high freestream Mach numbers, the sound field which radiates from the turbulent boundary layers on the wind tunnel walls is a major source of freestream disturbances and must be considered in all transition experiments. Recently Pate and Schueler[3] have shown that the effects of aerodynamic noise on boundary-layer transition may be related to a number of wind-tunnel parameters including Mach number and unit Reynolds number. However, the conclusions of Pate and Schueler cannot be extended to all wind-tunnel transition data. For example, the transition data of Mateer and Larson[4] show little unit Reynolds number dependence which would not be expected if the effects of aerodynamic noise were dominant. In particular, noise cannot explain the unit Reynolds number effect observed in the ballistic range experiments of Potter[5] where, in the absence of significant freestream disturbances the variation of transition Reynolds number with unit Reynolds number was comparable to those observed in noise-contaminated wind tunnels. It is apparent that more data are needed to determine the effect of freestream disturbances on boundary-layer transition.

A better understanding of the transition mechanism could be obtained if experiments were designed to obtain a more complete picture of the structure and extent of the transition region