Hot-Wire Measurements in the Hypersonic Wakes of Slender Bodies

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An exploratory study of the viscous wake of right-angle two-dimensional wedges have been made with a hot-wire anemometer at a Mach number of 6 The main emphasis was placed on studying the transition to turbulence and the lateral spreading of the turbulent wake The laminar near-wake thickness was found to be constant, but upon transition the wake spread laterally quite rapidly The distance between the model and the transition zone showed a Reynolds-number dependence reminiscent of that found for blunt bodies The near wake of the wedges, however, is strongly stabilized by the large lateral Mach number gradient The transition Reynolds number was found to be independent of body size but dependent on the wedge angle Meaningful comparisons were made with transition data obtained with blunt bodies Also, very reasonable similarities were found to exist between these data and results of experiments with cones fired in ballistic ranges

I Background

THE hypersonic wakes of slender bodies have several features distinguishing them from wakes behind blunt-bluff bodies Strong flow gradients generated by bow shocks are largely absent around slender bodies, with the result that the viscous wake grows into a region where the flow quantities are close to those of the freestream For this reason both the transition to turbulence and the growth of the slender body wake, and perhaps the magnitude of its turbulent fluctuations, should be different for these two types of geometries at least in an outward sense

Optical observations of the viscous wake of cones have been reported by Slattery[1] and Pallone et al [2] These data are useful as qualitative indicators of the over-all flow field, the region of transition to turbulence, and the thickness of the laminar and turbulent wake In a preliminary way they indicate that the distance between the transition zone and the body increases with decreasing ambient pressure, a phenomenon also observed with blunt-bluff bodies [3] However, Slattery's cone data show a clear dependence of the transition distance on flight velocity [1] This effect is much stronger than observed with spheres; in fact the Reynolds number of transition for blunt bodies was found[3] to be almost linearly related to the flight Mach number so that the velocity dependence disappeared Further, judging from the results of Ref 1 the transition distance for the cones again does not scale with the body size, a result already obtained with the blunt-bluff configurations [3] Finally, these preliminary transition data show the expected tendency of transition to "stick" to a region at or closely downstream from the wake neck because of the dynamical stability considerations discussed at some length by Webb et al [4] and by Lees [5]

Wake studies with slender wedges have been under way at Graduate Aeronautical Laboratory, California Institute of Technology (GALCIT) for some time In the course of this work, and in view of the fore going experiments, a diagnosis of the gross features of the wake region with the hot-wire anemometer became necessary Since the inviscid flow field downstream of a slender body is quite susceptible to the detailed body geometry, it became apparent that a hot-wire study involving a wider choice of body size and geometry than hitherto available, was in order In the present experiment, two-dimensional right wedges with very sharp leading edges were tested in continuous hypersonic flow The objective of this study was to measure qualitatively the turbulent fluctuations behind the wedges with the aim of determining the wake thickness and locating the transition distance as a function of wedge angle and size

II Procedure and Results

The procedure used was identical to that described in Ref 3 The wedge models were positioned 23 1 in downstream of the nozzle throat of the hypersonic wind-tunnel (Leg 1) at the California Institute of Technology (Fig 1) Hot-wire surveys were made within the first 12 in downstream of the wedge; all work was done on a plane normal to the wedge surfaces at the midspan position Seven wedge models were used The included wedge angles (Fig 2) were $\theta = 5°$ (base heights $h =$ 0 034 in , 0 072 in , and 0 141 in), $\theta = 20°$ ($h = 0\ 15$ in , $h = 0\ 30$ in), and $\theta = 45°$ ($h = 0\ 15$ in , $h = 0\ 30$ in) The low stagnation enthalpies and satisfactory purity of the air used have enabled the fine wedge leading edge to withstand many hours of continuous testing without melting or pitting The angle of attack was zeroed by turning the wedge till the fluctuation profile in the wake was symmetrical It is noteworthy that the present data were taken with a different DeLaval nozzle ($M_\infty = 6\ 0 \pm 0\ 05$) and different electronic apparatus than were the cylinder wake data[3]; experience has shown that such changes have not affected the consistency and repeatability of wake-thickness and transition-to-turbulence picture obtained over three years of experimentation

Two types of hot-wire traverses were taken "Transverse" traverses are taken at constant stagnation pressure and constant x [i e , distance behind the wedge (Fig 2)] "Streamwise" traverses were also taken at constant stagnation pressure P_0 and $y = 0$ (i e , on the wake centerline) The hot-wire output integrated over a certain range of frequencies was channeled into a vacuum thermocouple so that a signal proportional to the mean-square of the wire output could be plotted directly and continuously on an x-y plotter During

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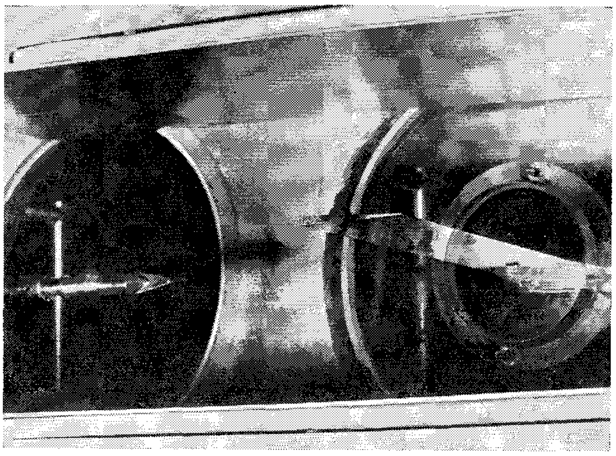


Fig 1 Experimental arrangement in the test section of the hypersonic tunnel showing 5 wedge model and anemometer probe

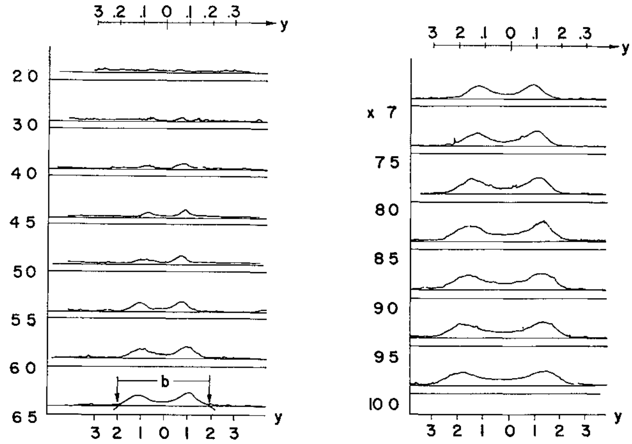


Fig 3 Variation of mean-square wire output with y $P_0 =$ 40psig, $h =$ 0 15 in

each traverse the wire was operated at constant current and fixed thermal-lag compensation Since the flow field in the viscous wake is quite nonuniform, the data as obtained cannot yield quantitative results, such as the fluctuation intensity for example However, the difference in the output between laminar and turbulent regions was so large that the observed wake thickness or transition zone remained unchanged over a wide range of overheat, compensation, and frequency band-widths

A sample of the integrated (mean-square) wire output thus obtained is shown on the accompanying raw-data graphs (Figs 3 and 4) The ordinate in these graphs represents the wire output and the abscissa the traverse or streamwise distance Data with a backward-facing wedge of $\theta = 45°$, $h =$ 0 15 in were also obtained and will be discussed further below

III Discussion

1 Thickness Measurements

A typical series of transverse traverses behind a wedge are shown in Fig 3 The wake seems to be free of fluctuations at the beginning, but further downstream a signal of appreciable magnitude develops A wake turbulence thickness is defined as in the last trace of that figure,† and some such thicknesses are collected and plotted in Fig 5 Three features stand out: 1) the wake remains very straight (to within a few per cent) initially, 2) the initial wake thickness is quite larger than h for the $\theta = 5°$ wedges and depends on wedge chord (and tunnel pressure), and 3) at some point along the wake the wake thickness begins to increase suddenly and almost linearly with x This event sets in at transition, as argued below

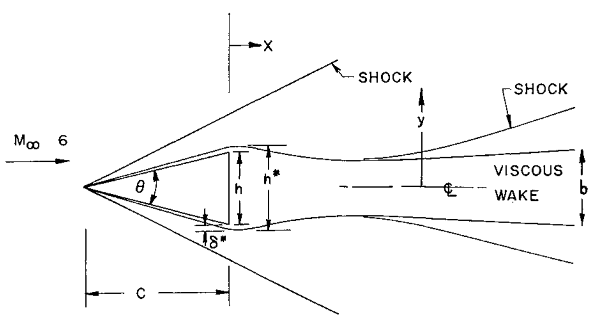


Fig 2 Geometry and nomenclature for wedge wake experiments

† This definition of thickness is identical to that used in Ref 3

Items 1 and 2 indicate that the viscous layer at separation is all important in forming the near wake (particularly for the 5° wedge) and that an "effective" body is now formed by the viscous displacement effect on the wedge surfaces We know that in the limiting case $\theta° \rightarrow 0$ (Fig 2) the initial wake thickness b^* should go as the displacement thickness δ^* at separation:

$$b^* \sim \delta^*$$

or

$$(b^*/h) \sim (\delta^*/h) \sim [(c^{1/2})h] = (c/h)[1/(c^{1/2})] \sim [1/(c^{1/2})]$$

at constant freestream Reynolds number and where c is the wedge chord For the three 5° wedges, data with which are shown in Fig 5, the chords are in the ratio 1:2:4 and the (b^*/h) values (see Fig 5 at $x/h = 7$) shown are in the ratio 3 1:2 1:1 5, almost exactly as $1:1/(2^{1/2}):1/(4^{1/2})$ Numerically, the (b^*/h) values of Fig 5 are also in good agreement with experiments on the displacement growth near sharp leading edges [6]

The conclusion is that for such small wedge angles the important body dimension is h^*, defined by

$$h^* = h + 2\delta^* \qquad h < \delta^*$$

or, alternatively, the wedge chord Replotted as (b/h^*) vs (x/h^*) the data are shown in Fig 6 This manner of presentation illustrates the rapid growth of the turbulent wake contrasted with the constancy of the laminar wake The growth

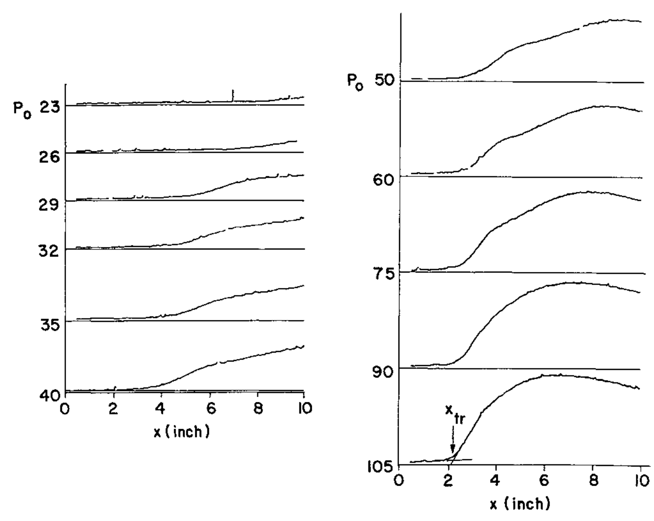


Fig 4 Variation of wire output with x and tunnel P_0 $\theta =$ 5°, $h =$ 0 072 in

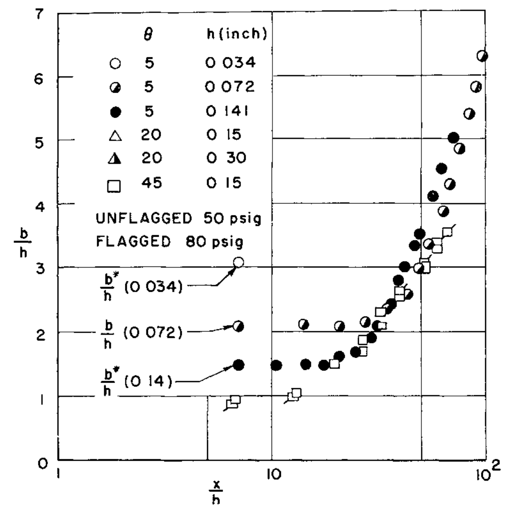


Fig 5 Wake thickness development downstream of the model, normalized to the body base height

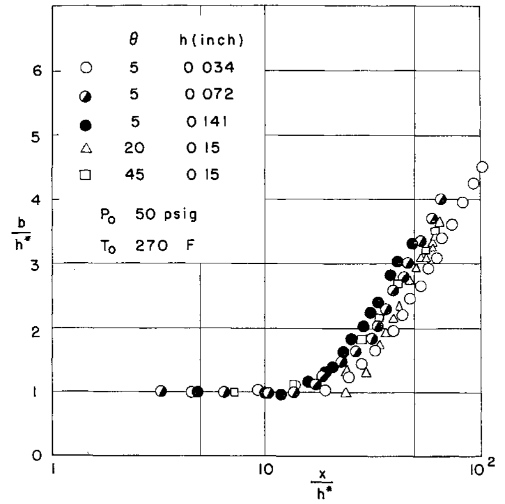


Fig 6 Wake thickness development downstream of the model For the 5° wedges the normalizing factor is the effective base height

rate is almost linear in the range $30 < (x/h^*) < 100$ Further manipulation of these data was not attempted Also, correlating the data with $(C_DA)^{1/2}$ was not attempted because the drag is difficult to calculate at these wedge sizes and Reynolds numbers Simple considerations dictate that, under circumstances similar to those of the present experiment, the turbulent wake of axisymmetric bodies (e g , cones) might not grow as rapidly

The surprising constancy of the laminar wake thickness behind the slender body has also been observed with cones fired in ballistic ranges No explanation of this phenomenon is available ‡

Measurements of the laminar wake thickness by the present technique were made possible by the appearance of a certain amount of fluctuations at the laminar wake edge, as Fig 3 indicates (cf first 4 in behind the body) Although such signals could be partly due to the changing sensitivity of the instrument as it traverses the wake, they also indicate the presence of actual flow fluctuations In the light of small disturbance stability theory a spectral analysis of these signals would be extremely interesting, particularly in the wake region immediately preceding transition

2 Transition

2 1 Transition measurements

The sudden increase of the wake thickness (Figs 5 and 6) is accompanied by a large increase of the wire output; at the same time the fluctuation profile of the wake begins to "fill up" near the center (Fig 3) If the wire is traversed in a streamwise direction along the wake centerplane, this increase in turbulent intensity shows very clearly (Fig 4) At the same time the wire output near the wake boundaries, viewed on the oscilloscope, shows the "one-sidedness" characteristic of turbulence All these facts indicate that transition to turbulence can be located conveniently by using the streamwise traverses In the present instance the transition "point" was defined as the beginning of the increase of the fluctuation intensity at the centerline§; this is illustrated in Fig 4

The streamwise traverses (Fig 4) characteristically show a very quiet wake up to the transition point, a steady rise to a certain value of turbulent intensity, and subsequently a decay process The transition distance decreases rapidly with increasing pressure, but eventually becomes "stuck" near the body; this sticking, present in all wedge tests, is explainable in terms of stability theory,[5] which predicts an increased stabilization of the flow as the Mach number difference between wake edge and centerline increases

Using the definition of the transition point or zone from Fig 4, the data obtained are plotted in Fig 7 For the 5° wedges the displacement effect was severe, and h^* (instead of h) was used as the normalizing factor

2 2 Transition Reynolds number

Near the body the transition distance varies slowly with the pressure (because of the "sticking"), and the data for each of the three wedge angles fall on nearly straight lines We can define a transition Reynolds number as

$$Re_{\infty\ t} = \left(\frac{x_{tr} - x_0}{h^*}\right)\left(\frac{1}{(1/Re_{\infty\ h^*})}\right) = \frac{x_{tr} - x_0}{h^*}\,\frac{\rho_\infty u_\infty h^*}{\mu_\infty} = \frac{(x_{tr} - x_0)\rho_\infty u_\infty}{\mu_\infty}$$

where x_0 is the sticking distance In this region (i e , close to the body) this Reynolds number is independent of body size but depends on the wedge angle θ as follows:

θ	$Re_{\infty\ t}$
5°	110,000
20°	300,000
45°	400,000

These Reynolds numbers are plotted in Fig 8; the same figure includes a point at $Re_{\infty\ t} = 56{,}000$ [7] Since this is the case where the freestream and local (i e , local at the wake edge at transition) quantities are identical, this point belongs to $\theta = 0$, that is, to the body that produces a negligible bow shock such as a flat plate Also, an asymptote at $Re_{\infty\ t} = 5 \times 10^5$ is included, which is the freestream Reynolds number of transition for blunt bluff bodies[7] (large θ) at $M_\infty = 6$ The transition Reynolds numbers as defined are seen to connect quite smoothly these two extreme values of θ The conclusion drawn here is that for extremely slender bodies the transition Reynolds number (based on freestream values and the distance between the sticking point and transition) is equal to about 56,000 (within some error), but this number increases as the body becomes blunter, to about 500,000 for large θ at $M_\infty = 6$

‡ At this writing, a detailed measurement of the near wake of a wedge at $M = 6$ 0 is under way at GALCIT by T Kubota and R Batt

§ This method of locating transition differs from that used with blunt bodies [3] In the latter case it was extremely hard to find fluctuation free flows in the wake, and the transition location was subject to greater error

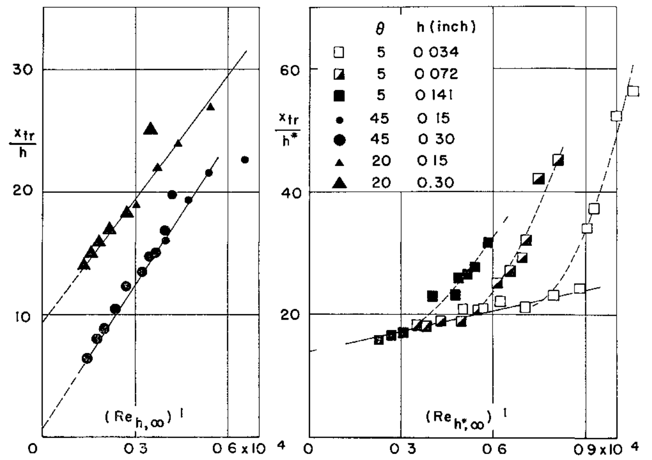


Fig 7 Transition in the hypersonic wake of wedges

The importance of the local Reynolds number of 56,000 and the attendant insensitivity of the transition distance to the physical size of the model has been at least partly explained by Lees who indicated that the amplification ratio for small disturbances growing in the wake might well be independent of the body size [5] More recent calculations by Gold[8] indicate that the local transition Reynolds number of 56,000 is indeed a very weak function of the body Reynolds number in the range of the latter in which the present experiments were carried out Details of this argument, which is based on the "inviscid" or dynamical stability of wake flows, are presented in Ref 8

An alternate representation of the wake transition to turbulence could be carried out with the aid of the parameters

$$Re_\Delta \equiv \frac{\tilde{\rho}(\tilde{u} - u_{\mathfrak{C}})x_t}{\tilde{\mu}}$$

$$M_\Delta \equiv \frac{\tilde{u} - u_{\mathfrak{C}}}{\tilde{a}}$$

where the conditions $\tilde{\rho}$, $\tilde{u}$, $\tilde{\mu}$, and $\tilde{a}$ are at some relevant position in the wake, such as the critical layer and those subscribed ℄ at the viscous wake centerline Reduction of data by setting the tilted quantities equal to those of the wake edge was attempted by Hidalgo[9] and more recently by Pallone [2] This representation has been hindered not only by the present meagerness of data, but primarily by the lack of knowledge of the exact velocity defect $u - u_{\mathfrak{C}}$ To obtain the latter, one must either make detailed field measurements (which has been attempted only once to date[10]) or calculate the viscous flow field beginning from the body base to many diameters downstream This calculation can be carried out with the linearized theory of Kubota[11] and Gold[12] when x_t/h is not too small, or with the strip method of Pallone[2] coupled with near-wake measurements such as made recently by Dewey [13] In any event, the reduction of transition data from slender-body experiments should be easier than from blunt body experiments because the calculation of the viscous wake flow is not complicated by large external (inviscid) field gradients ¶

2 3 *"Sticking" distance*

The definition and variation of the sticking distance x_0/h^* of the wedge is also shown in Fig 8 Note that this distance scales well with the body base height h^*, although the transition distance $(x_t - x_0)$ is independent of body size On the basis of these results, the sticking distance for a very thin flat plate at $M_\infty = 6$ should be about $15h^*$, where h^* is completely made up, now, of the boundary-layer displacement effect, i e ,

$$\lim_{\theta=0} h^* = 2\delta$$

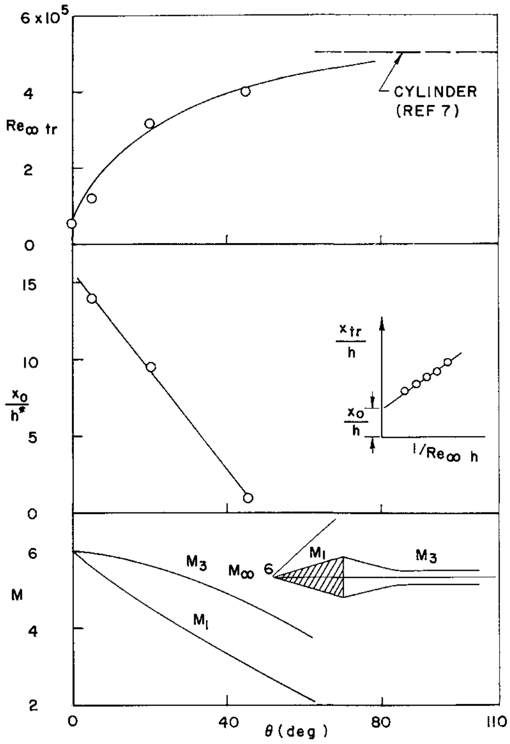


Fig 8 Variation of transition Reynolds number (top) and "sticking distance" (middle) with wedge included angle

In Fig 8 a reason for the increase in (x_0/h^*) with decreasing θ is at least partly given by the plot of the Mach number M_3 just after recompression at the neck (assuming isentropic recompression) We see that near $\theta \to 0$, M_3 (and hence also the relative wake Mach number) is very close to M_∞ and the wake should be quite stable, whereas at the higher θ's the relative Mach number, and hence the inherent wake stability, decreases rapidly

2 4 *Minimum Reynolds number*

Although the transition data near the body show the straight-line behavior on which the constant-transition-Reynolds-number argument is based, they soon curve upward at the lower values of $Re_{\infty\ h^*}$, and transition seems to move to far distances from the body In some cases this behavior is such that the straight line portions of the transition curves (Fig 7) are difficult to distinguish This behavior is strongly suggestive of the prediction[5] that below a certain body Reynolds number based on freestream quantities, the transition region moves completely off the wake From Fig 7 this number seems to be about 10,000 **

3 Comparison with Results for Blunt-Bluff Bodies

If the results of Fig 6 are compared with the growth of the two-dimensional wake of the blunt-bluff bodies (cylinders) under identical conditions (Fig 7, Ref 3), we observe that in the range $10 < (x/h^*) < 100$ the turbulent wedge wake actually grows faster than that of the cylinder, and that the former does not show the "break" shown by the latter around 40 base heights

¶ The much larger viscous wake gradients of slender bodies also makes photographic and other measurements much easier for such bodies

** Recent experiments by W Behrens at GALCIT show that the wake of very thin cylinders stretched across the tunnel remain laminar below a body Reynolds number between 8000 and 15,000

The short range of (x/h^*) available in the present experiment made these measurements difficult to compare with the wake asymptotic growth [which should be similar for bodies of the same $(C_DA)^{1/2}$] or even with the "drag-swallowing" theory of Lees and Hromas [14]

The transition characteristics of slender (small θ) and blunt (large θ) bodies have already been compared in Fig 8 A question often asked here is: Will the transition point (or region) move forward as the body becomes more slender? From Fig 8 we observe that the transition Reynolds number $Re_{\infty\ t}$ decreases with decreasing wedge angle; on this precept alone transition should move closer to the body as θ decreases However, the "sticking distance" increases with decreasing θ, so that these two effects tend to balance each other out A prediction of the location of the transition as a function of θ can thus be made only if due account of both effects is taken for specific cases

4 Comparison with Cones Fired in Ballistic Ranges

Several experiments with cones fired in ballistic ranges have been reported [1, 2] Photographs taken during such firings show clearly the transition to turbulence as well as the constancy of the laminar wake thickness Of these experiments, only those performed by Slattery[1] seem to have had sufficient control of the model velocity to admit some interpretation from the standpoint of this paper Results from these experiments are plotted in Fig 9 Here, because of the relatively high θ value (25°) no displacement correction to the body base size was made

The plot shows that 1) close to the body (20–30 base heights) a straight-line correlation again obtains within the data scatter, 2) no size effect is seen, as also indicated by the GALCIT data with wedges, 3) the transition Reynolds number increases with increasing velocity [this agrees with the blunt-body situation (see Ref 7, Fig 2) and also is supported by the fact that the higher the body velocity, the greater the differences between freestream and "local" Reynolds number], and finally, 4) the "sticking" distance appears to increase with increasing velocity (i e , free-flight Mach number) This also supports the view that the sticking distance is dominated by the relative Mach number between the centerline and the edge of the viscous wake

It would be interesting to see how the Reynolds number of transition varies with Mach number for a fixed body Using Slattery's 25° cone and the GALCIT 20° wedge, four points are plotted in Fig 10; here again we assume that the $Re_{x_t} = 56{,}000$ applies equally to any slender body at $M \to 0$ The resulting curve reinforces confidence in the data taken both at GALCIT and at Lincoln Laboratory[1] and further indicates the relative insensitivity to whether the body is axisymmetric or two-dimensional, exactly as observed with the blunt bodies [7] Additional constant-Mach-number firings of cones in ballistic ranges would be invaluable in extending the validity of this result

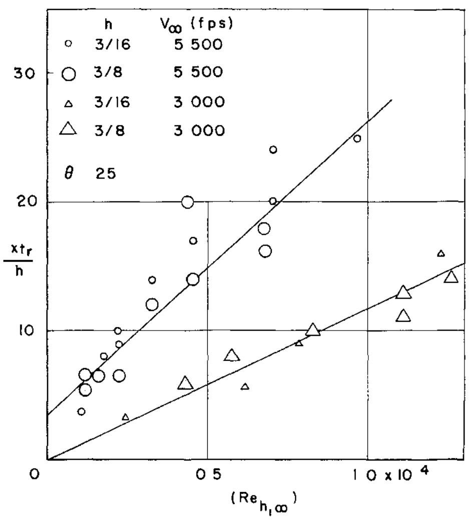


Fig 9 Cone transition data from Ref 1 reduced to the nomenclature of the present paper

One trend obvious from Fig 10 is that between Mach numbers 2 and 6 the relation between M_∞ and $Re_{\infty\ t}$ is almost linear, resulting in an apparent independence of the transition distance on the flight velocity However, a closer examination of Fig 10 shows that this is true only for the effective transition distance $x_t - x_0$, but not for x_0 Thus, the apparent sensitivity of the transition distance to the free-stream velocity (cf Fig 4, Ref 1) is explained by the fact that the sticking distance itself moves downstream with increasing velocity

We can best summarize our empirical knowledge of transition in the wake of slender bodies of included angle θ moving in a medium with Mach number M_∞ such that $M_{\infty_1} < M_{\infty_2} < M_{\infty_3}$ by Fig 11 For $\theta \to 0$ the Reynolds number 56,000 (within some error) obtains, where

$$\mathrm{Re}_{\infty\ t} = \rho_\infty u_\infty (x_t - x_0)/\mu_\infty$$

As the body is blunted an asymptote is reached such as shown by Fig 8 The movement of the sticking distance as well as the minimum Reynolds number of transition will have to be taken into account in these considerations

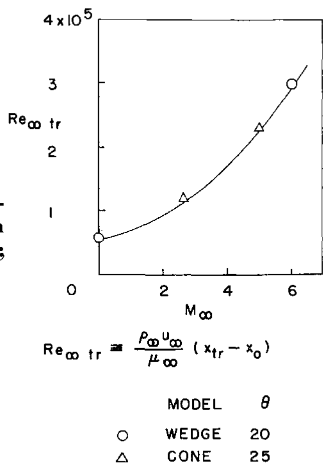
5 The Wake of a Backward-Facing Wedge

Some interesting results were obtained with the backward facing wedge, as seen from the attached curves (Figs 12 and 13) In this experiment a 45° wedge (h = 0 15 in) was positioned with its flat base normal to the oncoming stream Its wake was found to be free of turbulence (Fig 12) under identical conditions for which the same wedge showed a clearly turbulent wake when facing forward (Fig 13) The tentative explanation for this is that the flow attaches on the wedge surface immediately after expanding around the corner and that this produces an initially thin wake at very low local Reynolds number The physical distance x_t for transition then has to be so long that transition occurs, if at all, far downstream of the range (to 10 in) traversed by the hot-wire For this reason additional experimentation with wind-tunnel or ballistic range models are needed in order to clarify the flow details in the vicinity of a body such as a backward-facing wedge or cone

IV Conclusions

Hot-wire anemometer measurements in the wake of slender wedges were made at a Mach number of 6 0 The objective was to measure the wake growth and to detect the transition

Fig 10 Variation of Reynolds number of transition with flight Mach number; cone data from Ref 1



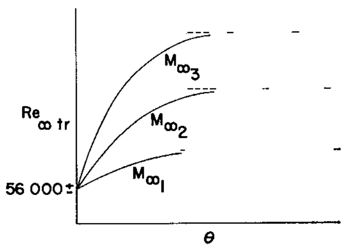


Fig 11 Schematic description of transition Reynolds number variation with included angle at various Mach numbers

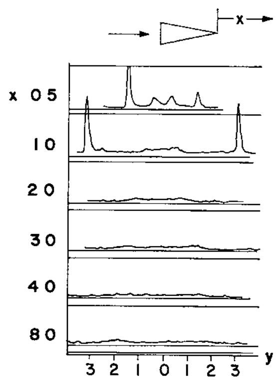


Fig 12 Variation of mean-square wire output with y Backward-facing 45° wedge Compare with Fig 13

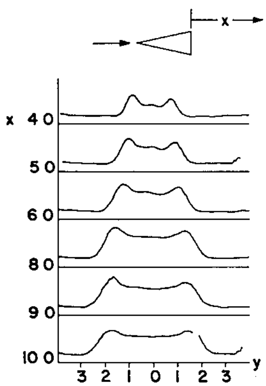


Fig 13 Variation of mean-square wire output with y Forward-facing 45 wedge Compare with Fig 12

to turbulence as a function of body size and wedge angle The following results were obtained:

1) The laminar wake width behind such wedges remains constant for tens of base heights

2) For very slender wedges (5° included angle) the initial wake characteristics are dominated by the laminar boundary layer on the wedge surfaces at the Reynolds numbers of the experiment

3) Beyond the transition zone the turbulent wake grows rapidly and almost linearly within the first 100 effective base heights

4) Transition to turbulence moves rapidly upstream as the pressure increases but eventually gets "stuck" at some characteristic distance behind the body; this behavior was predicted earlier by considerations of laminar stability The sticking distance increases with increasing slenderness and/or increasing flight Mach number

5) It was possible to correlate the data into a transition Reynolds number in accord with earlier wind-tunnel experiments and ballistic range firings of slender cones The transition Reynolds number decreases with increasing slenderness and increases with increasing Mach number This latter dependence is such that the effective transition distance is independent of flight velocity

6) Minimum Reynolds numbers for transition, based on effective body size, were found to be about 10,000

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