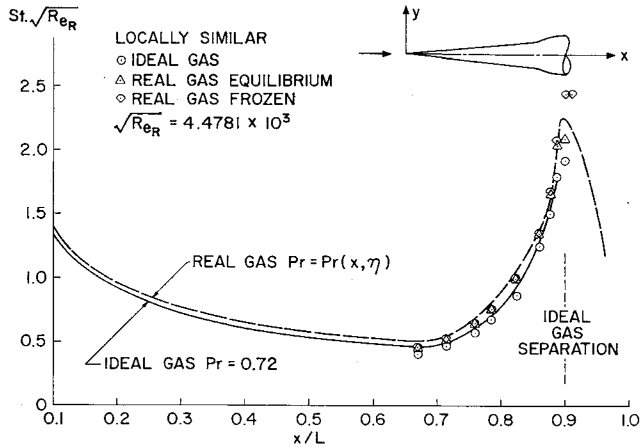

Fig. 2 Laminar heat-transfer parameter vs x/L on 50-ft flight vehicle at Mach = 20 and 154,000 ft.

by following a similar procedure as outlined for the equilibrium flow case. In Eq. (29)

$$\lambda_f = (1/H_e)(h_w - c_{pw}T_w)$$

and

$$\gamma_f \left(\sum_i c_{p_i}X_i - R\right) = \sum_i c_{p_i}X_i$$

Numerical Example

In Figs. 1 and 2 heat-transfer and skin-friction results obtained by the present method are compared with those of the more exact numerical equilibrium flow procedure of Ref. 4. The calculation was performed for an axisymmetric sharp-nosed compression body characteristic of a supersonic ramjet inlet forebody for flight conditions corresponding to $M_\infty = 20$ at 154,000 ft and for a wall temperature of 2300°R. Although the local similarity concept is restricted to flows with slowly varying external properties, its accuracy for the body contour considered proved to be remarkably good despite the limitations imposed on the Prandtl and Lewis numbers and on the variation of $\rho\mu$. For the conditions considered, very little difference was observed between the frozen flow results, for both catalytic and noncatalytic surfaces, and those of the equilibrium case. The only appreciable difference noted between the two calculations occurs near the end of the compression surface where the dissociation level is highest. This is not surprising, since for slender shapes the dissociation level in the stream is quite low, thereby minimizing the difference between the frozen and equilibrium assumptions. A complete development of the present method, together with additional numerical results and comparisons, is available in Ref. 5.

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Hypersonic Boundary-Layer Transition Data for a Cold-Wall Slender Cone

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Nomenclature

c_p = specific heat at constant pressure
M = Mach number
q = heat-transfer rate
r = nose or body radius
Re_∞ = Reynolds number per foot based on freestream conditions
Re_s = Reynolds number based on local properties and on distance along surface from stagnation point or tip = $\rho_e u_e s/\mu_e$
S_t = Stanton number = $q_w/\rho_e u_e c_p(T_{AW} - T_W)$
s = distance along surface from stagnation point or tip of body
T = absolute temperature
u = velocity component along the body
μ = coefficient of absolute viscosity
ρ = mass density

Subscripts

AW = adiabatic wall
B = body
e = local flow at edge of boundary layer
N = nose
t = transition
w = wall value
0 = stagnation value in freestream
∞ = freestream static values

Introduction

Some recent experimental data are presented concerning the effect of wall-cooling, nose-bluntness, and roughness elements on the transition of the hypersonic boundary layer on a slender cone. This data constitutes an extension to higher Mach numbers of available information on boundary-layer transition recently compiled and presented in Ref. 1.

Nose blunting and wall cooling are known in some cases to alter significantly the location of transition, giving rise to the phenomenon of transition reversal. The location of transition has important ramifications in vehicle design, in that it affects the local heat-transfer rate to the body surface, the skin-friction drag, and the susceptibility of the boundary layer to separation. In the design of hypersonic inlets, both the state of the boundary layer and transition location have a significant influence on the inlet performance. The data presented here comprise part of the results obtained in the experimental investigation of hypersonic inlet performance reported on in Ref. 2.

Discussion

The model used in the investigation was a right-circular cone configuration having a semivertex angle of 5° and a

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length of 60 in. as measured from the theoretical vertex. In addition to the sharp-nose tip, the model was furnished with two hemispherical blunt-nose shapes having a ratio of nose diameter to cone base diameter r_N/r_B of 0.0286 and 0.0572. In order to obtain variation of the ratio of wall-to-stagnation temperature, the model was provided with an internal cooling system utilizing liquid nitrogen and a heating unit comprised of several electric heating elements. Using these techniques, wall-to-stagnation temperature ratios T_W/T_0 from 0.075 to 0.365 were obtained. A boundary-layer trip device employed in some of the tests consisted of 14 spheres each of 0.093-in. diam, and equidistantly spaced circumferentially at an axial location 9.25 in. from the apex of the cone.

In order to determine the onset of transition, a comparison of the experimental heat-transfer distribution with predicted laminar and turbulent rates was made. The departure of the heat-transfer rate from the predicted laminar level is used to define the start of transition. Experimental values for the heat flux were determined from the transient temperatures measured by thin-walled heat gages arranged along a conical ray of the body. In order to account properly for any conduction losses from the heat gages, a three-dimensional transient heat-conduction analysis was applied to each gage. In addition, the model was instrumented for the measurement of surface static pressures as well as boundary-layer pitot pressures. All tests were conducted at a nominal Mach number of 10, stagnation temperature of 2000°R, and unit Reynolds number of 2×10^6/ft in Republic Aviation Corporation's 36-in. hypersonic wind tunnel. A description of this facility is given in Ref. 3.

The results of the tests exploring the effects of nose bluntness and roughness on transition are presented in Fig. 1 in the form of Stanton number vs Reynolds number for a wall temperature of 530°R. The Reynolds number is based on local flow properties, assuming sharp-nosed cone conditions, and on the distance along the body surface measured from the nose. Also shown in Fig. 1 is the theoretical prediction of the laminar and turbulent heat-transfer rates based on the Eckert flat-plate reference enthalpy method[4] as applied to cones. The flow properties used in the calculations were the average values for the tunnel test conditions. The effectiveness of nose blunting in delaying the boundary-layer transition is clearly illustrated. Similar results for tests conducted at a lower Mach number are shown in Ref. 5, together with an explanation of the mechanism by which nose blunting delays transition. For the range of nose bluntnesses tested here, there is also no indication of transition reversal.

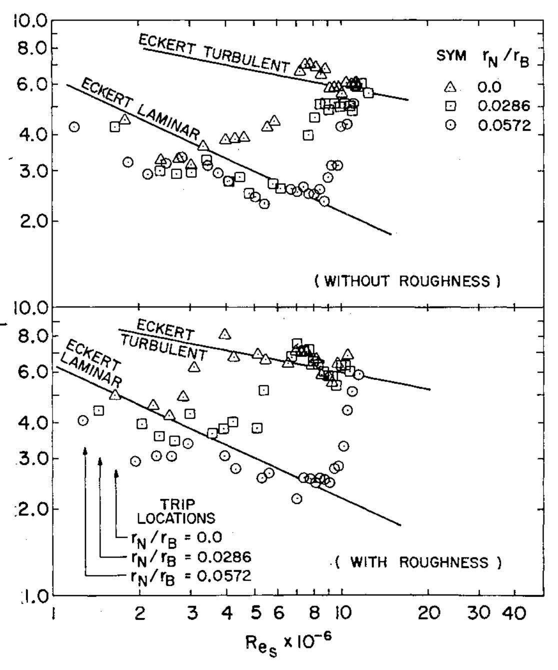

Fig. 1 Heat-transfer distribution on a slender cone with and without nose bluntness and surface roughness.

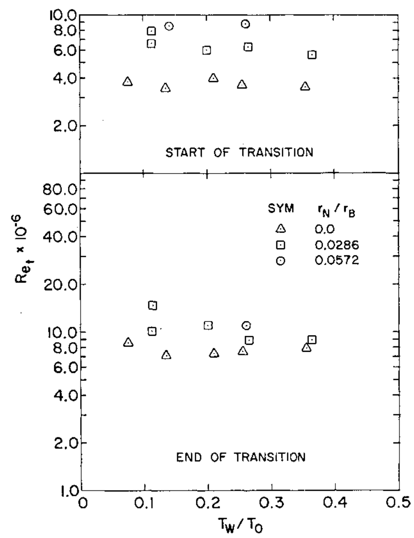

Fig. 2 Transition Reynolds number variation with wall-to-stagnation temperature ratio.

It is interesting to note that the length of the transition region for the sharp-nosed cone is greater than that observed for the blunt-nose cases. The addition of the blunt nose results in the introduction of vorticity associated with the shock curvature, a reduction of the local edge Mach number, and the delay of the onset of transition to a region of local Reynolds number higher than that for sharp-nose cone. Each of these effects acting alone or in concert may account for the reduction of the transition length observed for the tests on the blunt-nose cone configurations.

The tests discussed previously were repeated for the same tunnel conditions, with the boundary-layer trip installed on the model surface. Shown in the lower half of Fig. 1 are the heat-transfer data for the sharp- and blunt-nosed cone models with roughness elements attached. The results indicate that the sharp-nose cone laminar boundary layer is more sensitive to the disturbances generated by the roughness elements than are the laminar boundary layers of the blunt-nosed models. In fact, the data reveal that, whereas the boundary-layer trip results in earlier transition for the sharp-nose and medium-blunt-nose configurations, the presence of the trip is essentially ineffective when applied to the model with the largest nose bluntness. For the case of the blunt-nose cone with roughness elements, the increased stability of the laminar boundary layer induced by the lower local Reynolds number offsets the destabilizing influence of the boundary-layer trip.

For the sharp-nose cone, the use of roughness elements produced a marked decrease in the length of the transition region, when compared to the sharp-nose cone results obtained without the boundary-layer trip. For the tests of the blunt-nose models with the boundary-layer trip, no significant effects of roughness elements on the length of the transition region are discernible. The factors that were offered earlier in explanation of the effects of bluntness on transition length are also present for the case of bluntness with roughnesses; however, it appears that the bluntness-induced effects on the laminar boundary layer diminish the influence of the roughness elements on the transition length.

In Fig. 2, experimental points depicting the start and end of the transition region are shown for each of the three nose configurations over a range of wall-to-stagnation temperature ratios. No evidence of transition reversal is discernible over the range of wall temperature considered for any of the models; in fact, the data presented indicates that the transition Reynolds number is insensitive to the variation of wall-to-stagnation temperature ratio. A comparison of the data

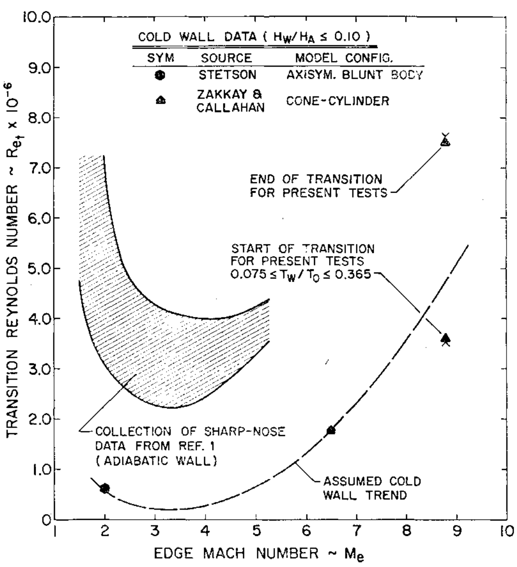

Fig. 3 Transition Reynolds number variation with local edge Mach number.

presented here with the compilation of data presented in Ref. 1 is given in Fig. 3, which depicts the variation of transition Reynolds number with local Mach number. The collection of data from Ref. 1 is for sharp-nose configurations having adiabatic-wall conditions. Cold-wall data of Stetson[6] and Zakkay,[7] also presented, form the basis of the assumed cold-wall trend depicted. The data obtained in the present investigation together with those of Refs. 6 and 7 corroborate the assumption that the transition Reynolds numbers increase with increasing edge Mach numbers.

Conclusions

On the basis of the data presented here, it can be concluded that transition reversal does not occur in the range of wall-to-stagnation temperature ratios of $0.075 \leq T_W/T_0 \leq 0.365$ and over the range of bluntnesses of $0.0 \leq r_N/r_B \leq 0.0572$ on a 5° semi-vertex-angle cone tested at a Mach number of 10. Of further interest are the significant effects of small amounts of nose bluntness on the observed transition Reynolds numbers, lengths of the transition regions, the insensitivity of transition Reynolds number to the variation of the wall-to-stagnation temperature ratio, and the apparent increase of transition Reynolds numbers with increasing edge Mach numbers.

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Nuclear Heating and Propellant Stratification

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Introduction

In order to obtain maximum vehicle performance for a nuclear system employing liquid hydrogen [$H_2(l)$], the vehicle must be designed to obtain optimized propellant utilization while minimizing system weight. A major problem encountered in this endeavor is caused by propellant heating.

Propellant heating has the undesirable effect of raising the temperature of the liquid to a value that is no longer acceptable for adequate main feed pump operation. To insure proper propellant utilization and to prevent pump cavitation, the propellant temperature distribution during pump operation must be accurately predicted.

The determination of the temperature history of the propellant leaving a nuclear vehicle tank involves many influencing variables. The problem is that of determining the flow field in the tank and the effect of mixing caused by density variations within the liquid. Recent experimental evidence indicates that bulk heating is an important effect in small tanks since the stratified layer in the conical section apparently mixes quite profusely.[1] For larger tanks, however, nuclear heating may contribute as much as 5–10% to the total increased heat content of a stratified layer.[2,3] Comparative information is based on severely simplified analytical models and inadequate test results.[2,4] This note suggests one method of analyzing stratification caused by nuclear bottom heating in large tanks and compares the results to bulk and inversion point calculations.

The system analyzed (see Fig. 1) is a closed cylindrical-cone-bottomed tank accelerating along its longitudinal axis and filled with liquid to some height. This liquid is subjected to a time- and position-varying group of heat fluxes; q_l = ullage, q = wall, and q_{up} = nuclear. The ullage temperature is above the saturation pressure corresponding to the liquid surface temperature. Wall-heat flux to the ullage is considered to be negligible, the ullage pressure being maintained by automatic control valving.

An approximate stratification solution is obtained by assuming a temperature profile in the stratified layer, the growth of which is determined by the evaluation of each of the three independent heat fluxes. The calculations follow those outlined in Ref. 5 with the inclusion of q_{up} in q.

Bottom Gravitational Convection (q_{up})

The turbulent gravitational convection mechanism appears to be one means of describing the upward flow of liquid from a tank heated by nuclear deposition within the bottom bulk. For a unified treatment of all kinds of convection which can take place in a gravitational field, the excess temperature must be replaced by the equivalent deficiency of density under that of the surroundings. But the sole relevant effect of a deficiency of density is to create a buoyancy force. The strength of a source of heat in a region of fluid is measured by the total heat output to the neighboring fluid in unit time. Similarly, the strength of a source of buoyancy is the total rate of release of buoyance to the nearby fluid. In the present analysis, each segment of tank bottom is viewed as a possible source of upward mass and energy flow. Boundary segment movement alters the conditions within neighboring segments. Through a balancing and summation routine, the warm mass that moves upward and joins the side-wall boundary

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