Boundary-Layer Transition Experiments on Pre-Ablated Graphite Nosetips in a Hyperballistics Range

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Nomenclature

B' = nondimensional blowing rate
k = surface roughness height
$k_{.5}, k_{.2}$ = 50, 20 percent of elements in distribution possess heights greater than this value
P = pressure
Re_θ = momentum thickness Reynolds number, $\rho_e V_e \theta / \mu_e$
R'_N = effective radius after ablation
S = arc length from stagnation point
T = temperature
t = time of flight from muzzle
V = velocity
θ = smooth-wall momentum thickness
μ = viscosity
ρ = density

Subscripts

e = at boundary-layer edge
TR = at transition point
w = at wall or surface
∞ = freestream

Theme

Re-entry vehicle nosetip thermal response and shape change, and thus vehicle survivability and accuracy, are strongly influenced by the onset and location of boundary-layer transition. Under the Passive Nosetip Technology (PANT) program[1] a data base was generated by exposing roughened, nonporous, thin-skin calorimeter models to supersonic wind-tunnel environments. These results, in conjunction with a mathematical extension to account for mass-addition (ablation) effects, were used to formulate a correlation for nosetip boundary-layer transition onset and location.[2] The objective of the present effort[3] was to test the validity of extrapolating this correlation to actual nosetip materials exposed to actual re-entry environments.

Contents

The algebraic form of the PANT transition parameter is shown on the ordinate of Fig. 1; it is comprised of a smooth-wall Re_θ, a relative roughness parameter (k/θ), and a term ψ' which models wall temperature (density) and mass-addition effects (a brief review of this correlation is presented in Ref. 3 for those readers unable to obtain Ref. 2). In application, a computed value of 255 must be reached or exceeded at the sonic point location; if this onset criterion is satisfied, then the transition zone is predicted to physically begin at the upstream surface point where this parameter attains a value of 215 (the location criterion).

The nosetip thermal response and shape change computer code of Ref. 4, updated for roughness effects on laminar heating,[5] was utilized to define the present experiment, i.e., to define specific ballistics-range trajectories on which the PANT parameter would cross its critical value of 255. Figure 1 summarizes post-test predictions for all trajectories actually flown. The predicted monotonic decay of the PANT parameter is a result of wall temperature increasing with time, a behavior observed in the original wind-tunnel experiments. In fact, observations of transition "offset" were used to formulate the onset criterion, i.e., transition-zone aft

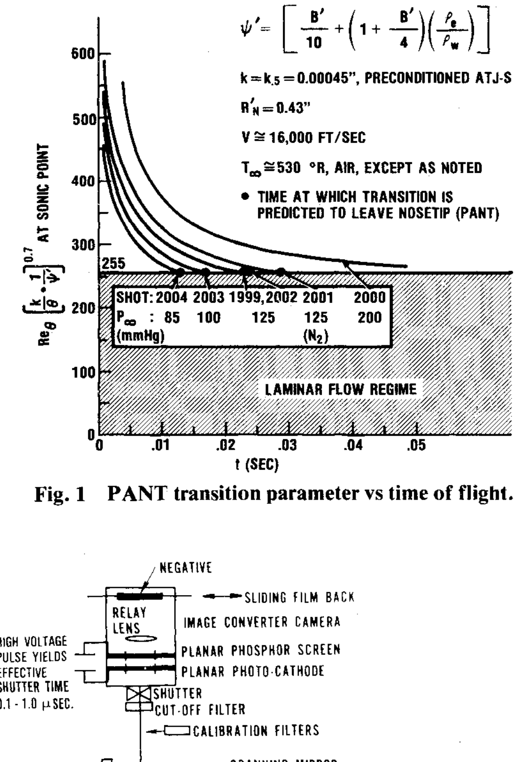

Fig. 1 PANT transition parameter vs time of flight.

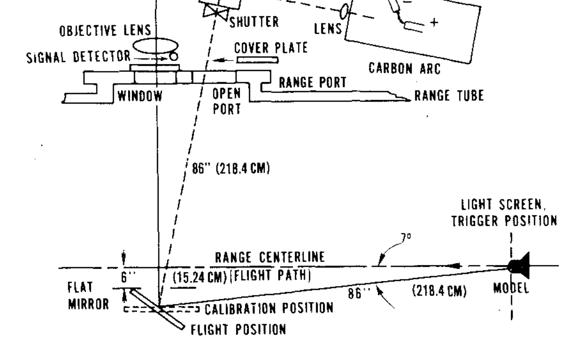

Fig. 2 Electro-optical pyrometer schematic.

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Index categories: Boundary-Layer Stability and Transition; Supersonic and Hypersonic Flow.

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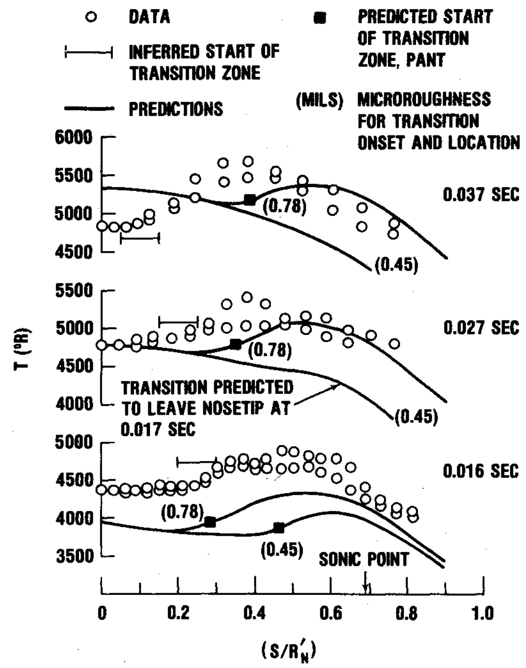

Fig. 3 T vs (S/R'_N), shot 2003.

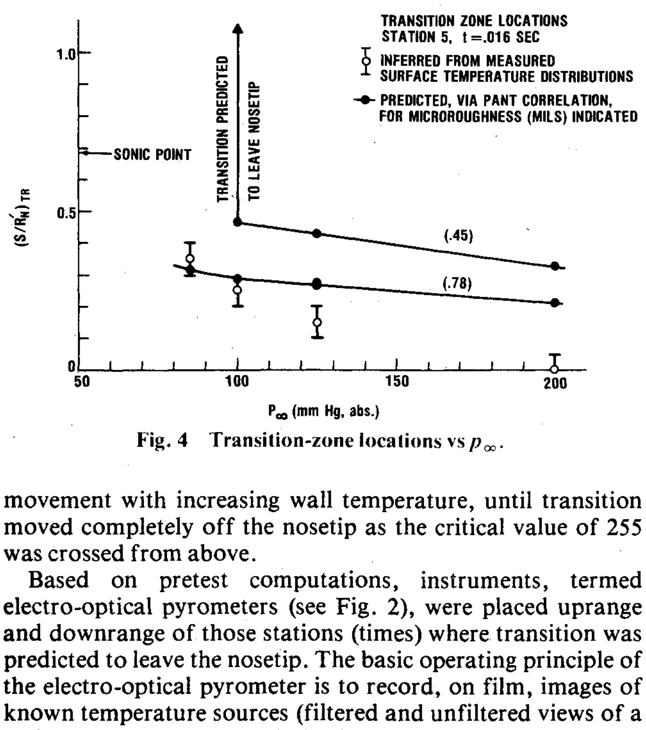

Fig. 4 Transition-zone locations vs p_∞.

movement with increasing wall temperature, until transition moved completely off the nosetip as the critical value of 255 was crossed from above.

Based on pretest computations, instruments, termed electro-optical pyrometers (see Fig. 2), were placed uprange and downrange of those stations (times) where transition was predicted to leave the nosetip. The basic operating principle of the electro-optical pyrometer is to record, on film, images of known temperature sources (filtered and unfiltered views of a carbon-arc electrode) and the image of an unknown temperature source (the nosetip); application of the resulting calibration relationship between source brightness temperature and film density allows temperature distributions on the unknown temperature source to be determined. All aspects of this experimental technique are discussed in detail in Ref. 3. The concept of detecting transition-zone presence and location from such measurements was defined by pre-test computations, i.e., predicted surface temperature distributions in the presence of a transition zone were noted to possess a definite change in slope at the physical beginning of the transition zone. Further, sufficient thermal response time was predicted to exist between measurement stations such that if the transition zone moved off the nosetip, then the occurrence of this event would be observable in measured distributions at downrange stations.

Initially polished ATJ-S graphite nosetips were ablated under a laminar-flow arc-jet environment in order to establish the material's characteristic surface microroughness prior to range flight. This microroughness distribution was characterized in detail and two values of surface roughness were selected from it for use in subsequent analyses of experimental results, $k_{.5}=0.45$ mils (the median value) and $k_{.2}=0.78$ mils (the twenty percentile value, arbitrarily chosen as representative of the "significant" roughness elements). Pre-ablated nosetips were mounted on flare-stabilized models and launched at hypersonic velocities utilizing fully enclosed sabots. This latter technique served to shield the nosetip from heat transfer within an undefined launch-tube environment, thereby ensuring a known uniform initial temperature distribution throughout the graphite upon its exposure to the freeflight environment.

Tests were conducted at a nominal Mach number of 14, at stagnation pressures from ~ 30 to ~ 70 atm and stagnation enthalpies ~ 5000 Btu/lbm. Resulting sonic point values of (k/θ) and (T_W/T_e) were ~ 1 and $\sim .4$, respectively, at times of predicted transition offset, and thus were within regimes of the original PANT data base.

Figures 3 and 4 show sample results obtained for flights through air, i.e., in the presence of mass addition. Both the presence and location of a transition zone were clearly evident from measured surface temperature distributions. Levels of surface temperature were well predicted by the updated code[4,5]; predicted shapes of these distributions were, however, strongly dependent on predicted transition zone presence and location.

Observed transition-zone locations were more closely approximated by predictions generated with $k=k_{.2}$, indicative of the dominant role played by those "largest" or "most significant" roughness elements in an ablated surface microroughness distribution. However, significant discrepancies were noted between predicted and observed transition-zone movement with increasing wall temperature and freestream Reynolds number. Experimental results showed that the transition zone did not move aft with increasing wall temperature as predicted by the PANT correlation; rather a slight forward progression was noted. Further, present results showed a more rapid forward progression of the transition zone with increasing Reynolds number (i.e., P_∞), to the immediate vicinity of the stagnation point, versus PANT. These observations indicated a destabilizing influence of mass addition (ablation) in the presence of roughness, in contradiction with the stabilizing trend predicted by PANT.

It remains to obtain and correlate an expanded data base for boundary-layer transition on real nosetip materials in actual re-entry environments. Present experimental techniques have been shown well suited to this task.

References

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