Preliminary Note on a Correlation of Boundary-Layer Transition Results on Highly Cooled Blunt Bodies

By Richard J. Wisniewski

Abstract

Transition data on highly cooled blunt bodies are correlated in terms of the ratio of wall to local-stream enthalpy, Reynolds number based on displacement thickness, and location of transition. The proposed correlation, although not sensitive enough to predict the exact location of transition does predict the enthalpy ratio below which very early transition on blunt bodies is expected. The correlation is not altered by moderate amounts of surface roughness; however, the location of transition may well be affected by roughness.

Index Headings

Flow, Laminar 1.1.3.1
Flow, Turbulent 1.1.3.2
Heat Transfer, Aerodynamic 1.1.4.2
PRELIMINARY NOTE ON A CORRELATION OF BOUNDARY-LAYER TRANSITION RESULTS ON HIGHLY COOLED BLUNT BODIES

By Richard J. Wisniewski

SUMMARY

Boundary-layer transition data on highly cooled blunt bodies are correlated in terms of the ratio of wall to local-stream enthalpy, Reynolds number based on displacement thickness, and location of transition. The proposed correlation is not sufficiently sensitive to predict the exact location of transition, but it does predict the enthalpy ratio below which very early transition on blunt bodies is expected. The correlation is not altered by moderate amounts of surface roughness; however, the location of transition may well be affected by roughness.

INTRODUCTION

The problem of transition on blunt, highly cooled bodies in hypersonic flow has been one of particular concern ever since Allen and Eggers (ref. 1) first proposed high-drag configurations for atmospheric reentry of ballistic missiles. In recent years, a respectable amount of experimental transition data on such bodies has been obtained; in fact, the Lockheed X-17 reentry test vehicle program was initiated for the specific purpose of obtaining transition data under conditions simulating actual reentry of an intercontinental ballistic missile. The Pilotless Aircraft Research Division (PARD) of the NACA Langley laboratory and the Hypersonic Test Vehicle (HTV) program of Aerophysics Development Corporation also have obtained a substantial amount of transition data on cooled blunt bodies.

As a whole, these data demonstrate two rather disturbing facts: First, transition on a cooled blunt body occurs at very low Reynolds numbers; and second, the results obtained under apparently similar conditions are often vastly different and quite contradictory.

Correlations of these results were attempted by Stewart and Donaldson (ref. 2) and by Tellep and Hoshizaki (ref. 3). The correlation given in reference 3 indicates that surface roughness is exceedingly important.
and that transition can be delayed by keeping the body very smooth; however, this correlation was not wholly successful for all X-17 reentry data. In many instances, it failed completely when transition during the ascending portion of the X-17 trajectory was considered or when data other than the X-17 data were used.

Stewart and Donaldson's correlation (ref. 2) is plotted as wall to local-stream enthalpy ratio against transition Reynolds number based on momentum thickness, with body position as a parameter. In this representation, surface roughness did not significantly alter the correlation. This correlation was quite adequate for all X-17 reentry data, but it does not satisfactorily correlate the X-17 exit data or portions of the HTV and PARD data. Reference 2 also implies, as was suggested in reference 4, that the early transition on blunt bodies and the transition reversal on slender bodies (ref. 5) are essentially the same phenomenon.

The purpose of this report is to present a new correlation of the aforementioned data. Not all of the consequences or implications of this correlation are understood as yet, and contradictory evidence may exist. However, in view of the urgent need for a method of predicting transition on highly cooled blunt bodies, it was felt that distribution of this preliminary report is warranted.

SYMBOLS

The following symbols are used in this report:

- \( A \) cross-sectional (frontal) area of body, sq ft
- \( C_D \) body drag coefficient
- \( d \) body diameter, ft
- \( H \) form factor, \( S^* / \theta \)
- \( H_{tr} \) low-speed form factor (ref. 7)
- \( h \) enthalpy
- \( k \) roughness height, microin.
- \( M \) Mach number
- \( \dot{\rho} e^{\mu e V e^{-0} ds} \)
- \( \dot{Re} \) integrated Reynolds number, \( \frac{\int_0^s \rho e^{\mu e V e^{-0} ds}}{\rho e^{\mu e V e^{-0} ds}} \)
Re_{D,l} \quad \text{free-stream Reynolds number based on body diameter,} \quad \frac{\rho_l V_1 d}{\mu_1}

Re_{\delta^*} \quad \text{displacement-thickness Reynolds number,} \quad \frac{\rho_e V_e \delta^*}{\mu_e}

Re_{\theta} \quad \text{momentum-thickness Reynolds number,} \quad \frac{\rho_e V_e \theta}{\mu_e}

r_n \quad \text{nose radius, ft}

r_0 \quad \text{axial radius, ft}

s \quad \text{surface distance, ft}

T \quad \text{total temperature, ^\circ R}

t \quad \text{time, sec}

V \quad \text{velocity, ft/sec}

W \quad \text{weight, lb}

\alpha \quad \text{angle of flight path to horizontal, deg}

\beta \quad \text{pressure-gradient parameter}

\gamma_{\text{eff}} \quad \text{effective ratio of specific heats (given as } \gamma_e \text{ in ref. 3)}

\delta^* \quad \text{displacement thickness, ft}

\theta \quad \text{momentum thickness, microin.}

\theta_c \quad \text{cone half-angle}

\mu \quad \text{viscosity}

\rho \quad \text{density}

\Phi_T \quad \text{angle between normal to body surface and free-stream direction}

Subscripts:

e \quad \text{local free-stream conditions at edge of boundary layer}

TR \quad \text{transition conditions}

w \quad \text{conditions at wall}
stagnation conditions behind shock
free-stream conditions ahead of shock

REDUCTION OF DATA

The Location of Transition

The present correlation uses data obtained on hemispheres, hemisphere-cones, and slightly blunted cone-cylinders; all of the data used in this report are listed in table I. Transition locations during the X-17 test vehicle reentry and the PARD and HTV flight tests are given in reference 2. During the exit phase of the X-17 R-9 flight (ref. 3) transition was determined from a plot of the heating rates. However, the exact time of transition was difficult to determine because of the low heating rates and uncertainties in analyzing the data. Hence, the transition points listed in table I for the exit phase of the R-9 flight are subject to question. Transition locations for the NACA Lewis laboratory data are given in references 5 and 6.

Displacement-Thickness Reynolds Number

In addition to the quantities presented in reference 2, the Reynolds number based on displacement thickness is needed for the present correlation. This was obtained from the momentum-thickness Reynolds number as follows:

\[ \text{Re}_* = H \text{Re}_\theta \]  

where

\[ H = \frac{\delta_*}{\theta} = \frac{T_0}{T_e} (H_{tr} + 1) - 1 \]

\[ \text{Re}_\theta = 0.664 (Re)_1^{1/2} \]

The function \( H_{tr} \) depends on the pressure-gradient parameter \( \beta \) and is obtained from reference 7. Curves of \( H_{tr} + 1 \) as a function of \( \beta \) and the wall to total enthalpy ratio of \( h_w/h_0 \) are plotted in figure 1. The value of \( \beta \) for the angular position \( \varphi_T \) on a hemisphere or hemisphere segment was approximated by the values listed in the following table:

<table>
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<th>( \varphi_T )</th>
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<th>20</th>
<th>45</th>
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<td>0.75</td>
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Along conical bodies, $\beta$ equals zero. The temperature ratio $\frac{T_0}{T_e}$ was approximated by

$$\frac{T_0}{T_e} \approx 1 + \frac{\gamma_{\text{eff}} - 1}{2} \frac{M_e^2}{h_0}$$

where the effective specific-heat ratio $\gamma_{\text{eff}}$ was taken as 1.40 for $M_e < 5$ and was varied as suggested in reference 3 for $M_e > 5$. Local external Mach numbers $M_e$ were found with the aid of modified Newtonian flow theory and perfect gas relations. Computed values of $\text{Re}_\theta^*$ are also given in table I, in which many of the values are of slide-rule accuracy only.

**CORRELATION OF DATA**

**Transition Reynolds Number Based on Displacement Thickness**

The correlations of blunt-body transition data proposed in the past were generally based on momentum-thickness Reynolds number. A typical plot of wall to local-stream enthalpy ratio as a function of the transition momentum-thickness Reynolds number $\text{Re}_{\theta,\text{TR}}$ is shown in figure 2. Although this correlation may be satisfactory for any given set of transition points, it is not adequate when data from many sources are compared. In particular, it is apparent that the same value of $\text{Re}_{\theta,\text{TR}}$ is obtained for an appreciable range of enthalpy ratios.

There is no analytical reason why transition should be described by the momentum thickness. Some other length that can describe the growth or shape of the boundary layer may be more satisfactory insofar as transition is concerned. Furthermore, if some arbitrarily chosen length can be used successfully in correlating the data presented in figure 2, then that length must depend on temperature. The displacement thickness is such a length.

In figure 3(a), the X-17 reentry data obtained on hemispheres are shown on a plot of wall to local-stream enthalpy ratio against transition Reynolds number based on displacement thickness. These data are well correlated, and it is apparent that surface finishes from less than 2 microinches to 30 microinches are represented by a single curve. From figure 3(b) the same conclusions can be drawn for reentry data obtained on the GE 3.1 shape.

In figure 4, the X-17, PARD, and HTV data of reference 2 and the NACA Lewis laboratory results of reference 6 are presented in terms of $\text{Re}_{\theta^*,\text{TR}}$. Only the results obtained on segments of hemispheres are
included in figure 4; all data points shown in figure 2 (with the exception of three points yielding negative displacement thickness) are represented in this figure. It is apparent that the correlation is an improvement over the $Re_{\theta,TR}$ correlation (fig. 2) but still is far from adequate. A careful examination of the individual points plotted in figure 4 indicates that, as suggested by Stewart and Donaldson (ref. 2), body position also affects transition. It is rather evident, however, that the results presented in terms of $Re_{\theta,TR}$ are not sensitive to moderate amounts of roughness.

Also shown in figure 4 are the transition-reversal data obtained on a slender, slightly blunted cone-cylinder (ref. 5). Although body position again enters into these results, the trend of the blunt-body transition data and the slender-body reversal data appears to be similar.

Modified Displacement-Thickness Reynolds Number

In figure 5, the effect of body position on transition is taken into account by dividing the abscissa by $s/r_n$, which, for a hemisphere, corresponds to the angular position along the nose. All available X-17 reentry data and PARD, HTV, and NACA Lewis data on cooled hemispheres are included in figure 5; surface finishes up to 30 microinches are also represented. Excluded are the reversal data that were obtained on a different type of body and the three points for which $Re_{\theta,TR}$ is negative. Considering the normal amount of scatter present in any transition data, the correlation appears to be good. The solid line in figure 5 will be discussed in a subsequent section.

The effect of nose shape as indicated in the X-17 reentry data obtained on hemispheres and on the GE 3.1 shape is shown in figure 6. For the GE shape, $s$ is again the distance to transition, while $r_n$ is the radius of the hemispherical nose segment. Laminar flow is sustained to slightly lower enthalpy ratios for the GE shape than for the hemisphere.

**DISCUSSION OF CORRELATION**

**Application to Previously Contradictory Results**

Wind-tunnel transition results obtained on a cone capped with a 1.40-inch-diameter spherical segment were reported in reference 8. The enthalpy ratios were of the same order as those for the PARD and HTV flights, and the momentum-thickness Reynolds number at the sonic point was about 375. These conditions caused transition in flight; yet the flow on the entire spherical segment in the tunnel tests was always laminar. However, when these results are examined in terms of the
present correlation, it is apparent that the flow should have been laminar. The solid line in figure 5 represents the values of $\frac{h_w}{h_e}$ and $\left(\frac{Re_5}{s/r_n}\right)$ on the spherical segment of the wind-tunnel model. This line is well within the laminar region of the present correlation.

Results that hitherto have been unexplained by the correlations suggested in references 2 and 3 are the X-17 exit data obtained during the R-9 flight. Under exit conditions, the enthalpy ratio was relatively high and the free-stream Mach number was low; this yielded transition results similar to those of the PARD flights. Significant portions of the R-9 trajectory are reproduced in figure 7 in terms of the present correlation. It should be noted that the flow is turbulent only in the vicinity of the correlation curve, both in the exit and in the reentry phase of the trajectory. The fact that the exit data do not agree as well with the correlation as the reentry data can be attributed to the uncertainties present in the exit flight data (see ref. 3 for a detailed discussion). In fact, if possible time discrepancies are considered, much better agreement is possible between the correlation and the exit data.

The Prediction of Transition

It has been demonstrated that all available transition data on cooled hemispheres can be correlated in terms of $\left(\frac{Re_8}{s/r_n}\right)_{TR}$. The question naturally arises as to how successful this correlation is in predicting transition. Unfortunately, in many cases it is not possible to determine the exact location where transition will occur, but generally it is possible to predict the lowest possible enthalpy ratio where laminar flow can be expected.

If, at a given time of flight, all points of a hemisphere lie above the correlation curve, the flow should be laminar. If, on the other hand, all points fall below the curve, the flow should be turbulent. However, if points on the forward portion of the body approach the correlation curve (without crossing it) while the rearward points do not, the flow over the entire body still may be laminar. This observation is illustrated with the aid of the following sketch of an X-17 trajectory:
In this sketch the solid line represents the correlation curve, and the symbols represent various body positions at a given time \( t \) during re-entry. At the times \( t = 0 \) and \( t = 1 \), the entire body is above the correlation curve, and transition should not, and does not, occur. At \( t = 2, 3, \) and \( 4 \), the forward portions of the body approach the correlation curve, and transition might be expected. Yet, in flight, transition did not occur until \( t = 5 \), when the entire hemisphere fell along the correlation curve.

As pointed out earlier, the correlation is not sensitive to moderate amounts of surface roughness. This fact, however, does not imply that the location of transition on the nose portion of the body is independent of roughness. The aforementioned sketch indicates that, at the time when transition occurred, all stations along the body fell on the correlation curve; hence, the location of transition could be altered by roughness and still fall along the correlation curve. This discussion does not preclude the possibility that a larger amount of roughness could alter the correlation curve.

In spite of the fact that the proposed correlation cannot be used to predict the exact location of transition, its implications concerning the state of the boundary layer on the reentry body of a 5500-mile-range ballistic missile are serious. Presented in figure 8 in terms of the correlation parameters is the trajectory of a 5500-mile-range
ballistic missile with \( \frac{W \sin \alpha}{C_p A} = 133 \). The calculation has been made for the 20° and 80° stations on a 6-foot-diameter hemisphere at a constant wall temperature of 500° R. In order to determine the effect of temperature level, conditions at the 20° station also have been computed for a constant wall temperature of 2000° R. An examination of figure 8 shows that the enthalpy ratio on such a body will, at times, be well below any of the enthalpy ratios thus far obtained. Therefore, based on an extrapolation of the present correlation, transition is to be expected on the body during a large portion of the reentry flight. In drawing this conclusion, however, it must be realized that the extrapolation of transition results always is dangerous, and that the present correlation may not really apply to very low enthalpy ratios of ballistic missile reentry. However, the correlation should apply at the higher enthalpy ratios that occur at altitudes corresponding to peak heating rates. Moreover, although it is recognized that surface roughness may affect the location of transition, it is quite evident from figure 8 that transition cannot be avoided by making a body exceedingly smooth.

**CONCLUDING REMARKS**

A correlation of transition on highly cooled blunt bodies has been presented. The significant parameters in this correlation are the ratio of wall to local-stream enthalpy, displacement-thickness Reynolds number, and location of transition. This correlation is successful in explaining previously contradictory transition results. However, although the correlation can be used to predict the wall to local-stream enthalpy ratio below which turbulent flow is expected, it cannot be used to predict the exact location of transition on a body. Specifically, the following conclusions may be drawn:

1. Decreasing the wall to local-stream enthalpy ratio promotes early transition on blunt bodies. The early transition on blunt bodies and the transition-reversal phenomenon observed on slender bodies exhibit similar trends.

2. The transition correlation is insensitive to moderate amounts of surface roughness; this indicates that the enthalpy ratio necessary to promote transition anywhere on the body is unaffected by moderate roughness. However, the location of transition, once it does occur, may be affected by roughness.

3. The proposed correlation suggests that transition will occur on a blunt body of a 5500-mile-range intercontinental ballistic missile during a large portion of the reentry flight.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, October 15, 1957
REFERENCES


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| 5        | Cone-cylinder  | 85.25         | 3.20    | 3.10  | 0.98  | 0.451 | 334        | 747  | 12          | 0.094    | 0.01    | NACA Lewis wind-tunnel tests |
|          |                | 85.25         | 3.20    | 3.10  | 0.98  | 0.451 | 334        | 747  | 12          | 0.094    | 0.01    | NACA Lewis wind-tunnel tests |
|          |                | 75.0          | 1.17    | 1.71  | 1.09  | 1.89  | 1.22    | 1.28  | 2.58        | 1.14     | 0.01    | NACA Lewis wind-tunnel tests |
|          |                | 90.0          | 1.17    | 1.69  | 1.22  | 1.89  | 1.35    | 1.28  | 2.58        | 1.14     | 0.01    | NACA Lewis wind-tunnel tests |
|          |                | 135.0         | 1.17    | 1.69  | 1.22  | 1.89  | 1.35    | 1.28  | 2.58        | 1.14     | 0.01    | NACA Lewis wind-tunnel tests |

| 3        | Hemisphere     | 50            | 0.873   | 2.67  | 7.70  | 0.875 | 668        | 824  | 943         | 30       | 4.5     | X-17 R-9 Exit data (10 to 20 sec turbulent flow) |
Figure 1. - Variation of form factor function with pressure gradient and enthalpy ratio.
Figure 2. - Boundary-layer transition on hemispheres, as obtained in free flight.
Figure 3. - Transition on X-17 research test vehicle during reentry.
Figure 3. - Concluded. Transition on X-17 research test vehicle during reentry.
Figure 4. - Attempted correlation of hemisphere data in terms of displacement-thickness Reynolds number.
Figure 5. - Correlation of transition data obtained on hemispheres.
Figure 6. - Variation of correlation parameter on X-17 reentry body hemisphere and GE 3.1 shape.
Correlation parameter, \( \frac{\text{Re}_{\text{c}}}{\text{In}} \)

Figure 7. - Conditions at 90° position during exit and reentry of X-17 R-9 flight.
Figure 8. - Conditions at 20° and 80° positions during reentry of a 6-foot-diameter hemisphere ballistic missile (trajectory obtained from ref. 9). \[
\frac{\sqrt{\sin \alpha}}{CpA} = 133.
\]
Unclassified when detached from rest of report

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