Prediction Techniques for Three-Dimensional Shock-Wave/Turbulent Boundary-Layer Interactions

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The design of efficient flight vehicles for sustained operation at high Mach numbers requires the understanding of the aerodynamic heating generated in interfering flowfields. The three-dimensional shock-wave/turbulent boundary-layer interaction is typical of such flowfields and is one that produces severe localized heating. The Air Force Flight Dynamics Laboratory has conducted an extensive experimental investigation into such interactions. This investigation began with a simple fin/flat-plate model through which a substantial data base was obtained for Mach numbers of 3 to 6 and Reynolds numbers of 1.5×10^6 to 28.0×10^6/ft. The study then was extended to a fin/ogive-cylinder model. This paper presents the correlation of peak aerodynamic heating in the interaction region as derived from the fin/plate model and the methods by which the correlation is applied to the missile configuration at arbitrary pitch and roll attitudes. This paper also documents the observed effects of boundary-layer tripping on peak heating levels. It was found that the process of tripping significantly reduces the peak heating magnitude. The implications of this on experimental and vehicle design are yet to be explored.

Nomenclature

M = Mach number
n_p = exponent in peak pressure correlation
n_{st} = coefficient in peak heating correlation
P = pressure
St = Stanton number
X = distance in direction of freestream
Y = distance normal to freestream
Z = distance normal to model surface
α_F = fin deflection angle
α_M = missile model angle of attack
β = missile fin roll angle
δ = boundary-layer thickness at fin apex
θ = fin shock-wave angle
ϕ = angle to the peak heating location
ψ = inviscid streamline turning angle

Subscripts

calc = calculated value
exp = experimental value
E = boundary-layer edge condition
L = local condition
pk = peak value
T = total or stagnation value
U = undisturbed value
∞ = freestream value

Introduction

In the past several years, there have been a series of technical papers and reports dealing with data and analyses of data measured within a region of three-dimensional shock-wave/turbulent boundary-layer interaction. These interactions are typically those caused by the disturbance of a basic flowfield by a fin shock. The works of Vas,[1] Token,[2] Neumann and Burke,[3] and Neumann and Token[4] are representative of this base information. All of these reports and a substantial amount of unreported data are the result of an intensive investigation by the Air Force Flight Dynamics Laboratory (AFFDL) to understand the levels and distributions of aerodynamic heating about complex flight vehicles. This investigation was a complimentary effort blending the fundamental approach of the academic community, the practical engineering of an airframe contractor, and empiricism necessary to arrive at techniques that could be made available for the preliminary design of new systems. Elements of this overall program have been presented. It is the intent of this paper to discuss the overall program and to place the preceding papers into the proper perspective. The work is empirical in nature (clearly all papers dealing with this subject in the past have been empirical), but we trust that the utility of this work will offset the limitations of empirical correlations which persist despite the laborious flowfield mapping effort of Vas and co-workers.[1]

Data Base

Table 1 indicates the data that were taken during this technical effort. In all cases, the data were taken within a fully developed turbulent boundary layer. The majority of these

Table 1 Data base

MACH NO.	RUNNING LENGTH TO FIN APEX–IN.	REYNOLDS NO. PER FOOT$\times10^{-6}$	REFERENCE	SYMBOL
2.95^b		19.2	1	⬭
3.0^a	31.0	3.5	5	▽
3.01^a	10.5	3.24	4	▽
$3.71^{a,b}$	31.0	1.5	2	✣
$3.71^{a,b}$	31.0	3.5	2	✣
3.75^a	10.5	3.28	4	▷
4.5^a	10.5	3.23	5	△
4.75^a	19.0	7.76	5	□
5.04^a	19.0	7.38	5	○
5.85^a	8.5	11.0	7	☆
5.85^a	8.5	28.0	7	☆
5.95^d	42.0	5.0	6	FILLED
6.05^c	17.8	3.48	3	FLAGGED

[a] Fin/plate. [b] Fin/tunnel sidewall. [c] Tripped fin/plate. [d] Tripped ogive/cylinder.

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data were taken without resorting to tripping techniques to induce turbulent flow. The underlying approach in developing this data base was 1) to exercise all parameters of the problem in order to be assured that the resultant correlations are valid within the domain of the data; 2) to overlap data from facility to facility to reduce the possibility of tunnel perculiar effects; and 3) to adequately cover the Mach number range of interest from Mach 3 to Mach 6. Table 1 indicates that most of the data are on the fin/plate model, as our intent was to evaluate phenomena on a more simple model and then to contrast these data with more complex fin/ogive-cylinder test data.

Clearly, in the space available here it is not possible to cover the details of each test program. The reader is referred to the indicated reports for such details and to the two summary reports on this program by Hayes[5] and Neumann.[6]

Fin/Plate Interaction

Characteristics of the fin/plate interaction were addressed by Neumann and Token[4] and will be reviewed briefly. Figure 1 indicates the flow model, the typical heating and pressure distributions, and the characteristic oil flow tracing of the three-dimensional interaction. The interaction process extends outboard of the fin-induced shock wave, with the portion external to the shock wave in a turbulent separated state that is predictable by two-dimensional methods. High localized heating occurs inboard of the fin-induced shock wave where the flow is dominated by vorticity. This is the subject of the current discussion.

The magnitude of the peak pressure varies with the shock strength $M_L \sin\theta$ and with the nondimensional distance from the fin apex X/δ. Correlation of these data indicate that empirically this relationship is represented by

$$P_{pk}/P_u = (M_L \sin\theta)^{n_p}$$

where n_p is a function of X/δ, as shown in Fig. 2. Note that the oblique shock pressure exponent is in reasonable agreement with the data; however, the experimental data consistently overshoot oblique shock pressure levels for large values of the nondimensional distance X/δ.

Corresponding values of the peak heating ratio were found by systematically varying the shock strength (by varying the wedge angle) during a particular experiment and then cross-plotting the derived curve fit as a function of X/δ. The empirical equation for the peak heating ratio is

$$St_{pk}/St_u = (M_L \sin\theta - 1)\, n_{St} + 0.75$$

where n_{ST} is a function of X/δ given in Fig. 3. Figure 4 presents the peak heating data as a function of X/δ for several values of $M_L \sin\theta$.

There are several features of this correlation to point out. First, note that the heating in the interaction increases with X/δ. Note also that for $X/\delta > 3$ the heating is greater than would be predicted using pressure interaction theory[3] alone. All data presented in this figure are for untripped fin/plate experiments.

Fin/Ogive-Cylinder Interaction

Placing a wedge cross-sectional fin on an ogive-cylinder and allowing the model to pitch and roll in an arbitrary manner introduces another degree of complexity into the prediction of the resultant levels of aerodynamic heating. This section of the paper will discuss the correlation of such data.

A test program was conducted in Tunnel B at the Arnold Engineering Development Center to measure the heating resulting from the interaction of fins on an ogive/cylinder as shown in Fig. 5. The model was large and resulted from our interest in obtaining detailed information in turbulent

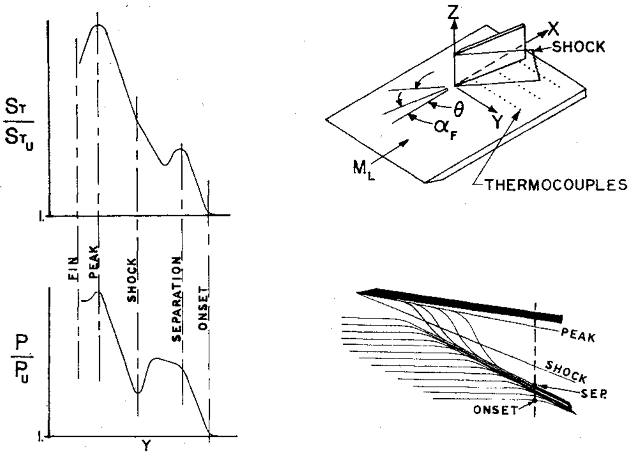

Fig. 1 Basic interaction characteristics.

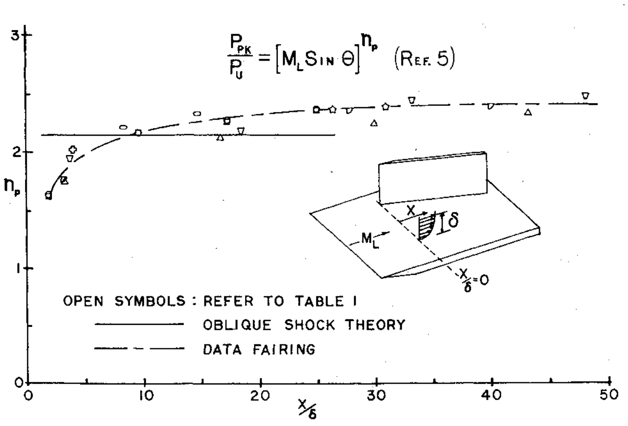

Fig. 2 Exponent in peak pressure correlation.

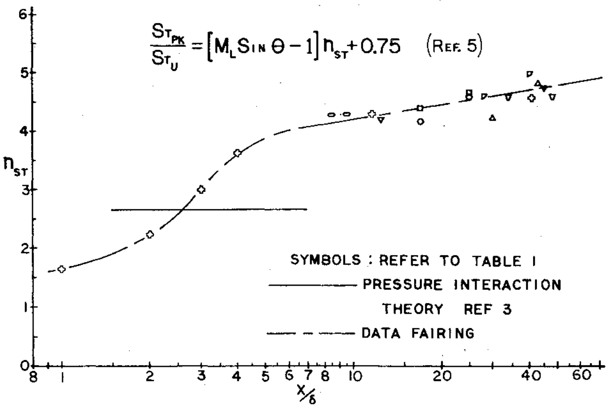

Fig. 3 Coefficient in peak heating correlation.

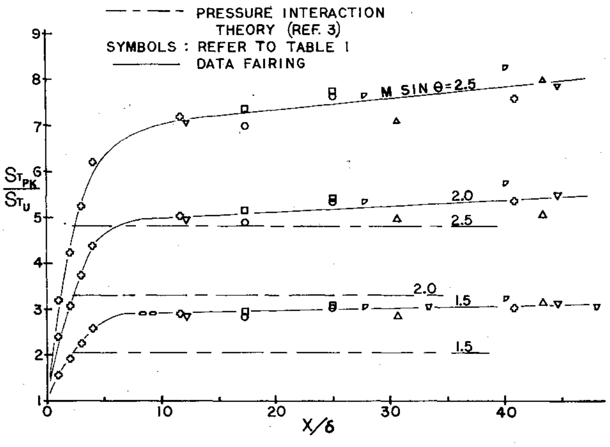

Fig. 4 Peak heating on fin/plate model.

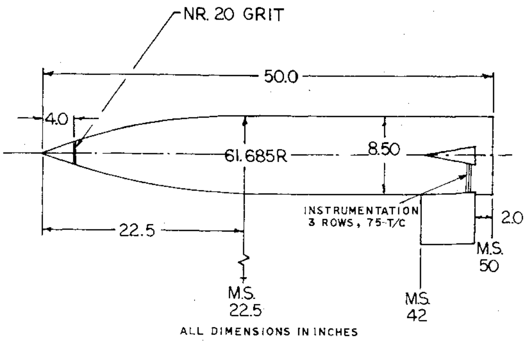

Fig. 5 Ogive/cylinder model.

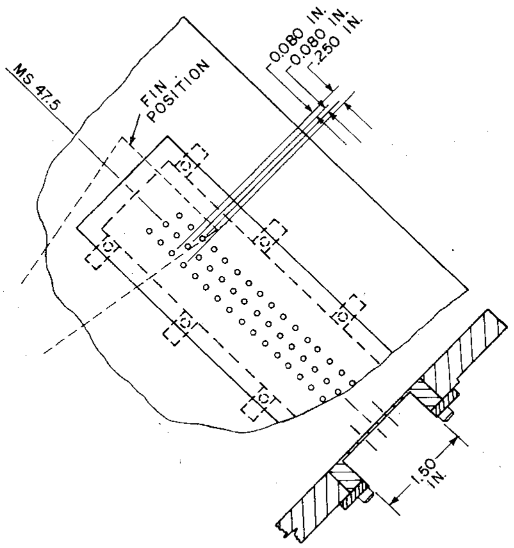

Fig. 6 Ogive/cylinder instrumentation.

boundary layers. There were 75 thermocouples (one every 1.2 deg) placed in three rows centered at station 47.5. These gages, shown in Fig. 6, were 5.5 in. downstream of the fin apex. Data were taken at angles of attack of 0, 4, 8, and 12 deg and with fin roll angles of 0, 30, 60, 90, and 120 deg with respect to the lower surface (compression) centerline. The angle of attack was limited to 12 deg by a flow disturbance produced by the model injection doors at the floor of the tunnel. At pitch angles greater than 12 deg, the aft end of the model intersected this disturbance and invalidated the data.

Correlation at Zero Angle of Attack

Figure 7 indicates that the ogive/cylinder interaction data contrasted with comparable fin/plate data taken in Ref. 7. The correlation procedure of Hayes[5] for the fin/plate data also is shown. Although the two sets of data were at equivalent freestream Mach and Reynolds numbers, there were obviously parameters that were not matched and that dominated the data. One such parameter was the nondimensional distance X/δ. A subsequent test entry indicated that X/δ for the ogive/cylinder data was 8.73 compared to 31 for the fin/plate data and that the local Mach number was 5.6 compared to 5.85 for the fin/plate data. However, the aggregate change introduced by these refined measurements did not affect the correlation, as noted in Fig. 7 by the correlation line for Mach 5.6. One final element was different. The ogive/cylinder model was, of necessity, tripped to achieve a fully turbulent interaction. Sufficient heat-transfer data were taken on the ogive/cylinder to demonstrate that the flow was turbulent at the fin location. The Stanton number times the turbulent distribution parameter $X^{0.2}$ was plotted as a function of model station, as shown in Fig. 8. It was observed that 1) the turbulent parameter is constant with X, indicating that there is no upstream history, and 2) the turbulent theory level is attained at the fin location.

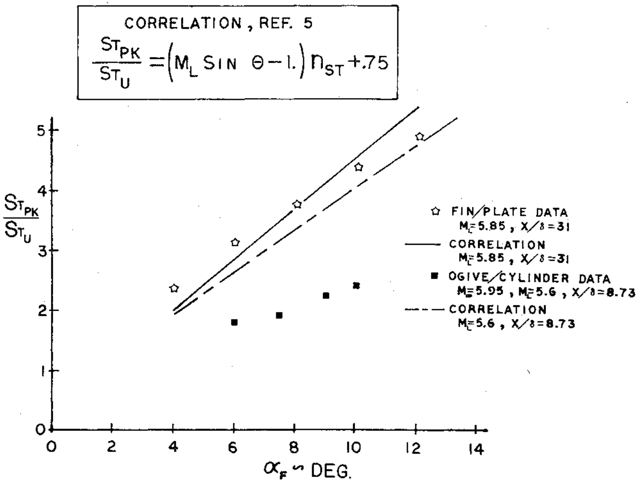

Fig. 7 Peak heating on ogive/cylinder and untripped fin/plate.

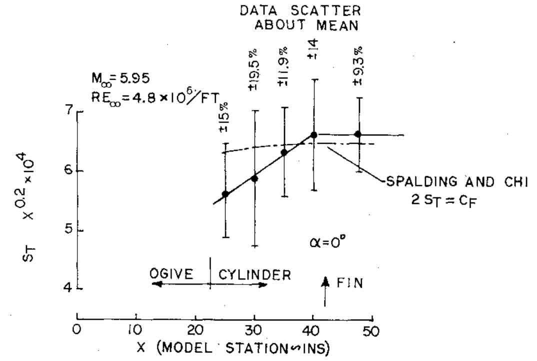

Fig. 8 Ogive/cylinder undisturbed heating.

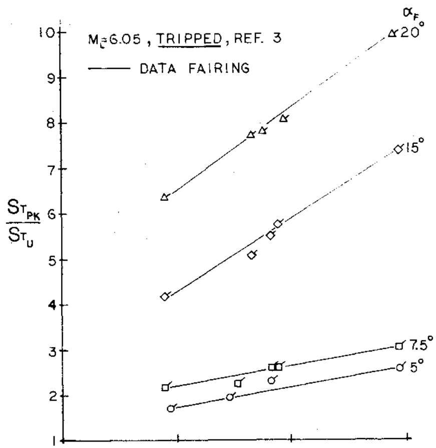

Fig. 9 Peak heating on tripped fin/plate.

There was only one set of fin/plate data which was tripped. These data,[3] shown in Fig. 9, were cross-plotted for an $X/\delta = 8.73$ together with the ogive/cylinder data in Fig. 10. Excellent agreement clearly is observed. Also plotted on this figure is the pressure interaction theory, which is also in excellent agreement with the data.

This exercise demonstrated that at this station the tripped ogive/cylinder data may be predicted by the pressure interaction theory and also agree with tripped fin/plate data. It also strongly implied that we had encountered a case where

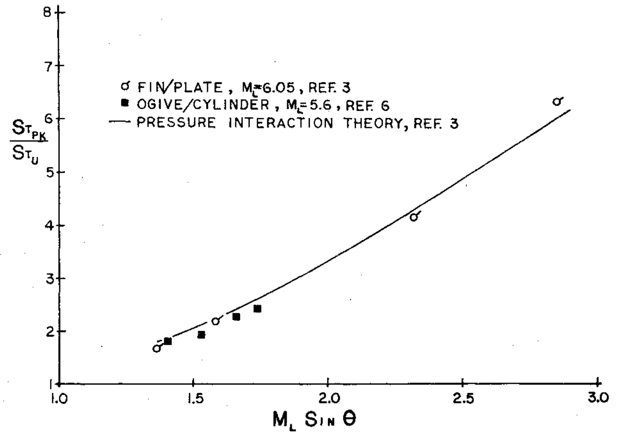

Fig. 10 Peak heating on ogive/cylinder at zero pitch and roll.

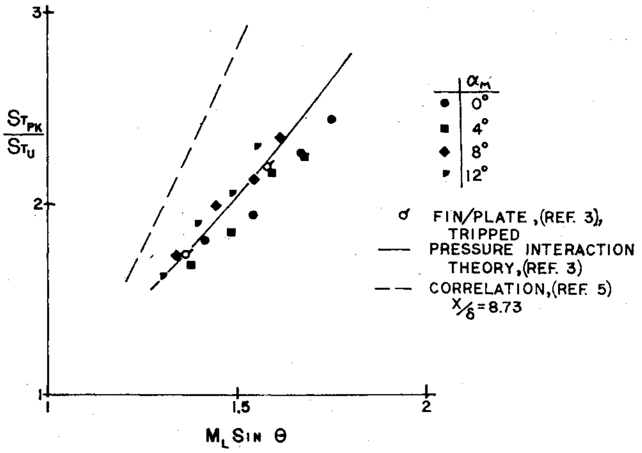

Fig. 13 Peak heating on ogive/cylinder at arbitrary pitch and zero roll.

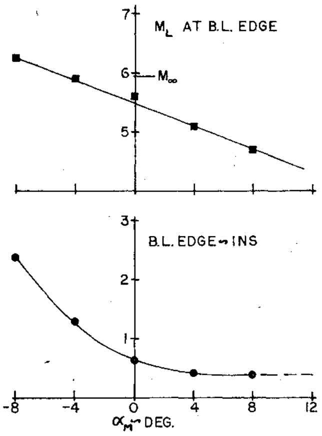

Fig. 11 Stagnation line properties on pitched ogive/cylinder at fin apex.

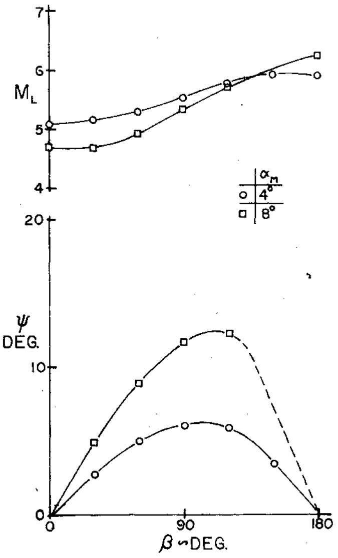

Fig. 14 Inviscid flow properties at fin apex.

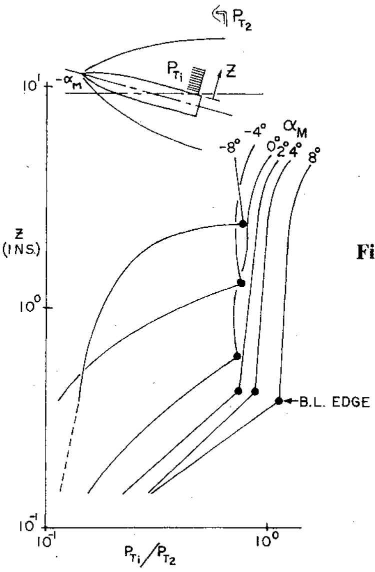

Fig. 12 Pitot pressure profiles.

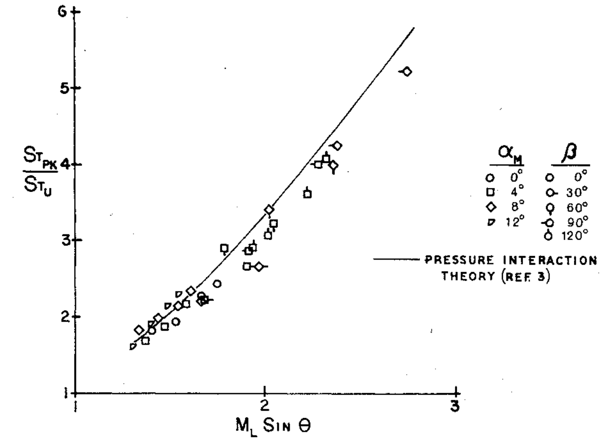

Fig. 15 Peak heating on ogive/cylinder at arbitrary pitch and roll.

tripping influenced downstream measurements in a drastic manner. The three-dimensional peak heating levels had, in fact, dropped to those predicted for a two-dimensional interaction as a result of tripping the boundary layer.

Correlation at Angle of Attack, Zero Roll

Let us now consider the somewhat more general case of the interaction produced by a fin on the lower compression surface centerline. For this case, the Mach number at the fin leading edge decreases as the ogive/cylinder is pitched to angle of attack. The local Mach number and boundary-layer thickness at the fin apex were evaluated by analysis of pitot pressure data. The variation of these quantities is shown in Fig. 11. The boundary-layer edge was defined as the point where a kink occurs in the pitot profile, as shown in Fig. 12. Figure 13 indicates the fin interaction data taken for pitch angles up to 12 deg. Also shown are the earlier tripped fin/plate data and the line describing the pressure interaction theory. Data scatter is within ±10% of the pressure correlation.

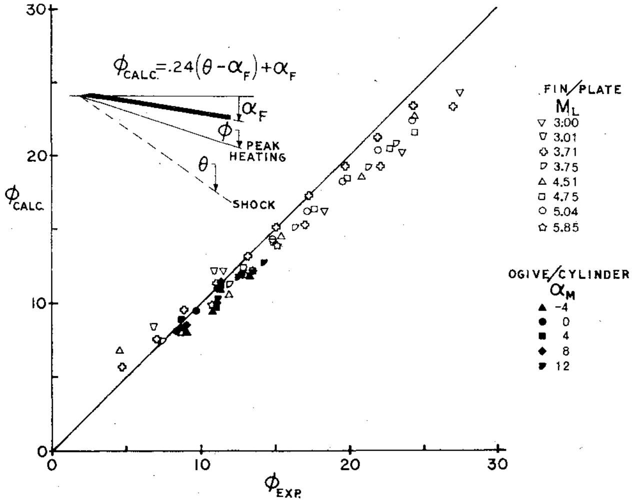

Fig. 16 Peak heating location.

Correlation at Angle of Attack, Arbitrary Roll

In the most general case, the ogive/cylinder is free to pitch and roll. Intuitively, as the fin roll angle increases for a given pitch angle, the flow streamline angle and local Mach number at the fin apex increase. Correlation of the peak heating data depends upon understanding these variations in a quantitative manner.

The impact pressure data taken are satisfactory for evaluating the boundary-layer edge, but they are insufficient to evaluate the local Mach number and flow turning angle at locations off the windward centerline. As a result, a numerical flowfield program developed by the Naval Surface Weapons Center (NSWC) was employed. The program calculates inviscid flow streamlines and local Mach numbers in the shock layer. This output, coupled with the pitot pressure data on boundary-layer thickness, was used to generate streamline turning angles and local Mach numbers at the boundary-layer edge for use in the peak heating correlation. Figure 14 indicates these computed values for 4- and 8-deg angle of attack.

Using these numerically and experimentally derived data, a correlation of the peak heating data for arbitrary orientation was established and is presented in Fig. 15. The local Mach number is that calculated from NSWC program, and the oblique shock angle θ is calculated from the sum of the fin deflection angle and the inviscid flow turning angle at the boundary-layer edge. The line in the figure is again the pressure interaction theory. Agreement of the data is within ± 10% of the pressure correlation.

Location of Peak Heating

The peak aerodynamic heating location on the fin/plate model and the ogive/cylinder model was evaluated against the correlation suggested by Token[2] as applicable to the fin/plate case. This relation derived by Token is

$$\phi = 0.24(\theta - \alpha_F) + \alpha_F$$

This correlation is shown in Fig. 16. A reasonable correlation of the data is noted for the ogive/cylinder at both positive and negative angles of attack and zero roll.

Conclusions

A detailed study on the effects of three-dimensional shock impingement on a flat plate and a missile-like body has been conducted. The following conclusions were drawn from this study:

1) The peak pressure and peak heating generated with the fin/plate configuration may be predicted accurately by two simple correlations. The correlating parameters are shock strength $M_L \sin\theta$ and the nondimensional distance X/δ.

2) The complexities introduced to the interaction phenomena by the ogive/cylinder geometry can be accounted for by numerical computations for inviscid flow turning angle and resultant local Mach number at the fin location. Once these are accounted for, the pressure interaction theory may be applied directly for prediction purposes.

3) Tripped fin/plate data and tripped ogive/cylinder data agree with one another; however, they are significantly lower than untripped fin/plate data. This observation indicates that the process of tripping the boundary layer may reduce the peak aerodynamic heating in the three-dimensional interaction to that predicted for a two-dimensional interaction.

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