Calorimeter Measurement of Heat Transfer at Hypersonic Conditions

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An experimental method of determining heat-transfer rates up to 15,000 Btu/ft² sec on ballistic range models traveling at hypersonic Mach numbers is described. Measurements of the instantaneous melt location on the surface of a specially designed copper calorimeter are obtained from laser lighted photographs. Heating rates are inferred using a 2-D transient heat conduction analysis. Data generated using this technique are shown to be in agreement with exact numerical boundary-layer predictions. Sensitivity studies also show that heating rates can be measured within ±10%. The procedure is useful for studying several energy transport mechanisms at hypersonic conditions.

Nomenclature

k = thermal conductivity, Btu/ft sec°R
L = axial length of sleeve, ft
$\dot{q}$ = incident heat-transfer rate, Btu/ft² sec
T_i = slab temperature, initial, °R
T_s = surface temperature, °R
X_{melt} = axial length to melt location, ft
α = thermal diffusivity, ft²/sec
δ = thickness of sleeve, ft
θ = exposure time, sec

1. Introduction

RE-ENTRY vehicles traveling at hypersonic velocities must contend with significant aerodynamic heating. Stagnation point heating rates at Mach 20 can be higher than 50,000 Btu/ft²sec.[1] The proper specification of heat shield materials for such conditions requires an understanding of relevant flowfield energy transport phenomena. Measurement of the spatial and temporal distributions of heating rates on body configurations of interest has been very difficult. Wind tunnels cannot conveniently obtain the desired aerodynamic conditions, and actual flight vehicles are generally too costly to use for the acquisition of specific fundamental data. Thus, design criteria and analysis techniques have been based upon extrapolation of theoretical and empirical relations and have been verified only by comparison to data from low Mach number experiments. Recent improvements in the testing and measurement capabilities of ballistic range facilities have, however, provided a means of obtaining high quality heat-transfer data at hypersonic conditions. Ballistic range facilities provide test environments not attainable with other ground test techniques. In this paper, a means of calorimetrically measuring heating rates to blunt bodies at hypersonic conditions is described. Experimental results obtained during the development and verification of the measurement concept are shown to agree favorably with predictions. Sensitivity studies are described which indicate measurement accuracies within ±10% at heat flux levels on the order of 15,000 Btu/ft²sec.

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Index categories: Boundary Layers and Convective Heat Transfer—Turbulent; LV/M Aerodynamic Heating; Thermal Modeling and Experimental Thermal Simulation.

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2. Measurement Technique

Calorimetric measurements are, in general, obtained using an energy balance device. That is, heat-transfer rates to an instrument are derived from measurements of temperature and rate of temperature change using energy conservation considerations. Numerous devices of this type such as the null point calorimeter[2] and the Gardon gage[3] have been developed. For such instruments, thermocouples are used to measure the changing temperature levels at one or more locations. In a hypervelocity ballistic range application, use of thermocouples is impossible because the calorimeter is in free flight at conditions where telemetry signals are blocked by flowfield ionization. Primary data from ballistic range experiments come from close-up laser lighted photographs of model vehicles at various distances along the range.[4] The most reliable means of determining the temperature of a metallic material from such photographic data is by the observation of surface melt occurrence. This simple concept is the key to the measurement of heating rates at hypervelocity conditions. As with any calorimeter, the design of the calorimetric configuration must be optimized so that energy transfer events in and about the device can be properly considered in the data reduction.

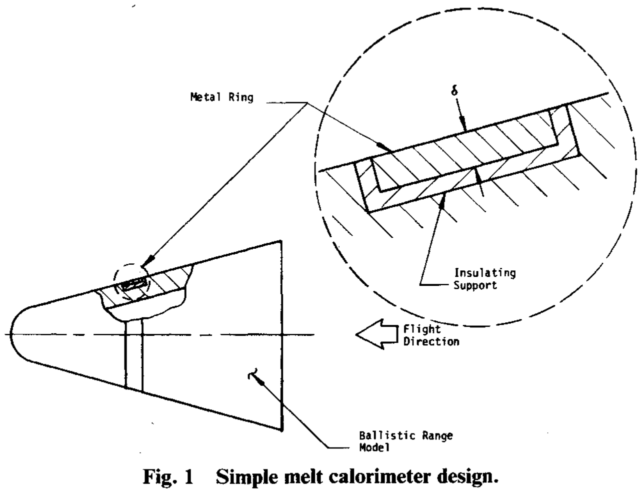
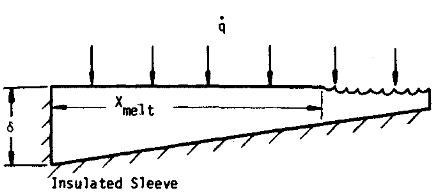


Fig. 1 Simple melt calorimeter design.



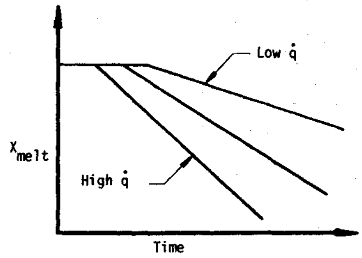


Fig. 2 Response of a variable thickness melt calorimeter sleeve.

The melt calorimeter measurement technique can be illustrated for the simple configuration shown in Fig. 1. In this example, the calorimeter consists of a thin axisymmetric metal ring which is insulated along its side and inner surfaces. For this configuration, the one-dimensional heat equation can be solved[5] to relate surface temperature response to the incident heat-transfer rate. For a constant heat flux boundary condition and Fourier number greater than 0.5, the solution takes the form

$$\dot{q} = \frac{k(T_s - T_i)}{(\alpha\theta/\delta) + (\delta/3)} \tag{1}$$

All quantities on the right-hand side of Eq. (1) are known at the time when the first surface melt occurs. In the ballistic range experiment the melt time can be obtained from model photographs taken at various locations along the range. Equation (1) does not account for variations of heating rate with time or distribution over the ring, but it does demonstrate how the calorimetric concept is applied. The variable boundary condition problems can be solved using finite difference analysis techniques.

The design shown in Fig. 1 can be used to infer heat transfer to only one point on a blunt body. By proper design of the calorimeter model, data can be obtained from more than one body location. One may conceive of a design which has several separately insulated rings. However, such a design would be impossible from structural considerations since ballistic range models must withstand large acceleration loads during launch. The actual calorimeter configuration which has been developed and tested at the AEDC§ Aeroballistics Range G facility consists of a continuous sleeve of high purity copper with a varying section thickness (δ). The thickness variation is defined such that the melt location moves along the surface as a function of time. The schematic shown in Fig. 2 illustrates the response of the variable thickness melt calorimeter to different imposed heating rate boundary conditions. For this configuration, the two-dimensional transient heat conduction effects are significant. The heating rate distribution must be evaluated using a suitable 2-D thermal analysis procedure.

3. Experimental Results

Numerous verification tests of the continuous sleeve, hypersonic calorimeter concept have been performed in the AEDC Aeroballistics Range G facility. The model design used in the majority of these tests is shown in Fig. 3. The large, flat nose on the model serves to reduce the effects of vortical layer interactions on the heat transfer to the 45° conic surface. The calorimeter sleeve is thinner at the aft end to insure that melt begins at the end of the calorimeter and progresses towards the nose.

Models tested to date have been fabricated from oxygen free high conductivity (OFHC) copper because this material provides the best tradeoff between strength, ease of fabrication, and time-to-melt property considerations. For fabrication, the OFHC copper is threaded into the beryllium-copper base and final machining is performed. The parts are then disassembled, dimensionally checked, and reassembled with the 0.005 in. shim in place (see Fig. 3). The shim produces an insulation gap behind the calorimeter sleeve. A photograph of the model is shown in Fig. 4.

Launch velocities for the test were approximately 16/kfps with range static pressures of 0.3, 0.4, and 0.5 atm.¶ The stagnation point enthalpy and pressure corresponding to these conditions are given in Fig. 5. Also, the effect of aerodynamic drag on the velocity, pressure, and enthalpy conditions are demonstrated in Fig. 5.

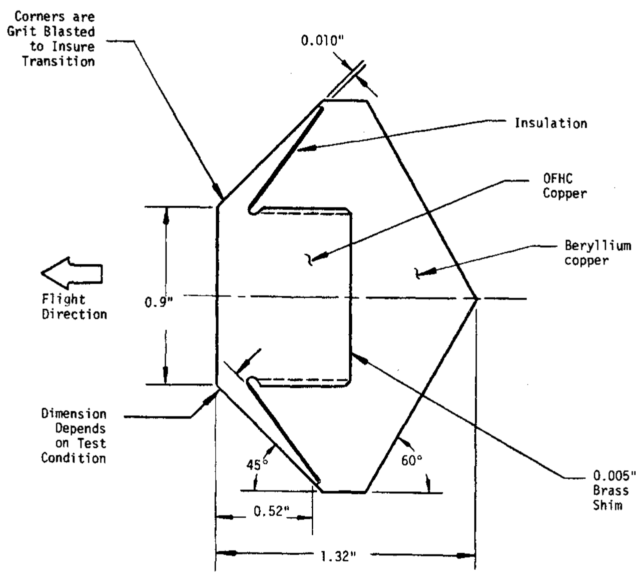


Fig. 3 Hypersonic calorimeter model design.

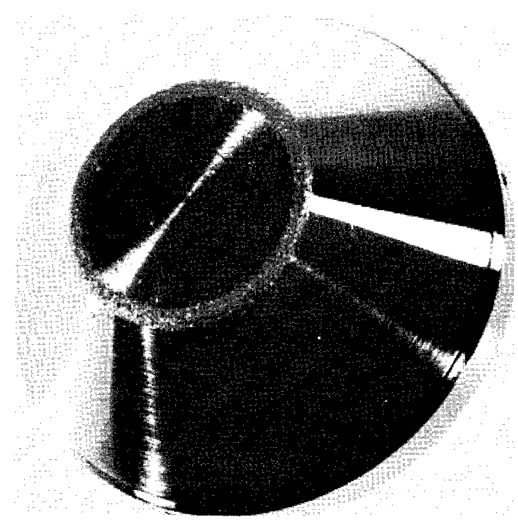


Fig. 4 Ballistic range calorimeter model.

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¶ Air at 75°F.

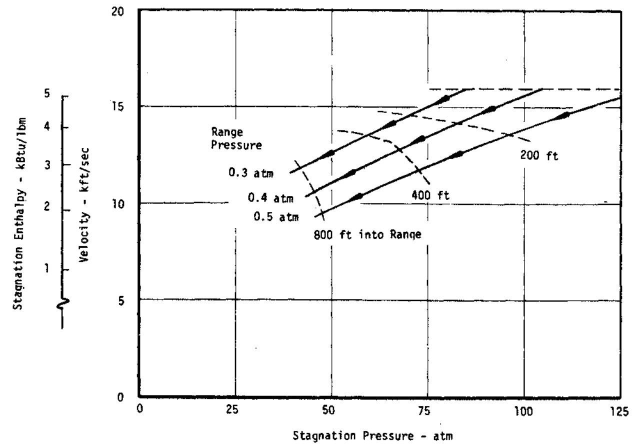

Fig. 5 Calorimeter model trajectory conditions.

Two typical laser lighted photographs of the calorimeter model during one range shot are shown in Fig. 6. In the photograph, taken at 23 ft into the range, no melt has occurred. At 733 ft, however, a considerable portion of the calorimeter sleeve has melted and left the model. Melt location is seen as the forward most indication of surface removal and is characterized by the dark axisymmetric band on the conic surface. Photographs taken at range stations between 23 and 733 ft show that the melt location progressed from the thinner aft end of the calorimeter sleeve towards the forward end as anticipated. The melt location data from three shots at the 0.4 atmosphere condition are given in Fig. 7. The prediction shown in Fig. 7 is discussed in Sect. 5. The only differences in these shots were: 1) the minor machining variabilities noted in Fig. 7; and 2) the technique used to insulate the calorimeter sleeve. The ability of the instrument to repeat the data trend despite these differences is encouraging.

4. Data Reduction Procedure

The evaluation of heat-transfer data from the measured melt line progression data is performed using the Aerotherm Axisymmetric Transient Heating and Material Ablation computer code (ASTHMA).[6] This is a two-dimensional, finite-difference, thermal analysis procedure which predicts the response of axisymmetric blunt bodies to specified, time varying thermal boundary conditions. In the code, a surface energy balance procedure relates the energy conducted into the material to the boundary-layer film coefficient distribution.[7] The ASTHMA procedure accounts for the effects of material temperature change on the

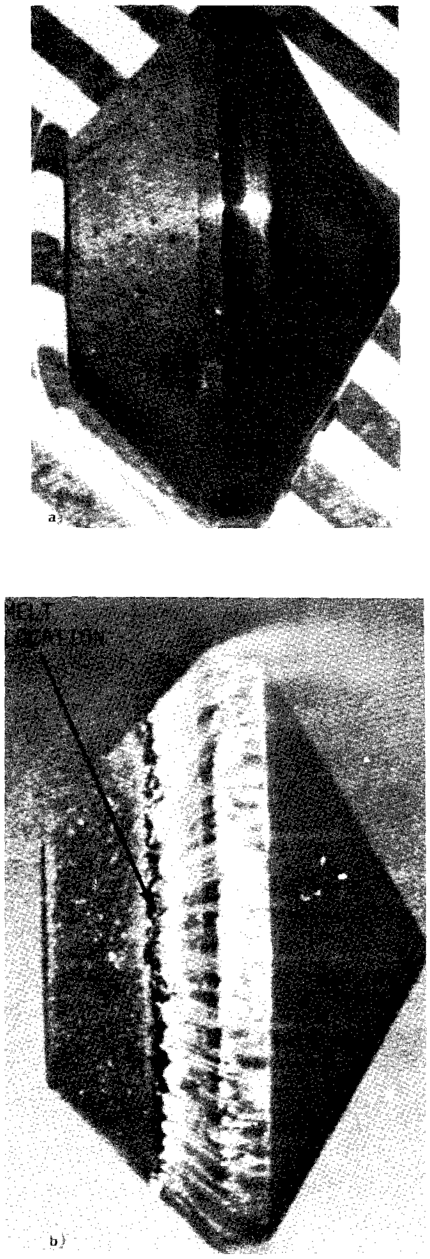

Fig. 6 Laser-lighted photographs of the calorimeter model; a) 23 ft into range, b) 733 ft into range.

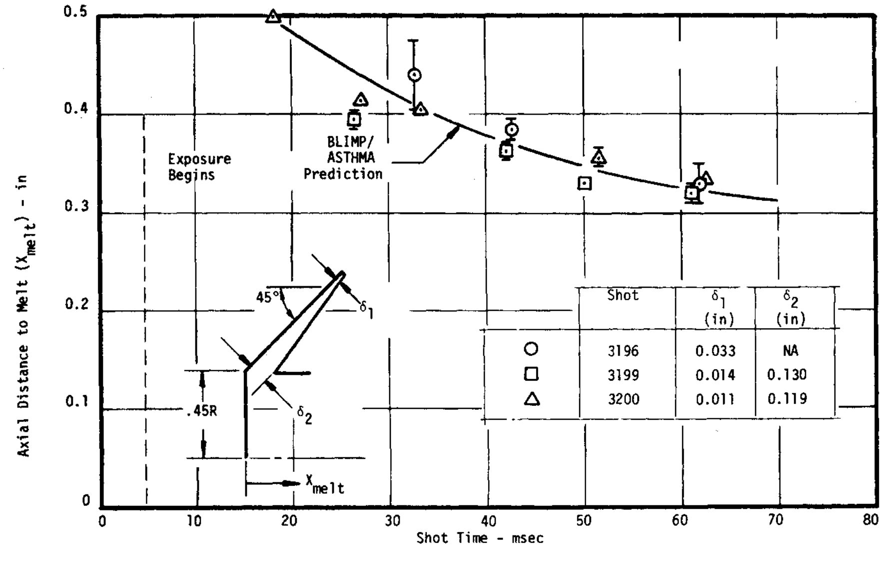

Fig. 7 Calorimeter melt location data for 0.4 atm range pressure.

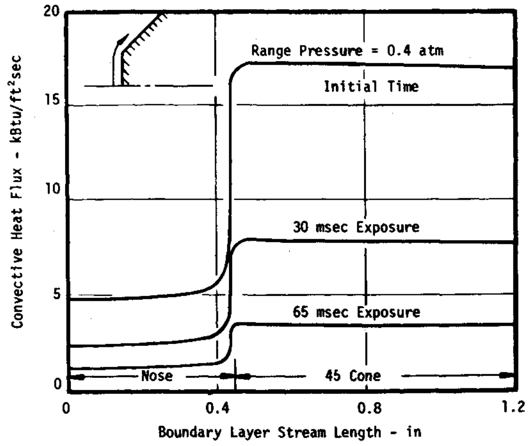

Fig. 8 BLIMP predictions of heat transfer to the cone calorimeter.

thermal properties and the surface energy transport quantities. The information required to perform the ASTHMA analysis includes a nodal grid, material thermal property data, boundary-layer edge-to-surface enthalpy potential, and appropriate convective and radiative transport properties.

The nodal grid is a quasi-orthogonal, finite-difference representation of the axisymmetric body. For the calorimeter designs tested to date, approximately 250 nodes are arranged to yield optimum computational accuracy and speed. Copper property data including the effective black body emittance (0.7 for oxidized copper) are found in materials handbooks.[8] The enthalpy potential across the boundary layer at the hypersonic conditions of interest is best defined as the local boundary-layer recovery enthalpy minus the enthalpy of the air at the instantaneous surface temperature. The recovery enthalpy is accurately approximated by the total stream enthalpy so that the enthalpy variation with time may be derived from the measurements of model velocity history.

The heat-transfer coefficient information needed to make an ASTHMA prediction of the calorimeter response is essentially the unknown to be found from the melt line data. Given the code as it exists, the data reduction procedure entails iterative and/or parametric predictions. The procedure starts with a prediction of the melt progression resulting from the best possible estimate of the actual heat transfer to the calorimeter. A comparison between the predicted melt response and the melt location data provides a basis for parametrically varying the imposed specified heat transfer until agreement is achieved. These parametric solutions also provide a means of evaluating the sensitivity of the calorimeter response to incident heating rates. Thus melt location uncertainty can be related to uncertainty in the inferred heat-transfer rate distributions.

5. Data Analysis and Comparison to Theory

The best estimates of boundary-layer energy transport for the ballistic range calorimeter tests performed to date have been obtained using the Aerotherm Boundary Layer Integral Matrix Procedure[9] (BLIMP computer code). In this code, the integral boundary-layer equations are solved considering among other things, nonsimilar terms, real gas thermochemistry, multicomponent diffusion, and turbulent transport mechanisms. Typical predicted heat-transfer rates for three times during a 0.4 atm shot are shown in Fig. 8. These predictions are obtained assuming the following: 1) surface temperature is specified to be 2441°R (copper melt temperature); 2) transition occurs at the grit blasted corner of the flat nose; and 3) all mass flow in the boundary layer enters the shock layer through the normal shock created by the flat nose. The assumed surface temperature represents an upper limit to that existing in general on an unmelted section of the calorimeter. This is satisfactory because the heat-transfer coefficient values used in the ASTHMA computation (= heating rate/enthalpy potential) are only weakly sensitive to surface temperature. Design analysis calculations also showed the validity of assumptions 2 and 3.

The variations in heat-transfer rate shown in Fig. 8 were used in the ASTHMA code to predict the melt response of the calorimeter. The prediction and the corresponding test data are shown to agree favorably in Fig. 7. The preliminary conclusion, therefore, is that the predicted heating rate distributions shown in Fig. 8 are a valid description of the heat transfer to the calorimeter model at the Mach 15, 0.4 atmosphere launch condition. The observed agreement lends credibility to the measurement technique and serves to verify the design analysis procedures. Similar agreement exists for other test conditions.

6. Response Sensitivity Studies

Although the heat-transfer distributions predicted by BLIMP enable an accurate prediction of melt progression, it is yet to be shown how sensitive the calorimeter response is to perturbations in heat-transfer level and distribution. Clearly if the same melt progression would occur for heating levels a factor of two higher or lower than those predicted by BLIMP, then the measurement technique would not be valid. It is apparent that the time-to-melt at a location is most sensitive to local surface conductive heat fluxes. Thus the heat-transfer data is most accurate over those regions of the calorimeter which actually melt. Less information is obtained from surface locations which do not melt.

The sensitivity of melt location to heat-transfer level and distribution is addressed by four parametric predictions. These cases may be identified as follows.

1) The heat-transfer coefficient everywhere is 1.25 times the nominal BLIMP predictions.

2) The heat-transfer coefficient everywhere is 0.75 times the nominal.

3) The heat-transfer coefficient is 0.75 times nominal at forward end of sleeve and 1.25 times nominal at aft end with a linear variation between the extremes.

4) The heat-transfer coefficient is 1.25 times nominal at forward end of sleeve and 0.75 times nominal at aft end with a linear variation between the extremes.

The melt progression prediction for each of these cases is compared to the corresponding data in Fig. 9. The conclusions from the comparison are as follows:

1) A 25% increase in heating significantly enhances the melt progression rate, case 1.

2) A 25% decrease in heating significantly reduces the melt progression rate, case 2.

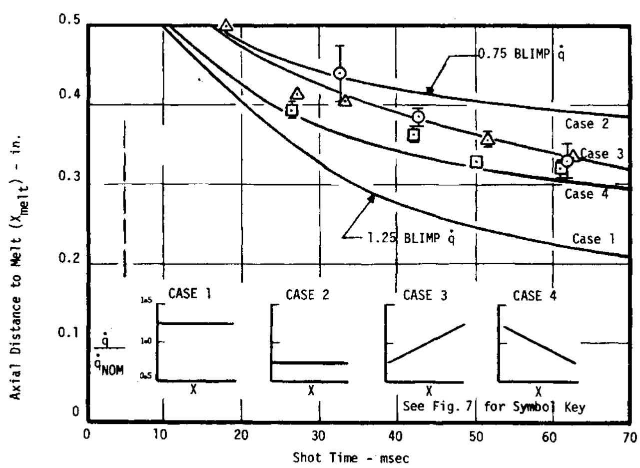

Fig. 9 Sensitivity of melt progression to heat-transfer perturbations.

3) Thus the melt progression rate is very sensitive to the heat-transfer rate level (data scatter represents less than $\pm 10\%$ on heat transfer at 50 msec).

4) Melt progression is sensitive to heating distribution but current data are not sufficient to provide definitive results.

In general, it may be stated that a properly designed hypersonic melt calorimeter does provide heat-transfer data at suborbital flight conditions in a ballistic range. However, it is also important to note that if the calorimeter were incorrectly designed such that either no melt occurred or the entire model melted at once, then the data would be of negligible utility. Furthermore, with innovative model design and detailed design analysis, it is now possible to study numerous aerothermodynamic phenomena of current interest.

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