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Ducts for Material and Ablation Studies

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Simulation of a re-entry environment at vehicle stations away from the stagnation point using an arc heater with a supersonic nozzle-duct arrangement is described. Hollow ducts machined from candidate ablators and instrumented to directly record the static pressure, surface and in-depth temperature, heat transfer, and wall shear stress are tested under supersonic laminar, transitional, and turbulent boundary layers. Wall shear stress data are presented. Cracks in the heat shield are simulated by machining cracks into the ablator. A procedure for quick insertion of an instrumented ablating "plug" into a nonablating duct is described.

Nomenclature

A = cross-sectional area
b = crack width
C_D = drag coefficient
C_q = blowing rate parameter $(\rho v)_w/(\rho u)_\infty C_H$
C_H = Stanton number with ablation
C_{Ho} = Stanton number without ablation
D = diameter
f = friction factor
H = enthalpy
h = crack height
L = length
M = Mach number
p = pressure
$\dot{q}$ = heat-transfer rate
R = radius
Re = Reynolds number
T = temperature
U = freestream velocity
u = local velocity in the X direction
v = local velocity in the Y direction
W = weight
X = streamwise coordinate
Y = normal coordinate
δ = boundary-layer thickness
δ^* = boundary-layer displacement thickness
γ = ratio of specific heats
ρ = density

Subscripts

o = supply
∞ = freestream
w = wall conditions
NE = nozzle exit
θ = momentum thickness
τ = wall shear stress

Background

GROUND testing of ablative materials presents severe challenges for adequate simulation. Orbital and superorbital re-entry regimes are characterized by high stagnation pressures and temperatures, Mach numbers, heat-transfer rates, and wall shear stress. The splash testing technique has become rather sophisticated at approximating some of the stagnation point parameters, but is generally restricted by facility size to small plug samples.

Techniques for simulating the re-entry regimes for regions away from the stagnation point have been more elusive. Wind-tunnel tests are unable to simultaneously produce proper Mach number, stagnation pressure, and stagnation temperature. However, for blunt bodies, such as a sphere-cone, the existence of a normal or near normal shock in the stagnation region, (Fig. 1), has suggested alternate techniques

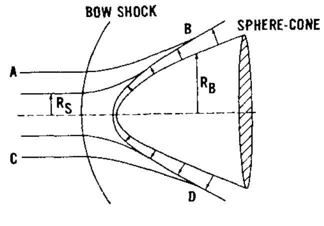

Fig. 1 Sphere-cone flowfield.

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to several investigators. The simulation of the near-stagnation-point flow about an axisymmetric re-entry vehicle, such as a blunted cone, by a contoured nozzle-duct arrangement can be accomplished as proposed by M. C. Adams of the AVCO Everett Research Laboratory, and is discussed in its principle in Ref. 1, for example. Experiments, achieving high subsonic Mach numbers have been carried out by J. Duggan and R. Shaw of the AVCO Research and Advanced Development Division in Wilmington, Mass.[2] prior to the present program. The NOL investigations endeavored to establish and maintain supersonic flow through a duct made of an ablative material, and to directly measure, in addition to the usual flow parameters, the skin friction on an ablating surface, and the heat transfer to the walls of cracks machined into the ablative material.

Justification

The introduction of the nozzle can be justified by an examination of the entropy gradient about the vehicle. Consider Fig. 1. Let the streamlines *AB* and *CD* define the limit of the region of negligible entropy gradient at the edge of the boundary layer about the body. These streamlines define an annulus of radius R_s at the shock front. It is then possible to consider the flow in the annulus *ABCD* to be a quasi-isentropic expansion about the forward portion of the body. The flow will produce stagnation point conditions, say P_o and H_o, upon the body. It is the coupling of the quasi-isentropic expansion with the stagnation point conditions, P_o and H_o, that suggests replacing the streamtube of radius R_s with a nozzle of radius R_s. By expanding the flow isentropically through the nozzle from reservoir conditions P_o and H_o, corresponding to the stagnation point conditions on the vehicle, the quasi-isentropic flow about the forward portion of the vehicle is produced.

Placing limits upon the region of quasi-isentropic flow requires a solution of the shock shape to determine what shock angle the streamlines cross, and then to determine the entropy change along the streamlines. A limit of the radius of the streamtube may now be obtained by the solution of the mass balance equation written across the shock; the last term of the equation accounts for mass addition effects

$$\rho_\infty U_\infty \pi R_s^2 = 2\pi R_B \int_0^\delta \rho u dy - 2\pi R_B \int_0^x (\rho v)_w dx$$

Some calculations by R. E. Wilson[3] for small, blunted cones without blowing and with adiabatic walls suggest the point of negligible entropy gradient may extend to the vicinity of the cone tangent point for sphere-cone bodies.

It follows that test results obtained for measurements on the inside wall of a duct, for example, will have equal validity with those obtained on the outside surface of a model for the region near the nose of the model. This prompted us to select a duct for the study of laminar and turbulent boundary-layer ablation characteristics. Experimentally a nozzle-duct arrangement is quite convenient. Even small ducts can be easily instrumented for obtaining pressures, temperature, heat-transfer and skin-friction data. In this case, the experimental setup would be an axially symmetric nozzle producing the desired Mach number flow which is then discharged into an axially symmetric duct whose surface, and/or in-depth response is to be studied. Instrumentation supports and leads can be arranged externally to this duct, thus eliminating the difficulty of providing aerodynamic and thermal shields for them.

Table 1 Design conditions for duct tests

Mach No.	p_o atm	H_o BTU/lb	H_w/H_o	$\dot{q}$ nozzle exit BTU/ft^2 sec	$Re_{\theta NE}$
2.3	20	1134	0.38	284	1780
2.3	28	1150	0.44	320	2670
3.0	22	3000	0.17	120	300

Experimental Procedures

In connection with Independent Exploratory Development (IED) and Defense Atomic Support Agency (DASA) supported research programs, the present investigations endeavored to simulate the local flow conditions on the forward section of a slender, blunted, ballistic missile. Two cases were considered: one, an ICBM with a ballistic coefficient of 1000 psf that enters at a minimum energy trajectory; and that of an IRBM with a ballistic coefficient of 700 psf. For both cases the altitude of maximum heating was considered. The conditions along the conical parts of the heat shield are as follows: ICBM (10° half angle, 0.25 inch nose radius);

$$2.0 \leq M \leq 9.5$$

$$0.2 \leq H_w/H_o \leq 0.4$$

$$260 \text{ BTU/ft}^2 \text{ sec} \leq \dot{q} \leq 930 \text{ BTU/ft}^2 \text{ sec}$$

For this calculation it was assumed that the heat shield is made of carbon phenolic, and that it heats up to 6700°R before char recession occurs, and that the boundary layer becomes turbulent when the momentum-thickness Reynolds number becomes 400. For an IRBM of a W/C_DA of 700 psf at an altitude of 50,000 ft typical stagnation conditions are 35 atm and 4100 BTU/lb.

These are conditions that can be reached, at least for part of their range, in an arc tunnel. This can be seen from Table I which gives selected operating conditions of the NOL 3 MW Arc Tunnel. The ratio H_w/H_o in this case applies to Teflon. If one, therefore, expands air from a reservoir having the listed supply conditions to the specified Mach number, the correct flight conditions, i.e., H_w/H_o, $\dot{q}$ and Re_θ, can be produced.

For the study of the substructure heating due to cracks in the heat shield, additional parameters need to be considered: a) the friction Reynolds number, Re_τ, characteristic sizes such as b/δ^* and h/b, as well as the geometry of the cracks, that is, the orientation of the cavity with respect to the flow direction, spacing of the cavities, if there are more than one, and the cavity edge geometry. With ablation present, the blowing rate parameter, C_q, also has to be considered. For the ICBM and trajectory conditions considered earlier the following range of parameters is probably representative for the conical part of the heat shield:

$$2 \leq M \leq 10$$

$$70 \leq Re_\tau \leq 2000$$

$$0.05 \leq b/\delta^* \leq 10$$

It was estimated that a reasonable range of these conditions could be achieved with good accuracy in NOL's arc tunnel.[4]

On the basis of this analysis two sets of experiments were designed. One, that would result in a laminar boundary layer over the test specimen, and the other in a fully turbulent boundary layer. The over-all size of the nozzle-duct arrangements was determined by the ability to attach the nozzle to the arc heater and the mass flow limitation of the tunnel system.[5] The schematic of the nozzle-duct system is shown in Fig. 2.

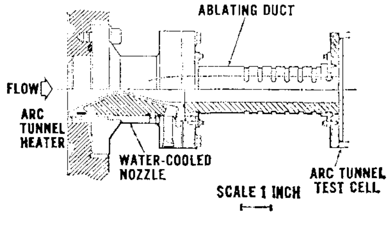


Fig. 2 Nozzle and ablation duct arrangement.

The first system, designed for laminar flow conditions, gave a nozzle exit Mach number of 3.03 for heater conditions of 10–40 atm and temperatures between 3500°K to 4900°K. Boundary-layer corrections were applied to the nozzle and the duct contour following the procedure of Ref 6. Solomon's method had been found very adequate for predicting the laminar boundary-layer growth on nonablating surfaces of controlled surface temperature. It was realized that this procedure gave, at best, an estimate for the ablating duct surface. In lieu of a more sophisticated program, which will be described in a later section, Solomon's method was accepted. A correction to the duct contour was made after the first test to allow for the effect of ablation on the increase of the boundary-layer displacement thickness.

The second system, designed for turbulent flow conditions, gave a nozzle exit Mach number of 2.3 for heater conditions of 20 to 30 atm and temperatures of approximately 2500°K. The method of Glowacki[7] was used to design the nozzle and apply the boundary-layer corrections to nozzle and duct walls.

The majority of the ablation tests conducted at NOL have used Dupont's polytetrafluoroethylene (Teflon, TFE-7). The choice of the length of the duct is the result of balancing a number of considerations involving the flow in the duct and the need for adequate room for instrumentation. The flow within the duct has a profound effect upon the choice of length. Wall friction reduces the Mach number of the supersonic flow, increasing the pressure and tending to choke the flow. The mass injection from the ablation process has the same effect. The mass ablated and added to the stream will be heated and this will result in a loss of total temperature (T_o) of the stream. The loss of T_o will tend to increase the Mach number. An increase in area ratio can be used to compensate for the losses.

These effects may be clearer if studied in more detail. Shapiro[8] gives influence coefficients for a duct with a flow having constant specific heat and molecular weight. Using the appropriate coefficients the Mach number variation is

$$dM^2/M^2 = [1 + (\gamma - 1/2)M^2] \times$$
$$[-2(dA/A) + (1 + \gamma M^2)(dT_o/T_o) +$$
$$4\gamma f M^2(dx/D) + 2(1 + \gamma M^2)(dw/w)]$$

If the specific heats of the ablated material and the duct core flow are similar, and assuming that the ablator must be heated from ambient levels, the loss of energy from the stream will be a function of the ablation rate, i.e.

$$(dT_o/T_o) \cong -(dw/w)$$

In a supersonic flow $(1 - M^2)$ is negative, therefore an increase in area will increase the Mach number while increasing length or increasing ablation rate will decrease Mach number. The effects of mass addition and duct length can be balanced by giving the duct a slight divergence, increasing its diameter. Total mass addition to the duct flow should be small enough that the core flow is not contaminated by the ablation products.

For a friction factor of 0.0025, and a duct length to diameter ratio (L/D) of 10, and an inlet Mach number of 3.0, the exit Mach number will be reduced to 2.45 with friction effects only. Similarly, a mass injection dw/w of 3% will reduce the Mach number to 2.77 if only injection effects are considered. Such large Mach number changes would require large increases in area ratio to maintain constant Mach number in the duct.

Numerical calculations indicate that for low Mach number ducts (L/D)'s of 5–10 can produce good results. Longer ducts would suffer from ablation product contamination and choking effects. A length to diameter ratio of 6 was chosen for the tests.

The instrumentation of the ducts included static pressure taps, thermocouples in the walls, heat gauges, and skin-friction balances. Direct measurements of wall shear stress during ablation were accomplished by an NOL-developed floating element balance.[9] The balance records continually; its small time constant and insensitivity to tunnel noise have made transient measurements possible. The balance is shown in an exploded view in Fig. 3. The force on the ablating sensing head is resisted by a four-arm flexure, shown in Fig. 3. The movement of the head is transmitted to the core of a linear variable differential transformer where the signal is read with a carrier amplifier system.

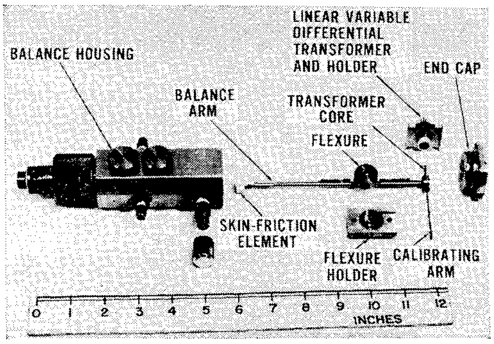


Fig. 3 Skin-friction Balance.

Duct specimens made as one unit from the ablative material have limitations in operation because: a) they have to be fastened to the nozzle initially, and therefore, experience the transients during tunnel start-up; b) the exact time of exposure to a constant flow condition is not known too accurately; c) tests are fairly expensive. A technique to partially circumvent these limitations and to retain the desirable uniform flow of a duct has been developed. A duct the same size and shape as the Teflon duct is made of water-cooled copper. An opening in the side of the duct is fitted with an insert holding the sample to be tested. A mechanism to insert and hold the sample is fixed to the face of the arc heater and the duct.

The insert (Fig. 4) has two parts, a mounting shoe and the sample piece. The mounting shoe supports the sample, protects the sample instrumentation and adapts it to the injection mechanism. It is made so as to fit properly into the duct and serves as a stop on the movement of the sample into the duct.

The normal test procedure is to start the arc heater with the insert and sample out of the duct. When steady-state conditions are reached, the sample is moved up into the duct for a predetermined period of time. When the sample withdraws, the arc heater is shut down. Recordings of the wall temperatures during the run allow the heat-transfer rates to be evaluated.

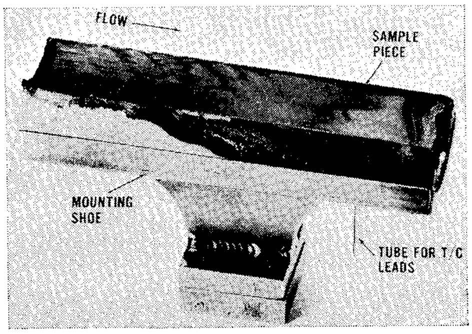


Fig. 4 Cooled duct insert.

Analytical Procedures

BLIMP-CMA

The analysis of the flow through the nozzle and duct was performed with the aid of the Aerotherm Corp. BLIMP computer program.[10] The version of this program used by NOL for their duct testing calculated the nonsimilar, chemically reacting, laminar boundary-layer properties through the axisymmetric contoured nozzle and ablating Teflon duct. There are options within this computer program to allow the user to select: 1) body shape as either axisymmetric sharp or blunt, planar sharp or blunt, or axisymmetric or planar with no sharp or blunt tips, e.g. a nozzle; 2) the inclusion or exclusion of chemical reactions in the flow; 3) similar or nonsimilar solutions, and 4) streamwise discontinuities. Under contract with NOL, this version of the BLIMP was modified to include a relation expressing the surface recession of Teflon as a function of wall temperature;[11] chemical species corresponding to the possible degradation products of other heat shield materials have their thermodynamic properties entered by the user.

Such sophisticated computer programs are regarded as necessary a part of experimentation as the hardware itself. For example, the placement of the skin-friction balance was decided with the aid of the BLIMP calculations. By calculating the magnitude of the wall shear stress, and by calculating the growth of Re_θ through the duct, regions of laminar boundary-layer flow could be separated from possible regions of transition and turbulent boundary layer-flow. The agreement between the computed and measured values was good.

In addition to the BLIMP program, NOL also used the Aerotherm Corp. Charring Material Ablator (CMA) program.[12] The program calculates the transient, in-depth, heating response of an ablator. In particular, the CMA describes the one-dimensional, transient, heat-transfer response of a three-component material which ablates at the front surface and decompose in depth. There are options to allow various boundary conditions, material compositions, and body geometries to be considered. As used at NOL, the CMA was modeled for a homogeneous material,Teflon, with surface recession rate and wall temperature furnished by the BLIMP. The coupled use of the BLIMP and CMA allows the complete specification of the boundary-layer flow and internal material response.

A turbulent boundary-layer option was not available for the BLIMP procedures. However, a numerical procedure was devised to analyze the experimental data to the extent considered essential for the substructure heating studies. It combines a computation applicable to turbulent boundary layers on nonablating walls,[7] experimental information, and wall-species and temperature data obtained from the use of BLIMP. The turbulent boundary-layer program was first used to calculate the flow and boundary layer through the nozzle and duct for the start of the test. The measured pressure variation in the duct during the test was then used to correct the boundary-layer edge condition as a function of time. This was found necessary because of the rapid ablation of the duct under a turbulent boundary layer. The measured wall shear data, together with the BLIMP predicted wall conditions, were used to calculate the wall heating rates, assuming the validity of Reynolds analogy, and quasi-steady-state conditions. This appears to be justifiable because the recording of the shear stress data shows a rapid adjustment to a steady state reading.

Results

The experimental results were, in general, very satisfactory and gave us confidence in the approaches that were used, both experimentally and analytically.

Pressure data: The boundary-layer growth along the laminar duct was found to be underestimated, giving cause to a pressure pulse at the onset of ablation. It was self-correcting as the steady-state ablation was approached. A faster displacement thickness growth was taken into account after the first test run. For the turbulent ducts, there was always a slight favorable pressure gradient due to the rapid ablation. Test duration was therefore limited to about 6.5 sec (as compared to 13 sec and more that could be tolerated for the laminar runs) to keep variation of test conditions to a minimum. Steady-state conditions were established in less than a few seconds.

Temperature results: Because of the low thermal conductivity of Teflon, the thermocouples for wall-temperature gradient measurements had to be very closely spaced and the location of junctions had to be precisely known. This was not accomplished; therefore, temperature gradient data were not evaluated. Single thermocouples, precisely placed, gave good agreement with the in-depth temperature prediction of the BLIMP-CMA procedures. The surface thermocouples failed to recede as designed, but allowed the determination of the onset of ablation at their respective locations.

Skin-friction: The balances responded extremely well, allowing the recording of the wall shear-stress variation almost from the start of the test. The lower experimental curve of Fig. 5 was obtained from the first use of the balance. This type of response was not expected for a laminar boundary layer. It was later analyzed that the balance had been located at a station where transition most likely had occurred as ablation proceeded.[13] A later test with two balances in one duct, one in the transitional location, the other in the definitely laminar region, gave a repeat for the transitional station and the expected behavior for the laminar station as shown in Fig. 5. The behavior is very well predicted by theory, though not in absolute value. It is speculated that inadequate knowledge of the material's properties, such as the viscosity of Teflon vapour, can account for this discrepancy.

Heat-transfer results: The simple copper slab gauges of prescribed thickness with a thermocouple attached to the back surface responded very well and gave results in good agreement with theory for conditions for which a theoretical description was available. It is hoped that the data obtained for conditions (or geometry) not yet covered by analysis will assist the formulation of such analysis.

Ablation: The behavior for laminar, transitional and turbulent boundary-layer conditions was found to be distinctively different. Under a laminar boundary layer, the surface was smooth, with a satiny finish; preferential ablation was observed downstream, and also upstream of pressure orifices. The total amount of ablation is very well predicted by the transient version of the BLIMP-CMA procedure, Fig. 6. In the transitional regime, increased ablation is observed. In some cases, the boundary-layer instability caused longitudinal striations, as shown in Fig. 7 and as observed by

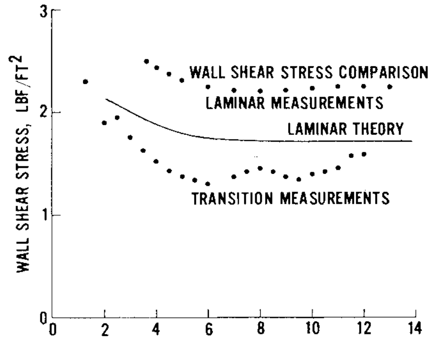


Fig. 5 Wall shear stress variation at two stations in a Teflon duct.

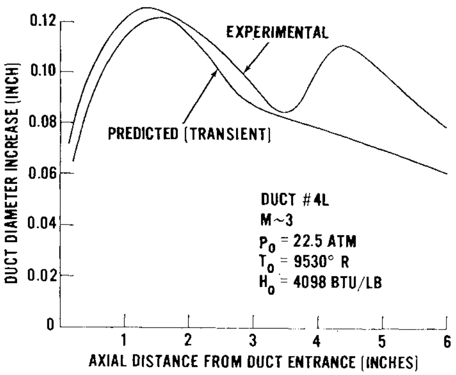
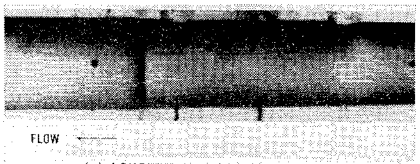
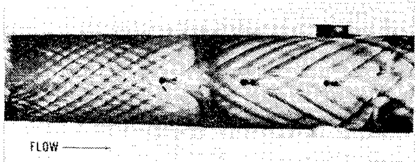


Fig. 6 Predicted and measured total recession.

other investigators.[14,15] Ducts tested under turbulent flow conditions exhibit the characteristic cross hatch pattern as also shown in Fig. 7. Testing with a duct insert, as discussed in a previous section, produced essentially the same results, as seen from Fig. 4. It shows a specimen of AVCOAT 8021 which is very similar in its properties to Teflon. The excessive ablation or erosion at the rear end of the test specimen is unrelated to the recorded test period and is the result of flow attachment as the specimen is withdrawn from the duct.



(a) LONGITUDINAL GROOVES IN DUCT



(b) CROSS-HATCHED STRIATON PATTERN

Fig. 7 Interiors of Teflon ducts after testing.

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