Technical Notes

Pressures in the Stagnation Regions of Blunt Bodies in Rarefied Flow

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Nomenclature

M_∞ = freestream Mach number
p_i = indicated impact pressure
p_0' = ideal, inviscid impact pressure
R = characteristic nose dimension = radius
r = radius of orifice
Re_2 = Reynolds number based on radius and conditions immediately downstream of a Hugoniot shock = $\rho_\infty U_\infty R/\mu_2$
T_{aw} = adiabatic recovery wall temperature
T_w = wall temperature
T_0 = freestream total temperature of gas
U_∞ = freestream velocity
γ = ratio of specific heats
Δ = shock-layer thickness
μ_2 = viscosity based on conditions immediately downstream of a Hugoniot shock
ρ_2 = density immediately downstream of a Hugoniot shock
ρ_∞ = freestream density

Introduction

THIS concerns the impact pressure and pressure distribution in the stagnation region on hemispherical and flat noses of axisymmetric bodies in flow of very low Reynolds number and supersonic or hypersonic freestream Mach number In particular, conditions of heat transfer to the body, varying gas molecular structure, and nose geometry have been examined Special effort was made to establish the state of affairs in the intermediate, low range of Reynolds numbers where there is interest in the question of whether impact pressure may decrease below the level corresponding to otherwise identical conditions at high Reynolds numbers

Flow conditions for these experiments were such that the Knudsen number of a full-scale nose, having a radius of 1 ft and moving with hypersonic speed at altitudes of roughly 300,000 ft was duplicated Thus, this paper concerns the viscous-layer to merged-layer regimes of flow at altitudes above earth where thermochemical reactions in the shock layers of blunt bodies are believed to be essentially frozen

Discussion of Experiments

Wind tunnel

The wind tunnel used is a continuous-type, arc-heated, ejector-pumped design [1] The working gas normally is nitrogen or argon, although other gases may be used Test-section conditions have been established on the basis of measured or calculated reservoir conditions and determination of the existence of an inviscid core flow along the nozzle, plus measurements of impact pressure, local mass flow rate, static pressure, and local total enthalpy [1–3]

When nitrogen was the gas, enthalpies were such that only vibrational excitation required attention insofar as non-equilibrium flow processes are concerned Theoretical analysis of molecular vibrational relaxation was relied upon for final interpretation of calibration measurements On this basis, it is considered that molecular vibration was essentially frozen at all stations downstream of the nozzle throat when nitrogen was the medium Argon was treated as a perfect gas at the enthalpy levels of these experiments

Details of construction of the probes and models, as well as added information on all phases of the investigation, may be found in Ref 4

Influence of orifice size

It has been shown[5–6] that cooled impact probes in hypersonic streams experience an effect whereby the pressure measured with a probe of fixed outside radius may vary with changes of the radius of the pressure sensing orifice when either r or R is small enough to cause very low Reynolds numbers based on those dimensions Another report[7] discusses this orifice effect for cases when r/R is very near unity and the flow is incompressible Information in the cited references leads to the belief that orifice effects were negligible in the present case It may be noted, however, that orifice radius and length, cavity temperature, and freestream velocity all are factors to consider when free-molecular flow is approached Thus, at Reynolds numbers lower than those represented herein, an orifice effect must be expected

Correlation parameters

Expressions for p_i/p_0' derived from the Navier-Stokes equations with assumptions of a Hougoniot normal shock wave, Newtonian velocity gradient, no slip at the wall, and constant density and viscosity in the shock layer suggest that the parameter $Re_2(\rho_2/\rho_\infty)^{1/2}$ is superior to Re_2 alone for correlating data on impact pressure in the continuum-flow regimes [4] The data are presented later as a function of that parameter

Results

Impact pressure

The quantity of data collected in this investigation cannot be presented here because of the limited space allowed Only four typical sets of data are shown, with some of the other data from the same source[4] represented in the form of curves given for comparative purposes in Figs 1–4 It is particularly interesting to observe the apparent limit to the theory of Levinsky and Yoshihara[8] implied in Fig 4 Other data, for $T_w = T_{aw}$, support the theory in the initial decrease of p_i/p_0' [4]

Pressure distribution

Argon was the gas medium used in this phase of the investigation for reasons having to do with a separate study There is theoretical evidence that the difference between argon and nitrogen would not be highly significant, insofar as distribution of pressure is concerned, when M_∞ is large

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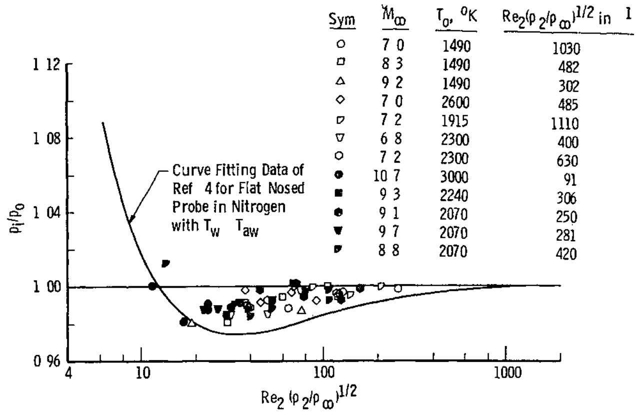

Fig 1 Arnold Engineering Development Center VKF data for flat-nosed probes in nitrogen with T_w = 0 2 to 0 3 T_0

as in the present experiments [9–10] Data, which may be seen in Ref 4, lead to the conclusions given in the next section

Conclusions

1) Impact-pressure ratio p_i/p_0', on flat-nosed and hemispherical-nosed bodies, first decreases below unity and later rises above it as Reynolds number decreases This occurs for either cooled or insulated probe surfaces, with cooling seeming to slightly minimize the amount of the decrease in p_i/p_0'. It also occurs in both monatomic and diatomic gases, the minimum of p_i/p_0' being slightly lower in the monatomic gases studied

2) Hemispherical-nosed bodies experience the effect of rarefied flow on p_i/p_0' at higher values of Reynolds number than flat-nosed bodies in both monatomic and diatomic gases studied

3) There is no more than approximately 3% difference in p_i/p_0' due to differences in gas medium or wall cooling for a given nose shape at a given value of $Re_2(\rho_2/\rho_\infty)^{1/2}$ throughout the viscous-layer to merged-layer regimes under the conditions studied Furthermore, the effect of nose shape is small when $Re_2(\rho_2/\rho_\infty)^{1/2} \gtrsim 100$

4) Analysis based on the Navier-Stokes equations as described by Probstein and Kemp[11] and later refined by Levinsky and Yoshihara[8] is found to be adequate for $Re_2 \gtrsim$ 100 in the case of the hemisphere This limit may drop to $Re_2 \gtrsim 30$ for flat noses

5) There appears to be a qualitative relationship between the behavior of impact pressure and Probstein's and Kemp's regimes of rarefied flow [11] The decreasing trend of p_i/p_0' at intermediate Reynolds numbers seems related to viscous-layer phenomena, whereas the reversal to an increasing trend seems to be related to merged-layer phenomena as shown in Ref 4

6) Differences due to nose shape may be reduced by using Δ instead of R in defining Re_2

7) Pressure distributions on highly cooled, flat, and hemi spherical noses show a discernible but very small effect of reduced Reynolds number, even when Re_2 is as low as 20 Inviscid, hypersonic theories were found to agree closely with the experimental data, provided local pressures are normalized by the measured p_i rather than p_0'

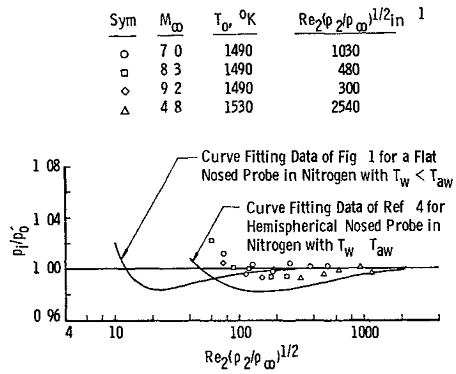

Fig 3 Arnold Engineeing Development Center VKF data for hemisphei ical-nosed probes in nitrogen with T_w = 0 2 T_0

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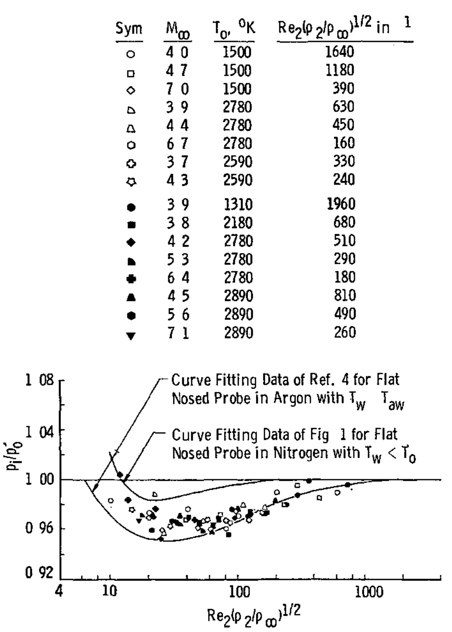

Fig 2 Arnold Engineering Development Center VKF data for flat-nosed probes in argon with T_w = 0 1 to 0 3 T_0

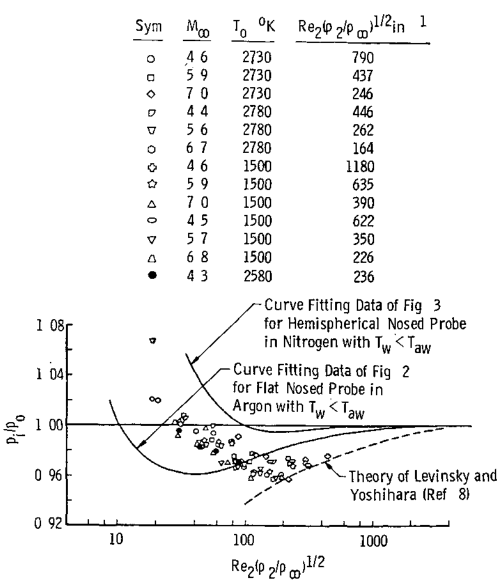

Fig 4 Arnold Engineering Development Center VKF data for hemisphei ical-nosed probes in argon with T_w = 0 1 to 0 2 T_0

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Re-Entry Wake in an Earth-Fixed Coordinate System

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Introduction

INVESTIGATIONS of the re-entry wake have largely been based on a solution of the steady-state problem [1–3] It is true that, for many problems of interest in aerodynamics, phenomenological effects follow so rapidly on a change of freestream conditions that the steady results, used on a quasi-steady basis, offer realistic answers In general, this is not true for the wake problem, since wake cooling is a relatively slow process in many cases, so that it may be necessary to consider the actual trajectory of a re-entry vehicle The present note is a description of such a technique, summarizing the results of Ref 4 The simplifying assumptions are such that the present results are contained implicitly in the steady-state solutions under the coordinate transformation $x = tV_\infty$, with x the distance along body trajectory, t the time, and V_∞ the freestream velocity In Ref 5, the steady-state results are used to describe the wake in the same manner as the present description Even so, neither the present results nor the results of Ref 5 can be considered quasi-steady, since the complete instantaneous wake solution is not merely a function of the current freestream conditions, but depends strongly on the history of vehicle motion along its trajectory

In the present case, the solution of the complete flow field is carried out by considering the body flow field and near wake separately from the far wake (following the techniques of the cited steady-solution references)

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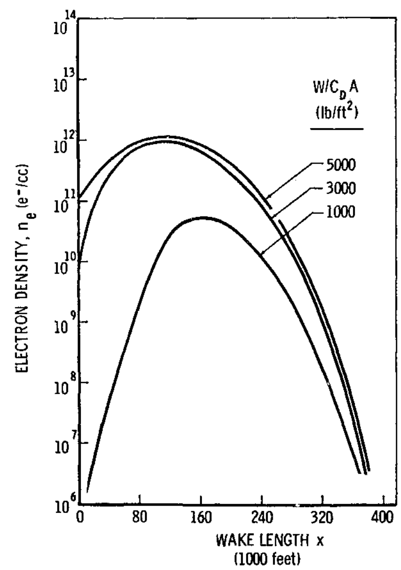

Fig 1 Axial electron density distribution — hemisphere at 20,000-ft alt

Body Flow Field and Near Wake

This portion of the flow field is considered to be an isentropic expansion from the conditions behind the shock Streamlines are thus constant entropy lines The equation

$$\left(\frac{dp}{dT}\right)_S = \frac{(1/T)(\partial h/\partial T)_p}{(RZ/p) - (1/T)(\partial h/\partial p)_T} \tag{1}$$

is integrated with respect to temperature until the pressure decays to the freestream value, using the thermodynamic properties of real air in chemical equilibrium [6] In Eq (1), T is the temperature, p the pressure, S the entropy, h the enthalpy, Z the compressibility, and R is the gas constant In order to determine the conditions behind the shock from which to start the integration, a bow shock shape is assumed For highly blunted bodies, such as hemispheres, the Van Hise[7] shock correlation is used A modified correlation[8] is used to give more accurate shock shapes in those cases for which the Van Hise correlation is not strictly applicable, that is, for slightly blunted bodies such as high fineness ratio spherically capped cones The radial distribution of flow properties at the beginning of the far wake is obtained from continuity considerations

The Far Wake

As the nose cone proceeds along its trajectory, it leaves behind a radial distribution of flow properties at each axial station in the wake This distribution, which is a function of altitude, velocity, and the body properties, as was ex-

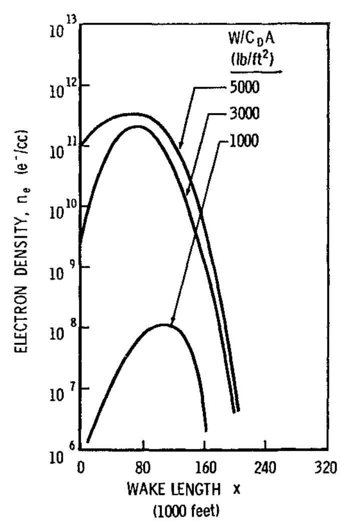

Fig 2 Axial electron density distribution — 15° blunted cone at 20,000-ft alt