Experiments on Turbulent Mixing in a Partially Ionized Gas

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Experimental studies were performed on the turbulent mixing of a partially ionized primary jet with a cool secondary stream The round primary jet was partially ionized argon, and the annular secondary stream was helium at ambient temperature Both flows were at atmospheric pressure and were subsonic Local physical measurements of total gas enthalpy, dynamic pressure, and secondary gas concentration were obtained using a new calorimetric probe technique No electric or magnetic fields were applied, so that the plasma was neutral, and prior analytical estimates had indicated that the existence of equilibrium between the electrons and the heavy particles could be assumed These conditions then allowed the calculation of temperature, velocity, and specie concentiation profiles at the vaiious axial positions Peak temperatures were found to be 23,800°R, corresponding to about 25% singly ionized argon concentration The existence of a potential core was verified, and it was found that the decay of the plasmajet was extremely rapid relative to pieviously published results on jets at lower temperatures It was also found that mass spreads more rapidly than energy, which in turn spreads more rapidly than momentum The boundaries defining the spreading of these quantities were nonconical, as compared with the conical result of earlier researches at low temperature The effects of ionization, as distinct from those due purely to high temperature, appeared to be negligible except for the onset of radiation, which can become a significant energy transfer mechanism above about 21,000°R

Nomenclature

a = primary nozzle radius = 0 375 in
C_{He} = helium concentration, particle fraction
C = $1 - C_{He}$ = argon + argon ion + electron concentration
r = radial coordinate
r_0^C = outer concentration boundary
r_0^E = outer energy boundary
r_0^M = outer momentum boundary
R = r/a
T = temperature
$T_{0,0}$ = temperature at $R = 0$, $\xi = 0$
T_0 = temperature at $R = 0$, centerline
T_∞ = temperature of secondary stream
u = velocity
$u_{0,0}$ = velocity at $R = 0$, $\xi = 0$
u_0 = velocity at $R = 0$, centerline
u_∞ = velocity of secondary stream
U = u/u_{00}
x = axial coordinate
ξ = x/a
θ = $T/T_{0\,0}$

I Introduction

IN recent years there has been considerable interest in the study of partially ionized gases The turbulent mixing of a hot, dense plasma with a cool secondary stream is not only of fundamental interest from the standpoint of gas-gas heat transfer and fluid mechanics, but is also important in such possible applications as arc or plasma engines and gaseous core nuclear-rocket concepts

Although considerable experimental data[1–4] exist on the turbulent mixing processes in a free jet of axially symmetric geometry (see Fig 1), very little work has been done at high temperatures The basic experimental difficulty has been the inability to make precise local measurements in regions having high gradients and temperatures above the range of thermocouple melting points This paper describes a series of experiments peiformed at temperatures sufficiently high to produce significant ionization of the primary gas

In particular, measurements were made within the plasma of local values of species concentration, gas enthalpy, and dynamic pressure by means of a unique water cooled calorimetric probe, shown in Fig 2 This probe was calibrated by the method of energy and mass balances described in Ref 5 Results of 28 such numerical integrations were consistently in excellent agreement within an average of ½% and a standard deviation from the mean of approximately 3% This is generally believed to be quite superior to other methods of high-temperature measurement in multicomponent fields with strong property gradients

II Physical Apparatus

Of the apparatus used in these tests, the only special items were the calorimetric probe and its drive system, the radiation probe, and the arcjet torch assembly

The water-cooled calorimetric probe has been described in detail in Ref 5 It consists of three concentric copper tubes having an over-all outer diameter of 0 140 in , which is sufficiently small to provide the capability for local measurements within the plasma (More recent versions having outer diameters as small as 0 075 in have been successfully applied under similar conditions [6]) The probe diive system permitted continuous axial and radial traversing of the jet and mixing region with position measurements accurate to approximately 0 001 in A photograph of the calorimetric probe mounted in position appears in Fig 2, and a diagram of the instrumentation is shown in Fig 3

The radiation probe was a simple commercial vacuum thermopile fitted with a jacketed collimating tube capable of insertion directly into the arcjet The window used to prevent convection at the thermopile surface was made of lithium fluoride to reduce ultraviolet absorption to a min-

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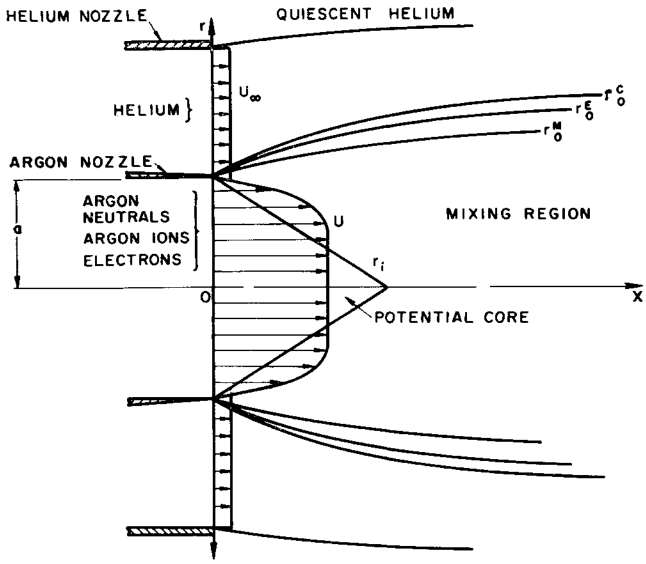

Fig 1 Diagram of turbulent mixing region

imum, and the collimating tube was provided with a continuous purified helium bleed to further decrease absorption in the ultraviolet range Calibration of the probe indicated transmissivity down to below 1100 Å Further details of the apparatus and results of the radiation study appear in Refs 7 and 8

The commercial arcjet used in these tests had a peak power capacity of 80 kw and was modified for this study by the use of a longer primary nozzle and a secondary annular helium nozzle Power was obtained from a 440-v shunt-wound generator driven by a diesel engine Five selenium rectifiers were used to convert to direct current

The cathode was constructed of ground tungsten, and the copper anode served as the primary argon nozzle The nozzles employed in the experimental studies were 0 750 in -diam straight bore, with lengths of 4 and 8 in This provided length/diameter ratios of 5 33 and 10 67, respectively The efficiencies (net gas power/electrical input power) ranged from 14% for the 8-in nozzle to about 26% for the 4-in nozzle

One problem of special interest was that of cathode concentricity and the related gas swirl angle In order to prevent the electrical discharge from striking the same point on the nozzle at all times, which would soon result in a thermal failure, it was necessary to obtain a rotational arc pattern This was accomplished by introducing the primary gas in a vortex or swirl Excessive swirl would make measurement of velocity near the nozzle boundaries impossible with a pitot-type device such as the probe Too little swirl would result in asymmetric profiles or thermal failure of the nozzle The optimum swirl for this study was found to be 15° from axial and 15° from radial, measured upstream of the arc This resulted in less than 1° swirl at the nozzle exit (downstream of the arc), which had no effect upon the instrumentat on

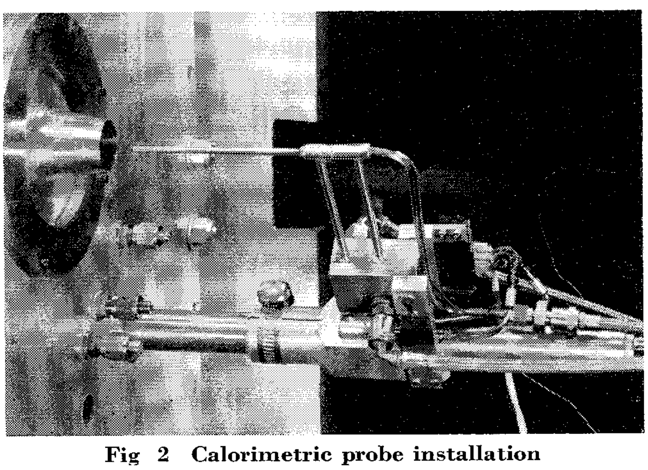

Fig 2 Calorimetric probe installation

III Physical Measurements

The following direct physical measurements were made in the course of this study:

1) Gas enthalpy: This was measured directly by the probe, requiring the following subsidiary measurements: a) inlet and exit coolant temperature rise from the probe as measured by standard copper-constantan thermocouples with electrical output observed on a recording potentiometer; b) probe exit gas temperature, as measured with a chromel alumel thermocouple, with output on a recording potentiometer; c) probe gas flow rate, as measured with a calibrated critical orifice (see Fig 3), where upstream and downstream orifice pressures were measured with mercury manometers (knowledge of the probe sample gas com position was necessary to determine the flow rate)

2) Gas composition: The composition of the gas was determined in terms of the helium-argon fraction by means of a thermal conductivity cell (see Fig 3) whose output was observed on a recording potentiometer The temperature of the gas within the cell, cooled by passage through an oil bath, was measured with a mercury thermometer The cell was calibrated with known prepared gas samples of varying argon-helium fraction and was repeatably accurate to better than 1% [9]

3) Dynamic pressure: The dynamic pressure (Mach number < 0.1) was measured by means of a pressure trans ducer (Fig 3) and observed on a recording potentiometer

4) Probe radial position: The radial position of the probe was measured with a potentiometer and observed on a recording potentiometer

5) Probe axial position: The axial position of the probe was measured with a simple scale amplified by a hairline magnifying glass

6) Arcjet voltage: The arcjet voltage was measured directly with a calibrated voltmeter

7) Arcjet current: The arcjet current was measured directly with a calibrated ammeter

8) Arcjet coolant temperature rise: The arcjet coolant temperature rise was measured by copper-constantan thermocouples with output on a recording potentiometer

9) Probe coolant flow rate: The water flow rate through the probe (necessary for the gas enthalpy measurement) was measured with a standard calibrated rotameter

10) Arcjet coolant flow rate: The arcjet coolant flow rate was also measured with a calibrated rotameter

11) Argon mass flow rate: The argon volumetric flow rate was measured with a calibrated rotameter Argon pressure at the rotameter was measured with a simple bourdon gage and argon temperature at the rotameter by a mercury thermometer These data were sufficient to calculate the mass flow rate

12) Helium mass flow rate: The measurement of the

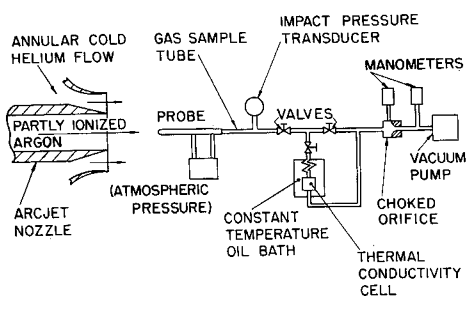

Fig 3 Diagram of gas sample instrumentation

flow rate of the secondary gas was accomplished in the same manner as that of the primary argon

From the foregoing physical measurements, the condition of equilibrium,[10] and a known equation(s) of state for the multicomponent system[11 12] it was possible to calculate directly the following important quantities: gas temperature, gas composition, and flow velocity

IV Experimental Method

The basic purpose of the experimental program was to obtain direct local measurements over the entire flow field of interest This was accomplished in the manner described below

After determining the various parameters of interest and assuring that the arcjet was yielding reasonably symmetric profiles (this was essential in the calibration phase since one diametral pass was used to represent the exit plane conditions), the primary jet and mixing region were investigated with the calorimetric probe This was done by placing the probe in a fixed axial plane and then moving it radially in a series of small increments through the entire jet At each location, steady-state readings (i e , the time average of the turbulent fluctuations, whose frequency was observed to be of the order of 2000 cps as shown in Fig 4) of all the physical measurements just listed were taken The probe was then moved to about 15 such locations in the given transverse plane A different axial position was then selected and the procedure repeated The number of such axial positions was typically 6 or 7

The procedure just outlined resulted in data for one fixed set of flow conditions The need for variation of such basic flow parameters as peak temperature, peak velocity, primary-to-secondary velocity ratio, scale and intensity of turbulence, etc required collection of data for 16 separate sets of operating variables Only a small portion of the data is included in the present paper

From the previously stated physical measurements it was possible to determine the following for various values of the flow parameters: 1) velocity, concentration, and temperature profiles at various axial positions (see Figs 5–7); 2) the axial decay of velocity, temperature, and concentration (see Fig 8); 3) the axial and radial gradients of these properties over the flow field (see Fig 9); and 4) the radial spreading of these same quantities as functions of axial position, temperature, etc (see Figs 10 and 11)

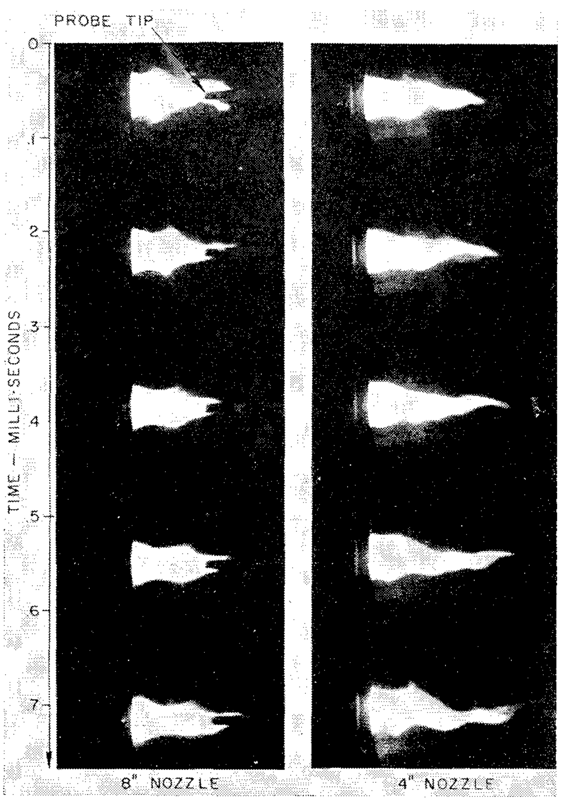

Fig 4 Turbulence in high-temperature argon plasma

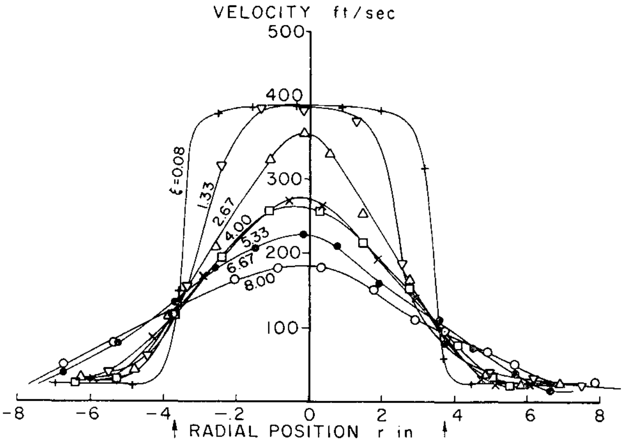

Fig 5 Typical radial velocity profiles (experimental)

Determination of the radial spreading of the field variables shown in Figs 10 and 11 stemmed from inspection of the radial profiles For example, since the energy or temperature outer boundary is defined as the locus of points nearest the centerline where $T = T_\infty$, then by determining the value of the radial position at which this condition is met, for a profile at a given axial position, the outer boundary can be related to the axial position This was done for all the various axial positions and, of course, the other field variables Since the exact point at which a variable "reaches" its asymptotic limit was very hard to ascertain, a value slightly removed from this limit was selected By repeating this procedure for different arbitrary values, it was then possible to extrapolate to the true boundary criteria This procedure was employed for determination of all experimental boundary spreading

Although measurements using the calorimetric probe were essentially unaffected by radiation, because of the "tare" measurement made at each point,[5] it was nevertheless quite important to estimate the extent of thermal radiation from the argon plasma and the arcjet assembly A separate series of measurements was performed[7 8] to determine both the magnitude and nature of the arcjet radiation, using the collimated probe described previously The measured radiation loss was found to be less than 12% of the total jet energy for the temperature range of these studies and was smaller than 4% for most of the experimental cases This conclusion regarding radiation was verified by the experi-

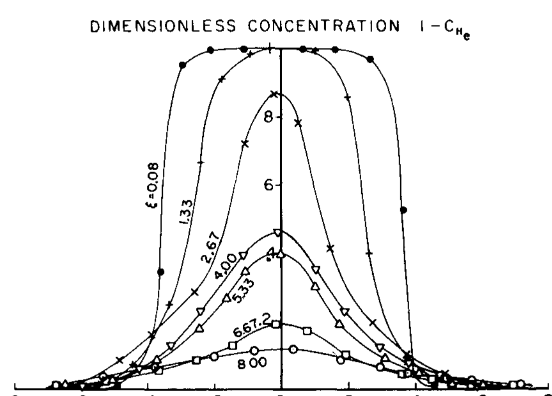

Fig 6 Typical radial concentration profiles (experimental)

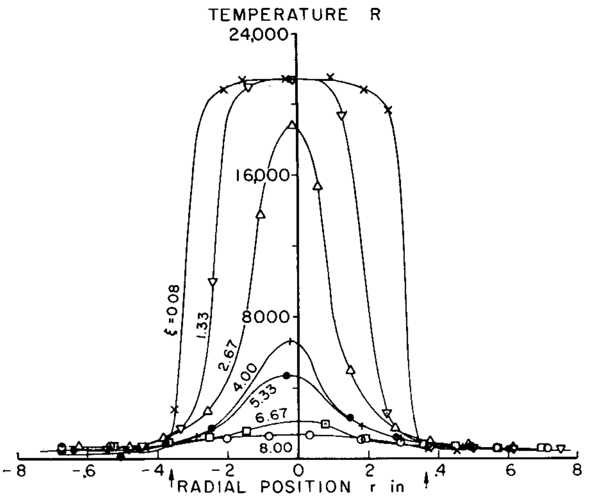

Fig 7 Typical radial temperature profiles (experimental)

mental data of Figs 8 and 9 in that the measured centerline temperature was approximately constant within the potential core This would not have been the case if radiation losses were significant This result is also independent of the absolute accuracy of the probe measurement since it is a function only of repeatability

V Discussion of Results

The data obtained in these experiments, as well as the results of a numerical analysis of the problem that is presented in detail in Ref 9, are shown in Figs 5 and 11 The numerical analysis employed the conventional integral form of the boundary-layer equations The empirical constants needed to describe the turbulent transport of mass, momentum, and energy, as well as the initial velocity, temperature, and concentration profiles (at $\xi = 0$), were determined from the experiment Hence, the "analytical" curves are forced to

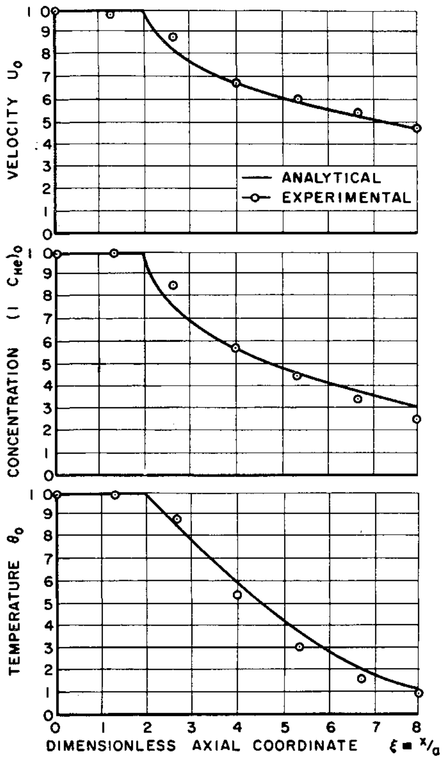

Fig 8 Typical axial decay of centerline velocity, concentration, and temperature

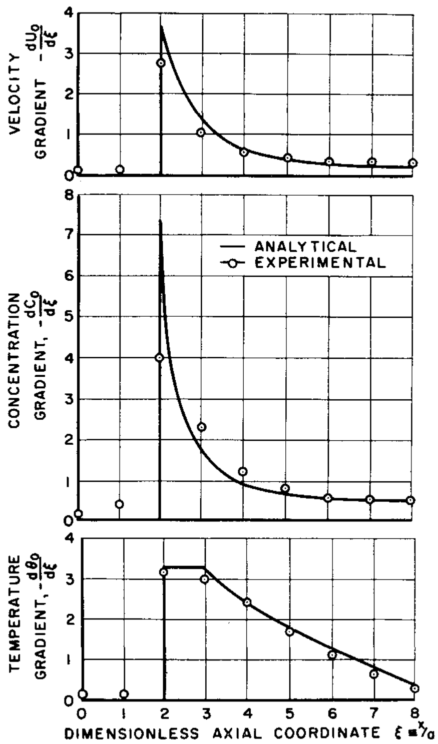

Fig 9 Typical axial gradients of centerline velocity, concentration, and temperature

conform with the experimental results at $\xi = 0$ but are free to determine their own form further downstream

Figures 5–7 show, respectively, the velocity, concentration, and temperature profiles for seven different axial positions ranging from approximately the nozzle exit ($\xi = 0\ 08$) to a position eight radii downstream ($\xi = 8\ 00$) The small arrows located on the radial coordinate indicate the edges of the primary nozzle We note the following:

1) Initial profiles are almost flat as is characteristic of turbulent flow

2) There is a finite axial distance in each figure up to which the centerline value of the given property is approximately constant This region, therefore, constitutes the "potential core" normally observed with the coaxial geometry [1, 3]

3) All profiles are quite similar beyond the potential core

The most striking feature of the results was the extremely rapid decay of the turbulent jet, as shown in Fig 8 We note:

1) The length of the region of constant centerline properties (i e , the potential core length) is approximately the same for velocity, concentration, and temperature

2) From a thermal standpoint the jet is very strongly decayed within only eight radii Although the qualitative nature of the decay is in good agreement with results of prior work at much lower temperatures,[1, 2] full decay occurs at length/diameter ratios about five times smaller

3) The constancy of temperature for over one radius of physical length indicates that radiation cannot be an important energy transfer mechanism at the peak temperature of 21,800°R observed on the illustrated test

Figure 9 shows the negative of the gradients of the three flow parameters along the centerline The magnitude of the maximum observed gradients, e g , 18,000°R/in , is of some interest Identification of these severe gradients as a possible cause for the observed rapid decay of the jet was attempted by making a series of "cold" tests Although, as anticipated, the data from these tests did not correlate well with the high-temperature runs (see Fig 11), the expected order-of-magnitude decrease in decay rate was not observed However, because of the extremely low velocities necessitated by the available experimental apparatus in the absence of arc heating, this result must be considered inconclusive; that is, the cold-flow experiments did not establish conclusively that the high gradients either were or were not responsible for the rapid decay of the jet

A second possible explanation for the rapid decay was the apparently large scale of turbulence Although an adequate Schlieren system was not installed until after completion of the test series described in this paper, Fastax photographs (e g , see Fig 4) appeared to indicate that the scale was quite large in all hot tests (i e , of the order of the jet radius) This was significantly larger than would be expected in the test configurations of the cited literature, and hence represents a major possible cause for the observed rapid decay Unfortunately, the scale of turbulence was apparently generated within the nozzle, possibly by the arc itself, and could not be controlled by flow parameter variations; thus this dependence could not be established Although an estimate of the effect of scale might have been possible by the use of "cold" test data, the lack of an optical system for nonluminous flows, as well as the forementioned restriction to extremely low gas velocities, precluded the use of these tests for such a determination

One significant effect of the apparently high degree of turbulence might be the sampling error introduced by coupled turbulent fluctuations in flow parameters However, in the present series of tests, independent mass and energy balances using probe-measured data indicated that any errors of this type were within the measurement accuracy limits Nevertheless, since the probe technique assumes simple averaging of conditions at the probe stagnation point, the presence of significant turbulent cross-product terms in energy, momentum, and species concentration could conceivably lead to some inaccuracy in these measurements

Another feature of the results was the observed departure of the mixing boundaries from the "conventional" conical form[3 4 13] Figure 10 clearly indicates a "cusped-paraboloid" shape of all three boundaries for the high-temperature ($T_{0,0}$ = 21,800°R) plasmajet This may be compared with the conical boundaries of Squire and Trouncer,[13] Willis and Glassman,[3] and Pitkin and Glassman[4] for the isothermal (cold) case One possible explanation for the nonconical boundary shape might be the slight departure from "flatness" of the nozzle-exit velocity profile (see Fig 5) However, the curved boundaries are most likely the result of the rapid drop in temperature, causing an increase in gas density with distance sufficiently great to overbalance the density-decreasing effect of helium influx This behavior has been observed previously[14] in homogeneous mixing studies, but the results of Fig 11 indicate the dominance of energy

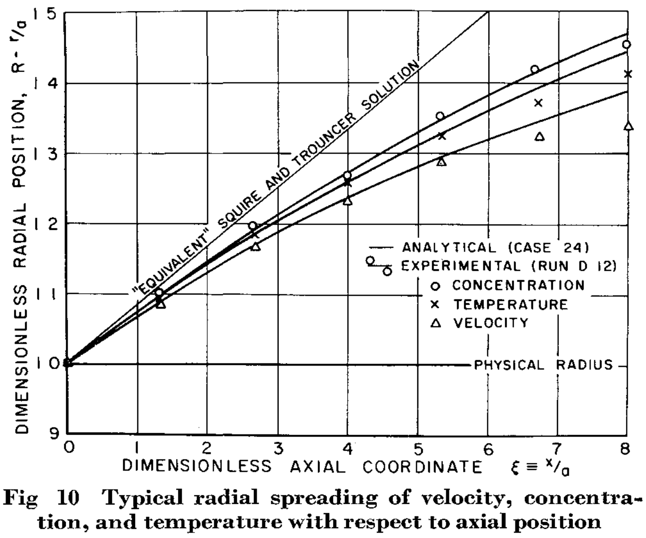

Fig 10 Typical radial spreading of velocity, concentration, and temperature with respect to axial position

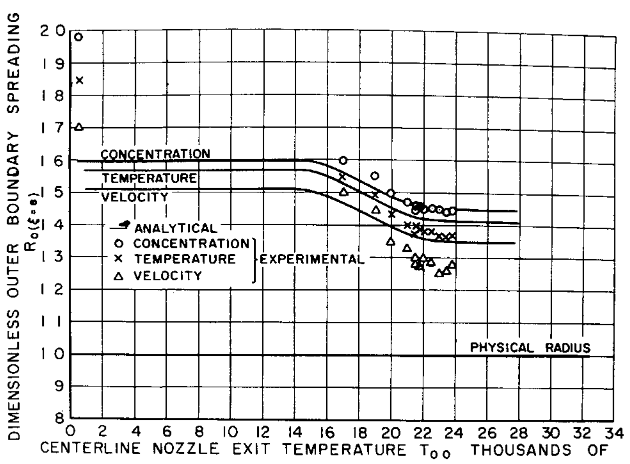

Fig 11 Typical radial spreading of velocity, concentration, and temperature with respect to peak temperature

transport in defining the character of the jet It should be pointed out that the boundaries were found to spread approximately conically in the "cold" test case

Figure 11 confirms conclusively that the change in shape as well as the magnitude of the spreading boundaries is heavily dependent on temperature or temperature gradient (by the relation between data at 530° and 17,000°R) and possibly on degree of ionization (by the data between 17,000°, the approximate inception of significant ionization, and 23,800°R) The results of this figure also identify a noticeable boundary-shape change with the onset of ionization, but only in the neighborhood of the maximum rate-of-change of ionized fraction with temperature It would therefore appear from the "leveling-off" at the extreme high-temperature end of Fig 11 that the mere presence of ions and electrons does not constitute a major "new regime" with regard to turbulent mixing, a tentative conclusion of some significance Unfortunately, limitations of the existing apparatus precluded conclusive confirmation of this apparent trend, which can be provided only by tests at appreciably higher degrees of ionization than the 25% limit of the present study

Finally, the experimental data of Figs 5–11 clearly indicate the capability of this experimental technique in providing reproducible, consistent data in a previously inaccessible regime The clear, experimental definition of radial profiles and axial gradients and, in particular, unambiguous identification of the three separate mixing boundaries, represent a significant first step in the investigation of turbulence in the ionized-gas regime Possibilities for subsequent studies of importance in this area have been illustrated by the foregoing discussion

VI Conclusions

The following conclusions may be drawn from the experimental results:

1) The plasmajet was observed to decay much more rapidly than jets of similar configuration at much lower temperatures

2) The existence of a potential core was verified Its length was the same (approximately 1 diam) for temperature, velocity, and concentration, and was relatively insensitive to temperature level

3) The effects of ionization on turbulent mixing characteristics do not appear to be significant, except for the onset of significant radiant energy transfer at temperatures above 21,000°R

4) Mass spreads more rapidly than energy, which in turn spreads more rapidly than momentum

5) The spreading boundaries of the high-temperature, partially ionized jet were found to depart from the conical shape of isothe mal jets

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Laminar Heat Transfer to Spherically Blunted Cones at Hypersonic Conditions

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Heat-transfer distribution data obtained on a 9° half-angle spherically blunted cone at Mach numbers near 20 and freestream Reynolds number between 8000 and 15,000/in in the hypervelocity (hotshot) tunnels are presented The test data are compared with Lees' laminar heat-transfer theory and available shock-tunnel data on similar cones Good agreement between Lees' theory and the experimental data is obtained Experimental pressure and heat-transfer distributions were correlated over a wide range of nose-bluntness ratios, cone half-angles, and Mach numbers by modifying the correlation parameters proposed by Cheng A simple formula is given which is adequate for engineering estimates of the heat-transfer rate to the conical afterbody of a spherically blunted cone at hypersonic conditions

Nomenclature

C = correlation constant [Eq (8)]
C_* = form of Chapman-Rubesin viscosity coefficient, $\mu_*/\mu_\infty = C_* T_*/T_\infty$
C_H = heat-transfer coefficient, $\dot{q}_w/\rho_\infty U_\infty(h_0 - h_w)$
C_p = pressure coefficient, $(p_u - p_\infty)/q_\infty$
c_p = specific heat at constant pressure
D_B = base diameter, in
d = nose diameter, in
g = $C_p/2\theta_c^2$
h = enthalpy of gas, ft²/sec²
h_r = Wilson's reference enthalpy [Eq (5)]
K = constant in Fay-Riddell equation [Eq (2)]
k = nose drag coefficient (0 964 for spherically blunted cone)
L = model length, in
M = Mach number
p = pressure
Pr = Prandtl number
q_∞ = dynamic pressure, $\rho_\infty U_\infty^2/2$
$\dot{q}$ = heat transfer rate, Btu/ft²-sec
$\dot{q}_0$ = stagnation heat-transfer rate behind a normal shock
$\dot{q}_0$ = computed stagnation heat transfer rate [Eq (2)]
$\dot{q}_{0w}$ = inferred stagnation heat rate, $\dot{q}_w/(\dot{q}/\dot{q}_0)_{\text{Lees}}$ ($\dot{q}/\dot{q}_0$ = 0 0465 for a hemisphere cylinder at S/R_0 = 2 32, $M_\infty \sim 18$)
R = radius, in
R_B = base radius, in
R_0 = nose radius, in

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