Experiments with Two Flow-Swallowing Enthalpy Probes in High-Energy Supersonic Streams

Lewis A. Anderson*
NASA Ames Research Center, Moffett Field, Calif.

AND

Robert E. Sheldahl†
Sandia Corporation, Albuquerque, N. Mex.

Certain arc-heated plasma facilities are capable of producing plasma streams with enthalpies to 200 Mjoule/kg. However, these test streams are obtained at low densities ($\rho_\infty < 10^4$ kg/m^3) with large local gradients, which, in turn, make total energy determinations difficult. Because of the importance of this stream property, a program was undertaken to determine it by measuring local total power balances on captured stream tubes. Two flow-swallowing enthalpy systems were studied, one with an attached shock and the other with a detached shock. The probe system having a detached shock was not scaled to sample sufficient mass flux at the low densities and, therefore, produced no meaningful data. However, with the attached shock-probe-system centerline total enthalpy up to 98 Mjoule/kg in air, nitrogen, and argon was measured. The error in these measurements is estimated to be less than 12%.

Nomenclature

A = area
c_p = specific heat
D = diameter
h = gas enthalpy
I = arc current
m = calorimeter mass
$\dot{m}$ = mass-flow rate
M = Mach number
p = pressure
Δp = pressure difference between venturi inlet and throat
$\dot{q}$ = local heat-transfer rate
$\dot{Q}$ = heating rate
s = surface area
t = time
T_{in} = temperature of water entering the calorimeter
T_{out} = temperature of water leaving calorimeter
U = velocity
V = arc voltage
x = axial distance
γ = specific heat ratio
ρ = density

Subscripts

0 = probe inlet station
2 = conditions behind normal shock
3 = exit station in the calorimeter
∞ = freestream station
c = arc chamber station
e = subsonic cylindrical calorimeter section of the attached shock and mass-flow probes
F = plasma flow in the calorimeter
i = ith element of the calorimeter
p = probe
t = total conditions
v = venturi
AV = total mass average value
℄ = centerline test region at x = 2.54 cm downstream from the nozzle exit
cs = compression surface
H_2O = water
in = station where water enters the calorimeter
NF = no captured mass flux
out = station where water leaves the calorimeter
tare = value not assigned to captured plasma

Presented as Paper 68-390 at the AIAA 3rd Aerodynamic Testing Conference, San Francisco, Calif., April 8–10, 1968; submitted April 8, 1968; revision received May 14, 1971.
* Research Scientist.
† Research Scientist. Associate Member, AIAA.

Introduction

CERTAIN arc-heated plasma facilities produce supersonic streams with total enthalpies to 200 Mjoule/kg at low densities,[1] but local distributions of total enthalpy in the test region have not been determined accurately. All of the methods used to obtain local total enthalpy to date, with the exception of local flow-sampling probes, require indirect measurements which rely in one way or another on theoretical calculations. A flow-swallowing enthalpy probe, which depends only upon a power balance in the test region and not on any theoretical assumptions, provides a direct method for obtaining local enthalpy. A knowledge of radial and axial enthalpy distributions allows for quantitative assessment of the validity of other indirect methods for obtaining enthalpy and for determining correction factors which may apply to them. The purposes of this paper are to discuss some of the problems associated with direct measurement of enthalpy with flow-swallowing probes and to describe some of the techniques required to overcome them. Prior work with flow-swallowing enthalpy probes is listed in Refs. 2–10. Although these references are not a complete survey of the literature, they show that a large effort has been made using this technique for determining local total energies. Each of the probes referenced has been designed for a specific application and, therefore, the designs represent compromises in such details as scaling, heat loads (convective, radiative, chemical), flight regime, type of atmosphere, density, etc., imposed by the particular application. Experience has shown that an enthalpy probe must be tailored to satisfy the particular range of state conditions of the plasma stream, and other restricting parameters (e.g., stream diameter, Mach number) which affect the accuracy of measurement. The enthalpies reported[2–10] ranged to 31 Mjoule/kg, and the present investigation extends this energy range in a low density supersonic plasma stream to 100 Mjoule/kg. Probe performance is illustrated with data from centerline measurements in a constricted-arc facility using argon, nitrogen, and air as test gases.

Two types of flow-swallowing probes were investigated. One was a blunt, or detached-shock probe, and the other a sharp-edged, or attached-shock system (mass-flow probe and transient heating-rate probe). The blunt probe has the advantage of inherently lower inlet heat-transfer rates. The attached-shock design has the advantages of an increased captured mass with the same over-all diameter (this sacrifices to some extent spatial resolution) and a well defined capture area. Experience with the two types of probes indicates that a relatively large capture mass is required to minimize the energy that enters the system that is not attributable to the captured mass. This tare heating rate, it will be shown, plays the major role in determination of local enthalpy for the conditions investigated.

Test Apparatus

Facility

The facility used for this experiment was a constricted-arc supersonic jet (Fig. 1). The plasma was generated by a direct current electric arc from the cathode, located in the plenum chamber, through a 1.27-cm-diam constrictor, or throat region, to 23 anodes located near the exit of a 15° half-angle conical supersonic nozzle. The system is completely water-cooled, and is capable of producing centerline enthalpies as high as 200 Mjoule/kg at corresponding freestream densities of 10^{-5} kg/m^3. The facility can operate with many reacting gases, provided a 5% inert shield gas-flow rate is supplied at the cathode. The plasma expands from the 1.27-cm-diam constrictor to an exit diameter of 15.4 cm. The freejet test chamber has a volume of approximately 1m^3. The facility permits 1-hr tests and thereby allows for adequate time to attain steady-state measurements at the low densities. For all tests described here, the measurements were made 2.5 cm downstream of the nozzle exit.

A bulk, or mass average, enthalpy was obtained for the plasma by applying a power balance to the complete system. Both the total power input and the losses were monitored for a given gas-flow rate, $\dot{m}_t$, to obtain a mass average enthalpy as determined by the equation

$$h_{AV} = VI/\dot{m}_t - \Sigma(c_{p_{H_2O}} m_{H_2O} \Delta T_{H_2O}/\dot{m}_t) \qquad (1)$$

Further details on the performance of this facility may be obtained from Ref. 1.

Flow-Swallowing Enthalpy Probes

There are problems associated with all methods of determining enthalpy. The flow-swallowing probe technique is no exception, although, in principle, it is a simple device. A known mass of gas is collected and its energy content is determined by conventional heating-rate methods. Practically, however, the high enthalpy stream of a plasma jet introduces a variety of complexities into the design and measurement techniques. At present, a universal probe that will cover the full enthalpy and pressure range that constricted-arc facilities are capable of producing does not exist.

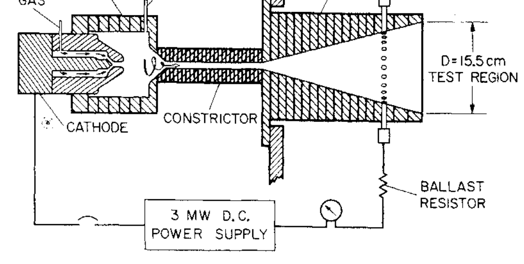

Fig. 1 Schematic drawing of the 1.27-cm-diam throat low-density constricted-arc supersonic jet.

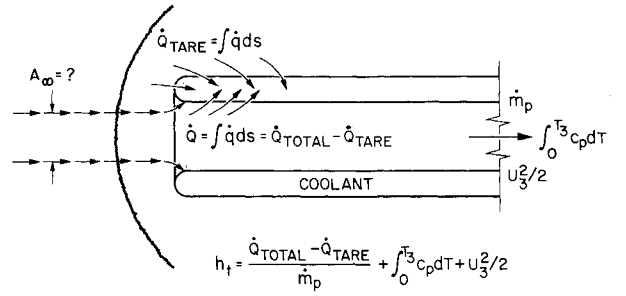

Fig. 2 Schematic drawing of the flow-swallowing enthalpy system.

Shown schematically on Fig. 2 are some of the conditions that must be satisfied for the successful application of flow-swallowing enthalpy probes. First, the captured plasma mass-flow rate must be determined accurately. Second, a probe power balance must account both for the energy, which is transferred internally through the probe walls into the coolant, and for the residual thermal and kinetic energies at the probe exit. When the working gas is air, provision should be made to account for the chemical energies which may be bound in the very slow reactions such as those for the various nitrogen oxides. In most probes, the total integrated heat absorbed by the walls includes a "tare" value, because not all of the heat can be attributed to the captured mass (i.e., external heating of the coolant enters as a tare). An energy balance applied to the probe points out the important quantities associated with the flow-swallowing enthalpy probe.

$$h_t = \frac{\dot{m}_{H_2O} c_{p_{H_2O}} [(T_{out} - T_{in})_F - (T_{out} - T_{in})_{NF}]}{\dot{m}_p} + \int_0^{T_3} c_p dT + \frac{U_3^2}{2} \qquad (2a)$$

or

$$h_t = \frac{\dot{Q}_{total} - \dot{Q}_{tare}}{\dot{m}_p} + \int_0^{T_3} c_p dT + \frac{U_3^2}{2} \qquad (2b)$$

One notes that the net heating rate to the probe coolant must be divided by the captured flow rate. In practice, it is difficult to assign a freestream tube area to the captured mass because both pumping rate and the shock-wave configuration influence the freestream tube area. Moreover, the location of the stream-tube stagnation line on the front surface, which divides the captured mass from the flow that is spilled, is not known. This accounts for a major uncertainty in the use of blunt probe designs. Because the heat-transfer rate in the inlet region is relatively very high, a large error can be introduced by improper assessment of the tare. Another requirement, apparent in Eq. (2), is that the total tare heating rate to the interior of the probe must be small to allow for the development of maximum temperature differences in the probe coolant. A further requirement is that the captured gas-flow rate be large enough to result in large differences between total and tare heating rates in order to attain a high precision of measurement. Local heat-transfer rates on the water sides of the probe cooling passages must be maintained below 10 kw/cm^2 to insure survival. The maximum coolant water temperature rise should not exceed the local boiling temperature, otherwise an error will occur because the latent heat of vaporization entrained in the two-phase flow cannot readily be accounted for by temperature measurements. These are the conditions that must

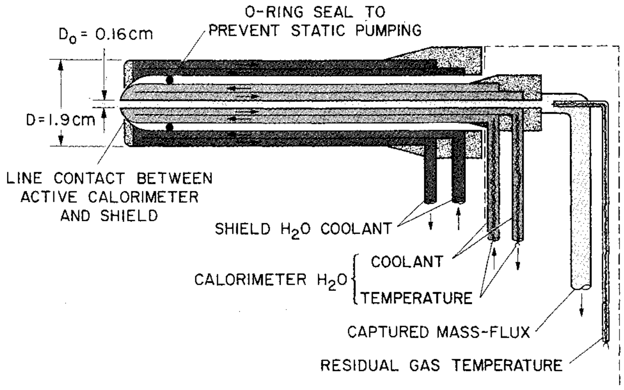

Fig. 3 Blunt or detached-shock flow-swallowing enthalpy probe.

be considered when flow-swallowing enthalpy probes are used. Some of the demands are contradictory. For example, an increase of bluntness to decrease inlet heating rates results in excessive spillage. Also, spatial resolution is sacrificed with increased capture area. Therefore, two types of probes, blunt and sharp, were considered in this study.

Blunt Enthalpy Probe

A shrouded, detached-shock, flow-swallowing enthalpy probe was evaluated in the low-density facility. Although it was not possible to measure the enthalpy of the stream accurately because the probe was not optimized for the test conditions in this facility, a brief review of its design features may be helpful as a guide to improvement of future designs. Figure 3 is a schematic drawing of the blunt probe. The over-all diameter was 1.9 cm, and the active tube diameter was 0.16 cm. The energy of the captured plasma was transferred into a water jacket that surrounded the active tube. The captured gas was pumped through a 0.63-cm-diam tube for approximately 250 tube diameters where the mass flux was measured with a calibrated venturi. The probe water passage had thermocouples at both the coolant inlet and outlet to measure the water temperature rise over the active (inner) section of the calorimeter. Distilled water was bled from a constant-press storage vessel (to eliminate pulsations) through a calibrated venturi to obtain a coolant flow rate. The venturi was capable of measuring water-flow rates from 0 to 9 gm/sec with less than 2% error. The active calorimeter was surrounded by an outer water-cooled shield to reduce the tare resulting from convective heating of the external surface. The water was in parallel flow between the active passage and outer shield to further minimize the tare heating rate. In the stagnation region, as shown in Fig. 3, a shroud extended inward to a diameter of 0.3 cm where it touched the active calorimeter surface in line contact.

Attached-Shock Enthalpy Probe System

The probes in this system have a supersonic inlet with an attached shock. The sharp leading edge will survive the high-energy plasma environment at low densities because slip flow effects on the leading edge reduce the local heat-transfer rate. To simplify the design, two probes were made as shown in Fig. 4. One probe measured mass flow under steady-state conditions, and the other measured the total energy of this captured mass on a transient basis. For each test point, both probes were traversed into the plasma stream at the nozzle exit in succession.

The 2.54-cm-diam inlet of the mass-flow probe has a 15° convergent ramp followed by a cylindrical section and a divergent conic section, all of which is water cooled. The external surface of the lip also has a ramp angle of 15°. The captured mass is pumped through a heat exchanger to cool the gas temperature to near ambient (20°C) in order to maintain the Reynolds number through the venturi system within calibration limits ($240 < Re < 320$). The venturi was calibrated at its normal operating pressure of 1 to 3 torr against a laboratory standard rotometer. The inlet converges the stream through a contraction ratio of 1.17 for a distance of one inlet diameter. The flow then expands through a 15° half-angle conic section to a diameter of 3.8 cm and flows through a cylinder 64 cm long. The 64 cm length was required to extract most of the heat energy from the captured mass. The internal shape is exactly the same for both probes.

The sharp inlet probe design has several advantages over the blunt or detached-shock probe. The inlet area was 250 times the capture tube area on the blunt probe, which provided a greater captured mass. Equally important, provided that the flow is swallowed supersonically, the sharp lip with attached shock gives a known free-stream capture area without correction. Geometric symmetry was designed into the lip, which has a line contact between the 15° conical external ramp and 15° convergent internal ramp (see insert 1 in Fig. 4b). With this arrangement the tare heating rate by conduction was virtually eliminated, and the requirements for accurate instrumentation at the leading edge were thereby reduced. The wall thickness of the calorimeter was 0.127 cm in the convergent, throat, and divergent section. The calorimeter is instrumented with 0.0127-cm-diam copper-constantan thermocouples spaced at 0.25-cm intervals in the axial direction and circumferentially spaced at 45° intervals to account for any asymmetry in the captured plasma. The subsonic cylindrical afterbody of the calorimeter duct has a 0.165-cm-thick copper wall with thermocouples located every 2.54 cm in the axial direction, again spaced circumferentially at 45° increments around the cylinder. The transient response time for one-dimensional heat-transfer rate was estimated to be approximately 40 msec.[11] With this calorimeter system, the total energy transferred from the captured flow is obtained from the integrated heating rate. Therefore, even though local heat-transfer rates are affected by longitudinal conduction in the calorimeter, the total heating rate is not affected. The energy transfer between the shield and active surfaces of the transient calorimeter was assumed to be zero because of symmetry in the lip region between the shield and active surface provided zero heat-transfer gradient at the line contact point. This assumption is valid if the leading edge is exposed to symmetric heat loads and if the wall thicknesses for the copper surfaces in the region of high heat-transfer rate

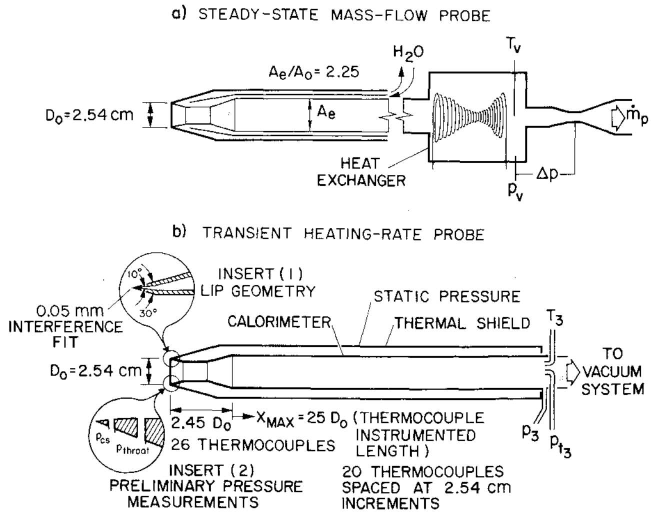

Fig. 4 Attached-shock, flow-swallowing enthalpy system; contraction ratio = 1.17.

near the lip are identical. This feature produces a minimum temperature difference between surfaces.

The thermocouple wire of 0.0127-cm diam minimized conductive heat loss into the wire. The 0.159-cm-thick calorimeter shroud had a copper forebody and a brass afterbody. The space between the active calorimeter was maintained at test static pressure by venting through the probe sting. The cold junctions of the thermocouples were maintained at ambient temperature. An average specific heat of 440 joule/kg °K was assigned to the copper calorimeter.[12] The exit of the subsonic cylindrical section was instrumented with impact and static pressure sensors and an unshielded stagnation temperature probe to measure residual energy in the discharge gas from the calorimeter.

Each thermocouple was assigned a specific calorimeter volume based upon the thermocouple spacing. Thus, the heating rate to the calorimeter in the vicinity of each thermocouple was determined from

$$\dot{Q}_i = m_i c_{p_i}(dT_i/dt) \tag{3}$$

A summation of the heating rates to the 46 individual elements gives a total heating rate to the entire calorimeter

$$\dot{Q}_t \simeq \sum_{i=1}^{46} m_i c_{p_i} \frac{dT_i}{dt} \tag{4}$$

Conductive tare heating rate was minimized at the sharp leading edge by building symmetry into the contact point between the copper shroud and active surface as shown in insert 1 of Fig. 4b. The shroud over the active calorimeter shields it from the freestream plasma and reduces the convective and radiative tare heating rates. These two features reduced the total tare heating rate essentially to zero, thereby allowing the assumption

$$\dot{Q}_{\text{tare}} = 0 \tag{5}$$

The total stream enthalpy is then the total heating rate divided by the captured mass-flow rate plus the residual enthalpy (internal plus kinetic energy).

$$h_t = \frac{\dot{Q}_t}{\dot{m}_p} + \int_0^{T_3} c_p dT + \frac{U_3^2}{2} \tag{6}$$

In preliminary tests both the contraction ratio and lip angle for attached flow and the maximum stream energy which a sharp leading edge would withstand were determined. The copper leading edge survived in a stream where a stagnation-heat-transfer rate of 2 kw/cm² was measured at the stagnation region of a 2.5-cm-diam hemisphere. A transient inlet with pressure taps located as shown in insert 2 of Fig. 4b established that supersonic flow existed in the throat section, and thus, that an attached shock existed at the lip.

Results and Discussion

No meaningful enthalpy could be measured with the blunt probe in the low-density plasma flow because of the small captured mass flux and the relatively large tare heating rate. The largest error occurred in the evaluation of the tare heating rate with no captured flow because of uncontrollable changes in the shock position and streamlines in the stagnation region where the maximum heating rate occurs. The blunt probe was also tested in a second constricted-arc facility in which the stream density was approximately 30 times greater than that in the facility used for this present investigation. The higher density tests were initiated in an attempt to obtain higher flow rates and reduce the uncertainty in enthalpy determination in the low-density tests. The integrated mass average enthalpy determined by the higher density tests was 5 to 30% lower than the value obtained by means of gross power balance for this facility. In these tests the tare heating-rate term accounted for 5 to 50% of the total heating rate. At the higher density, the blunt probe gave realistic values of all measurements. In contrast, the results of tests in the low-density facility showed a tare heating rate equal to 99% of the total value. The largest differences in the tare heating-rate measurement for the two conditions of density occurred because of changes in the shock standoff distance and changes in the local stream gradients at the stagnation region when the probe was operated in the no-flow condition. Because the maximum captured plasma flow rate was only 200 μg/sec for the low-density tests, it is evident that even a very small error in the tare heating-rate measurement will introduce a large error in enthalpy. To obtain valid local enthalpy determinations in the low-density stream, it is believed that the captured mass flux should be increased approximately 40 times. If the capture tube diameter of the blunt probe were increased to 1 cm, an accuracy of 70% or greater on the integrated enthalpy should be achievable in the low-density stream. It should be noted that any increase in captured stream tube area to increase the mass flux through any probe will decrease the spatial resolution.

Preliminary tests with the attached-shock heat-transfer probe indicated that a minimum length of 15 inlet diameters was required to convert all forms of energy in the nitrogen plasma to thermal and kinetic energy. After the gas traversed this length, its stagnation temperature was reduced to 525°K or lower in argon and 340°K or lower in nitrogen. Thermal energy of the gas was reduced to 0.43 Mjoule/kg or less.

The impact and static pressures at the exit of the calorimeter indicated a velocity of approximately 0.1 km/sec. The corresponding Mach number was 0.3 and the maximum residual kinetic energy was 0.06 Mjoule/kg. Thus, the energy transferred to the calorimeter surface from the captured mass flow, as the stream energy ranged from low to high values, varied from 94 to 99.5% of the total energy swallowed, respectively. The steady-state mass-flow probe gave mass-flow rates repeatable to within 5%.

A critical item in the employment of the sharp-lip probe is to establish whether or not the flow enters the inlet supersonically. If so, the metered flow through the probe can be directly related to a geometrically defined stream tube. Three criteria were used to determine whether or not the system was operating as a supersonic inlet. The first was to utilize static-pressure measurements on the internal compression surface and at the throat, and a stagnation pressure measurement at the probe exit. (The auxiliary model of Fig. 4b, insert 2, was actually used for this test.) The ratio of p_{cs}/p_{t_2} was 0.46 and $p_{\text{throat}}/p_{t_2}$ was 0.42 in a nitrogen plasma. If the pressure p_{cs} is considered to arise from a two-dimensional 15° compression surface, both of these ratios would provide supersonic flow in the throat at freestream Mach numbers greater than 1.5. A second argument in favor of an attached-shock wave was the high local heat-transfer rate measured at the junction of the internal expansion and the cylindrical afterbody, which indicates the presence of a terminal shock (Fig. 5). The third argument indicating that the shock wave was attached is that, when integrated, radial surveys of local mass flux captured by the probe agreed with an independent measurement of the total mass flux through the system.

The local centerline enthalpy in the test section was determined by means of Eq. (6) and data from both the mass-flow and the transient heating-rate probes. The local enthalpy so determined, normalized with respect to the mass average enthalpy determined from the power balance on the entire arc-heater system, is shown in Fig. 6. The scatter in these enthalpy ratio determinations is less than 10% over the mass average enthalpy range of 15 to 50 Mjoule/kg for nitrogen. The measurement errors are assessed in Table 1.

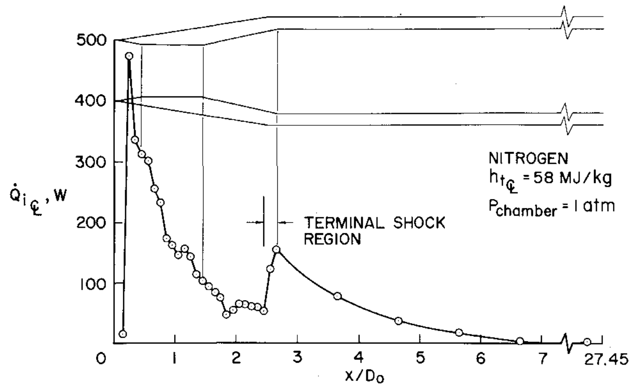

Fig. 5 Variation of heating rate along the transient flow-swallowing calorimeter, D_0 = 2.54 cm.

The ratio of centerline to average enthalpy decreases from 2.4 at 15 Mjoule/kg to 1.9 at 50 Mjoule/kg mass average enthalpy level. Theoretical analyses[13] of the arc constrictor predict this same trend. However, the results giving the ratio of centerline to mass average enthalpy may be typical only of the particular arc heater used in the investigation.

The centerline to mass average enthalpy ratio was essentially unchanged when an air atmosphere was used instead of pure nitrogen. Increasing the plenum chamber pressure from 1 to 2 atm in the nitrogen plasma had no effect on the ratio of centerline to average enthalpy; but reducing the pressure from 1 to 0.5 atm reduced the ratio by 14%.

In addition to enthalpy measurements, the stream velocity and density in the freejet plasma were obtained from the local stagnation pressure, freestream static pressure, and the local captured mass flow. Because the stagnation pressure behind the shock wave was measured with an impact probe, the following relations can be combined to obtain the freestream velocity and density. The continuity equation for the mass-flow probe with an attached shock, where $A_0 = A_\infty$, is

$$\rho_\infty U_\infty = \rho_2 U_2 = \dot{m}_p/A_0 \tag{7}$$

The momentum equation across the shock is

$$p_\infty + \rho_\infty U_\infty^2 = p_2 + \rho_2 U_2^2 \tag{8}$$

and if the flow between the shock and the body in the stagnation region is assumed to be incompressible

$$p_{t_2} = p_2 + \tfrac{1}{2}\rho_2 U_2^2 \tag{9}$$

The density and velocity are determined from Eqs. (7), (8), and (9) to be

$$\rho_\infty = (\dot{m}_p/A_0)^2\{[1 - (\rho_\infty/2\rho_2)]/(pt_2 - p_\infty)\} \tag{10}$$

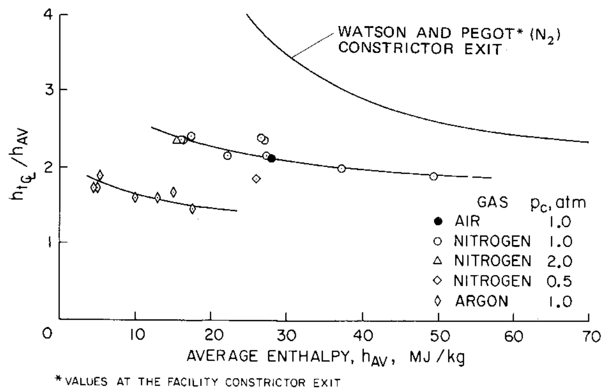

Fig. 6 Ratio of centerline total enthalpy to average enthalpy vs average enthalpy in the constricted-arc facility.

Table 1 Precision of measurements summary

Value	Method	Maximum error, %
ρU	Calibrated venturi	5
$h_{t℄}$	Enthalpy probe system	12
p_{t_2}	Pressure transducer	5
p_{static}	McLeod gage	15
ρ_∞	Derived; Eq. (10)	11
U_∞	Derived; Eq. (11)	11
ρ_∞/ρ_2	Derived; Eqs. (10), (14)	12
h_{AV}	Over-all power balance	8

and

$$U_\infty = (A_0/\dot{m}_p)\{(p_{t_2} - p_\infty)/[1 - (\rho_\infty/2\rho_2)]\} \tag{11}$$

The density ratio across the shock is the only term to be evaluated for obtaining the density and velocity. The density ratio can be obtained by an iterative process which will satisfy both the momentum and continuity relations where

$$p_2 = p_{t_2} - (p_{t_2} - p_\infty)\{(\rho_\infty/2\rho_2)/[1 - (\rho_\infty/2\rho_2)]\} \tag{12}$$

and

$$p_{t_2} = p_\infty + \rho_\infty U_\infty^2[1 - (\rho_\infty/2\rho_2)] \tag{13}$$

The first approximation for obtaining freestream density is to assume that U_2 is small and thereby $p_{t_2} \simeq p_2$; then the density behind the shock can be obtained from the equation of state

$$\rho_2 = p_2/Z_2RT_2 \tag{14}$$

where Z_2 and T_2 are determined from equilibrium gas tables[14,15] using the local total enthalpy. This first approximation for the density ratio is applied to Eq. (12) to obtain p_2 from which new values of ρ_2 and ρ_∞ can be obtained. The values converge in three iterations. The appendix discusses details of errors in these calculations.

With the density ratio determined, the centerline velocity of the freejet plasma shown in Fig. 7 was obtained as a function of centerline enthalpy. The curve, presented for comparison, represents the maximum centerline velocity that could be obtained if all the stream energy were converted to kinetic form. The centerline freestream density obtained from the attached-shock mass-flow probe measurements is shown in Fig. 8, again as a function of centerline enthalpy. For constant plenum chamber pressure, the density decreases from 10^{-4} kg/m^3 as the enthalpy increases in argon. The density measurements in nitrogen at higher enthalpy levels approach an asymptotic value of 1.5×10^{-5} kg/m^3. The two dashed lines on Fig. 8 indicate the extrapolations of the data obtained for each gas by applying molecular weight corrections to the other gas.

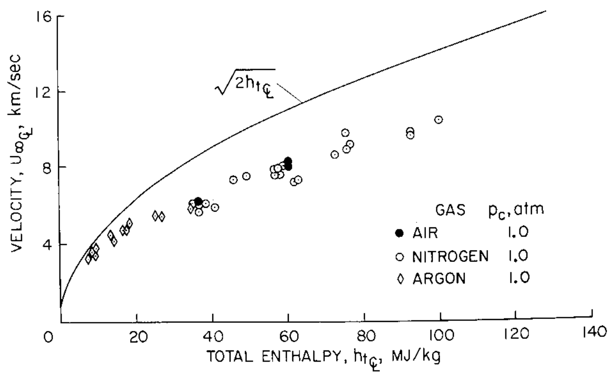

Fig. 7 Variation of centerline velocity with local total enthalpy in the constricted-arc facility.

The velocity for the nitrogen atmosphere was also determined by assuming an isentropic nozzle flow process. The centerline value of the total enthalpy as determined by the enthalpy probe system was used as the plenum chamber total enthalpy along with the measured plenum chamber total pressure to determine an equilibrium value for entropy. A constant entropy expansion process was followed to the measured freestream static pressure by means of data from Ref. 5. A check of the power losses to the nozzle wall and electrical power input in the supersonic nozzle shows that the two values are approximately equal for all operating conditions encountered in this investigation. Thus, adiabatic flow in the nozzle is closely approximated. This result can be seen in Fig. 9, which presents the centerline velocity as a function of the centerline stream total enthalpy for nitrogen. The calculated results agree very well with the results determined from the probe system. That the results agree so well seems to be fortuitous.

Two other calculations for the determination of the centerline velocity are also presented in the figure. When the gas was considered to be fully frozen at chamber conditions, the calculated kinetic energy was always lower than the measured value but followed the same trend. In the other flow model, it is assumed that the dissociation energy is frozen at the chamber conditions but all the ionization energy is allowed to be converted to kinetic form in the freestream. The bases for this flow model are the facts that molecular recombination rate is slow as compared to the de-ionization rate[16] and the nozzle transit time is from 50 to 80 μsec. This calculation results in velocities which are low in the low enthalpy range and too high in the range of enthalpies above 60 Mjoule/kg. According to the measured velocities, approximately half of the total energy in the test stream is in thermal and chemical forms.

A mechanism that possibly explains why the measured velocities agree with equilibrium calculations is the ionization of molecular nitrogen. According to Ref. 17 the activation energy for the molecular ionization process is 8.6 ev less than that for the atomic ionization process as referenced from the ground state. Furthermore, the reaction rate constants are both of the order 10^{-27} cm^6/sec. Consequently, both atomic and molecular ions might form in the arc constrictor. In the nozzle, an exothermic reaction is postulated, which provides a mechanism for recovering the energy existing in N_2^+

$$N_2^+ + e^- \rightarrow 2N + 5.9 \text{ ev (Refs. 16 and 17)}$$

This reaction can account for higher kinetic energy in the nozzle.

Sufficient chemical energy can be released to account for the difference between calculated frozen and measured kinetic energy shown in Fig. 9 if the reactive molecular ions are 11% of the total mass. It should be noted that only 5.9 ev of the original 15.6 ev chemical energy was released

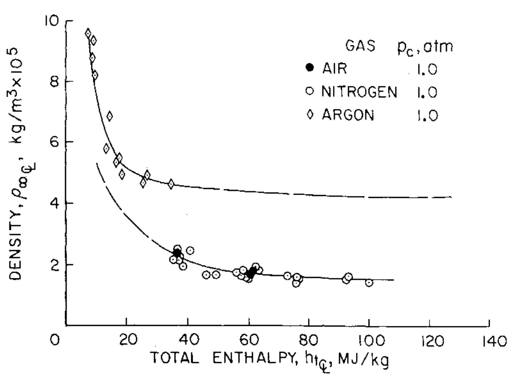

Fig. 8 Variation of centerline density with local total enthalpy in the constricted-arc facility.

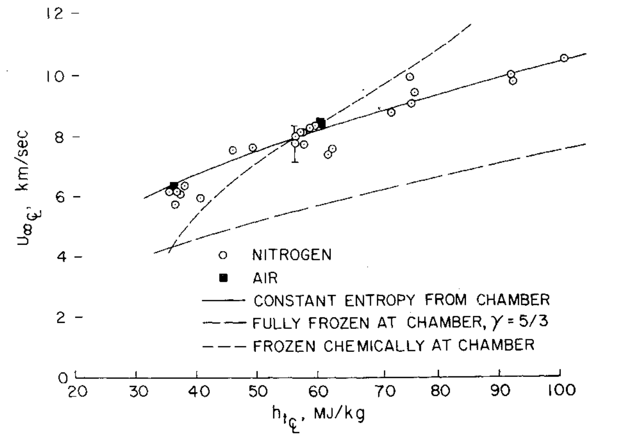

Fig. 9 Variation of centerline velocity for a nitrogen atmosphere with local total enthalpy in the constricted-arc facility.

to increase the plasma velocity. This is in agreement with the rate equations since the atom-molecular reaction rates are five to seven orders of magnitude slower than the ion recombination rates. Spectrographic measurements of the gas in the test region confirm the existence of N_2^+ in this arc facility. Furthermore, heat-transfer measurements on catalytic and noncatalytic surfaces show that the stream is frozen with larger amounts of atomic nitrogen than can be attributed to reactions in the shock layer for freestream species corresponding to calculated equilibrium values.

Conclusions

Local values of enthalpy, density, and velocity were measured with flow-swallowing probes in plasma streams of argon, nitrogen, and air at enthalpy levels up to 100 Mjoule/kg. Two probe designs were studied: 1) a blunt, detached-shock probe and 2) a sharp-lip, attached-shock probe. At low densities, which are characteristic of high enthalpy supersonic plasma jets, the attached-shock probe gave repeatable data for all parameters measured. An error analysis on the attached-shock probe for obtaining local enthalpy yielded a maximum error of 12%. This probe system has the advantage of capturing a known freestream area, thereby allowing the local kinetic energy and density to be determined accurately. Survival of the sharp-lip probe is promoted at high enthalpies by slip-flow effects on the leading edge. This probe functions in a plasma stream where stagnation heat-transfer rate was no greater than 2 kw/cm^2 on a 1.27-cm-radius hemisphere. The blunt probe did not produce satisfactory data at low density because of a very large tare heating rate associated with a relatively small captured mass flux. However, the blunt probe used for these tests was not optimized for the facility operating conditions as was the attached-shock probe. The improvement in performance which could accrue by increasing the captured mass was indicated by limited tests at a density level 40 times that of the low-density stream. Under these conditions, the blunt probe uncertainty decreased from 100 to 30%.

Nitrogen and air plasma exhibited essentially the same properties although their detailed compositions are different. However, because residual chemical energies in the form of nitrogen oxides possibly present in the cooled air plasma were not evaluated, air and nitrogen plasmas should be compared with reservation.

Appendix

Error Considerations

An examination of the data for maximum possible errors resulting from the inaccuracy of the measuring devices, recording instruments, and assumptions led to the results in Table 1. In general, large errors result from using conventional measuring devices under conditions of low density where output is low. The values in Table 1 are representative of state-of-the-art laboratory equipment.

The stream momentum, ρU, was determined from the gas-flow rate through the probe and the probe capture area. The flow rate was determined by a venturi which was calibrated (2% error) at the exact operating temperature, pressure, and flow rate encountered during the actual tests. This error, combined with a maximum error of 3% for the entire pressure-sensing and recording system, gives a maximum error of 5%. This same method of estimating errors on the impact pressure and static pressure of the test chamber resulted in the errors as tabulated. Determining the stream total enthalpy required the use of the determined gas flow rate and the heating rate to the calorimeter and a summation to determine the total heat input to the calorimeter. The accumulation of the possible errors introduced here resulted in an estimated maximum error of 12%.

A very small error resulted from the assumption of incompressibility between the shock and the body. The binomial expansion of the relationship for total pressure behind the shock

$$p_{t_2} = p_2\{1 + [(\gamma - 1)/2]M_2{}^2\}^{\gamma/(\gamma-1)} \qquad \text{(A1)}$$

where

$$M_2{}^2 = \rho_2 U_2{}^2/\gamma p_2$$

resulted in

$$p_{t_2} = p_2 + \tfrac{1}{2}\rho_2 U_2{}^2[1 + (M_2{}^2/4) + \ldots] \qquad \text{(A2)}$$

Substituting this relation into the normal shock momentum equation

$$p_\infty + \rho_\infty U_\infty{}^2 = p_\infty + \rho_2 U_2{}^2$$

with the use of the continuity equation

$$\rho_\infty U_\infty = \rho_2 U_2$$

resulted in the following equation:

$$p_{t_2} - p_\infty = \rho_\infty U_\infty{}^2 \left\{1 - \tfrac{1}{2}\frac{\rho_\infty}{\rho_2}[1 - (M_2{}^2/4) - \ldots]\right\} \qquad \text{(A3)}$$

The error introduced to $(p_{t_2} - p_\infty)$ when the incompressible relation behind the shock was used to obtain

$$p_{t_2} - p_\infty = \rho_\infty U_\infty{}^2[1 - (\rho_\infty/2\rho_2)] \qquad \text{(A4)}$$

is less than 0.5% if M_∞ exceeds 3.

The method for obtaining the stream velocity required the use of the equation

$$U_\infty = (p_{t_2} - p_\infty A_0)/\dot{m}_p[1 - (\rho_\infty/2\rho_2)]$$

Thus, the derivation of the freestream velocity results in an estimated maximum error of 11%. The same analysis holds true for the freestream density, so its estimated maximum error is also 11%.

The determination of the density ratio across the shock used an equilibrium value for the density behind the shock based on the total stream enthalpy and the stagnation pressure. The error involved in this process is again of the order of 12%. However, the actual density behind the shock may be considerably lower than the equilibrium value because of nonequilibrium effects. Large errors in the density ratio, however, affect the determination of the freestream velocity and density only slightly.

The mass average enthalpy h_{AV} was determined by a heat balance on the total power input and power losses in the facility. The error involved is no greater than 8% with maximum error at the low power levels. The effect of the induced magnetic field (with the axial current) inside the constrictor and nozzle of the arc facility has been considered and found to have a negligible effect on the stream velocity. Radiation effects were examined and found to be small, less than 0.3% of the total energy of the captured stream tube.

References

[1] Stine, H. A., Watson, V. R., and Shepard, C. E., "Effect of Axial Flow on the Behavior of the Wall-Constricted Arc," AGARD Specialists' Meeting on Arc Heaters and MHD Accelerators for Aerodynamic Purposes, Rhode-Saint-Genese, Belgium, Sept. 21–23, 1964, pt. 1, pp. 451–485.

[2] Grey, J., Jacobs, P. F. and Sherman, M. P., "Calorimetric Probe for the Measurement of Extremely High Temperatures," *The Review of Scientific Instruments*, Vol. 33, No. 7, July 1962, pp. 738–741.

[3] Grey, J., "Thermodynamic Methods of High-Temperature Measurements," *ISA Transaction*, Vol. 4, No. 2, April–June 1965, pp. 102–115.

[4] Christensen, D. and Buhler, R. D., "Arc Jet Tunnel Development and Calibration for Re-entry Simulation," 1 FR011-1872, 3 June 1961, Plasmadyne Corp., Santa Ana, Calif.

[5] Vassallo, F. A., "Miniature Enthalpy Probes for High Temperature Gas Streams," ARL 66-0115, June 1966, Cornell Aeronautical Lab., Buffalo, N.Y.

[6] Vassallo, F. A., "A Fast Acting Miniature Enthalpy Probe," AIAA Paper 68-391, San Francisco, Calif., 1968.

[7] Potter, J. L., Arney, G. D. Jr., Kinslow, M., and Carden, W. H., "Gasdynamic Diagnosis of High-speed Flows Expanded from Plasma States," AEDC TDR-63-241, Nov. 1963.

[8] Esker, D. W., "A Probe for Total-Enthalpy Measurements in Arcjet Exhausts," *AIAA Journal*, Vol. 5, No. 8, Aug. 1967, pp. 1504–1506.

[9] Fischer-Schlemm, W., "Sonden zur Messung von Enthalpie und Druck hocherhitzter Gase," Deutsche Luft- und Raumfahrt (Res. Rept. 67-17) Deutsche Versuchsanslalt fuer Luftond Raumfahrt, Stuttgart, West Germany, March 67 (NASA TT F-11, 486).

[10] Huber, F. J. A., "Probes for Measuring Mass Flux, Stagnation Point Heating, and Total Enthalpy of High Temperature Hypersonic Gas Flows," AIAA Paper 66–750, Los Angeles, Calif., 1966.

[11] Carslaw, H. S. and Jaeger, J. C., *Conduction of Heat in Solids*, 2nd ed., Oxford University Press, London, 1959.

[12] Goldsmith, A. and Waterman, E. E., *Handbook of Thermophysical Properties of Solid Materials: Elements* revised ed., Vol. 1, Macmillan, New York, 1961.

[13] Watson, V. R. and Pegot, E. B., "Numerical Calculations for the Characteristics of a Gas Flowing Axially through a Constricted Arc," TN D-4042, 1967, NASA.

[14] Sewell, K. G., "The Thermodynamic Properties of High Temperature Nitrogen," LTV Research Center Rept. 0-71000/2R-25, July 1962.

[15] Sewell, K. G., "The Thermodynamic Properties of High Temperature Argon," LTV Research Center Rept. RE-1R-26, Oct. 1961.

[16] Eschenroeder, A. Q., Daiber, J. W., Golian, T. C., and Hertzberg, A., *Shock Tunnel Studies of High-Enthalpy Ionized Airflows in the High Temperature Aspects of Hypersonic Flow*, edited by W. C. Nelson, Macmillan, New York, 1964.

[17] Nawrocki, P. J. and Papa, R., *Atmospheric Processes*, Prentice-Hall, Englewood Cliffs, N. J., 1963.