phenomena. Future development of strong interaction theories awaits acquisition of more detailed experimental data on conductive turbulent shear flows in the presence of magnetic fields.

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Recombinations in the Decay of Argon Plasma Jet Surrounded by Ar, He, N_2, and H_2 Gases

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Nomenclature

i = double probe current
k = thermal conductivity
k_B = Boltzmann constant
m_i = mass of species i
n_i = number density of species i
Q_{ij} = collisional cross-section of the pair $i-j$
r = cylindrical coordinate
T = local thermal equilibrium temperature
$T_{\mathfrak{c}}$ = centerline temperature
T_e = electron temperature
T_h = heavy-particle temperature
t = time
u_I = ionization energy
V = potential difference between the wires of double probe
x = cylindrical coordinate, cm
α = degree of ionization
ϵ = correction factor

Subscripts

1 = argon atom
2 = argon ion
3 = electron
∞ = infinite

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Introduction

WHEN a plasmajet is ejected into different surrounding gases, the degree of ionization and temperature profiles vary characteristically. Temperature and velocity fields depend on the type of surrounding gas. An important aspect of plasma chemistry is to investigate the decay of the centerline temperature and mole fraction, or the variations of the state of a recombination reaction.

Several authors have studied the interaction between a plasmajet and a single surrounding gas. Grey et al.[1] investigated the interaction between an atmospheric argon plasmajet and a coaxial flow of helium gas at 500°R, and attempted to analyze jet mixing and heat transfer. Smith et al.[2] ejected an argon plasmajet into atmospheric nitrogen gas flow and optically measured the temperature of argon atoms and nitrogen molecules, individually.

In this study, a laminar plasmajet is ejected into several types of coaxial gas flows at low pressure. The decay of centerline temperature and mole fraction are measured, and the recombination reaction in the plasmajet is investigated.

Experimental

The plasmajet generator is located at the bottom of a vacuum tank (0.5 m diam × 1.5m length). The plasmajet is ejected upward through a 20-mm-diam nozzle. A coaxial gas flow is ejected upward through a coaxial nozzle of 40-mm diam.[3] The jet axis and the radius of the jet are denoted by x and r, respectively, with the origin at the exit plane of the plasmajet nozzle. The flow rates of the plasmajet and coaxial gas flow are 4 and 11 l/min, respectively.

The d.c. plasmajet generator is constructed of an 8-mm-i.d. copper anode nozzle and a 6-mm-o.d. tungsten cathode rod.[3] Argon gas is allowed to flow for ½ hr prior to and ½ to 1 hr following ignition to substitute for residual gas and to stabilize the arc. Ar(100%), He(100%), N_2(100%), or H_2(25%) + Ar (its purity is 10^{-4}) is used for the coaxial flow. In each case, the chamber pressure is kept constant at 507 Pa.

An electron temperature T_e was measured by a double probe. The probe is constructed of two parallel platinum wires (0.2 mm diam × 150 mm long, 2 mm separation) and a support, which are insulated electrically from the plasma. The probe can be traversed through the plasmajet. The current i between the two wires is measured as a function of the potential difference V and the position. The measured values of the probe current are transformed to the r distribution values by the well-known Abel integral equation; then we can obtain the radial distribution of the electron temperature.[4]

A water-cooled 2-mm-i.d. tube is used as a sampling probe to measure the mole fraction. Low gas sampling rates are maintained in order not to affect the values of mole fraction. The sampled gases are first drawn into a 3000-cc buffer bulb and introduced into a measurement section; then its mole fraction is measured by a gas chromatograph.

Theory

We calculate exact numerical solutions for the simple case of argon coaxial flow using exact properties,[5] and similarity solutions for the other cases, using rather approximate values for the properties.

Numerical solutions are based on conventional conservative equations and assumptions; boundary-layer approximation, ambipolar diffusion, no pressure gradient, and so on. Von Mises transformation[1] is employed; convergence was rapid. The initial conditions are given at $x=0.5$ by observed r values of dynamic pressure and electron temperature, etc.

For recombining flow, argon ion-electron recombination rate in the species conservation equation is given by the ordinary three-body recombination:

$$Ar^+ + e^- + e^- \rightarrow Ar^* + e^- \tag{1}$$

and its rate constant is given by Hinnov et al.[6] multiplied by

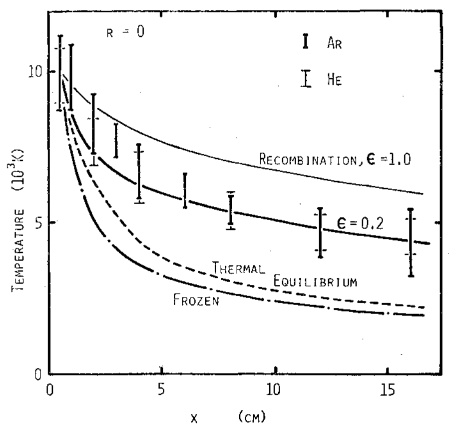

Fig. 1 Numerically calculated and observed temperature distributions for argon and observed for helium.

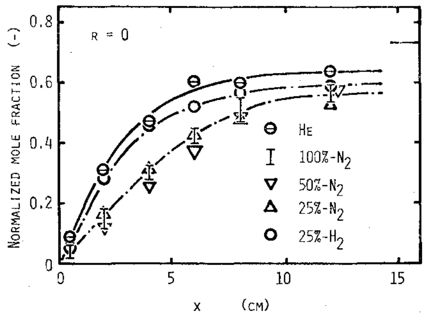

Fig. 2 Mole fraction distributions.

the correction factor ϵ. When the recombination is frozen, the recombination rate is zero. When the recombination is thermal equilibrium, the species conservation equation is replaced by Saha's equation.

Electron temperature T_e is not equal to heavy-particle temperature T_h in the case of the low-density plasmajet. Two-temperature-type properties have not been calculated sufficiently, although a few reports[7,8] have dealt with this. In the case of a small degree of ionization, T_e may be obtained as follows. Temperature T is calculated as $T_e = T_h$ at first, using one-temperature-type properties. Then the difference of T_e and T_h is evaluated from

$$n_3\left(\sum_{i\neq 3} Q_{3i}n_i\right)\sqrt{\frac{8k_BT_e}{\pi m_3}}\,\frac{2m_3}{m_I}\,\frac{3}{2}\,k_B(T_e-T_h) = -u_I(n_I+n_2)\frac{\mathrm{d}\alpha}{\mathrm{d}t} \qquad (2)^{[8]}$$

where T_h is substituted by T, calculated as in the preceding. The resulting T_e is shown with a solid line in Fig. 1.

On the other hand, similarity solutions[9] are obtained by assuming boundary-layer approximation, constant heat and momentum flow with respect to x, and simple temperature dependency of thermal conductivity (k for argon and argon-rich mixture gases $\sim T^2$). The decay of centerline temperature $T_{℄}$ is given by

$$\log(T_{℄} - T_\infty) = -\tfrac{1}{3}\log k - \tfrac{1}{3}\log x + \text{const} \qquad (3)$$

Experimental and Analytical Results

Mole fraction distributions are plotted on Fig. 2. The ordinate is mole fraction normalized by its initial value. In each case, the values above $x = 6$ or 9 reach a constant value. This saturation is explained by the fact that the amount of gas flow is finite in comparison with that of the plasmajet. The correct saturation value is 0.73, and is shown by a straight segment on the upper right corner of Fig. 2.

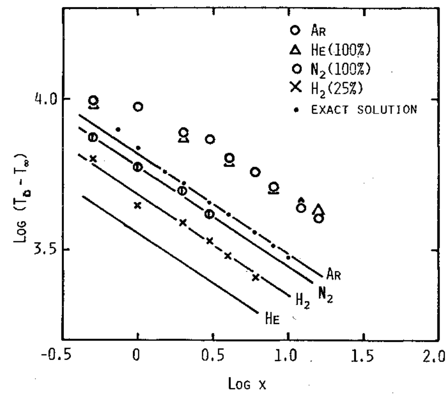

Fig. 3 Similarity solutions and observed values of Ar, He, N_2, and H_2, and numerical solution of Ar.

Observed Ar and He electron temperatures T_e, and numerically calculated T_e and $T(=T_e=T_h)$ distributions of Ar are shown in Fig. 1. Solid, broken, and one-dotted lines are numerical solutions calculated for finite recombination, thermal equilibrium, and frozen, respectively. Vertical bars indicate observed values. Temperatures T $(=T_e=T_h)$, calculated for frozen and thermal equilibrium, decrease abruptly, whereas the observed T_e does not decrease as much, and shows rather a large change above the frozen and thermal equilibrium values. T_e observed in argon is consistent with T_e calculated with $\epsilon = 0.2$.[3] This means the ordinary three-body recombination dominates in the case of argon.

However, in case of nitrogen and hydrogen in Fig. 3, observed T_e equals T_h calculated by Eq. (3). This means that the type of the recombination reaction of nitrogen and hydrogen differs from that of argon. Considering the fact that observed T_e of diatomic gas differs, we can presume that the recombination reaction of diatomic gas is

$$\mathrm{Ar}^+ + e^- + M_2 \rightarrow \mathrm{Ar}^* + 2M \qquad (4)$$

which does not lead to a large change in T_e.

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