An Investigation of Nonequilibrium Effects in an Argon Freejet Plasma

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Theme

NONEQUILIBRIUM effects present in the formation of a shock wave in a low density, slightly ionized flow, particularly as evidenced by the appearance of a dark region preceding the shock wave, have been analyzed both theoretically and experimentally. A theoretical model for the shock wave predicted a precursor region of high electron temperature. An experimental investigation was performed in an arc heated freejet flowfield. Electron temperature and ion density were measured through the normal shock wave in front of a cooled blunt body using a new type of cooled Langmuir probe. The existence of a precursor region of elevated electron temperature coincident with the observed dark region was experimentally verified.

Content

It can be shown that in weakly ionized gases a heavy particle shock wave is unaffected by the presence of charged particles. The ion specie property variations tend to follow those of the neutral specie, and the electrons are bound closely to the ions through strong electrostatic forces. The electron density variation is then forced to follow the ion density variation through the shock wave and the electrons are compressed. Since the electrons are very subsonic their flowfield cannot support a jump in properties across the heavy particle shock, and their temperature distribution through the shock wave tends to be very broad. Because of the high electron thermal conductivity the electrons readily transfer energy from the downstream side of the shock upstream, thus raising the electron temperature in the upstream side of the shock wave. This leads to a hot electron precursor region in front of the heavy particle shock wave.

The mathematical problem is seen to lie in the consideration of the electron internal energy equation in which the effect of the shock wave is imposed through an enforced jump in the electron number density and heavy particle temperature. The whole problem can be nondimensionalized in such a manner that the solution depends only upon the ratio of the upstream heavy particle to electron temperature and the heavy particle Mach number. The characteristic length of the precursor is seen to be scaled with a Peclet number.

Having been ionized in the arc heating process, the plasma is in the process of recombination as it passes through the freejet flowfield. The route is the collisional-radiative recombination process in which a free electron is captured into an excited state by means of a three body collision and transfers downward to a certain critical quantum level primarily by means of three body collisions. Below this critical quantum level the transitions to the ground state are primarily radiative, supplying the radiation emitted by the plasma. The over-all rate of recombination and with it the quantity of radiation emitted decreases with an increase in electron temperature. The critical quantum level moves down with increasing electron temperature. Thus hot electrons have the effect of removing the continuum and lower energy (visible) lines from the recombination spectrum as well as lowering the over-all quantity of radiation emitted. In this manner the hot electron precursor that was theoretically proposed and experimentally verified in this research quenches the recombination radiation of the plasma and moves the existing radiative processes out of the visible region, thus causing the observed dark region in front of a normal shock wave.

An arc-heated freejet test facility was built with which the hot electron precursor could be measured experimentally in an argon plasma. A water cooled settling chamber was incorporated which smoothly expanded the flow to an 0.25-in. diam sonic throat. The design goal of this facility was to obtain operation at low enough enthalpy levels to allow adequate diagnostic testing and yet at high enough levels to exhibit the interesting nonequilibrium effects. This operation was achieved at a mass flow of 0.2 g of argon per second and values of h/RT_0 in the range of 25–35. The total pressure in the settling area was measured at near 50 torr and the ambient pressure in the vacuum tank at near 0.060 torr resulting in a $5\frac{1}{2}$-in.-long flowfield. A source flow model was developed which adequately described the heavy particle flowfield in the freejet.

A theoretical description of the axial electron temperature profile in a slightly ionized argon plasma freejet is developed in this research. The electron energy equation is nondimensionalized and a characteristic time for each process is derived

$$t(\text{elastic}) = 1.02\times 10^{10} T_e^{3/2}/n_e \ln\Lambda \tag{1a}$$

$$t(\text{convection}) = R_0/U_{.0} \tag{1b}$$

$$t(\text{inelastic}) = 4.35\times 10^{19} T_e^{9/2}/n_e^{\,2} \tag{1c}$$

$$t(\text{conduction}) = 7.4\times 10^{-14} n_e R_0^{\,2} \ln\Lambda/T_e^{5/2} \tag{1d}$$

A process with a particularly short characteristic time will be the primary process by which the electron energy is controlled. For this experimental situation, conduction has the shortest characteristic time. A comparison of the convective and inelastic collisional characteristic times shows that the flow should be frozen to recombination. The theoretical electron temperature profiles drawn on the figures in which the experimental data are presented were calculated using this theory.

In the flowing plasma, ionization-recombination and irreversible processes such as heat transfer in the throat region invalidate any isentropic flow assumption, making the measurement of the ion density as well as the electron temperature necessary in order to obtain a full picture of the situation existing in the flowfield. For this purpose a new type of Langmuir probe known as the Langmuir tube was designed which is admirably suited to the high-enthalpy environment and also provides excellent spatial resolution in the measurements.

The Langmuir tube consists of a length of 0.018-in.-o.d.

Presented as Paper 71-591 at the AIAA 4th Fluid and Plasma Dynamics Conference, Palo Alto, Calif., June 21–23, 1971; submitted July 13, 1971; synoptic received January 13, 1972; revision received February 28, 1972. Full paper is available from AIAA. Price: AIAA members, $1.50; nonmembers, $2.00. Microfiche, $1.00. **Order must be accompanied by remittance.**

Index category: Plasma Dynamics.

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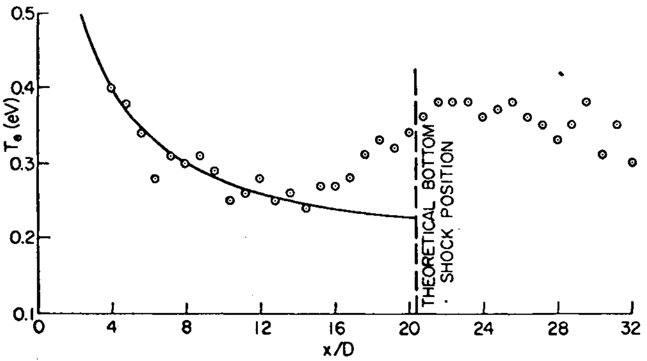

Fig. 1 T_e distribution in empty freejet.

tempered stainless-steel hypodermic tubing held as a "bow string" in a bow shaped frame and passed normal to the jet axis, through the barrel shock into the flowfield and out through the barrel shock on the other side. The tube is provided with an alumina insulating coating everywhere except at a 3.5 mm long cylindrical collector section at the center. Pressurized cooling water need only make one transit through the flowfield allowing the probe size to be much smaller than the sting mounted type. By piercing the barrel shock rather than the bottom shock, the probe will cause much less disturbance to the flowfield. The bow was attached to a three-dimensional traverse mechanism and positioned so that a blunt body could be placed downstream from the "bow string."

The novel design of the Langmuir tube necessitated the development of an appropriate theory by means of which its operation could be analyzed. Since the directed speed of the electrons is so much smaller than their thermal speed, the retarding field portion of the probe characteristic is relatively unaffected by the mass motion of the plasma, and T_e was calculated using standard methods. The mass motion strongly affects the collection of ions, however, and a theory must be developed for the collection of ions by a Langmuir probe from a moving plasma. The existing theories were inapplicable to the situation at hand, or were too complicated to be amenable to this type of experimental application.

The problem is to measure the ion density in a flowing plasma with a free molecular probe whose diameter is much larger than the Debye length. An exact theory would express this current as the directed flux of ions modified in some manner to account for their thermal motion. A heuristic theory is developed here which considers the contribution of the directed flux together with the diffusive flux of the ions and neglects any interaction between these two.

The diffusive flux is the same current that would be collected by the probe in a stationary situation. The directed flux is calculated

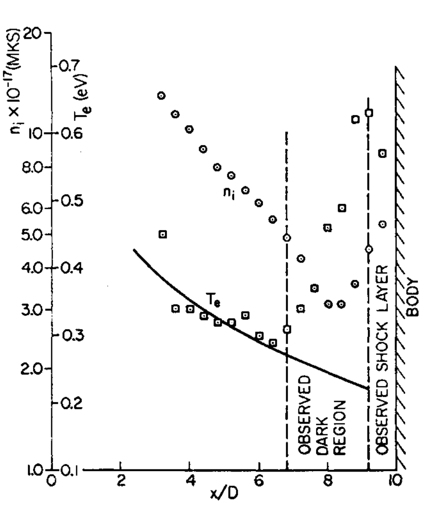

Fig. 2 T_e and n_i in front of blunt body.

Table 1 Experimental conditions for the figures (mks units, torrs)

Fig.	h/RT_0	P_t	T_t	α	ρ_t	n_{et}
1	30.3	52	8398	5.9−3	3.95−3	3.5 +20
2	25.9	48.5	7178	9.0−4	4.33−3	5.61+19

from an orbital theory for a finite length cylindrical collector in a flowing plasma with $T_e/T_i > 1$. The probe characteristic was calculated for many cases and compared with the characteristic taken experimentally. Very good agreement was obtained considering the simplicity of the theoretical treatment. Using this theory the ion density is calculated from the measured collection current and collection area, and is to be compared with the ion density calculated by assuming frozen flow in the freejet.

In order to determine the existence of this hot electron precursor in front of the blunt body unambiguously, it was first necessary to map the electron temperature profile along the axis of the empty freejet. These profiles then serve as a null from which the effect of any precursor can be measured by comparison.

Figure 1 shows a representative measurement of the electron temperature distribution through and downstream of the bottom shock. Experimental conditions are given in Table 1. The calculation of the theoretical electron temperature profile is denoted by the solid line. The hot electron precursor of the bottom shock, which is not accounted for in the theory, causes the electron temperature to deviate from and rise above the theoretical profile as the bottom shock is approached. The results of many such tests proved that the theory adequately describes the experimental data for the empty freejet electron temperature distribution in the region of interest.

The Langmuir tube is a very sensitive instrument with which ion density variations may be measured. The measured density profile shape was found to closely follow the shape of the frozen source flow profile upstream of the bottom shock, and the measurements accurately sensed the freejet bottom shock at a position calculated from the source flow model.

A 0.7-in.-diam, water cooled cylinder was placed with its flat front face normal to the flow 10 orifice diameters downstream of the sonic orifice to investigate the effect of a strong normal shock on the centerline axial electron temperature distribution in the freejet. The electron temperature distribution was measured in the same manner as in the empty freejet. The results of a representative test are shown in Fig. 2, together with the observed dark region and the observed luminous shock layer. The electron temperature profile follows the distribution dictated by the source flow model (solid line) quite well until the observed dark region is approached, where the profile begins to rise. This electron temperature rise forms the hot electron precursor of the blunt body shock wave which quenches the recombination radiation from the plasma and causes the appearance of the observed dark region.

It has been proposed that the primary physical cause for the dark region is only the elevated electron temperature and not any change in the charged particle densities caused by the shock wave. It is now necessary to show that this region of decreased luminosity and elevated electron temperature does indeed precede the shock wave. The normal shock wave may be defined as that region through which the density of heavy particles deviates from the distribution predicted by the source flow model. The measured electron temperature profile and ion density profile are plotted on the same abscissa in Fig. 2. It is seen that the electron temperature profile begins to rise and thus deviate from empty freejet behavior much further upstream than the ion density profile begins to deviate. This proves the existence of an elevated electron temperature precursor which precedes the heavy particle shock wave. The observed dark region coincides with this hot electron precursor region in front of the shock.

In summary, this research program formulated a physical model for the nonequilibrium phenomenon of a hot electron precursor in a slightly ionized plasma and verified its existence by the means of an experimental study.