A Microwave Probe for Plasma Plumes

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A SWINGING-ARM microwave probe has been developed to measure the electron-density (n_e) profile and effective electron-collision frequency (ν_c) profile transverse to a plasmajet plume. The arm, as shown in Fig. 1, is so constructed that the transmitting and receiving horns are maintained at a fixed but adjustable distance from one another, the gap between them passing over the centerline of the plume as the arm swings. The microwave circuitry is arranged to determine the amplitudes of the K-band microwaves [nominal frequency ω = 24 Gc (gigacycles)] transmitted through and reflected from the plasma flowing between the horns.

The microwaves are generated outside the vacuum tank and ducted through a bulkhead to the arm proper via a rotating joint. Crystal detectors, used to detect the reflected and transmitted microwave energy, are mounted within the arm, their position near the rotating joint selected so as to reduce, as much as possible, the effects of heating from the plume and of impulsive loading from the latching and delatching of the arm.

One frame from a motion picture (taken at 250 frames/sec) of the arm traversing a supersonic argon plume generated by a plasma jet is shown in Fig. 2. The quartz plates over the microwave horns serve to channel the plasma into a well-defined slab between the horns. These plates were matched to the horns so that the voltage standing-wave ratio (VSWR) with no plasma is 1.05, thereby reducing to a negligible level the effect the presence of these plates would have upon the signals being measured. The copper tips affixed to the leading edges of these plates, because of their excellent heat sink properties, retain sharp leading edges and therefore insure virtually shock-free flow between the horns. The distance between the plates is 2.50 cm, corresponding to two free-space wavelengths.

In operation the arm is latched by a permanent magnet to one side of the vacuum tank. On command, a solenoid-actuated plunger is energized, thrusting the arm away from the latch. Under the action of gravity (and the initial impulse), the arm swings through the plasma and is automatically latched on the other side. When the solenoid is energized again, the arm swings back, so that repeated traversals can be made in a reasonable time span. The outputs of the reflected and transmitted crystal detectors are correlated with the angular position of the arm and therefore, because of the arm's fixed geometry, with calculable spatial positions within the plume. Data are recorded by an oscilloscope. The angular position of the arm is sensed by a one-turn linear potentiometer, the output of which is used as the horizontal input to the oscilloscope. A test record is shown in Fig. 3. As is apparent, the transmitted signal is "saturated" ($n_e > 7 \times 10^{12}$ cm^{-3}) in the core of the plume, the saturated core in this case being some 18 cm in diameter.

In order to take advantage of the theoretical solutions available for the case of a plane, plane-polarized, monochromagnetic wave interacting with a homogeneous, isotropic plasma slab,[1] it is mandatory that the electron-density and collision-frequency gradients be small[2] over the interaction region. The interaction region is approximately represented by the volume between the horns: a 2.5-cm gap $\times$ 3 cm (in a direction transverse to the plume) $\times$ 7 cm (in a direction parallel to the plume), for the K-band probe developed, using 20-db horns. Therefore, measurements are limited to plume diameters larger than the horn gap distance where transverse gradients in n_e and ν_c/ω are small on a scale of 3 cm and where recombination is slow enough so that longitudinally the gradients are small over a characteristic distance of 7 cm.

The insert in Fig. 3 represents the calculated electron density vs radial position in the plume. The limited size of the

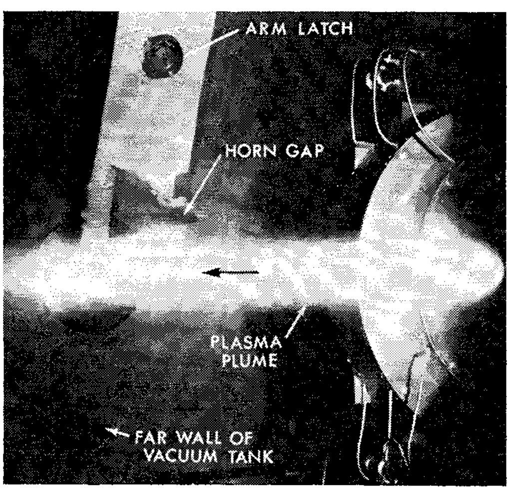

Fig. 1 A view through one port of a vacuum tank, in which the swinging microwave arm is about to intercept the plume from a plasma jet; the tank is 7 ft in diameter and 14 ft long.

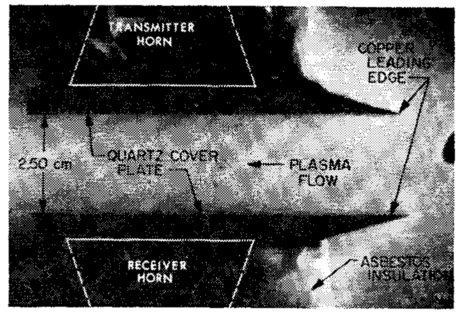

Fig. 2 One frame from a motion picture (250 frames/sec) of the plasma plume flowing between the microwave horns.

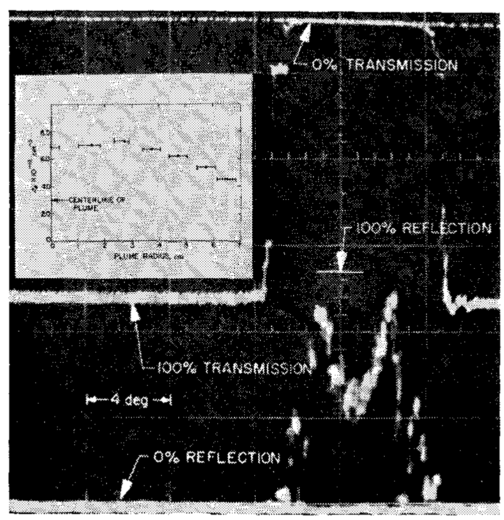

Fig. 3 Test record showing microwave signal transmitted through and reflected from the plasma plume as a function of angular position; the insert shows calculated electron density vs radial position in the plume.

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plume precluded the simultaneous unambiguous measurement of both the reflected and the transmitted signal, which would have permitted the collision frequency (ν_c) to be determined in addition to the electron density. Estimates of ν_c/ω for the plume used in these preliminary tests indicated a value in the range of 0.005 to 0.015. For a given value of the reflected signal, the calculated electron density is relatively insensitive to the precise value of ν_c/ω when this quantity is small, as it is in the case in question. This uncertainty is indicated by the error brackets shown on the data points.

The arm is well suited for higher microwave probing frequencies where the "saturation core" will be reduced and the spatial resolution increased because of the shorter wavelengths involved. In addition, the restrictions on plasma size will be lessened since the characteristic dimensions for permissible gradients will also be reduced. The probe can also be used to take time-resolved data at selected positions within the plume where the observation time is small in comparison with the dwell time in the plume.

References

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[2] Kritz, A. H.," Microwave interactions with inhomogeneous partially ionized plasmas," Western States Section/Combustion Institute Paper 62-20, Space Science Lab., General Dynamics/Astronautics, San Diego, Calif. (no date).

Energy Partition in the Current Layers in Plasma

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1. Introduction

Many plasma propulsion systems are based on the principle that the moving current layer sweeps out the gas.[1] This principle seems to lead to devices of limited efficiency as the internal energy becomes a significant fraction of the total energy.

The stationary rarefaction ("deflagration") type of discharge layer provides a decrease in internal energy across the layer, and therefore should lead to much more efficient devices. It seems that the deflagration type of current layer occurs in the Giannini Corporation device.[2]

In the present paper, these two types of discharge layers are discussed from the gasdynamic point of view rather than propulsion application. The quantitative analysis of the discharge layer requires solution of the structure of such a layer, a difficult problem because of the multifluid nature of the discharge layer. However, quantitative information can be obtained by discussing only conservation relations across a layer.

2. Conservation Relations across the Current Layer

Conservation relations across the discharge layer in the form presented below can be derived from the differential equations for one-dimensional nonsteady multifluid model obtained by taking the moments of Boltzmann's equation.

Subsequently these equations have been transformed to the system of coordinates moving with the velocity of the back of the current layer ($\xi = \int V_p dt - x$, $\tau = t$. Integrating these

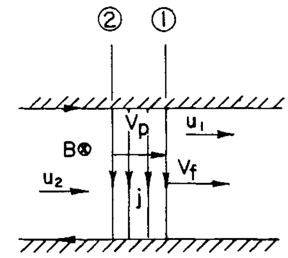

Fig. 1 Current layer geometry.

differential equations across the current layer between two sections, 1 and 2 (Fig. 1) where there are no gradients of flow parameters, and applying the rule of differentiating the integral with variable boundary

$$\int_0^{\delta_1} \frac{\partial F}{\partial \tau}\, d\xi = \frac{d}{d\tau}\int_0^{\delta_1(\tau)} F d\xi - F_1 \frac{d\delta_1}{d\tau}$$

with $d\delta/d\tau = V_f - V_p$, one obtains the conservation relations in the following form†:

Conservation of Mass (Fig. 1)

$$\rho_1(V_f - u_1) - \rho_2(V_p - u_2) = \frac{d}{d\tau}\int_0^{\delta_1} \rho d\xi \equiv \frac{dM}{d\tau} \quad (1)$$

where

V_f = the velocity of the front of the discharge layer
V_p = the velocity of the back of the discharge layer
ρ = nm = the mass density
δ_1 = the thickness of the discharge layer

and u_1 and u_2 are the gas velocities (in laboratory frame) ahead and behind the discharge layer, respectively.

The left-hand side of Eq. (1) represents the difference between the mass flux entering and leaving the current layer; the right-hand side represents mass accumulated in the current layer.

Conservation of Momentum:

$$\rho_1(V_f - u_1) - p_1 - \frac{B_1^2}{2\mu} - \rho_2 \times (V_p - u_2)u_2 + p_2 + \frac{B_2^2}{2\mu} = \frac{d}{d\tau}\int u dM \quad (2)$$

The energy equation can be written as follows[4]:

$$(V_p - u_2)\left[\rho_2 \frac{u_2^2}{2} + \frac{kn_2T_2}{\gamma - 1}\right] - (V_f - u_1)\left[\rho_1 \frac{u_1^2}{2} + \frac{kn_1T_1}{\gamma - 1}\right] - u_2kn_2T_2 + u_1kn_1T_1 = \frac{d}{d\tau}\int_0^{\delta}\left(\rho \frac{u^2}{2} + \frac{knT}{\gamma - 1} + \frac{B^2}{2\mu}\right) d\xi - \frac{dq_{\rm rad}}{d\tau} + E_2'B_2 + u_2 \frac{B_2^2}{2\mu} - E_1' B_1 - u_1 \frac{B_1^2}{2\mu} \quad (3)$$

where $q_{\rm rad}$ is the energy loss by radiation, E, E' denotes electric field in laboratory frame and moving frame, respectively.

Equations (1–3) become the shock-wave matching conditions when time derivatives of integrals on the right-hand sides disappear (no mass accumulation effects).

3. Application to the Magnetic Piston Problem

Assuming

$$B_1 = 0,\ T_1 \cong 0 \qquad E_2' = -(V_p - u_2)B_2 \quad (4)$$

$$\frac{d}{d\tau}\left[\int_M e_{\rm int}\, dM + q_{\rm rad}\right] \equiv \frac{dW}{d\tau} = (2u_2 - V_p)\frac{d}{d\tau}\int_M u dM - \frac{d}{d\tau}\int_M \frac{u^2}{2} dM - (V_p - u_2)\left[\rho_2 \frac{u_2^2}{2} - \frac{kn_2T_2}{\gamma - 1}\right] - (V_f - u_1) \times \rho_1\left[\frac{u_1^2}{2} - u_1u_2 + \frac{kn_1T_1}{(\gamma - 1)\rho_1}\right] \quad (5)$$

where $e_{\rm int} = knT/(\gamma - 1) + (B^2/2\mu)$.

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† Full derivation of these equations is given in Ref. 3.