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Steadiness of a Plasmajet

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PLASMAJETS generated by means of electric arcs have attracted wide scientific and technological interest during the past decade. In spite of the widespread application of plasmajets, there is still little agreement of the temperatures and temperature distributions reported by different authors. One of the reasons may be found in fluctuations of the plasmajet.

A possibility exists that the temperatures reported for turbulent plasmajets might be too high. This is because the arc column in these cases may come out of the nozzle, make a hairpin turn, and attach to an interior or exterior wall in the neighborhood of the nozzle exit. This would be an intermittent process since the arc probably travels up and out of the nozzle, extinguishes, restrikes in the nozzle, and repeats the process. Such shapes of arcs in flowing gases have been clearly detected on simpler geometries[1] and are presently being studied in the Heat Transfer Laboratory of the University of Minnesota. Dooley et al.[2] call this effect the "blown arc," which has been investigated in a similar plasma torch with a segmented anode by Wheaton and Dean.[3] A more recent paper by Krülle[4] describes experiments with a nozzle-shaped anode. Brückner[5] shows photographs of a 300-amp turbulent

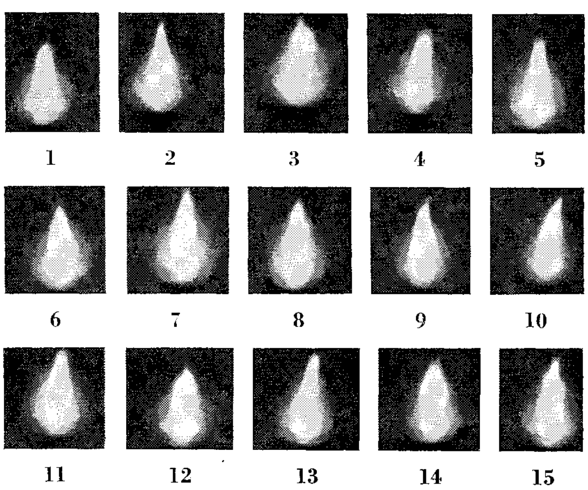

Fig. 1 High-speed Fastax pictures from an argon plasmajet, F-40 plasma torch: I = 400 amp, P = 1 atm, flow rate = 150 scfh.

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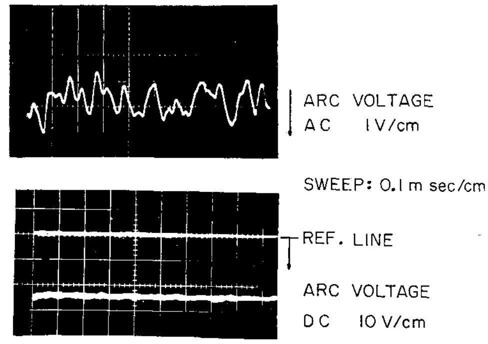

Fig. 2 Oscillograms taken of a turbulent argon jet: I = 400 amp, flow rate = 150 scfh.

plasmajet in which the plasma is shown leaving the nozzle in "blobs." A photo with an exposure time of $\frac{1}{500}$ sec shows two such entities.

If such an occurrence takes place, then the line and continuum intensities recorded would be higher than one should expect for the prevalent freestream gas temperature, since the detectors would see the very hot arc column on a high-frequency intermittent basis. The frequency would be on the order of 1 kc and so would not appear as a fluctuation in a relatively slow response detector-amplifier system. The magnitude of the effect would depend on how much of the arc column's lifetime was spent outside the nozzle.

Actually this effect could not be observed with the F-40 plasma torch‡ using argon as working fluid. High-speed Fastax pictures taken of the plasmajet (Fig. 1) as well as the behavior of the arc voltage (Fig. 2) did not indicate this type of fluctuation. The smooth traces of the small voltage fluctuations with a maximum amplitude of about 2.5 v show that the arc length may indeed vary within 1 cm or so but that there is no restriking of the arc which is symptomatic for the fluctuating mode of an arc. The nozzle used for all experiments has a length of 2.5 cm. The anode arc terminus usually stays in the vicinity of the nozzle entrance close to the cathode as indicated by erosion in the entrance region of the anode nozzle. According to the observed voltage fluctuations, the anode arc terminus may travel back and forth in the nozzle, but never reaches the nozzle exit, because the additional voltage required for this distance is higher than 2.5 v. Restriking of an arc with superimposed axial flow leads to a saw-tooth shape of the voltage fluctuations because the breakdown time of the restriking arc is very small as compared to the time required for the anode arc terminus to travel downstream to the nozzle exit. These effects were studied in an open geometry, which permitted unobstructed viewing of the entire arc column.

A rod-shaped thoriated tungsten cathode was positioned with its axis parallel to the surface of a plane water-cooled anode, and a gas flow (argon) was introduced parallel to the axis of the cathode. It was thought that this geometry represents the best compromise between the situation encountered in plasma generators and the accessibility of a simple model, because the flow conditions are quite similar to those with

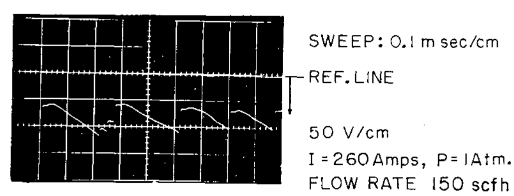

Fig. 3 Oscillogram of a nitrogen arc, F-40 plasma torch.

‡ Manufactured by Thermal Dynamics Corporation, Lebanon, N. H.

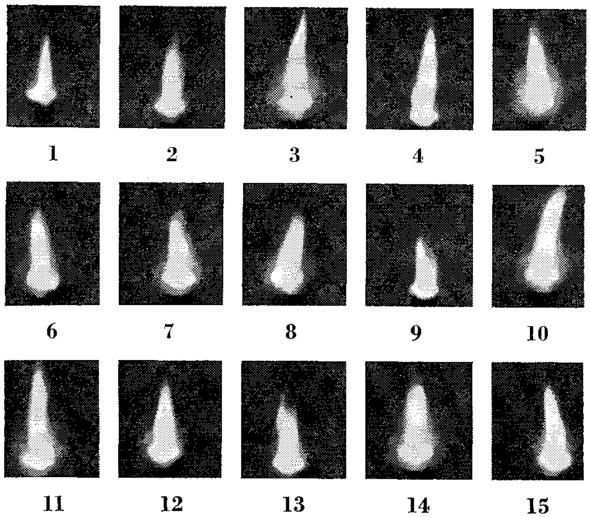

Fig. 4 High-speed Fastax pictures from a nitrogen plasmajet, F-40 plasma torch: I = 260 amp, P = 1 atm, flow rate = 150 scfh.

cylindrical or nozzle-shaped anodes of plasma generators. From a number of high-speed Fastax movies taken simultaneously with the voltage fluctuations, the characteristic behavior of the fluctuating mode of the arc could be established.[1]

In order to make sure that the geometry, which is of course quite different in this case, is not an important factor for the origin of such fluctuations, the same type of fluctuations in the F-40 plasma torch were generated by using nitrogen as working fluid. The results are shown in Figs. 3 and 4. The saw-tooth shape of the voltage fluctuations together with the high amplitude of about 50 v, which is almost half of the maximum arc voltage, indicate already the typical features of a restriking arc. Restriking occurs with a frequency of about 5 kc. In addition to these findings, Fastax high-speed pictures taken from the nitrogen plasmajet (Fig. 4) indicate irregularities in the plasmajet. From these investigations it may be concluded that the temperature measurements usually reported for argon jets at moderate gas flow rates[6] represent really steady-state temperatures rather than time-averaged values.

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Motion of Re-Entry Vehicles during Constant-Altitude Glide

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DURING re-entry into earth atmosphere, a vehicle can often be "flown" at a constant altitude by rolling about its velocity vector at a fixed angle of attack. Such a maneuver produces lateral range and also eliminates trajectory oscillation. The lateral range obtained during such a flight has been computed numerically and is presented in Ref. 1 and discussed in Ref. 2. This note, however, presents analytic solutions. For a re-entry vehicle "flying" at a constant altitude, the applicable equations of motion are

$$(2W/C_DA\rho)(dV/dt) = -gV^2 \tag{1}$$

$$V^2(L/D)\cos\varphi = (2W/C_DA\rho)[1 - (V/V_s)^2] \tag{2}$$

$$\frac{d\psi}{dt} = \left(\frac{L}{D}\right)\frac{Vg\sin\varphi}{(2W/C_DA\rho)} - \frac{Vg\cos\psi\tan\lambda}{V_s^2} \tag{3}$$

and the kinematic equations are

$$d\lambda/dt = Vg\sin\psi/V_s^2 \tag{4}$$

$$d\mu/dt = Vg\cos\psi/(V_s^2\cos\lambda) \tag{5}$$

The symbol φ is the bank angle measured from the local vertical, ψ is the turn angle measured from the vehicle's original heading, λ is the ratio of the lateral range (measured from the original great circle) to the radius of the earth, μ is the ratio of the down range (measured from the beginning of the glide) to the radius of the earth, and V_s is the orbital speed at sea level. The variation of the gravitational acceleration with altitude has been neglected. Other symbols have their usual meaning. Defining

$$C = 2W/(C_LA\rho\, V_s^2) \tag{6}$$

and eliminating Eq. (1), we obtain

$$-V(d\psi/dV) = (L/D)(\sin\varphi - C\cos\psi\tan\lambda) \tag{7}$$

$$-V(d\lambda/dV) = (L/D)(C\sin\psi) \tag{8}$$

$$-V(d\mu/dV) = (L/D)(C\cos\psi/\cos\lambda) \tag{9}$$

These equations can be solved analytically if $\sin\varphi = 1$ is assumed. This approximation has been thoroughly studied

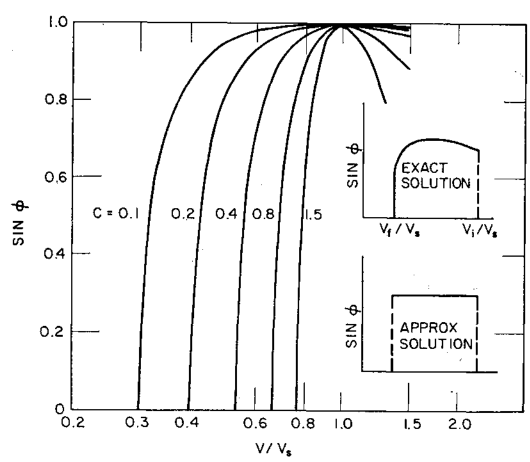

Fig. 1 Variation of $\sin\varphi$ as a function of V/V_s and C.

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