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Evaluation of Electron Quench Additives in a Subsonic Air Arc Channel

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I. Introduction

DECREASING the electron concentration of high-temperature flowing plasmas is useful toward improving communications with, and reducing, the radar observables produced by re-entry vehicles. The addition of small quantities of an electrophilic gas such as SF_6 to the ionized flow is a known effective method of electron removal from gases below 1000°K.[1] Electrophilic gases suppress the electron concentration of plasmas by electron attachment, with subsequent negative ion formation. Major questions concerning high-temperature effects, reaction rates, and flow transit times must be answered if such an electron-removal technique is to be used successfully on re-entry vehicles. Thus, screening tests in high-temperature flows are helpful in comparing the electron removal effectiveness of candidate quench additives.

High-temperature ionized flows can be produced in the laboratory using electrical arc jet facilities. The results of quenchant tests performed in a supersonic argon arc jet are given in Ref. 2. In the present study, a subsonic arc channel was used to provide a flowing high-temperature air plasma in which the electrophilic effects of various additives could be studied under simulated flight conditions. It was possible to monitor the electron concentration of the flow before and after quench injection, thus allowing direct comparison of the electron removal capability of many additives. This Note describes the experiments conducted, and presents results obtained using a variety of candidate additives.

II. Facility Description

A schematic of the d.c. arc channel arranged for quench experiments is shown in Fig. 1 and is described in detail in Ref. 3. The arc discharge is struck in the nitrogen flow through the anode region and is mixed with oxygen immediately downstream to produce an air plasma. The 2×0.5-in. rectangular arc channel begins downstream of a constant area circular-to-rectangular transition section. Enclosure of the plasma in a water-cooled heat balance channel permits evaluation of many flow, thermodynamic, and electrical properties at the axial location of interest. Also, in such a channel the large effective length-to-diameter ratio permits flow mixing in a controlled velocity environment.

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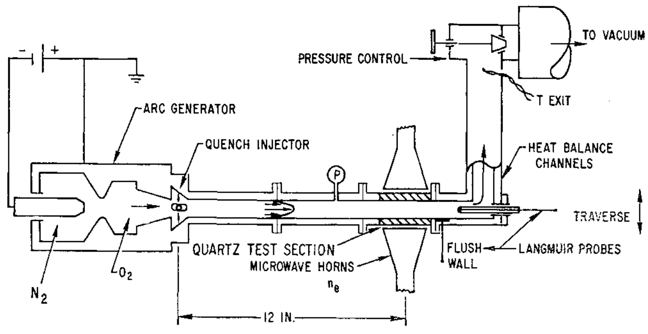

Fig. 1 Arc channel schematic.

For the tests of this study, the basic arc channel arrangement consisted of a quench injector station followed by two 4-in.-long channel sections plus a 4-in.-long interchangeable test section with selectable chambers comprised of either quartz or copper sidewalls. The channel was terminated by a heat exchanger and flow control valve at the vacuum duct. Quenchant was injected in several ways using midstream crossflow, centerline axial flow, and flush wall injection techniques in different arc runs. Additional details of the channel are given in Ref. 4.

III. Flow Diagnostics

The average enthalpy of the plasma at several axial channel locations can be determined by using the heat balance segments. Stream bulk average enthalpy is decreased by about a factor of 2 due to cold wall heat transfer as it traverses the 12-in. distance downstream of the additive injector. Typical equilibrium profiles of velocity, enthalpy, ion number density, and temperature calculated from probe measurements made across the 0.5-in. channel dimension are given in Ref. 3. A calculated ratio of centerline to average enthalpy of 1.37 was found, and is in good agreement with the analysis of Ref. 5.

Integrated electron number density across the 0.5-in. channel dimension was determined by using X- or S-band microwave interferometer systems[6] in conjunction with the quartz test section walls. Use of such a system is confined to a limited electron number density range which, in these tests, limited the maximum monitoring range to about a factor of 10. At electron concentrations below the lower sensitivity limit of the microwave equipment, Langmuir probe measurements were used. Both flush wall and free-stream stagnation point continuum Langmuir probes were mounted immediately downstream of the microwave test section as illustrated in Fig. 1. The single electrode Langmuir probes were referenced to the channel and measured from positive through negative saturation currents as the applied voltage E was swept through negative-to-positive 50 v. Probe positive saturation current was repeatedly confirmed to be directly proportional to electron number density in the unquenched plasma by comparison of probe and microwave data.

Figure 2 shows the type of Langmuir probe trace obtained prior to and subsequent to each significant decrease in n_e due to quenching as observed over the dynamic range of the microwave interferometer. The major effect observed at the probes was a large decrease (up to several orders of magnitude) in negative saturation current to a value nearly equal to that for positive saturation, resulting in a symmetrical probe characteristic. If we assume positive saturation current proportional to the product of ion mean speed and positive charge number density at the sheath edge,† and negative saturation current proportional to the sum of similar

† This proportionality has been found to hold[7] for a continuum probe when the ion sheath thickness is somewhat larger than the ionized-neutral gas mean free path as calculated for these tests.

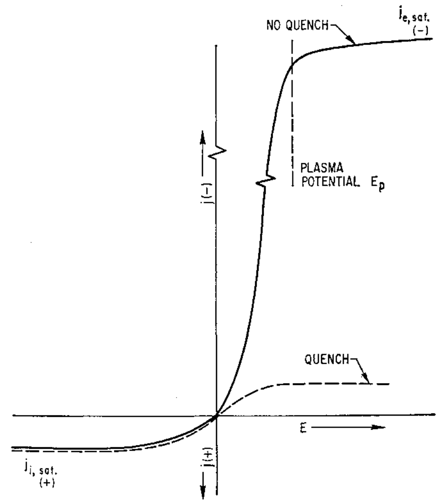

Fig. 2 Langmuir probe characteristic curves.

negative ion and electron terms, we obtain the saturation current ratio

$$\frac{j_{(-)}}{j_{(+)}} = \frac{n_e\bar{c}_e + n_{i(-)}\bar{c}_{i(-)}}{n_{i(+)}c_{i(+)}} \quad (1)$$

for a partially quenched plasma. For the case where all temperatures are approximately equal, particle velocities are inversely proportional to the square root of the molecular weights m. Thus, for a neutral plasma where $n_e + n_{i(-)} = n_{i(+)}$ and if $m_{i(+)} = m_{i(-)}$,

$$\frac{n_e}{n_{i(+)}} = \frac{(j_{(-)}/j_{(+)}) - 1}{(m_{i(+)}/m_e)^{1/2} - 1} \quad (2)$$

The mass ratio factor in the denominator typically has a value of several hundred for heavy ions; therefore, if, as has been observed, $j_{(-)}/J_{(+)}$ is of order one, it follows that $n_e/n_{i(+)} \ll 1$, and the number of electrons is reduced to a negligible value compared with positive and negative ions. Notice that, as shown in Fig. 2, little change was observed in positive saturation current, indicating no significant change of plasma ionization level.

IV. Results

Most of our tests were performed at a channel static pressure of 30 mmHg and an average velocity of about 2000 fps. The average plasma equilibrium temperature was 3300°K at the quench injector station and 2500°K at the downstream diagnostic region where the electron number density was $4(10)^{10}/cm^3$. From the many additives tested,[4] the fluorine compounds listed in Table 1 were effective midstream quenchants when added in a mass ratio to air of a few per cent or less, as indicated. Quench effectiveness was determined by a decrease in integrated n_e to less than the microwave interferometer sensitivity range, and/or a decrease of 30 to 100 in the Langmuir probe negative saturation current, so that $j_{(-)}/j_{(+)} = 1$–3. As shown in Table 1, the flush wall probe results indicate that near the cool wall, quenching was effective at mass ratios about 10 times less than the midstream values. Results were found to be independent of the injection scheme used. Operation of the channel at higher temperatures and $n_e = 3(10)^{11}/cm^3$ indicated that for these compounds quenching was not obtained in those portions of the test region profile where temperatures exceeded 3000°K. The fact that quenching was most effective near the cool wall and not at all effective in high-temperature regions indicates possible attachment to compounds only present in the flow below their dissociation level near 3000°K. Considerable experimentation was performed with water injected both as superheated steam and in liquid form. No effective quenching was noted even when the water was injected in quantities up to 15% of the air flow.

Table 1 Test results

Additive	Mass ratio	$[j_{(-)}/j_{(+)}]$ centerline	$[j_{(-)}/j_{(+)}]$, wall
SF_6, $CBrF_3$, CF_4	$3(10)^{-2}$	1 – 2	1
	$3(10)^{-3}$	∞^a	5
$C_2F_4{}^b$	$5(10)^{-1}$	3	1
	$2(10)^{-1}$	∞	3
$NF_3{}^b$	$5(10)^{-3}$	2	1
	$2(10)^{-3}$	∞	2
$C_2F_4{}^b$	$1(10)^{-2}$	3	1
	$1(10)^{-3}$	∞	2

[a] Indicates $j_{(-)} >> j_{(+)}$ (no quenching).
[b] Injection 4 in. downstream (transit length 8 in.).

It is interesting to note that, as previously mentioned, little change was noted in the probe positive saturation currents prior to and subsequent to quenching, whereas major decreases in positive current were reported for the argon tests of Ref. 1. This points out the different mechanisms responsible for quenching in the two experiments. In our tests negative charge exchange alone appeared to be dominant; the results of Ref. 1 indicate that in the argon experiments a deionization of the plasma occurred.

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Vibrational Energy Exchange on N_2-O_2 Collision

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RECENTLY, some studies on vibrational energy exchange of gas mixtures by using shock tube technique have been reported.[1–3] White and Millikan[4] found that small amounts of CO in N_2 represented the vibrational state of N_2 and they used CO as a tracer of N_2 in observing the vibrational relaxa-

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