Operating Characteristics of a Hydrogen-Argon Plasma Torch for Supersonic Combustion Applications

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The residence time of the combustible mixture in the combustion chamber of a scramjet engine is much less than the time normally required for complete combustion. Hydrogen and hydrocarbon fuels require an ignition source under conditions typically found in a scramjet combustor. Analytical studies indicate that the presence of hydrogen atoms should greatly reduce the ignition delay in this environment. Because hydrogen plasmas are prolific sources of hydrogen atoms, a low-power, uncooled hydrogen plasma torch has been built and tested to evaluate its potential as a possible flameholder for supersonic combustion. The torch was found to be unstable when operated on pure hydrogen; however, stable operation could be obtained by using argon as a body gas and mixing in the desired amount of hydrogen. The stability limits of the torch are delineated and its electrical and thermal behavior documented. An average torch thermal efficiency of around 88% is demonstrated.

Introduction

SEVERAL concepts are under active consideration for transports that will take off from conventional runways and fly into space. Examples of these include the U.S. National Aerospace Plane and the British Hotol. Scramjet engines remain the leading candidate to power these aircraft through at least a part of their flight regime.

Flow through the combustor of a scramjet is supersonic. This means that, for an engine of reasonable length, the residence time of the fuel/air mixture in the combustion chamber will be much less than that normally required for complete combustion. Hydrogen and hydrocarbon fuels require an ignition source under conditions typically found in a scramjet combustor.[1,2] These two facts imply the need for some sort of active flame initiating and augmentation scheme.

One viable concept for active flame initiating and holding involves the injection of pyrophoric liquid silane.[3] An alternative approach is suggested by analytical studies[4,5] that indicate that the presence of hydrogen atoms can also play a major role in reducing ignition delay. Because hydrogen plasmas are known to be prolific sources of both hydrogen atoms and ions, a low-power hydrogen plasma torch might well serve as a flame initiator and holder in supersonic combustion. One soon learns, however, when trying to put this idea into practice, that plasma torches operating on pure hydrogen are inherently unstable. Fortunately, this problem can be circumvented by using argon as a body gas and carefully mixing in the desired amount of hydrogen while simultaneously adjusting other operating parameters to maintain stability. The electrical and thermal performance and the stability limits of a low-power, hydrogen-argon plasma torch suitable for use as a scramjet flameholder are documented in this article.

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The overriding design considerations for a plasma torch flameholder are that it be passively cooled, small and lightweight, and that it consumes as little power as possible. Also, the plasma jet should enter the combustion chamber with sufficient velocity to ensure its deep penetration into the mixture crossflow. Finally, due to stability considerations, flow through the torch should not be influenced by pressure fluctuations in the combustion chamber. Both of these latter two constraints are met if the plasma jet enters the combustion chamber through a choked orifice.

The advantage of an uncooled or passively cooled torch is that heat losses to the electrodes are minimized. This maximizes the thermal efficiency of the torch, where thermal efficiency is defined as the net heat transfer to the gas passing through the torch divided by the electrical power input. This is an important consideration because the size, weight, and power demand of the electrical supply needed to power the torch, and the size and weight of the torch itself, are all inversely related to its thermal efficiency. Another advantage of passive cooling is that a separate coolant supply is not needed. The disadvantage is that the concomitant high operating temperature of the torch places stringent limitations on the electrode materials and torch life expectancy.

In a preliminary study, Northam et al.[4] report that an uncooled torch consuming about 2 kW of electrical power could be an effective igniter and flameholder for high-speed combustion. Therefore, the torch in the present study has been designed to operate at between 500 and 2500 W electrical.

Experimental Apparatus and Procedure

The torch tested and an integral calorimeter used for performance measurement are shown in Fig. 1. The anode and cathode are both fabricated from 2% thoriated tungsten. Thoriated tungsten was chosen over pure tungsten for the cathode because of its lower work function and for the anode because of its superior machinability. A disadvantage of using thoriated tungsten for the electrodes is that it erodes more rapidly than pure tungsten.

The torch is 38 mm in diameter and its overall length, including the cathode holder, is 100 mm. The torch body is only 37.8 mm long. An insulated stainless steel Conax fitting centers and holds a pointed tungsten cathode in the convergent section of the anode. The ceramic insulator can support temperatures of up to 1300 K. A lava sealant having a similar temperature limit prevents gas leakage around the cathode. A silver-plated inconel O-ring provides a gas seal between the removable anode and the anode holder. The silver plating is necessary to provide a relatively soft impermeable film between the mating surfaces when operating with hydrogen. The maximum working temperature of this O-ring is about 1200 K.

The cathode is a 3.175-mm diam rod of 2% thoriated tungsten that has been ground to a 40-deg cone at one end. A micrometer drive is used to position the cathode after first loosening the Conax fitting. Early tests using flat-ended cathodes resulted in operation of the torch in one of two voltage modes, depending on the gas mass flow rate. When operating in the high-voltage mode corresponding to relatively high gas flow rates, a visible plasma jet was observed to issue from the anode orifice. No such jet was visible in the low-voltage mode corresponding to relatively low gas mass flow rates. It is hypothesized that in the low-voltage mode, the arc anode attachment is on the convergent section of the anode nozzle, while in the high-voltage mode, aerodynamic effects are sufficiently strong to move the arc attachment outside to the divergent section of the anode nozzle. The high-voltage mode is desirable because it results in higher power operation of the torch. The pointed cathode design was chosen because it permits operation in the desirable high-voltage mode at much lower mass flow rates through the torch. However, even with a pointed cathode, the low-voltage mode could occur if the cathode was not well centered.

In early versions of the torch, the anode converged to a throat that was flush with the anode face; that is, there was no divergent section. This resulted in unstable operation as the arc hunted for an aerodynamically stable attachment point on the converging section of the anode wall. Also, the throat tended to overheat because of the small cross section offered for heat conduction away from its sharp edge. The resulting rapid erosion of the throat increased its area, causing it to unchoke. The anode actually used in the studies reported here has a 5.5-mm-long, 45-deg half-angle converging section, 1.02-mm-long throat, and a 2.68-mm-long, 45-deg half-angle diverging section. The throat diameter is 0.813 mm, giving a throat length-to-diameter ratio of 1.25. This anode design was found by experience to be very robust in that the torch could be operated for at least 2 h without unacceptable erosion.

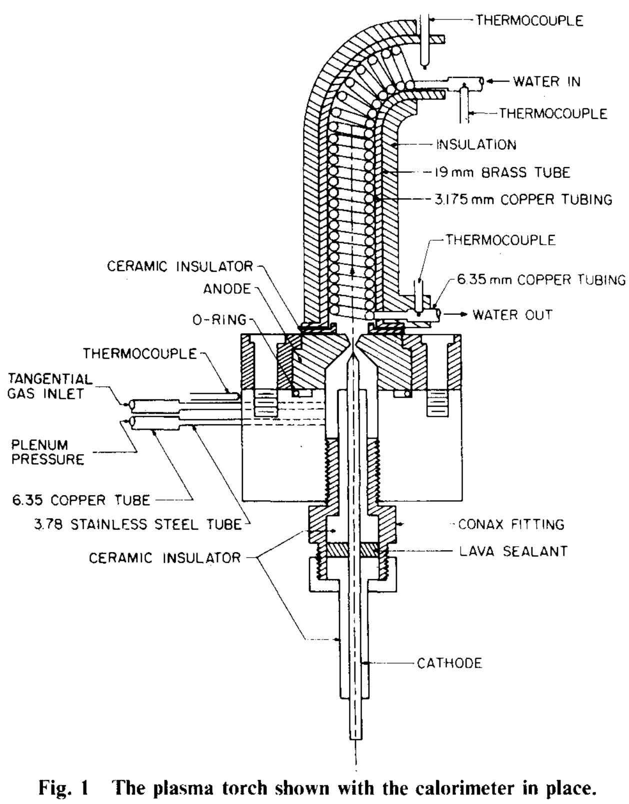

Fig. 1 The plasma torch shown with the calorimeter in place.

Direct-current (dc) electrical power is provided by two constant-current welding supplies wired in series. Current from this combination can be varied continuously from 5 to 170 A. The arc is initiated using a high-frequency arc stabilizer of the type used in welding applications.

The torch could not be started or operated on pure hydrogen. The procedure was to initiate the arc on pure argon using the high-frequency arc stabilizer. Once a stable dc arc had been established on argon, an increasing fraction of hydrogen was mixed with the argon upstream of the torch while simultaneously adjusting the power supply to maintain stable operation. When pure argon is used as the working fluid, stable dc arcs can be maintained with electrode gaps as great as 0.8 mm, where the electrode gap is defined as the shortest distance from the tip of the conical cathode to the wall of the converging section of the anode. However, as soon as significant amounts of hydrogen are added, the arc becomes unstable and is extinguished when this gap exceeds 0.178 mm.

The torch input power is computed as the product of torch current and supply voltage. This is justified by the negligible ripple observed on the dc voltage and current waveforms. Nupro "S" series fine metering valves are used as calibrated choked orifices in the hydrogen and argon supply lines. The mass flow rates are computed in terms of the measured pressure ratio across the valve orifice and the upstream temperature assuming reversible, adiabatic, steady flow of an ideal gas.

The net thermal power output of the torch is measured directly using the flow calorimeter shown on top of the torch in Fig. 1. The calorimeter consists of a coil of 3.175-mm diam copper tube wound against the inside wall of a 19-mm inside diameter brass tube. The outside wall is insulated. The calorimeter has a 90-deg bend near the exit to minimize energy loss by radiation. The total length of the calorimeter is 180 mm. A thin ceramic insulator electrically isolates the calorimeter from the anode. The temperature rise of the cooling water which flows through the calorimeter is measured at the inlet and outlet of the copper tube using iron-constantan thermocouples, and the gas temperature at the exit of the calorimeter is measured using a chromel-alumel thermocouple. The difference between the enthalpy of the gas leaving the calorimeter and the enthalpy of the gas entering the torch, computed using gas tables, the measured mixture volume ratio, and the measured temperatures, was determined to be less than 2% of the power absorbed by the calorimeter. The flow rate of cooling water through the calorimeter was measured using a rotameter. The power absorbed by the calorimeter was computed as the product of the temperature rise and mass flow rate of the cooling water and the specific heat of water.

The first step in the start-up procedure is to purge the torch of air. The arc is then initiated at an argon flow rate of 130 ml/s, which assures start-up in the high-voltage mode. The torch is allowed to warm up for 5 min before hydrogen is mixed in with the argon upstream of the torch. As hydrogen is introduced, the arc current is readjusted to maintain stable operation. Data are not taken until after the torch has operated at the set point for 2 min. Additional details of the experimental apparatus and procedure may be found in Ref. 6.

Experimental Results

The purpose of the research was to map out the torch operating characteristics over a wide range of total gas flows, hydrogen/argon mixture ratios, and arc currents. The chief dependent variable of interest is the torch thermal efficiency.

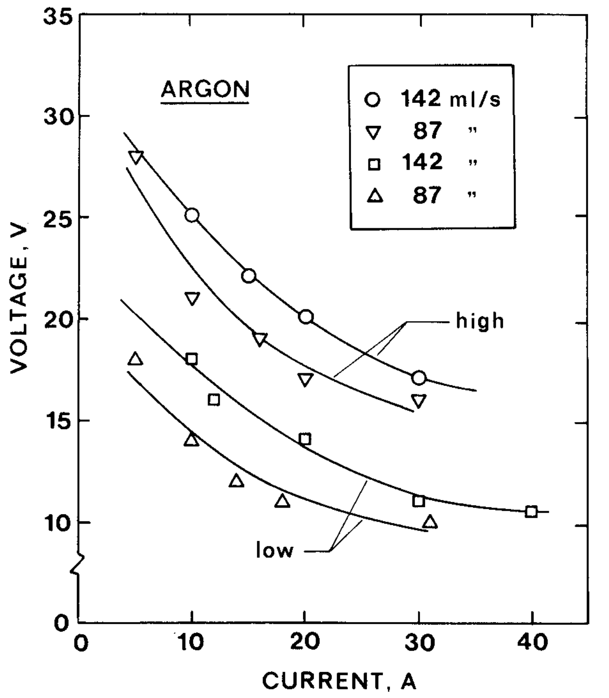

Fig. 2 Voltage-current characteristics for high- and low-voltage mode operation with argon flow (electrode gap = 0.8 mm).

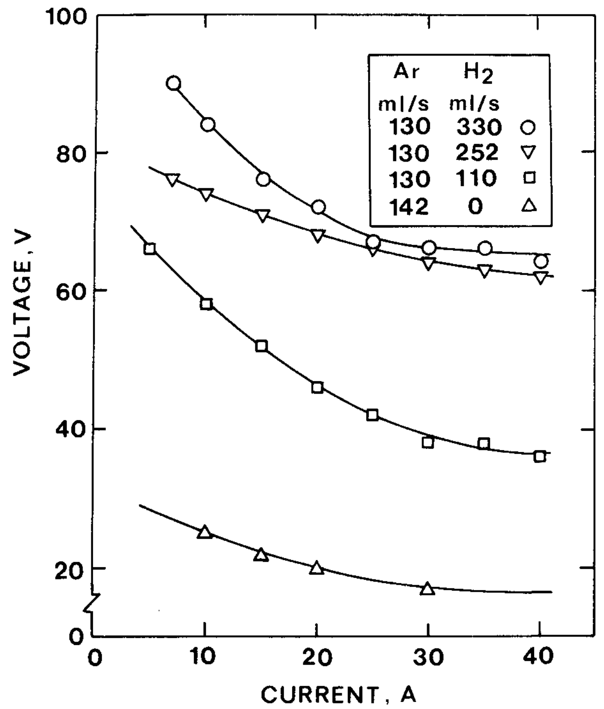

Fig. 3 Voltage-current characteristics for various hydrogen flows with constant argon flow (electrode gap = 0.178 mm).

Argon Arc in High- and Low-Voltage Modes

Figure 2 shows the torch voltage-current characteristics for two argon flow rates and two cathode designs. The two high-voltage curves were obtained using the pointed cathode and the two low-voltage curves were obtained using a flat-ended cathode. In both cases the electrode gap was 0.8 mm. The curves corresponding to the high flow rate are fourth-order regressions, and those corresponding to the low flow rate are parametric cubic splines.

In all four cases of Fig. 2, the voltage-current characteristics have negative slopes. This is typical of argon arcs at low pressures and currents;[7] however, when the current exceeds about 60 A, the characteristic slope is known to become positive for argon.[8] Indeed, the characteristics of Fig. 2 are nearly flat as the current approaches 45 A. In both the high- and low-voltage modes the higher mass flow rate of argon produces the higher voltage at a given current.

Characteristics of Hydrogen-Argon Arcs

For all of the results reported below, the pointed cathode has been used with the electrode gap set at 0.178 mm. It was consistently observed during operation of the torch that the arc was extinguished for arc currents less than 5 A when the hydrogen flow rate exceeded 200 ml/s. A current of 7 or 8 A was generally needed for stable operation with significant hydrogen flows. If the current or gas flow was increased so that the supply voltage exceeded about 95 V, the arc was extinguished. This was probably due to a power supply limitation, however. Finally, torch operation was smoothest for currents ranging between 20 and 30 A.

The voltage-current characteristics of the torch for various amounts of hydrogen mixed in with a constant argon flow are shown in Fig. 3. One of the characteristics from Fig. 2 for operation with pure argon is repeated in this figure for comparison. All of the curves drawn through the data are quadratic regressions. Just as in the case of the pure argon characteristics already discussed, the characteristics with a mixture of hydrogen and argon have negative slopes throughout the current range investigated. In two of the mixture cases, the slope at low currents is much steeper than in the pure argon case. However, in the third case, corresponding to the intermediate value of hydrogen flow rate, the characteristic is very similar to that for pure argon except that it is shifted upward in voltage. There is no ready explanation for this seeming anomaly.

Comparison of Figs. 2 and 3 shows that the arc voltage is generally more sensitive to hydrogen flow rate than to argon flow rate. For example, in Fig. 2 an increase in argon flow rate of 63% at 20 A (in the high-voltage mode) produces a voltage increase of only 4 V, while in Fig. 3 an increase in hydrogen flow rate of only 31% at the same current produces a voltage increase of 5 V. The anomalous behavior of the intermediate hydrogen flow rate characteristic produces a remarkable exception to this generalization, however.

In Fig. 4, the relative proportion of hydrogen and argon has been kept constant at 60% hydrogen by volume while the total gas flow rate has been varied. Once again, the curves are quadratic regressions through the data. The main observation here is that, at a given current, the arc voltage increases with the total gas flow rate, a result predictable from Figs. 2 and 3. It is interesting to compare the high flow rate curve in Fig. 4 with that in Fig. 3. These two independent curves are strikingly similar in that they both flatten with increasing current sooner than might be expected based on the other curves in the family. This seemingly anomalous behavior in both curves tends to confirm that it is a meaningful feature rather than an artifact of the experiment.

Figure 5 shows the arc voltage drop as a function of the fraction of hydrogen for three values of current, with the argon flow rate held constant. While there is considerable scatter in the data corresponding to the highest current 30 A, regression curves passing through data sets for the three values of current are remarkably similar. This suggests that a multiple correlation of voltage with fraction of hydrogen flow and current might be useful. When this is done, the actual voltage data lie within ±15% of a line whose ordinate value increases inversely with current to the 1/4th power and directly with hydrogen volume fraction to a power of 1.158. While this correlation applies only to the torch actually tested, it seems reasonable to expect similar trends from similar torches.

Finally, Fig. 6 shows the electrical power input as a function of volume fraction of hydrogen for a current of 30 A and a fixed argon flow rate of 130 ml/s. These values of current and

Table 1 Torch thermal efficiency (torch temp > 300°C)

Test no.	Flow Ar, ml/s	Flow H_2, ml/s	Torch temp., °C	Current, A	Voltage, V	Electrical power input, W	Plasma power, W	Torchthermal efficiency %
1	130	228	315	21	56	1176	1058	90.0
2	130	228	293	32	57	1824	1670	91.5
3	130	228	471	42	60	2520	2149	85.5
4	130	173	340	10	62	620	518	83.5
5	130	157	393	30	41	1230	1028	83.5
6	134	267	382	10	68	680	615	90.5
7	134	260	393	20	55	1100	970	88.0
8	134	260	427	30	53	1590	1428	90.0

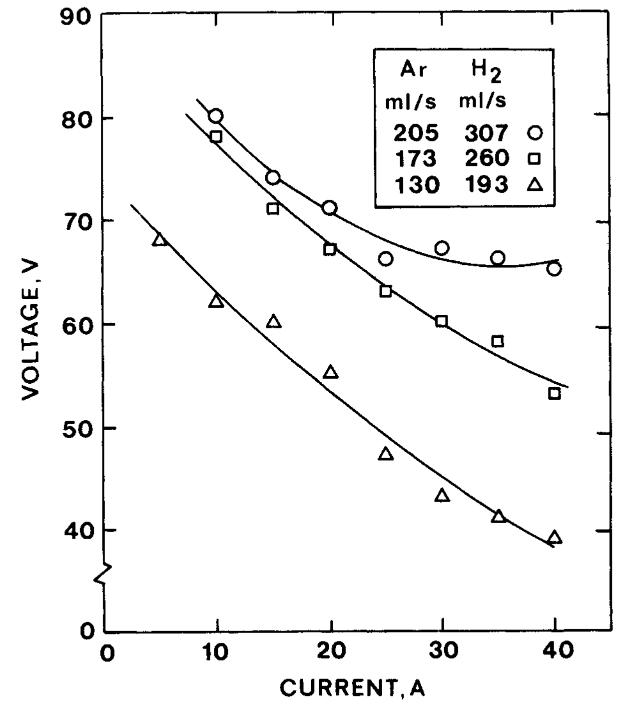

Fig. 4 Voltage-current characteristics with 60% hydrogen flow for a range of total flows (electrode gap = 0.178 mm).

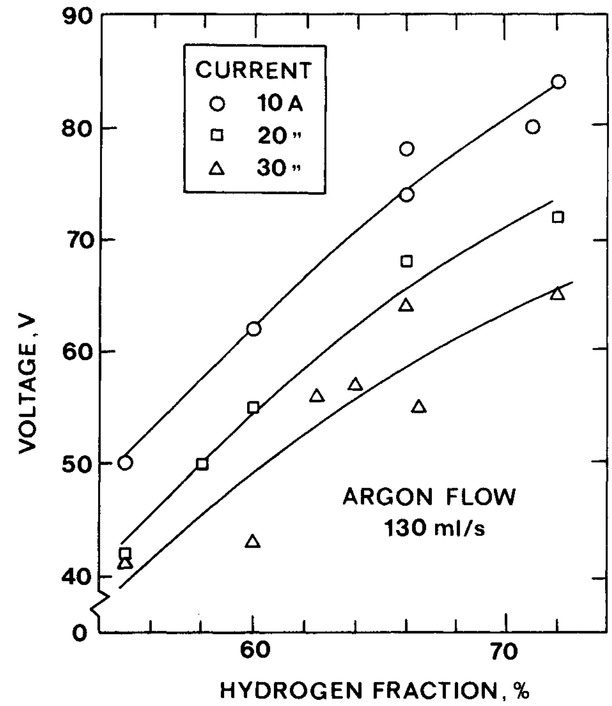

Fig. 5 Variation of arc voltage with percent hydrogen for a range of currents (argon flow = 130 ml/s).

argon flow rate were chosen because they represent nominal values that produce stable torch operation while permitting a wide range of hydrogen flow rates and resulting torch powers. The electrical power input is seen to vary between 0.84 and 1.68 kW as the volume fraction of hydrogen varies from 46 to 73% of the total flow rate. The torch power is an approximately linear function of the volume fraction of hydrogen (or of the flow rate of hydrogen since the flow rate of argon is constant), with a 41% relative increase in volume fraction of hydrogen yielding a power increase of 83%. Curran[9] obtained a similar result for a low-power (0.7 to 1.75 kW) arcjet thruster using nitrogen as a propellant.

Thermal Efficiency

Recall that the torch thermal efficiency is defined as the net power to the gas divided by the electrical power consumed. Measured efficiencies for various flow rates, mixture fractions, and currents are given in Table 1. In each case, the torch was allowed to warm up until the outer surface temperature stabilized above 300°C before data were taken. Average efficiencies of around 88% were obtained in each case, with a low of 83.5% and a high of 91.5%. These values of thermal efficiency are very high compared to those reported in the literature for cooled and even uncooled torches. Northam et al.[4] report a thermal efficiency of around 50% for a low-power water-cooled torch, while Curran[9] found that his arcjet thruster lost about 30% of the electrical power input to the electrodes. Warris and Weinberg[10] found a thermal efficiency of 80% for a 1-kW uncooled plasma torch. Therefore, the results reported here are encouraging.

Electrode Erosion

Cathode erosion was observed to be negligible compared to anode erosion. This is because the bulk of the heat loss by the torch is to the anode. Evidently, ion sputtering at the cathode was minimal for the experimental conditions. The cathode is naturally cooled by the evaporation of energetic electrons and by the relatively cold gas that enters at its base and swirls around it before being heated and ionized as it passes through the arc. The anode on the other hand must suffer the condensation of hot electrons. Also, much of the gas that flows along the anode surface has already passed through the arc and been heated to the plasma state.

The cold gas to be heated is introduced at the base of the cathode with a swirl component. The idea here was that the related aerodynamic forces would cause the arc foot to rotate around the anode surface, thereby diffusing the total anode heat load. Unfortunately, it was found that the swirl component did not persist through the throat with sufficient strength

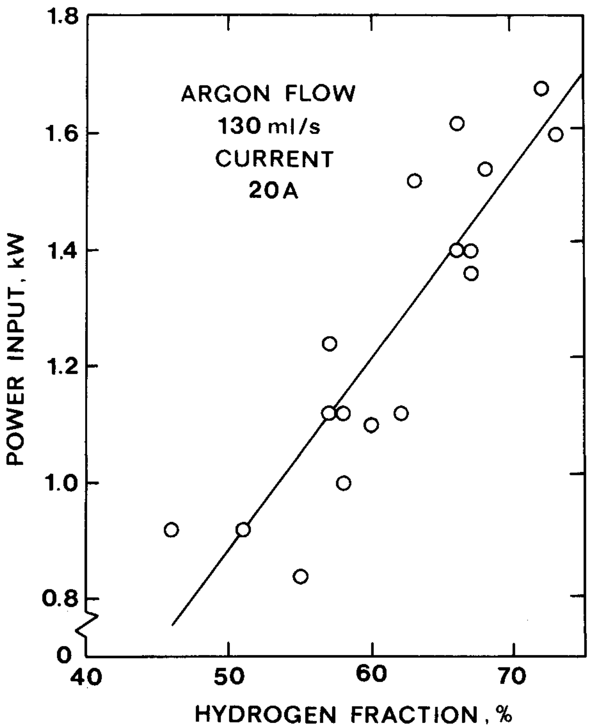

Fig. 6 Variation of torch electrical power input with percent hydrogen (argon flow = 130 ml/s, current = 20 A).

to dislodge and move the anode foot when operating in the favorable high-voltage mode.

The operating time for a typical experiment was 1 to 2 h. The anode erosion was accompanied by a decrease of the torch pressure due to the enlargement of the nozzle throat. For example, in one case, the pressure drop across the throat was observed to decrease by 1 atm, from 3.8 to 2.8 atm, during operation of the arc. In each case, the gas flow and arc current were readjusted to their original set values before data were taken.

Discussion and Conclusions

An uncooled, choked-flow, low-power plasma torch operating on a mixture of hydrogen and argon has been designed, built, and tested in a preliminary study to determine its suitability for use as a flame-holder in supersonic combustion. The stability limits have been delineated in terms of allowable electrode gap, current range, gas flow rate, and hydrogen/argon mixture ratio; and the torch electrical and thermal behavior have been documented within these stability limits. Specific conclusions of the study are as follows:

1) The torch operates stably over a wide range of hydrogen/argon ratios, total gas flow rates, and arc currents in the desired power range of 500 to 2500 W.

2) The arc voltage decreases with increasing current but increases with the hydrogen flow rate throughout the operating regime; therefore, the most effective way to increase the power output of the torch is to increase the hydrogen flow rate.

3) The torch thermal efficiency, defined as the net heat transferred to the gas divided by the electrical power input, is around 88% throughout the design power range.

4) Operation of the torch is limited by anode erosion, which results in a reduction in the nozzle throat pressure drop and eventually leads to unchoking of the flow through the throat. However, anode lifetimes of up to 2 h have been demonstrated.

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