Measurement of Energy Distribution in Flowing Hydrogen Microwave Plasmas

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An electrothermal propulsion concept utilizing a microwave plasma system as the mechanism to convert electromagnetic energy into kinetic energy of a flowing gas is investigated. A calorimetry system enclosing a microwave plasma system has been developed to accurately measure the energy inputs and outputs of the microwave plasma system. The rate of energy transferred to the gas can be determined to within ±1.8 W from an energy balance around the microwave plasma system. The percentage of the power absorbed by the microwave plasma system transferred to the hydrogen gas as it flows through the system is found to increase with the increasing flow rate, to decrease with the increasing pressure, and to be independent of the absorbed power. An upper bound for the hydrogen gas temperature is estimated from the energy content, heat capacity, and flow rate of the gas stream. A lower bound for an overall heat-transfer coefficient is then calculated, characterizing the energy loss from the hydrogen gas stream to the air cooling of the plasma discharge tube wall. The heat-transfer coefficient is found to increase with the increasing flow rate and pressure and to be independent of the absorbed power. This result indicates that a convective-type mechanism is responsible for the energy transfer.

Nomenclature

A = surface area of plasma discharge tube
C_p = heat capacity
F = flow rate
P = power
T = temperature
U = heat-transfer coefficient

Introduction

AN electrothermal propulsion concept[1] is illustrated in Fig. 1. The overall concept utilizes a microwave plasma system as the mechanism in the conversion of solar radiation into thrust. This investigation focuses on the conversion of electromagnetic energy into gas kinetic energy within a flowing hydrogen microwave plasma system. Two of the advantages in employing a microwave plasma system is the absence of any electrodes or metallic surfaces.

Simplistically, microwave radiation is coupled into the resonant plasma cavity, setting up electromagnetic fields. Electrons in the plasma are accelerated by these fields, increasing their kinetic energy. The electrons then transfer their energy to the other species in the plasma *via* collisions. Through relaxation processes, the hydrogen gas thermalizes and the energy becomes kinetic.

A calorimetry system has been designed and built enclosing the microwave plasma system to accurately measure the energy inputs and outputs of the microwave plasma system. A calorimetric technique has been developed to determine the distribution of the energy within the microwave plasma system. The energy ultimately transferred to the flowing hydrogen gas is determined from an energy balance around the microwave plasma system for various power levels, pressures, and flow rates. From knowledge of the energy distribution within the microwave plasma system, the energy transfer mechanisms involved in the energy loss from the plasma to the air cooling of the discharge tube wall are investigated for various power levels, pressures, and flow rates.

For the experimental conditions involved in this investigation, the following regimes are established:

1) The Reynolds number is on the order of 1 so that the velocity profile of the hydrogen plasma may be regarded as laminar.[2]

2) The ratio of the discharge tube diameter to the molecular mean free path is on the order of 100 so that the hydrogen plasma may be regarded as a continuum.[2]

3) The plasma parameter is on the order of 0.01 so that the hydrogen plasma may be regarded as an ideal gas.[3]

Experimental

A schematic diagram of the hydrogen flow system is given in Fig. 2. A regulated stream of 99.9999% hydrogen is fed through ¼ in. stainless steel tubing to a stainless steel needle valve that controls the flow rate as measured by a mass flow meter, which is calibrated for hydrogen gas and has a range of 0-1000 sccm (0-750 μmoles/s or 0-1.5 mg/s). The pressure upstream of the needle valve is measured by a Bourdon tube type of pressure gage and is maintained at 1100 Torr. The pressure drop across the needle valve is large so that fluctuations upstream of the valve will not effect the flow rate or downstream pressure.

The hydrogen gas is then fed through ¼ in. flexible stainless steel tubing to the discharge tube. The discharge tube has a 22 mm i.d. and a 30 mm o.d. air-cooling jacket and is fabricated from fused quartz. The hydrogen gas is then fed through 25 mm i.d. Pyrex tubing to the vacuum pump.

The pressure of the plasma is measured immediately downstream of the plasma cavity by a capacitance-type pressure gage with a range of 10^{-3}-10^3 Torr. The pressure of the plasma for a given hydrogen flow rate is adjusted by introducing 99.95% hydrogen downstream of the plasma.

A schematic of the microwave power delivery system is given in Fig. 3. Electromagnetic radiation is produced by a microwave power generator that has an output range of 0-500 W at a fixed frequency of 2.447 GHz. The radiation is directed through a rectangular waveguide to the circulator protecting the magnetron from reflected power. The radiation is then directed through the waveguide and coaxial cable to the directional couplers. The radiation is then critically coupled into

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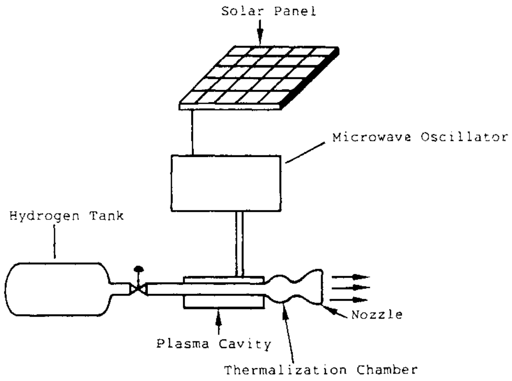

Fig. 1 Overall electrothermal propulsion concept.

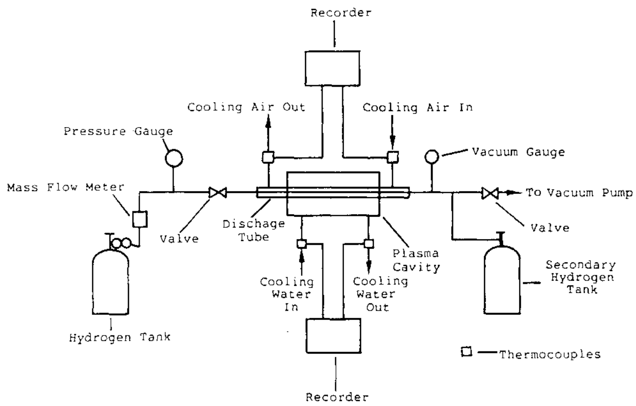

Fig. 2 Hydrogen flow system.

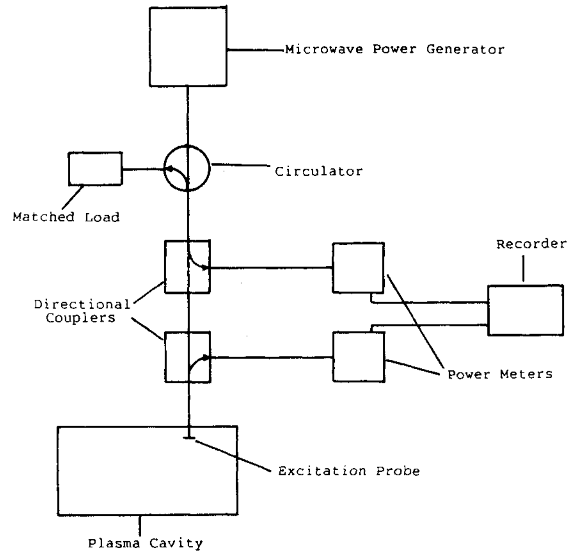

Fig. 3 Microwave power delivery system.

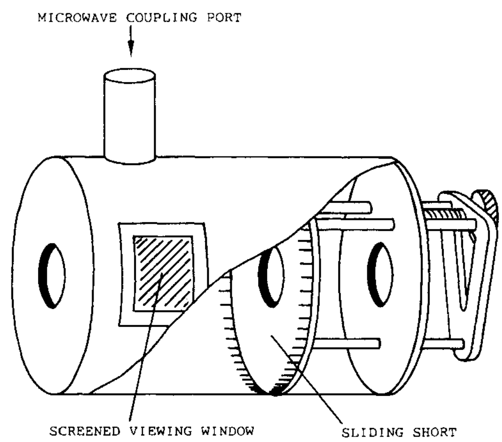

Fig. 4 Plasma cavity.

the resonant plasma cavity by a ⅞ in. coaxial excitation probe.

Power meters and 10 dB directional couplers measure the incident and reflected power levels. Recorders are connected to the power meters to give time histories of the experimental runs. The power meters and directional couplers are calibrated with a known power level of about 3 W at 2.447 GHz, which is produced by a variable-frequency sweep oscillator and amplified by a traveling wave tube.

A diagram of the plasma cavity is given in Fig. 4. The water-cooled cylindrical resonant cavity has a fixed diameter of 20 mm i.d. and a continuously variable length of 6-40 cm and is fabricated from brass. The cavity is capable of supporting a number of resonant modes that represent eigenvalues of the solution to Maxwell's equations involving the experimental parameters.[4] For all of the experimental data, the probe depth and sliding short length is adjusted to obtain a match (minimum reflected power) between the magnetron output and the loaded resonant plasma cavity.

A diagram of the calorimetry system is given in Fig. 5. The cooling air and water are delivered to the calorimetry system at a constant flow rate and temperature. Copper-constantan thermocouples measure the temperatures of the coolant streams. The thermocouples are connected to reference junctions that are maintained at 0°C in a constant-temperature ice bath. Solid copper wires are run from the reference junctions to the recorders that measure the thermocouple voltages and give time histories of the experimental runs. The thermocouples are calibrated with a calorimetric thermometer having resolution of ± 0.001°C.

Diagrams of the water and air cooling systems are given in Figs. 6 and 7, respectively. These systems are individually calibrated by utilizing a dummy load. Microwave radiation is fed into an insulated matched load that is cooled by one of the coolant systems. The flow rates of the coolant streams are measured by calibrated flow meters and kept constant. For an absorbed power range of 0-100 W, the microwave power absorbed by the matched load is measured by the calibrated power meters and directional couplers. An effective heat capacity is then calculated for each of the coolant systems. The overall calorimetry system is then double checked under zero hydrogen flow rate conditions.

Results

The energy inputs and outputs of the microwave plasma system are shown in Fig. 8. An energy balance around the microwave plasma system can be written

$$P_{abs} = P_{gas} + P_{air} + P_{water} + P_{rad}$$

P_{abs} is the power absorbed by the microwave plasma system and is measured by the power meters and directional couplers. P_{air} is the power absorbed by the air cooling of the discharge tube and is measured by the air flow rate and temperature rise. P_{water} is the power absorbed by the water cooling of the plasma cavity and is measured by the water flow rate and temperature rise. P_{rad} is the power contained in the plasma emission radiation that escapes the microwave plasma system.

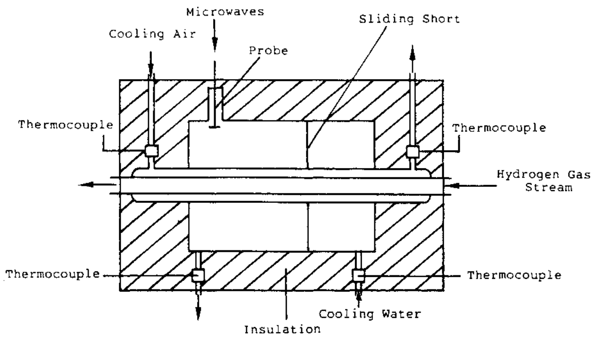

Fig. 5 Calorimetry system.

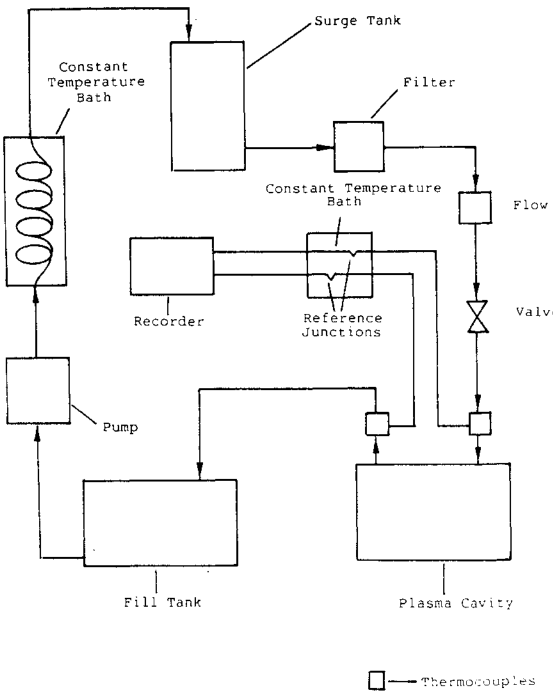

Fig. 6 Cooling water system.

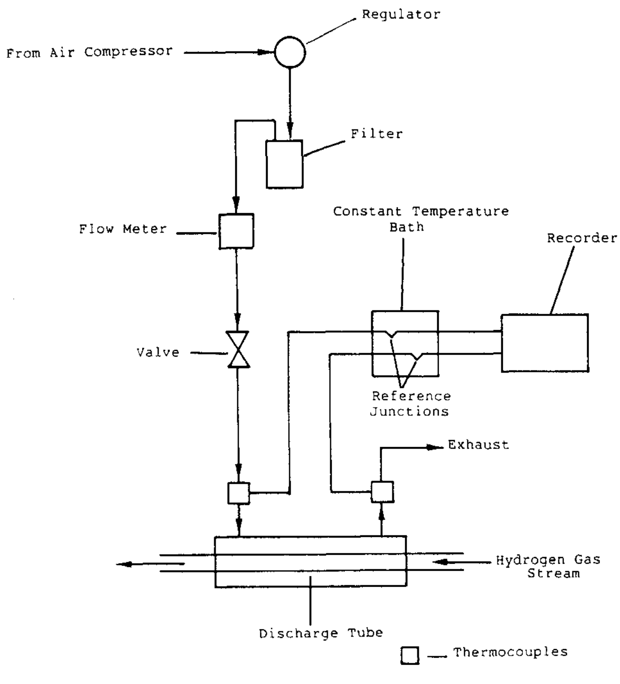

Fig. 7 Cooling air system.

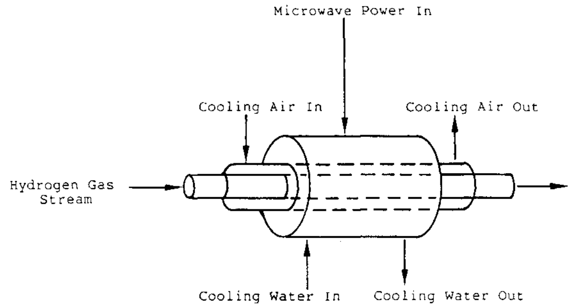

Fig. 8 Energy inputs and outputs.

For the purpose of this study, P_{rad} is neglected since the system is nearly completely enclosed. P_{gas} is the power absorbed by the hydrogen gas as it flows through the microwave plasma system and is determined by the difference

$$P_{gas} = P_{abs} - P_{air} - P_{water}$$

A detailed error analysis of the calorimetry system leads to the following error estimates:

$$\Delta P_{abs} = \pm 0.8\ \text{W}, \quad \Delta P_{air} = \pm 0.5\ \text{W}, \quad \Delta P_{water} = \pm 0.5\ \text{W}$$

resulting in an error for P_{gas} of $\Delta P_{gas} = \pm 1.8$ W.

The percentage of the power absorbed by the microwave plasma system accounted for by the hydrogen gas as it flows through the system is denoted $\%P_{gas}$,

$$\%P_{gas} = 100(P_{gas}/P_{abs})$$

Since P_{gas} is the energy in the gas that is available for thrust, $\%P_{gas}$ is regarded as the efficiency with which the microwave plasma system converts electromagnetic energy into gas kinetic energy. Likewise, the percentage of the power absorbed by the microwave plasma system that is absorbed by the cooling air and water is denoted $\%P_{air}$ and $\%P_{water}$, respectively,

$$\%P_{air} = 100(P_{air}/P_{abs})$$

$$\%P_{water} = 100(P_{water}/P_{abs})$$

$\%P_{gas}$, $\%P_{water}$, and $\%P_{air}$ are found to be independent of the power absorbed by the microwave plasma system for the power levels investigated (0-100 W).

Figures 9 and 10 show $\%P_{gas}$ as a function of flow rate and pressure, respectively. $\%P_{gas}$ is found to increase with increasing flow rate and decrease with increasing pressure. In this study, a maximum value of 24% was obtained for $\%P_{gas}$.

Since the cooling air is transparent to microwave radiation, the plasma first absorbs all of the power absorbed by the microwave plasma system except for that dissipated in the cooled plasma cavity walls through electromagnetic surface currents. The plasma then loses some of its energy through interaction with the cooled discharge tube wall. The plasma also loses additional energy through emission radiation, which is subsequentially reabsorbed by the discharge tube and plasma cavity walls.

Figure 11 shows $\%P_{water}$ as a function of pressure. $\%P_{water}$ is found to decrease slightly with increasing pressure and to be independent of the flow rate. The result is due to the fact that a better match is achieved as the pressure is increased. In general, $\%P_{water}$ is relatively constant; consequentially, the effects of flow rate and pressure on $\%P_{gas}$ are due to their effects on $\%P_{air}$.

Figures 12 and 13 show $\%P_{air}$ as a function of flow rate and pressure, respectively. $\%P_{air}$ is found to decrease with increasing flow rate and increasing pressure.

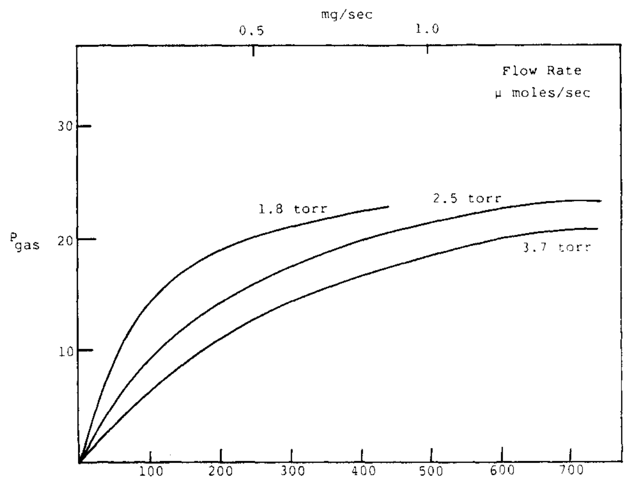

Fig. 9 $\%P_{gas}$ as a function of flow rate.

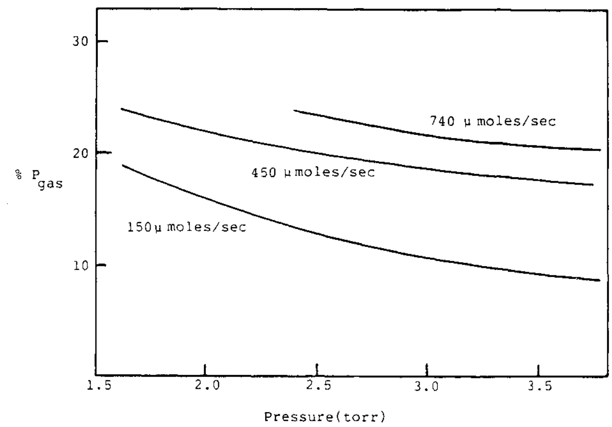

Fig. 10 $\%P_{gas}$ as a function of pressure.

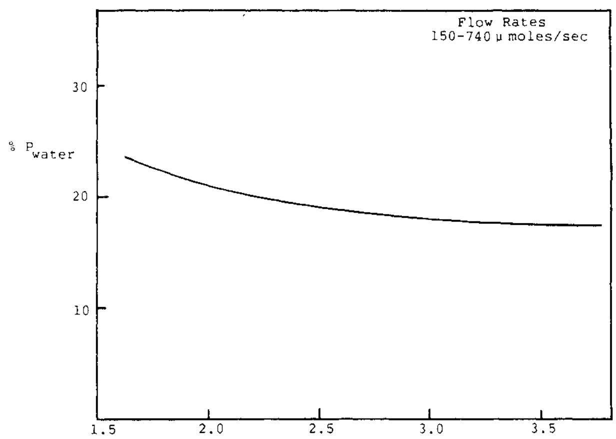

Fig. 11 $\%P_{water}$ as a function of pressure.

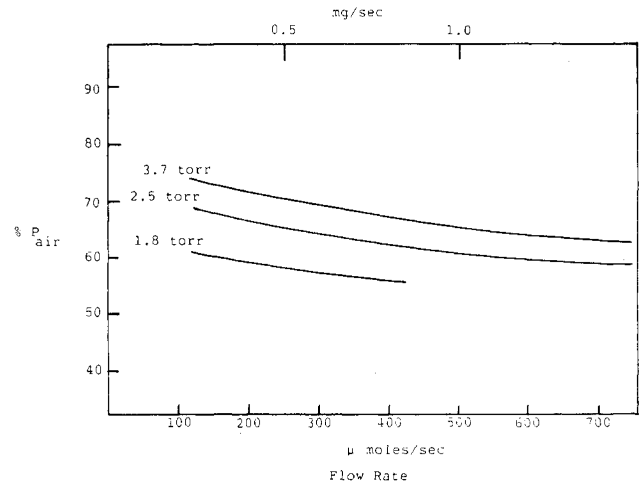

Fig. 12 $\%P_{air}$ as a function of flow rate.

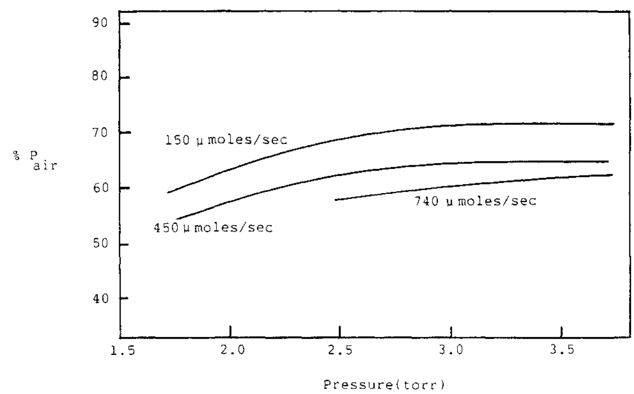

Fig. 13 $\%P_{air}$ as a function of pressure.

Since $\%P_{water}$ is relatively constant at about 19%, then 81% of the absorbed power is initially transferred to the hydrogen gas stream. However, this value is decreased due to the wall interactions. The problem is then reduced to one of keeping the energy in the flowing gas.

To gain some insight as to the dominant energy transfer mechanisms involved in the wall interactions, a simplistic heat-transfer model is utilized,

$$P_{air} = UA(T_g - T_w)$$

where U is an overall heat-transfer coefficient that characterizes the rate of energy transfer, A the surface of the discharge tube, T_g the average gas temperature, and T_w the average discharge tube wall temperature.

For the purpose of this study, T_w is assumed to be room temperature. T_g is estimated from P_{gas} to be

$$P_{gas} = FC_p\Delta T$$

where ΔT is the temperature rise that the hydrogen gas experiences as it flows through the microwave plasma system and F and C_p the flow rate and heat capacity of the gas, respectively.

For the purpose of this study, the dissociation of molecular hydrogen into atomic hydrogen within the plasma is neglected. This assumption yields an upper bound for the temperature of the hydrogen gas as it exits the microwave plasma system. The plasma is also assumed to be well mixed so that the exit temperature of the hydrogen gas is equal to the average gas temperature within the plasma. The temperature estimates obtained are consistent with previous temperature measurements.[5]

From these values of T_g, U is then calculated for various power levels, flow rates, and pressures. Figures 14 and 15 show U as a function of flow rate and pressure, respectively. U is found to increase with increasing flow rate and pressure and to be independent of the absorbed power.

Since the T_g used in the determination of U is an upper bound, the resulting U is then a lower bound. Previous work shows that the dissociation in a hydrogen microwave plasma system increases with increasing flow rate.[6] Therefore, the trend observed for U as a function of flow rate will be more pronounced.

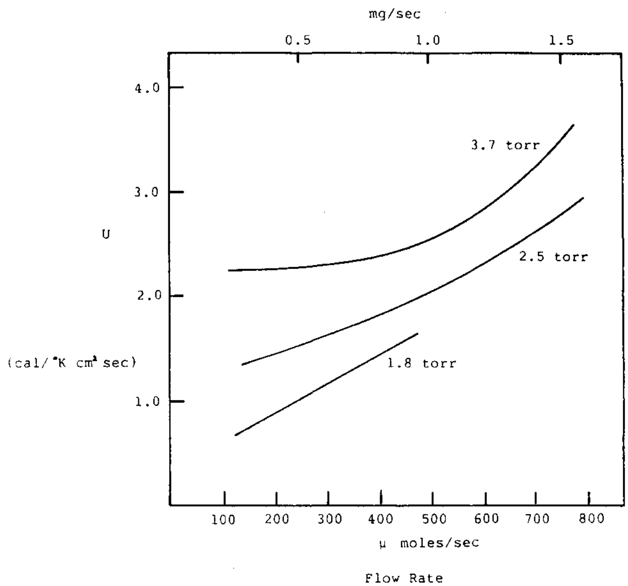

Fig. 14 *U* **as a function of flow rate.**

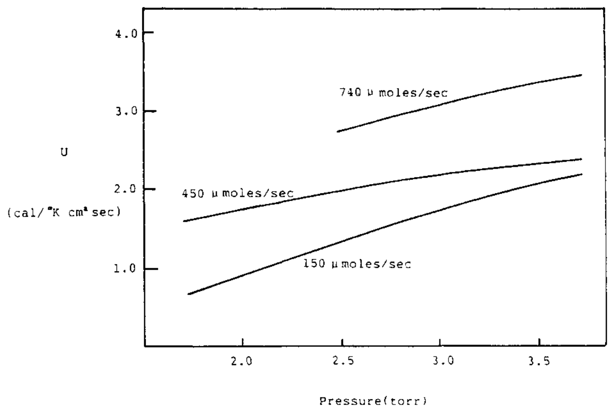

Fig. 15 *U* **as a function of pressure.**

Conclusion

The efficiency that a flowing hydrogen microwave plasma system converts electromagnetic energy into gas kinetic energy has been evaluated for various experimental conditions. For a fixed plasma cavity and discharge tube geometry, plasma cavity resonant mode, and driving frequency, the energy conversion efficiency is found to increase with increasing flow rate, to decrease with increasing pressure, and to be independent of the absorbed power.

Although the populations of the various species and the distribution of their energy states in the plasma are not known, through relaxation processes, all of the energy contained in the hydrogen gas stream as it exits the microwave plasma system is available for conversion to thrust.

It is shown that 81% of the power absorbed by the microwave plasma system is initially coupled to the hydrogen gas stream. The hydrogen gas then loses some of its energy to the cooled discharge tube wall. Therefore, a maximum value of 81% for the energy conversion efficiency is theoretically possible for this particular experimental apparatus.

An overall heat-transfer coefficient, characterizing the energy transfer from the plasma to the cooled discharge tube wall, is estimated for various experimental conditions. The heat-transfer coefficient is found to increase with increasing flow rate and pressure and to be independent of absorbed power. This result indicates that the energy loss of the hydrogen gas stream to the cooled discharge tube wall has a strong convective component.

Acknowledgment

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