Heat Flux Measurements in the Hall Thruster Plume

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Abstract: A heat flux probe has been developed for the purpose of measuring the heat flux density in the plume of the Hall thruster. The measurement is based on comparing the rates of heating and cooling of the probe during its exposure to and isolation from the plasma flow. In the case of a helicon plasma source this is accomplished easily by turning on and off the plasma flow. The measured heat flux into the negatively-biased probe is in a very good agreement with the calculated heat flux carried by the impinging plasma ions, indicating that there are no energetic neutrals. This method will be employed for the plume of the Hall thruster and is expected to provide an estimate of the heat flux carried by energetic neutrals.

Nomenclature

A = the collection area of the probe
C = thermal capacity of the probe material
K_i = ion energy at the presheath-sheath boundary
M = ion mass
M_W = mass of an atom of the probe material
m = electron mass
m_p = probe mass
δ = energy transfer coefficient
dT^+/dt = derivative of the probe temperature with respect to time, when the probe is exposed to the plasma
dT^-/dt = derivative of the probe temperature with respect to time, when the probe is isolated from the plasma

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I_i = ion current to the probe
n_S = plasma density at the presheath-sheath boundary
n = bulk plasma density
T_e = the electron temperature
Φ = the difference between the floating potential and the probe potential
u_B = Bohm velocity
q = total heat flux into the probe
q_i = heat flux into the probe due to the kinetic energy of the impinging ions
q_{rec} = heat flux into the probe due to the released recombination energy of the ions
q_{eout} = heat flux out of the probe due to leaving electrons
q_n = heat flux into the probe due to the impinging neutrals
q_{rad} = heat flux into the probe due to radiation

I. Introduction

Measurement of heat flux is potentially an important tool for understanding various processes in the Hall thruster. There are several techniques for measurement of heat flux: the water cooling probe[1], the temperature depended resistance[2], the gradient of the temperature along the body that one part of it is inserted into the plasma[3], the heat flux compensation[4], the change in temperature of the target[5], and the temperature-time derivatives [6-8] (TTD). The TTD measurement is based on comparing the rates of heating and cooling of the probe during its exposure to and insulation from the plasma flow. In this paper the relatively simple TTD technique for measuring the heat flux from plasmas of argon, xenon, helium, oxygen and nitrogen gases into a molybdenum plate. The measured heat flux into the negatively-biased probe is in a very good agreement with the calculated heat flux carried by the impinging plasma ions, indicating that there are no energetic neutrals. This method will be employed for the plume of the Hall thruster and is expected to provide an estimate of the heat flux carried by energetic neutrals. In Sec. II we describe the heat flux probe and the method of measurement. In Sec. III we describe the helicon plasma source that was used for the measurements and the experimental setup. In Sec. IV we present a theoretical modeling of the heat flux and compare the measurements with the theory. The results and the comparison of theory and experiment are presented in Sec. V.

II. Heat flux measurements

The Heat Flux Probe (HFP) shown in Fig. 1 consists of a molybdenum flat plate with glued chromel-alumel thermocouple. The probe is of dimensions 17.5mm × 19mm and thickness of 0.25mm. It is positioned on the axis of the vacuum chamber at a distance of 30cm from the helicon source, and its plane is parallel to the flow. The measurements of the molybdenum plate temperature are registered in real time by a digital voltmeter connected to a computer. The heat flux is found from the relation:

$$q = Cm_p\left(\frac{dT^+}{dt} - \frac{dT^-}{dt}\right), \tag{1}$$

where dT^+/dt and dT^-/dt are the derivatives of the temperature with respect to time , C and m_p are the thermal capacity and the mass of the molybdenum flat plate. The derivatives denoted by plus and minus signs are measured when the probe is exposed to and isolated from plasma, respectively. Both derivatives are calculated at the same temperature, and the calculated heat flux is found to be independent of the varying plate temperature. Figure.2 shows a typical time–temperature characteristic where the increasing part of the temperature is measured when our helicon plasma source operates and the decreasing part when the source is switched off. Figure 3 shows the derivatives

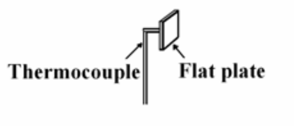

Figure 1. Heat Flux Probe

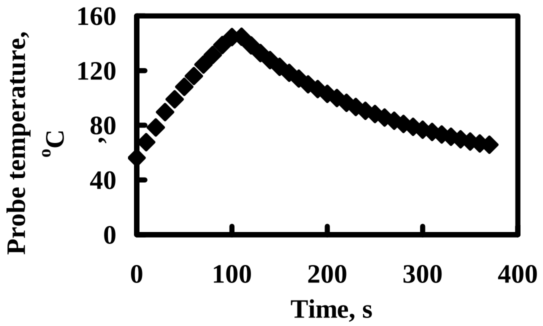

Figure 2. Time–temperature characteristic of the molybdenum heat flux probe operated in an argon plasma. The potential is –70V.

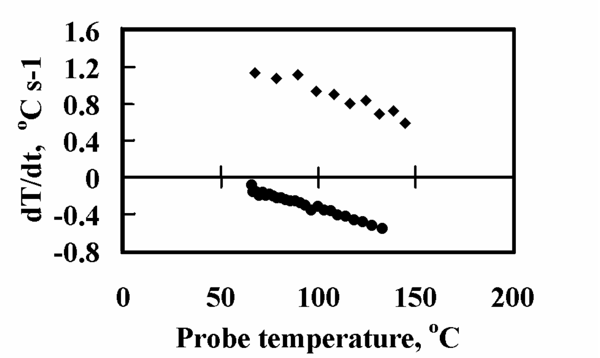

Figure 3. The derivatives of the probe temperature with respect to time versus the temperature.

of the probe temperature with respect to time versus the probe temperature. The constant difference between the two curves demonstrate that the heat flux does not depend on the probe temperature. The choice of the physical and mechanical properties of the HFP depends on the conditions of probe operation. In the next section we describe the helicon plasma source that was used for the measurements.

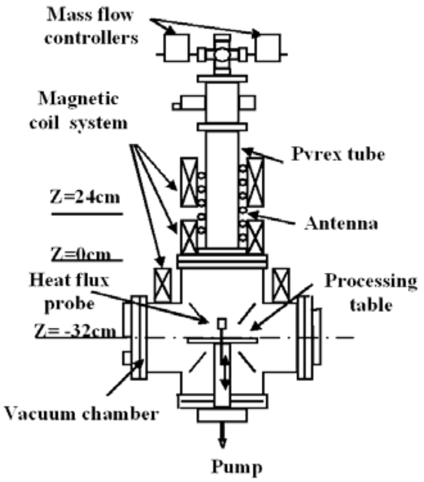

Figure 4. Experimental setup

III. Experimental setup

The experimental system is schematically shown in Fig.4. The plasma source is composed of a vacuum chamber, a mass flow controller, solenoids that generate an axial magnetic field, radio-frequency generator with matching units, and an antenna. The plasma is generated inside a Pyrex tube, 52cm in length, 10 cm outside diameter and 2.5mm thickness. The radio-frequency generator radiates at 13.56 MHz and the power varies here between 200W to 300W. The antenna is a helix of six turns of 35 cm length and 10.5cm diameter. The zero cross section of axis z is located on the place connection a Pyrex tube with a vacuum chamber. An antenna is located between z = 8cm and z =43cm. The magnetic field intensity in a helicon plasma source in the experiments here is 120G. The vacuum chamber and Pyrex tube are pumped to a base pressure of 5×10^{-6} Torr. Employing a flat Langmuir probe of diameter 1 mm, we have measured the plasma density and electron temperature. The Langmuir probe was protected by L-filter (L=0.46mH). The heat flux probe that was described in previous section can operate as the Langmuir probe. In order to increase the plasma density in the stainless steel chamber outside of the helicon source, where the measurements were taken, a magnetic field of intensity 100G and 150G was employed.

IV. Theory

The heat flux into the probe is

$$q = q_i + q_{rec} - q_{eout} + q_{rad} + q_n \quad (2)$$

Here q_i is the dissipated kinetic energy of the ion flux, q_{rec} the recombination ion heating, q_{eout} the cooling part when electron leave the surface of the probe, q_{rad} the radiation heat flux from the plasma and q_n the dissipated neutral energy. For our condition of collisionless plasma the radiation and dissipated neutral energy are small, so that we neglect them. In particular, we write

$$q_i = I_i \delta (K_i + T_e \ln \left(\frac{M}{2\pi m} \right)^{1/2} - \Phi) \tag{3}$$

The term in the parentheses is the difference between the voltage drop between the plasma and the probe, Φ is the voltage drop between the floating potential and the probe. Also $K_i = T_e/2$ is the ion energy at the presheath boundary. Here I_i is the ion current, T_e (eV) the electron temperature, M, m the ion and electron masses. For binary collisions the energy transfer coefficient is given by[7,10]

$$\delta = \frac{4MM_W}{\left(M + M_W\right)^2} \tag{4}$$

where M_W is the mass of probe atom. The ion current is determined from Bohm sheath criterion and given by

$$I_i = n_S u_B A \tag{5}$$

where n_S the plasma density at the sheath boundary is $0.6n$, n being the bulk plasma density, u_B the Bohm velocity, A the area of ion current collection by the probe. If this area grows with the increase in voltage we take it into account in the calculation.

V. Results

The heat flux of various gases was measured by molybdenum and ELERO (an alloy composed of 70% tungsten, 30% copper) probes. We also measured the electron density and temperature and the plasma and the floating potentials. Taking into account also the recombination energy of ions and the molybdenum work function, we calculated the heat flux according to Eqs (2)-(5). The agreement between theory (solid line) and experiment (dotted) that is shown in Figs. (5)-(8) is very good.

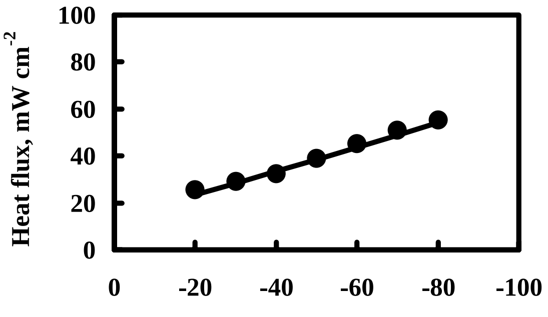

Figure 5. Molybdenum probe and a xenon plasma, $T_e = 4.3$ **eV,** $n = 2.2 \times 10^{16}\,\mathrm{m}^{-3}$**.**

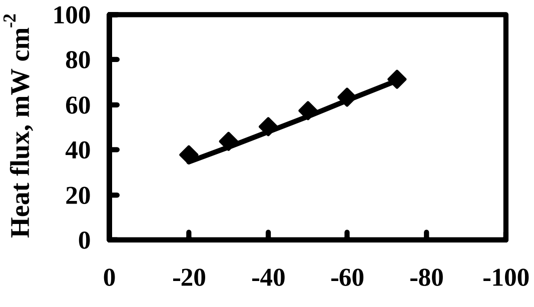

Figure 6. Molybdenum probe and an argon plasma, $T_e = 4.9$ eV, $n = 1.8 \times 10^{16}\,\mathrm{m}^{-3}$

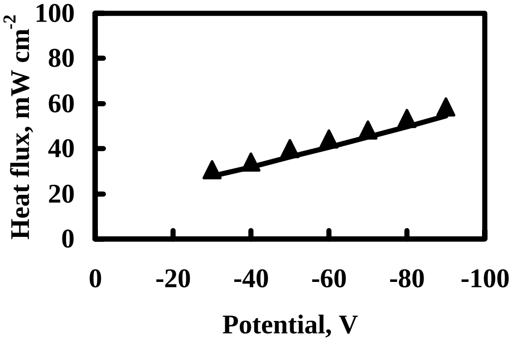

Figure 7. Molybdenum plate and a nitrogen plasma, $T_e = 7$ **eV,** $n = 8\times10^{15}\,\mathrm{m^{-3}}$

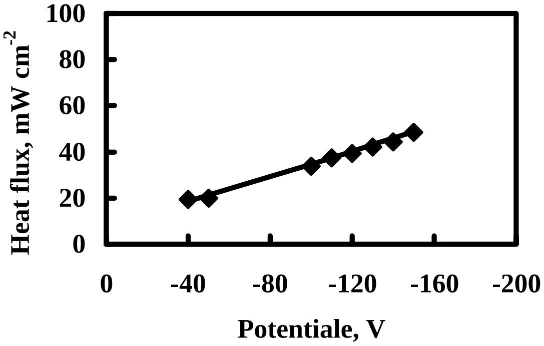

Figure 8. ELERO plate and a xenon plasma, $T_e = 5$ **eV,** $n = 1.3\times10^{16}\,\mathrm{m^{-3}}$

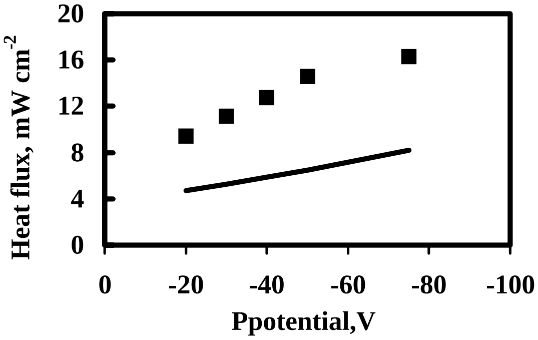

Figure 9. Molybdenum probe and a helium plasma. $T_e = 14$ **eV,** $n = 2\times10^{14}\,\mathrm{m^{-3}}$

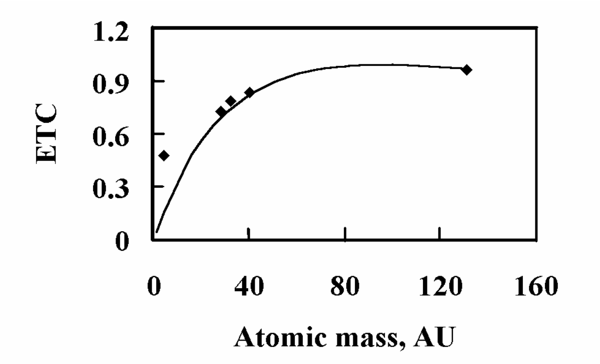

Figure 10. Energy transfer coefficient (ETC) for molybdenum probe versus atomic mass of the impinging ions..

It is interesting to note that the agreement between experiment and theory for nitrogen was obtained only when we assumed that the plasma is composed of N_2^+ and not of atomic ions. Similar indications to molecular oxygen plasmas were obtained (not presented here). Therefore, this measurement provides us indirectly with important information about the plasma composition.

A disagreement between theory and experiment is shown in Fig. 9. In order to examine the discrepancy, we take the measured heat flux, and find, according to Eqs. (2) and (3), the energy transfer coefficient. Figure 10 shows the dependence of the energy transfer coefficient on the atomic mass of the impinging ion. The solid line shows the coefficient calculated by Eq. (4) and the points are the values of the coefficient calculated according to the measured heat flux. The coefficient for argon is in a good agreement with early measured results.[11] Except for helium, there is an agreement between the theoretical and experimental results (nitrogen and oxygen ions are assumed molecular, as discussed above). The helium is shown not to fit Eq. (4). We suggest that the helium atoms are deposited on the molybdenum surface, and the helium-helium collisions cause an effective increase of the energy transfer coefficient.

VI. Conclusion

The method for measurement of the heat flux will be used in the Hall thruster measurement. The difference between the measured and calculated heat fluxes will be attributed to the neutrals.

Acknowledgments

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