Theory of a cylindrical emissive probe

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Abstract: We employ a theory that we recently developed for a cylindrical emissive probe to evaluate the plasma potential distribution in our Radial Plasma Source (RPS). Within the theory, the potential of a cylindrical emissive probe in plasma is calculated for an arbitrary ratio of Debye length to probe radius (Debye number). For a small Debye number, we derived analytical expressions for the potential drop and for the currents. The regime of a finite Debye number requires numerical calculation. For evaluating the plasma potential, we measured the potential of a floating probe once when the probe is cold and once when the probe is heated up to space-charge current saturation. We also measured the ion saturation current into a negatively biased Langmuir probe. By use of our theory of the emissive probe and these measurements, we plot the radial profiles in the RPS of the plasma potential as well as of the electron density and temperature.

Keywords: emissive probe, plasma potential, sheath, Radial Plasma Source

1. Introduction

Applying a voltage across plasma is used in many plasma devices. We are developing a Radial Plasma Source (RPS) [1, 2], a configuration that can be used for industrial applications as well as for electric propulsion. As we apply a voltage to accelerate the plasma flow, we would like to know the electric potential distribution. We have recently developed a theory that solves for the electric potential and the plasma flow around a cylindrical emissive probe [3]. In this paper we describe how we used this theory to interpret the measurements made with an emissive probe and a Langmuir probe and to obtain the spatial distributions of the plasma potential and of the plasma variables in the RPS.

2. The Radial Plasma Source

The RPS, shown in Fig. 1, consists of a ceramic unit, a molybdenum anode, a magnetic-field generating solenoid, an iron core, a gas distributor and a cathode employed for neutralizing the ion flow. The heated cathode neutralizer is located 4cm from the RPS edge. All the measurements are taken for a mass flow rate through the cathode of 4sccm (Standard Cubic Centimeter per Meter). An argon gas is injected through the gas distributor in the anode. A voltage that is applied between the anode and the cathode ignites a discharge and accelerates the plasma ions radially-outward across the axial magnetic field. The momentum of the mixed ion-neutral jet is balanced by magnetic field pressure. The ions are accelerated by an applied electric field across a magnetic field, while electrons perform an E×B drift. The RPS or a variation of it can be used for industrial applications as well as for electric propulsion.

Figure 1 The RPS in operation and a schematic [1].

3. The theory of an emissive probe

Our theory [3] enables us to calculate the normalized electric potential, $\psi = e\phi / T$, as well as the variation
of plasma parameters in the vicinity of the probe. Here, $\phi$ is the electric potential and $T$ the electron temperature. In all the cases we deal with here, the probe used for the potential measurements is floating. Our main interest is to know what is the normalized probe potential relative to the plasma, $\psi_e = e\phi_e / T$. A characteristic parameter is the Debye number, $\delta = \lambda_D / a$, where $\lambda_D$ is the Debye length and $a$ the radius of the cylindrical probe.

If the floating probe is cold and non-emitting, the probe potential is considerably lower than the plasma potential in order to repel the plasma electrons so that the ion and electron fluxes from the plasma to the probe are equal. When the floating probe is heated and emits electrons, current neutrality is partially maintained by the emitted electrons. This allows the electron current from the plasma to be larger, and the potential of the probe is closer to the plasma potential. As electron emission from the probe is increased the electric field at the probe decreases until the electric field becomes zero. This is the space charge limit and current saturation. The probe potential even then is still lower than the plasma potential, in order to draw electron current from the probe.

Figure 2 shows how the potential drop between the plasma and the probe $\psi_e$ and the three normalized currents, plasma ion and electron currents and electron current from the probe, vary when the electron emission from the probe is increased. The results are for $\delta \to 0$ and for argon plasma. The potential of the floating probe varies from $\psi_e = -5.2$, when the probe is cold and not emitting, to $\psi_e \approx -1.5$ when the probe is hot and emitting up to the space-charge limit current.

The probe potential crucially depends on the Debye number $\delta$. In order for the probe to emit electrons when it is heated, its radius has to be small and therefore often $\delta$ is finite. The probe potential gets closer to the plasma potential if $\delta$ is larger. The normalized potential difference between the plasma and the probe versus $\delta$, as found in our theory, is shown in Figs 3 and 4.

Figure 3 shows the probe potential relative to the plasma potential as a function of Debye number $\delta$ for a cold, non-emitting probe. When $\delta = 0$, the value of the potential coincides with the value obtained for a planar sheath. We note that in all the calculations in our model, the ions are assumed collisionless during their motion from the plasma to the probe. As is well known for the planar collisionless sheath, the potential difference when $\delta = 0$ depends logarithmically on the ion-electron mass ratio. The results in Fig. 3 are for argon plasma. The calculation for a cold probe without electron emission from the probe has also been done in [4].

Figure 4 shows the probe potential relative to the plasma potential as a function of Debye number $\delta$ for a hot, electron emitting probe at space-charge
current saturation. It is clear from the figure that even at current-saturation the probe potential does not reach the plasma potential. The probe potential is lower than the plasma potential, so that electrons emitted from the probe are drawn to the plasma. Also shown in Fig 4 are the normalized currents; plasma ion and electron currents and the electron current emitted from the probe at space-charge current saturation.

In the next section we describe potential measurements with an emissive probe in our RPS.

4. The measurements

Figure 5 shows probe potential measurements with our emissive probe, at various distances from the axis of symmetry of the RPS. The maximal intensity of the magnetic field in the mid-plane is 130 G. At each location shown are measurements for two values of the gas flow rate and for two modes of the probe. In one mode, the probe is cold and does not emit electrons. In the other mode the probe is hot, emits electrons, and is actually at current saturation.

Had we known the electron temperature and the Debye number, we could have used either one of the two measurements shown in Fig 5, either that with a cold probe or the other with the hot probe, to determine the plasma potential at each location. However, since we need two additional parameters, $T$ and $\delta$, in addition to the probe potential, there is one additional piece of data missing. This additional data is the ion saturation current, taken with a Langmuir probe. Figure 6 shows the ion saturation current of a Langmuir probe for the two different gas flow rates at various distances from the axis of symmetry.

The measurements shown in Fig 6 were taken with the Langmuir probe which was positioned in the $(r, \theta)$ plane, so that the plasma flow is parallel to the probe plane. The measurements with the two probes enabled us to calculate the distribution of the plasma potential and of the electron density and temperature.

5. Analysis and results

At each location and for each gas flow rate, we look for the plasma potential, the electron temperature, and the plasma density. For these three unknowns,
we have three measurements. Let us write the relations:

\[
\begin{align*}
  e\phi_{\text{plasma}} &= e\phi_{\text{probe,cold}} + T f_{\text{cold}}(\delta) \\
  e\phi_{\text{plasma}} &= e\phi_{\text{probe,hot}} + T f_{\text{hot}}(\delta) \\
  I_{\text{sat}} &= 0.4enA\sqrt{T/m_i}
\end{align*}
\]

Here, \(\phi_{\text{probe,cold}}, \phi_{\text{probe,hot}}\) and \(I_{\text{sat}}\) are measured. The functions \(f_{\text{cold}}\) and \(f_{\text{hot}}\) are calculated in Figs 3 and 4, \(A\) is the area of the Langmuir probe, and \(\delta\) is a function of the unknowns \(n\) (the plasma density) and \(T\). We solved these equations in each location for \(\phi_{\text{plasma}}, n, T\). The results (also of \(\delta\)) are shown in the figures below.

![Figure 7](image7.png)  
**Figure 7** The calculated plasma density versus the distance from the axis of symmetry of the RPS for the two gas flow rates.

![Figure 8](image8.png)  
**Figure 8** The calculated electron temperature versus the distance from the axis of symmetry of the RPS for the two gas flow rates.

![Figure 9](image9.png)  
**Figure 9** The calculated Debye number versus the distance from the axis of symmetry of the RPS for the two gas flow rates.

![Figure 10](image10.png)  
**Figure 10** The calculated plasma potential versus the distance from the axis of symmetry of the RPS for the two gas flow rates.

We note that for a higher gas flow rate the plasma density is higher, but the electron temperature and the plasma potential are lower.

**References**


