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Deduction of plasma flow in a collisional un-magnetized plasma

Yong-Sup CHOI[1], Hyun-Jong WOO[2], and Kyu-Sun CHUNG[2,3]

[1]*Samsung Mobile Display, YongIn, KyongGi, Korea,*

[2]*Department of Electrical Eng. and Center for Edge Plasma Science, Hanyang University, Seoul, Korea*

[3]*Coordination Research Center, National Institute for Fusion Science, Toki, Gifu, Japan*

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An argon plasma generated by a torch arc discharge with pressure of 50 torr and power of 800 watts is characterized by a single and Mach probes. A fluid model for the flowing un-magnetized plasma with the generic two-dimensional feature is established by taking moment of one-dimensional Boltzmann transport equation with contribution of ionization and ion-neutral collisions. Using a new relation between Mach number ($M_0 \equiv v_d/\sqrt{(T_e+T_i)/m_i}$, T_e=electron temperature, T_i=ion temperature, m_i= ion mass, and v_d=drift velocity) and ratio (R) of the upstream to downstream ion sheath current densities, the plasma flow at the center of the torch plasma is deduced about 1 km/sec, which is 5 ~ 6 times smaller than those by the previous collisionless models and is more close to those by other experimental and numerical results for the similar cases.

Keywords: ion-neutral collision, plasma flow, Mach probe, torch plasma

1. Introduction

Application of low atomic number (Z) neutrals, moving surface plasma facing component (PFC) or low-Z liquid metal to fusion edge plasma is a method of reducing power flux to the PFC's or reducing recycling of fuel plasmas [1–4]. As fuels of space propulsion systems, noble gases such as neon, argon, and xenon have been used in direct current (DC), radio-frequency (RF) and microwave ion generations [5, 6]. Interaction of these heavy isotopes with background hydrogen plasma affect the thrust or impulse. During these processes, neutrals are interacting with the background plasma and affect the flow to the plasmas facing components. However, all the data measured by a Mach probe, which is composed of two separate single electric probes located on the opposite direction of an insulator, have been analyzed by collisionless models.

As an example of a collisional plasmas to be generated in space propulsion systems and fusion edge plasmas, an argon plasma is generated at 50 torr by a torch arc discharge, and plasma flow is measured by a Mach probe. Mach probe (MP) has been generally used to measure the plasma flow velocity in strongly magnetized plasmas [7–10], and in unmagnetized plasmas [11–14]. Collisions in the presheath and sheath should be included, which have been neglected in the existing Mach probe models, to overcome the limitation to application to collisional plasmas such as atmospheric or high pressure plasmas, tokamak edge plasmas because of the high neutral densities due to recombination of charged particles and neutral gas feeding to detach the plasma from the wall. Although there are several papers concerning the collisionality around the sheath, they treat the stationary cases [15, 16].

To cover the case of the flowing plasmas, a kinetic treatment of the un-magnetized Mach probe given by Chung [17] can be considered. He treated the two dimensional problem of the Mach probe as a one dimensional problem by introducing particle inflow in the perpendicular direction to the wake region, which is driven by a density difference between the perturbed transition area and the external plasma. The ion saturation currents collected from the upstream and downstream sides are different from each other, and the ratio of the ion saturation current density of upstream side (J_u) to that of downstream (J_d) is a function of the drift velocity, which is generally expressed as an exponential form:$R = J_u/J_d = \exp[KM_0]$, where $M_0 = v_d/\sqrt{T_e/m_i}$ and v_d is the drift speed. Here the calibration factor K is a function of the magnetic flux density, ion temperature, plasma viscosity, or collisionality of plasma and neutrals, etc [17–22].

Engeln et al. [23] generated a cascade arc to expand into a vessel with 20 torr, and measured the speed and temperature of argon neutral by the laser-induced fluorescence(LIF) method. Juchmann et al. [24] measured the speed of argon and hydrogen mixture by putting nitrongen oxide(NO) into the torch plasma by LIF at the pressure of 25 torr. Rennick et al. [25] obtained the density distribution of carbon hydrate radicals after getting the speed of the argon neutral in a DC arc jet using the model of Engeln et al.However, a more reliable un-magnetized Mach probe theory for the plasma flow has to be developed for a general geometry and comparison with independent measurement technique such as LIF should be done. In this work, we have developed the collisional and un-magnetized MP theory including the collision terms with the Boltzmann equation.

2. A Torch Experiment

The experimental apparatus is composed of a discharge chamber (36 cm in diameter, 1 m in length), a DC power supply, a spectroscopy system, a fast scanning probe system with a single probe. Figure 1 shows a schematic diagram of the torch and operating systems. The spray gun is a non-transferred arc-type system that contains a cathode and a anode inside. The current of the arc generates joule heating to heat and ionize gas. The transition to the

author's e-mail: kschung@hanyang.ac.kr and chung.sun@nifs.ac.jp

plasma state is accompanied by a rapid expansion and a large plasma flow. In addition, the arc current interacts with the self generated magnetic field to accelerate plasma. The anode is made of oxygen-free copper that has a high conductivity and purity (64 mm in diameter, 40 mm in the height) while the cathode is made of thoriated tungsten (8 mm in diameter, 6 mm in height). The anode and the cathode are installed along a coaxial line and are cooled by water in order to prevent overheating. The fast scanning probe system, which is driven by a pneumatic cylinder with stroke of 510 cm with a maximum speed of 2.2 m/sec, measures the electron temperature and the plasma density by using a single probe (0.25 mm in radius, 1.5 mm in length). Experiments were performed at a base pressure of 50 mTorr and a working pressure of 50 Torr. After injection of the Ar gas with flow rate of 35 lpm, the spraying plasma (about 1 cm in diameter, 5 cm in length) was generated using about 800 watts of DC power (35-40 A and 20-25 V).

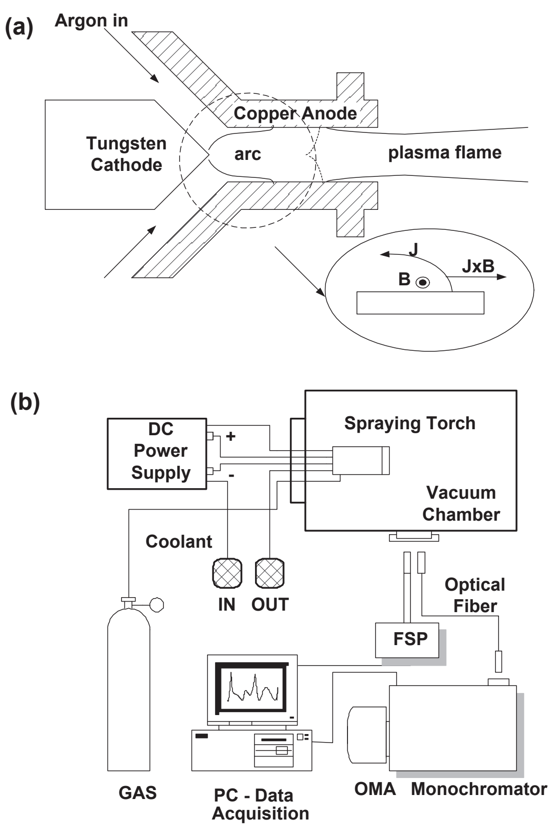

Fig. 1 Schematic diagrams of the non-transferred arc torch itself (a), and low pressure torch system (b). FSP = Fast-Scanning Probe, OMA= Optical Multichannel Analyzer

Figure 2 shows current-voltage(I-V) curves at the center ($r \sim 0$ mm) and edge ($r \sim 1$ cm) of present plasma as determined by using a single probe. The electron energy distribution function(EEDF) can be calculated from the second derivative of I-V curve; also, the plasma density (n_e) and the effective electron temperature (T_{eff}) can be calculated from integration of EEDF [26–28]:

$$n_e = \int_0^\infty \frac{4}{A_p e^2}(\frac{m_e \epsilon}{2e})^{0.5}\frac{d^2 I_e}{dV_b^2}dV_b,$$

$$T_{eff} = \frac{2}{3n_e}\int_0^\infty \epsilon\frac{4}{A_p e^2}(\frac{m_e \epsilon}{2e})^{0.5}\frac{d^2 I_e}{dV_b^2}dV_b,$$

where A_p, m_e, n_e, ϵ, e, I_e, V_b are the probe area, electron mass, electron density, electron energy, electron charge, electron current, and probe bias voltage, respectively.

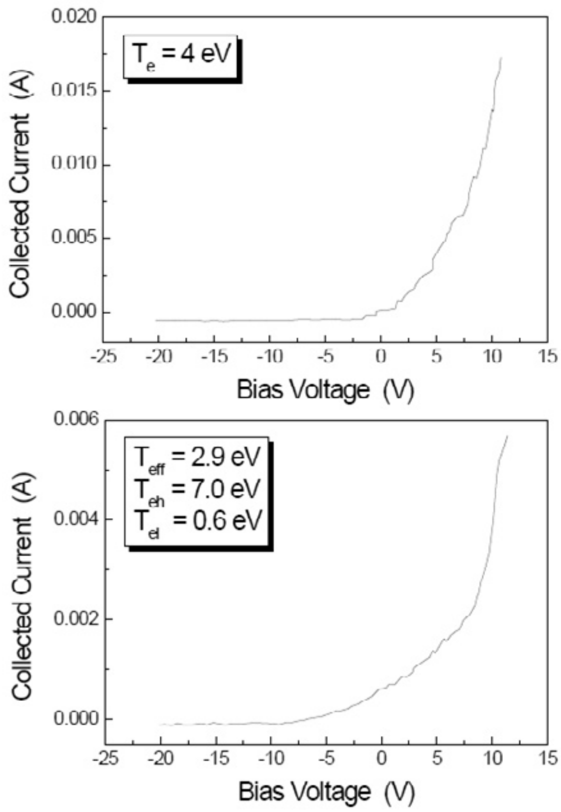

Fig. 2 Torch plasma parameters Center ($r = 0$):$T_e = 4$ eV, $n_e = 1.6 \times 10^{13}$ cm^{-3}, Edge ($r = 4$ mm): $n_e = 5.1 \times 10^{12}$ cm^{-3}. T_{eh}=high electron temperature, T_{el}=low electron temperature, T_{eff}=effective electron temperature.

The generated torch plasma has electron temperature of 3 – 4 eV and density of 10^{13} cm^{-3}, and tantalum probe of 0.25 mm diameter can survive about 500 ms according to a conservative heat transfer model [11]. Because the fast scanning system can provide maximum velocity of 2.2 m/sec, we can measure plasma properties without damaging the probe tip. From the single probe measurement, plasma parameters are evaluated as $T_e = 4$ eV and $n_e = 1.6 \times 10^{13}$ cm^{-3} at plasma center and $T_{eff} = 3$ eV, $n_e = 5.1 \times 10^{12}$ cm^{-3} at the plasma edge ($r = 4$ mm), as shown in Fig. 2. Because the single probe experiments were done in high pressure (50 Torr) plasma, collisional effect should be included in the single probe analysis.

Because the fluid model is calculated for plasma edge, one has to make sure that there is no ionization or collision in the sheath (i.e. from plasma edge to the probe surface). As a scale length of collision and ionization, Debye length (λ_D), momentum collision length (λ_m) and ionization mean free path(λ_{iz}) are given as $\lambda_D = f(n_e, T_e)$, $\lambda_m = f(p, T_n, T_i) \approx f(p, T_n)$, and $\lambda_{iz} = f(p, T_n, T_e)$, where p, n_e, T_e, T_i, T_n are neutral pressure, electron density, temperatures of electron, ion and neutrals, respectively. Then the applicable range of the collisional Mach probe theory should satisfy the following: $\lambda_{iz} \ll \lambda_D \approx L_{sheath}$.

For the maximum ionization cross section of argon (E=80 eV), ionization mean free path is given as 0.0015 mm at atmospheric pressure and it increase with pressure decrease. Because most of low temperature plasma has electron temperature less than 10 eV, practical ionization mean free paths are given as 16, 0.06, and 0.008 mm for Te= 2, 5, and 10 eV, respectively [29,30]. Most plasmas of interest has density of $10^8 - 10^{14}$ cm^{-3} and electron temperature of 1-10 eV. The Debye length (λ_D), which is the scale of sheath length, is given in the range of 0.0007 – 2 mm. Experimental conditions of Mach probe and normalized frequency are summarized as the following: Gas = Ar, Pressure = 50 torr, Power = 800 watts, Plasma density = 5.1 ~ 16.0 × 10^{12} cm^{-3}, T_e = 4 eV, T_i = 0.8 eV, Probe length=1 mm, Probe diameter=0.25 mm, Probe holder diameter=2 mm, λ_D = 0.005 mm. Figure 3 shows the ion saturation current densities measured by the directional probes at upstream-side and downstream sides, and their ratio along the radial direction.

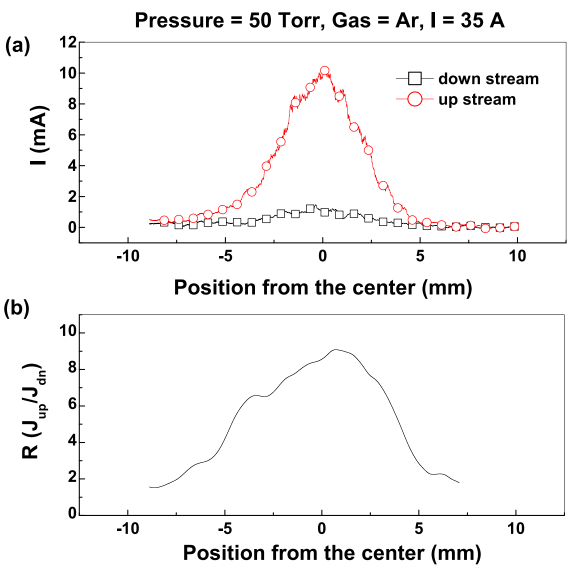

Fig. 3 Current ratio of Mach probe. Upstream and downstream ion saturation current densities (a) and their ratio (b)

3. Analysis

In modeling the Mach probe in un-magnetized flowing plasmas, the critical physics lies in the wake. Although the analysis of the wake should be analyzed by the two-dimensional or multidimensional model, it would be difficult to solve the two dimensional kinetic model, but it might be useful to use a one-dimensional model with inclusion of the two-dimensional transport information. Data of wake experiments using planar disk showed that the scale lengths of potential or density variation along the pre-sheath can be expressed in terms of the disk size for the stationary weakly collisional plasmas (v_d = 0) and for the subsonic to supersonic plasmas ($0.5 \le v_d/\sqrt{2T_i/m_i} \le$) [31]. Especially, for the experiment of wake with supersonic flows ($1 \le M_0 = v_d/\sqrt{T_e/m_i} \le 20$), the size of the wake is expressed in terms of the object size regardless of the shape for the following supersonic Mach numbers: $M_0 = 1 \sim 2$ [32], $M_0 = 2 \sim 4$ [33], $M_0 = 5 \sim 14$ [34], $M_0 = 10 \sim 23$ [35]. In describing the ion distribution and density in the wake of ionospheric plasmas, Gurevich et al. [36] expanded ion density in terms of the size of planar disk or cylindrical radius. From the analysis of a two-dimensional kinetic theory, Grabowski and Fisher [37] expressed the density variation in terms of the radius of cylindrical probe, a, (up to $6 \sim 8\ a$). They even calculated the weakly magnetized case which produces similar values to those without magnetic field, while for marginal case, $\rho_i \approx a$, density variation shows the oscillatory behavior along the magnetic field direction. Hutchinson [19] also described the particle motion around the spherical probe in terms of radius (up to $\sim 5\ R_0$). From this, it could be justified that one can describe the pre-sheath of the planar probe in terms of the size of the probe. And one can consider the source of the wake as the particle inflow from outside to fill the wake due to density gradient and potential gradient to pull the particles.

Chung [17] developed a one-dimensional model in order to deduce the flow velocity from the sheath current density, by treating the perpendicular component to the streaming direction as a source in the perturbed region, i.e., by taking into account the convective inflow toward the perturbed region (sheath-transition region) as a source. This model seems to simplify the models of Gurevich [36], Grabowski [37] and/or Merlino [33]. By adding a collision term ($(\delta f/\delta t)_c$) to Chung's kinetic model, and by taking moments, one can obtain the following systems of fluid equations :

$$n\frac{dV}{dz} + V\frac{dn}{dz} = \nu_{iz}n + \frac{v_{ti}}{a}(n_0 - n) \tag{1}$$

$$\begin{aligned} mnV\frac{dV}{dz} &= enE - k_B T_i\frac{dn}{dz} \\ &- mn(\nu_{iz} + \nu_m)(V - v_d) + \frac{v_{ti}}{a}m(n_0 - n)(v_d - V), \end{aligned} \tag{2}$$

where V, E, T_i, k_B, ν_{iz}, and ν_m are ion fluid velocity, electric field along the presheath, ion temperature, Boltzmann constant, ionization collision frequency, and momentum collision frequency, respectively. Electron density is assumed to follow the Boltzmann relation: $n = n_0 \exp(e\phi/kT_e)$.

Using the following dimensionless variables : $N \equiv n/n_0$, $x \equiv z/a$, $M \equiv V/C_s$, $M_0 \equiv v_d/C_s$, $C_s \equiv \sqrt{(kT_e + kT_i)/m}$, $\tau \equiv v_{ti}/C_s$, $\mu \equiv \nu_m a/C_s$, and $\sigma \equiv \nu_{iz} a/C_s$, the governing equations can be written as the following after re-arrangement:

$$\frac{dN}{dx} = \frac{\{\tau(1-N)+\sigma N\}(M_0-2M)+\mu N(M_0-M)}{1-M^2}, \quad (3)$$

$$\frac{dM}{dx} = \frac{(\tau+\sigma N)(M^2-M_0M+1)+\mu N(M^2-M_0M)}{N(1-M^2)}. \quad (4)$$

If the collision terms in Eqs. (3) and (4) are not neglected, solutions of $N(x)$ and $M(x)$ cannot be given by the analytical method. However, $N(M)$ can be given as Stangeby did [38] in his magnetized fluid theory like the following:

$$\frac{dN}{dM} = \frac{\{\tau N(1-N)+\sigma N^2\}(M_0-2M)+\mu N^2(M_0-M)}{(\tau+\sigma N)(M^2-M_0M+1)+\mu N(M^2-M_0M)}. \quad (5)$$

For most cases of obtaining the density profile ($n(M)$) or sheath density($n(M = 1)$), we solve Eq. (5) for the relation between the sheath current densities and the Mach number, yet there is a critical difference between the solution of the full Eqs. (3) and (4) and that of Eq. (5). Solutions of the simplified differential equation (dN/dM) often produce non-physical solutions in the range of interest ($-1 < M < M_0$), which not only produces the case that the normalized density(N) becomes larger than the unperturbed one($N_0 = 1$), but also gives oscillatory densities. However, those by full, or separate, differential equations for the density and fluid velocity (dn/dx, dM/dx) give physical solutions, i.e., $-1 \le N(M) \le 1$. So to avoid this inconsistency, it would be better to solve the full Eqs. (3) and (4) than to use Eq. (5).

In the previous collisionless models, the ratio of the current densities can be expressed as an exponential form: $R = \exp[KM_0]$, and K=1.2 from Chung's kinetic model, K=1.8 from Hudis and Lidsky's, and K=1.34 from Hutchinson's PIC model for $T_i/T_e = 0.2$. However, the result of present collisional model cannot be fitted in exponential form with constant calibration factor (K), rather K is a function of the Mach number, which is given as $K \approx 6.57(1 - 1.5M_0 + 5.67M_0^2)$. Here M_0 is normalized by $\sqrt{T_e/m_i}$ in order to be consistent with previous models for the comparison. Inclusion of the ion-neutral collision produces a much larger ratio for the same drift velocity than collisionless models. Hence from the same ratio of current densities, the deduced Mach number is much smaller than those from collisionless models.

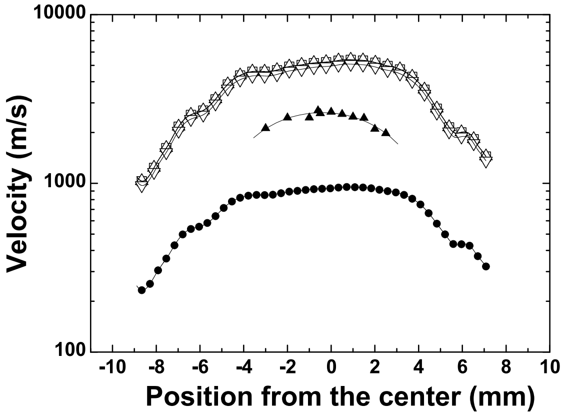

Fig. 4 Deduced flow velocities from collisional model(olid circle) and other : Hudis and Lidsky(open squere, collisionless, fluid), Chung(open up-triangle, collisionless, kinetic), Hutchinson(open down-triangle, collisionless, PIC), Rennick(solid up-triangle, collisional simulator, high power 6.5kW, high pressure 50torr), Juchmann(solid line along the solid up-triangles, experiment, low power(1.6kW), low pressure(25torr) with mixed gas).

4. Result

To calculate the current ratio for a collisional Mach probe, one has to find the collision frequency first. In a laboratory plasma, the ion temperature (or speed) range is given as 0.025 eV ~ $0.5T_e$ eV and in the low energy range of the cross section of ion collisions falls almost linearly in the range of 0 − 5 eV (Ar : 80 − 70 × 10^{-16} cm^2, charge transfer + elastic collision) [29]. For argon, the momentum collision frequency is given by, $\nu_m = 1.1 \times 10^7 \times P$[Torr] sec^{-1}, using the constant collision frequency model is more reliable than the constant mean free path model. The ionization collision frequency is given as $\nu_{iz} = \alpha P/T_n$ sec^{-1}], where α is 7.25×10^9 (Torr/K) for $T_e = 4$ eV in argon plasmas [29, 39]. The ionization cross section data are given on the NIST homepage [30].

We calculate the ratio of upstream and downstream currents from the full equation set for the following collisional conditions: $\sigma = 25$, $\mu = 350$, $\tau = 0.4$, which are obtained by the following condition for a torch plasma of current experiment: gas = argon, $P = 50$ Torr, $n_e \simeq 10^{13}$ cm^{-3}, $T_e \simeq 4$ eV, $T_i \simeq 0.8$ eV, probe size ≃ 2 mm. For these conditions, the ratio of ion saturation current densities (R) is measured as 8-9 for the core plasma of the torch ($0 < r < 2$ cm). Figure 4 shows the deduced axial speed according to present collisional model along with those by collisionless models.

Engeln et al. [23] generated a cascade arc to expand into a vessel, and measured the speeds and temperatures of argon radicals [$Ar^*(P_2^3)$ and $Ar^*(P_2^3)$] by LIF method: axial speed=1 $\sim$ 3 km/sec, temperature near nozzle exit $\sim$ 5000 K $\approx$ 0.5 eV, $P = 20 - 100$ Torr, arc current = 40 Amp., argon gas flow rate=3 lpm, hydrogen gas flow rate=0.12 lpm. Juchmann et al. [24] measured the speed of argon and hydrogen mixture by putting nitrogen oxide (NO) into the torch plasma by LIF: speed = 2.6 km/sec, gas temperature = 2000 $\sim$ 3000 K $\approx$ 0.2 $\sim$ 0.3 eV, torch power=1.6 kW, $P = 25$ Torr, mixture of argon, hydrogen and nitrogen oxide gases=54:46:0.1. Effective mass of this case would be 40×0.54+1×0.46 = 23. If one considers the case of pure argon gas from the same power, the speed of the argon plasma would be decreased by $(40/23)^{1/2} = 1.3$, which would become 2.0 km/sec.Rennick et al. [25] obtained the density distribution of carbon hydrate radicals after getting the speed of the argon neutral in a DC arc jet using the model of Engeln et al.: speed=2.3 km/sec, gas temperature $\approx$ 0.3 $\sim$ 0.5 eV, torch power=6.5 kW, $P = 50$ torr, mixture of argon and hydrogen gases=11.4 (lpm):1.8 (lpm). Effective mass for this case becomes $40 \times 11.4/13.2 + 1 \times 1.8/13.2 = 35$, then speed would decreases by $(40/35)^{1/2} = 1.1$ comparing all argon case with the same power, i.e., 2.3/1.1=2.2 km/sec. Since Engeln does not provide the torch power, and the pressure of Rennick's case is similar to our experiment, besides they adopt the same method of Engeln to deduce the speed, it would be an approximate comparison of our work with those of Rennick.

For this, assuming the same temperature of gas with ions, then from the momentum equation of charged particles,

$$mnV \cdot \nabla V = -\nabla p - Zen\nabla\phi = -T_{avg}\nabla n \rightarrow \nabla mV^2/2 = -\nabla n/(nT_{avg}). \quad (6)$$

From this, one can obtain the following result:

$$n = n_0 \exp\left[-\frac{mV^2}{2T_{avg}}\right], \quad (7)$$

where $T_{avg} = T_i + ZT_e \approx T_e$ ($Z = 1$) using the Boltzmann relation of the electrons for large negative bias: $n_e = n_0 \exp[e\phi/T_e]$. If one considers the neutral only, T_{avg} should be replaced with T_n.

If torch power (P_t) is proportional to the particle flux nv_d, then $P_t \propto M_0 \exp[M_0^2/2]$. So only applying the power variation(from 6.5 kW to 0.8 kW), the speed of our case based upon the similar method of Rennick would be $6.5/0.8 \approx 8 \approx (rM_0 \exp[(rM_0)^2/2])/(M_0 \exp[M_0^2/2]) = r\exp[(r^2-1)M_0^2/2]$, which produces $r \approx 1.95$ for $M_0 = 1$, and $r \approx 3$ for $M_0 = 0.5$, where r is a reduction factor. Hence conversion of Rennick's case to ours would be 2.2 (km/sec)/1.95 $\approx$ 1.1 (km/sec) or 2.2 (km/sec)/3 $\approx$ 0.7 (km/sec), which is close to our measured value $\sim$ 1 (km/sec). If one apply the same procedure for the experimental cases of Juchmach and Engeln, although they used mixed gases for the torch, then the reduction factor is about 1.65 for $M_0 = 0.5$, then the converted speed would become $2.0/1.65 = 1.2$ km/sec.

If one consider the torch power is proportional to the kinetic pressure of plasma particles, $P_k = nv_d{}^2/2$, Rennick's case would be $6.5/0.8 \approx 8 \approx (r^2M_0^2 \exp[(rM_0)^2/2])/(M_0 \exp[M_0^2/2]) = r^2\exp[(r^2-1)M_0^2/2]$, which leads to $r \approx 2$ for $M_0 = 0.5$. Then the converted speed to our case would be $2.2/2 \approx 1.1$ km/sec, and for the Juchmach case, $r \approx 1.35$, then the converted speed becomes 2.0/1.35=1.5 km/sec. These are also very close to that of our current collisional model ($\sim$ 1 km/sec), comparing with those of collisionless models ($\sim$ 5 – 6 km/sec). Although this would be very rough estimation because the experimental conditions are different and ion temperatures are assumed to be the same as those of neutrals or radicals, it definitely indicates that flow speed of the high pressure plasmas should be deduced by including ion-collision effect.

5. Conclusion

An argon plasma generated by a torch at the pressure of 50 torr is characterized by a single probe and a Mach probe. Plasma parameters are deduced as $T_e = 4$ eV, $T_i = 0.8$ eV and $n_e \approx 10^{13}$ cm^{-3}. Flow velocity is deduced from the relation $R = \exp[KM_0]$, where $K \approx 6.57(1 - 1.5M_0 + 5.67M_0^2)$, which is based upon a new un-magnetized collisional Mach probe theory. This collisional model produces $v_d \sim 1\ km/sec$, while the collisionless models give $\sim 5{-}6\ km/sec$ of drift flow velocity. If this is adopted to the case of magnetized flowing plasmas, it could change the deduced poloidal velocities in the scrape-off layer of existing tokamaks [40] and the driven mechanisms of the flow from outer leg to the inner leg of divertor, and can affect the deduction of the density and flow velocity (hence the flux) in the experiment of liquid metals or puffing or low-Z neutrals [1–4]. Reported experimental results [23–25] of high pressure torch (25 or 50 Torr) with high input power (1.6 or 6.5 kW) produce velocity of $\sim$ 2.3 $\sim$ 2.6 km/sec. If one converts this to our current case by comparing the torch power and effective mass, then the converted speed would be close to that of our collisional fluid model.

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