*32nd EPS Conference on Plasma Phys. Tarragona, 27 June - 1 July 2005 ECA Vol.**29C**, P-2.079 (2005)*

Effect of ion-neutral collision on the deduction of flow velocity

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A fluid theory on the ion collection has been developed for the deduction of flow velocity in unmagnetized plasmas with high collisionality of neutrals and ions, which are to be applicable to the deduction of $E \times B$ shear flow in divertor private region of fusion devices and deduction of flow velocity in space and processing plasmas. Experimental reinfication is performed by applying this fluid model to a collisional unmagnetized plasma generated by a dc plasma torch, comparing with theory by a collisionless kinetic theory and a particle-in-cell (PIC) simulation. Applicable range of these theories will be reviewed and the previously measured Mach probe data will be reanalyzed by considering collisional and low ion temperature ($T_i = 0.01T_e$) effects. Application to the deduction of $E \times B$ shear velocity in the private region of divertor will be addressed.

1. Introduction

Plasma flow plays important roles in control of impurities and in the advanced confinement. Measurements of flow in edge and scrape off layer (SOL) are important to understand edge physics in fusion devices and the Mach probe (MP) has been generally used to measure the plasma flow velocity in various fusion devices [1-3] along with the magnetized MP theory [4-6]. Although the unmagnetized has not been developed perfectly as magnetized MP theory, some plausible theories are introduced by Mott-Smith and Langmuir[7], Kanal [8], Hudis and Lidsky [9], Chung [10] and Hutchinson [11] and it has been used to determine the $E \times B$ shear flow velocity in fusion device.However, these thoeries have all assumptions of the collisionless sheath models, it has the limitation to apply in collisional plasma such as atmospheric or high pressure plasma, tokamak edge plasma because of the high neutral densities due to recombination of charged particles and neutral gas feeding to detach the plasma from the wall.In this work, we have developed the collisional and unmagnetized MP theory including the collision terms with the Boltzman equation and it is confirmed through the high pressure (50 Torr) torch experiments.

2. A collisional fluid model on unmagnetized Mach probe

Generally, the flow velocity is deduced by the following form: $M = ln(R)/K$ where R is the ratio of ion saturation current density of up-stream to that of down-stream, and K is the calibration factor which is model dependent, i.e., $K = 4\sqrt{T_i/T_e}$ for Hudis and Lidsky, $0.9(T_i/T_e = 2.0)$

- 1.2$(T_i/T_e = 0.2)$ for Chung's kinetic model, and 1.34 for Hutchinson's PIC simulation.

The collisional fluid model on Mach probe is expanded from the Chung's model by adding the collsion term and taking the moment as following:

$$v\frac{\partial f}{\partial z} - \frac{Ze}{m}\frac{d\phi}{dz}\frac{\partial f}{\partial v_z} = W(1-\frac{n}{n_\infty})f_\infty + (\frac{\delta f}{\delta t})_c, \tag{1}$$

where $W = v_{ith}/a$, v_{ith} and a are ion thermal velocity and probe radius. By taking moment, Eq. (2) is converted as followings:

$$n(du/dx) + u(dn/dx) = \nu_{iz}n + (u_t/a)(n_0 - n), \tag{2}$$

$$mnu(du/dx) = enE - kT_i(dn/dx) - mn(\nu_{iz} + \nu_m)(u - u_0) + m(u_t/a)(n_0 - n)(u_0 - u), \tag{3}$$

where ν_{iz}, ν_m ionization collision, frequency and momentum collision frequency, respectively, and the electron is assumed to follow Boltzmann relation, $n = n_0 exp(e\phi/kT_e)$. Then the nondimensional forms of the parameters are given as followings: $N = n/n_0$, $t = x/a$, $M = u/C_s$, $C_s = \sqrt{(kTe + kT_i)/m}$, $V_t = u_t/C_s$, $\mu = \nu_m a/C_s$, and $\sigma = \nu_{iz}a/C_s$. In terms of these parameters the equations become can be written as

$$\frac{dN}{dt} = \frac{M_0 - 2M}{1-M^2}(1-N)V_t - \frac{MN}{1-M^2}(2\sigma + \mu) + \frac{M_0 N}{1-M^2}(\sigma + \mu), \tag{4}$$

$$\frac{dM}{dt} = \frac{M^2 - M_0 M + 1}{1-M^2}\frac{(1-N)}{N}V_t + \frac{(1+M^2)\sigma + \mu M^2 - (\sigma+\mu)M_0 M}{1-M^2}, \tag{5}$$

which leads to the to the following as Stangeby tried:

$$\frac{dN}{dM} = \frac{(M_0 - 2M)N(1-N)V_t - MN^2(2\sigma+\mu) + M_0 N^2(\sigma+\mu)}{(M^2 - M_0 M + 1)(1-N)V_t + (1+M^2)\sigma N + \mu M^2 N - (\sigma+\mu)M_0 MN}. \tag{6}$$

There would be some singularities in Eq. (6) at the range of interest ($-1 < M < 1$) and the Eq. (6) cannot be used for calculation of ratio for Mach probe. In order to avoid this singularities, we calculate the ratio of upstream and downstream current from the full equation set, and it is shown in figure 1 for the following collisional conditions: $\sigma = 25$, $\mu = 350$, and $V_t = 0.4$.

3. Experiment

Collisional plasma flow measurement was done with a non-transferred arc plasma torch, where arc is generated by applied voltage between thoriated tungsten cathode and oxygen free copper anode. Fast scanning probe system was used to avoid melting probe tips. Since the fast scanning system can provide maximum velocity of 2.2 m/sec, we can measure plasma properties without damaging the probe tips. 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). The experimental condiations for MP and normalized frequency are the following: Ar gas, pressure of 50 torr, power of 800 watt,

$n_e = 5 - 15 \times 10^{12}$ cm^{-3}, $T_e = 8$ eV, $T_i = 0.8$ eV, $\sigma = 350$ and $\mu = 25$.

4. Analysis and Conclusion

Figure 3 shows the measured ion saturation current profile and the current ratio. Figure 4 shows flow velocities calculated by one collisional model and previous collisionless ones. For the highly collisional Mach probe experiments, collisional Mach probe theory shows about 5 times smaller value than the previous collisionless Mach probe theory. The collisionless models give 5 km/s of flow velocity. However, reported numerical simulation results of low pressure torch (50Torr), although there are few related papers, gives velocity of about 2 km/sec which is close to that of the collisional fluid model[12]. However, the input power (6.5 kW) of the simulation is much higher than the one experiment conditions (0.8 kW), although the pressure condition is the same. Therefore, a lower velocity is expected then the simulation results and the collisional fluid model give reliable results. The experimental data of torch flow measurement at low pressure is given by using LIF technique at 25 Torr with power of 1.6 kW, 750 mTorr with 40 A discharge current in dc torch[13]. Because our experimental conditions are 50 torr pressure, argon gas, power of 800W, it is hard to compare directly our result with other experimental results, yet from the other results, the lower velocity of 1km/s seems reasonable than the higher one (5 km/s). Further confirmation of the Mach probe results in the torch plasma should be done by comparing with LIF or other detailed numerical simulations.

Since the conditions of private regions of Alcator-CMOD [14] is the following: neutral pressure (P_n) of 30 - 60 mTorr, electron temperature of 10 - 100 eV and ion temperatures of 10 - 100 eV , which produced the following collision parameters: $\sigma \approx 0.1 - 1$, $\mu \approx 1 - 10$ present model can be applied to deduce $E \times B$ shear velocity, which leads to the reduction of previously calculated MP by factor of 0.5 or so.

References

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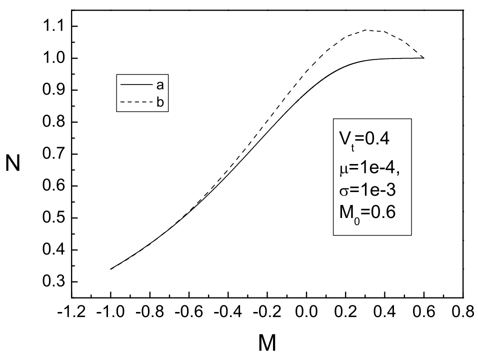

Figure 1: Singularity (b) from reduced equation and non-singularity (a) from full equations.

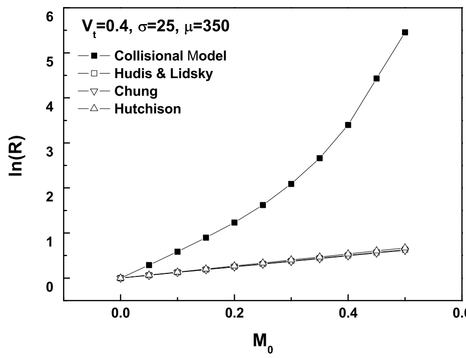

Figure 2: Theoritical ratios with mach number from various models.

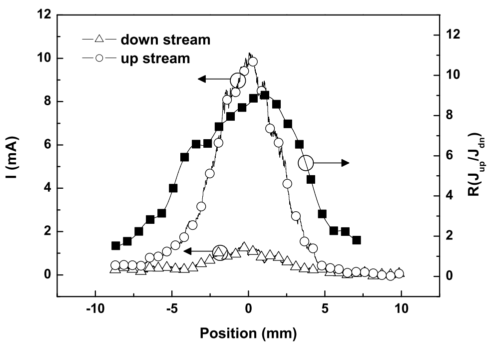

Figure 3: Ion saturation currents and their ratio from torch experiment.

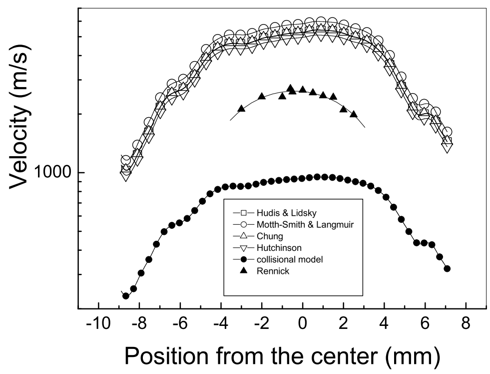

Figure 4: Deduced flow velocities with various models.