تغير معلمات الشحن على حبيبة الغبار في البلازما المختبرية باستعمال نظرية حركة المدار المحددة

مصطفى كامل جاسم

قسم الفيزياء،كلية التربية –أبن الهيثم، جامعة بغداد

الخلاصة

باستعمال نظرية المدار –المحدد بوصفها إحدى النظريات الدقيقة في حساب تيار الايونات والالكترونات في بلازما الغبار درست تغيرات أعداد الشحنة على حبيبة الغبار في بلازما الأركون بتغيير معلمات الشحن المختلفة. معظم اعتماد أعداد الشحنة على حبيبة الغبار في هذا البحث أخذت بنظر الاعتبار تأثير تجمع أعداد من الحبيبات في البلازما.

Variation of Charging Parameters on A dust Grain in Laboratory Plasma by Using Orbital-Motion Limited Theory

M.K. Jassim

Department of physics, College of Education Iben AL-Haitham, University of Baghdad.

Abstract

Using orbit- motion limited theory, as the exact theory in calculating the ion and electron current in dusty plasma, the variations of charge number on a dust grain in Ar-plasma are studied by changing various charging parameters. Most of dependences of charge number on plasma parameters in this paper take into account the close packed effect.

Introduction

Dusty plasmas are low-temperature ionized gases that contain dust particles in the size range of nm to μm. A dust particle immersed in plasma acquires electric charge by collecting electrons and ions from the background plasma. The simplest model that predicts the charge of particles in plasma is based on orbit-limited probe theory. This theory describes the way of how the study of the currents collected by a small probe leads to information on the plasma parameters [1]. Considering a finite-sized neutral dust particle immersed in unmagnified plasma whose constituents are electrons and ions, the particle is like a floating probe in the plasma. It collects charge carriers and attains a certain charge, negative or positive, depending on the dominant charging mechanism. The validity of orbit-limited theory is limited to the ideal case when the electrons and ions are collisionless, and when the density and velocity distributions of charge carriers are isotropic. [2].

Assuming that dust particles with zero charge are introduced into plasma, the charging of the dust grain particles arises from plasma currents due electrons and ion reaching the grain surface for spherical grains of radius a.

$$\frac{dQ}{dt} = I_e + I_i \qquad (1)$$

where Q is the charge accumulated on the dust particle, I_i and I_e denote the ion and electron current. Obviously, the charge on the dust grain is a dynamic quantity. Thus, the charge on the dust grain must be solved for self-consistency with other plasma parameters. At equilibrium $\frac{dQ}{dt} = 0$ then $I_e + I_i = 0$.

In a typical plasma, electrons are initially collected by a dust grain, due to their higher thermal velocity relative to the ions. Since grain is electrically floating, it charges to a negative surface potential ϕ_s in order to repel further electron collection and enhance ion collection. It is assumed that the electrons and the ions obey a Maxwellian distribution at temperatures T_e and, T_i respectively. For systems where the dust grains have a negative surface potential with respect to the plasma, the electron and ion currents are given by [3].

$$I_e = -4\pi a^2 n_e e\sqrt{\frac{KT_e}{2\pi m_e}}\, exp\left(\frac{e\phi_s}{KT_e}\right) \qquad (2)$$

$$I_i = 4\pi a^2 n_i e\sqrt{\frac{KT_i}{2\pi m_i}}\, exp\left(1-\frac{Z_i e\phi_s}{KT_i}\right) \qquad (3)$$

where K is Boltzmann's constant, e is the electron charge , n_e and n_i are respectively the electron and ion number density, Z_i is the ion charge, a is the dust particle radius, and m_e and m_i are the electron and ion mass respectively. The $exp\left\{\frac{e\phi_s}{k_B T_e}\right\}$ term in Equation (2) represents the electron repulsion, while the $\left\{1-\frac{Z_i e\phi_s}{k_B T_e}\right\}$ term in Equation [3] represents the ion collection (in what follows we will assume singly charged ions, i.e., $Z_i = 1$).

It is noted that the model for the charging currents given in Equations (2) and (3) are derived assuming the dust in plasma limit. This model for the grain charge is applied to the case where the grains are sufficiently far apart compared to the Debye length λ_D and for spherical grains of radius a usually much smaller than the Debye length i.e., $a \ll \lambda_D \ll d$, where d is the interparticle spacing. In this case, the variable dust grain charge is determined by the charge current balance equation: [4]

$$\sqrt{\frac{kT_e}{m_e}}\, exp\left(\frac{e\phi_s}{kT_e}\right) = \sqrt{\frac{kT_i}{m_i}}\left(1-\frac{e\phi_s}{kT_i}\right) \qquad [4]$$

The grain charge is related to its surface potential by the grain capacitance C, which for spherical grains of radius is simply $4\pi\varepsilon_o a$, and thus,

$$Q = 4\pi\varepsilon_o a\phi_s \qquad [5]$$

Single dust particle immersed in plasma is isolated; however, if more of dust particles immersed, the charge on the dust particle will be affected. Therefore, the assumption of a single isolated particle is often unsuitable for modeling the dust charge laboratory plasma because they can have high particle concentration. The ensemble of dust grains is known as the close-packed effect. The collection of dust grains effect is important when $d/\lambda_D \sim 1$, where ($d \sim n_d^{-1/3}$). The condition of quasineutrality requires that

$$n_i = n_e + Z_d n_d \qquad (6)$$

Taking into account the close packed effect, it is possible to solve for the potential of the dust particle or charge or/and charge number on the dust grain when the charging currents have reached an equilibrium value. It is found that [5].

$$\left[1 + P\left(\frac{e\Phi_s}{KT_e}\right)\right]\sqrt{\frac{m_i T_e}{m_e T_i}}\, exp\left(\frac{e\Phi_s}{KT_e}\right) = \left(1 - \frac{e\Phi_s}{KT_i}\right) \qquad (7)$$

where the Havnes parameter, $P = 4\pi n_d a\left(\frac{\varepsilon_0 KT_e}{e n_i}\right)$, is introduced. The Havnes parameter is a dimensionless quantity that describes an effective screening in a dusty plasma. By numerically solving equations (6) and (7) using software 'Maple 11', the surface potential, and the charge/ charge number of the dust grain are determined.

Effect of dust size on the charge number

It is noted that, for conducting dust grain no particle is perfectly spherical, the value of the capacitance does not depend sensitively on the grain shape as long as $a \ll \lambda_D$. A plot of dust radius vs. the charge number for isolated dust particle Z_o and for Z which takes into account the close-packed effect is shown in Fig.1. While the charge number on the dust grain reduces when taking into account the close-packed effect compared to the isolated dust grain, the charge number is reduced for both schemes as the dust radius is decreased. In spite of approaching both relations to each other in range of nm, detail calculations indicate that the close-packed effect still reduces the charge number for the same radius of dust particle by using the accuracy of 5 digits. The reason that Z is the smaller than Z_o is due to smaller potential between the grains, which reflects the effect of placing grains close to each other.

Effect of electron temperature

The variations of charge number with electron temperature is shown in Figure 2A.The plot shows that as the electron temperature increases, the collected charge number Z on the dust grain is decreased for the same size of the grain considering only the close-packed effect. However, the same effect occurs for isolated dust grain too. Fig.2B is a plot of dust radii vs. charge number for two electron temperatures. For the same size of the grain, the charge number collected by the grain is lower for smaller electron temperature.

Effect of ion density

Fig. 3A is a plot of ion density vs. charge number. For the values used here the relation is linear for lower values, but it becomes exponential when n_i is increased. Fig. 3B shows a plot of dust radius as a function of charge number but for three values of ion density as described. Obviously, the reduction of dust charge number occurs at a lower value of ion density. The charge number of higher value of ion density used for various dust radii approaches that of charge number for isolated dust grain.

Effect of dust density

Fig. (4A) shows a plot of the dust density vs. charge number. When the dust density n_d is small, the charge number approaches the isolated single grain value. If the dust density is increased, the magnitude of the charge number is reduced. The dust charge number is significantly diminished when the dust density is higher than ion density, while it approached the values for isolated particle when the dust density is too much lower than ion density. Fig. 4B shows a plot similar to Fig 4A, but here it is for a normalized charge number (Z/Z_o) for two values of dust radii in a plasma. The smaller radius of dust grain leads to the higher charge number accumulated on the dust as indicated in Fig.1. If the grain density is relatively high, the normalized charge number is lower due to the difference between electron and ion densities because of the charges on the grains. The percentage of collected electrons on the dust under the condition of quasineutrality, for example, at charge number 4828.2 is above 4% from local plasma. When most of the electrons are trapped on the grains, the dusty plasma consists mainly of positive ions and negatively charged massive grains.

Effect of ion mass

Fig (5A) describes that the increas of mass number of atom yields more charge to concentrate on the dust grain. Fig (5B) is a plot dust radius vs. charge number for atoms used in Fig. 5A. The relations approximately have the same behaviour; however, they approach each other at lower dust radii but heavier atoms still acquired higher charges. The plots are a numerical solution of equation [7] which takes into account the close-packed effect for ion mass. However, the solution of equation 6 for ion mass yields higher charge number on the same dust grain.

Effect of Havnes parameter

Fig. (6A) shows the dependence of charge number on Havnes parameter for described variables. As Havnes parameter increases the charge number on dust grain exponentially increased. When Havnes parameter is approximately equal to one $\frac{Zn_d}{n_i} \sim 1$, the charge number on a grain is very small; one should consider the close-packed effect instead of isolated dust grain since the collective electrostatic effects are negligible. Fig. (6B) is a plot of Havnes parameter vs. normalized charge number. Clearly, the normalized charge number dimishes at higher values of Havnes parameter while the lower values of Havnes parameter have higher normalized charge number.

Effect of ion temperature

Fig. (7) is a plot of charge number as a function of ion temperature for two values of P. As the ion temperatures is increase the charge/ charge number on the dust grain increased. However, the plot indicates that lower value of P has lower charge number accumulated on the dust due to higher value of ion density. The higher value has charge number approaches the value of isolated grain.

Conclusions

Among several theories to calculate potential and charge/ charge number on grain dust both in laboratory plasma and space physics, the orbit-limited theory seems to be an exact theory. We study different variables that affect the charge number on the dust grain in plasma. The electron and ion interactions at the particle surface depend on the plasma parameters. The negative charge on the grain can reach high level of elementary charges, depending on the particle radius and the plasma density. Large grains acquire higher charge number and small grains collect a smaller current. If the electron temperature is reduced, the charge or charge number will decrease. Increasing the ion density leads to higher collected charge number on the dust which may reach to high levels depending on local conditions. Lower values of dust density lead to values of charge number approach to that for isolated system. Lighter atoms plasma provides lower charge number to accumulate on the dust grain. At higher values of Havnes parameter, the charge number collected by the dust grain is lower. Higher ion temperatures cause high charge number on the dust grain. In dusty plasma experiments [6], it is usually considered that the charge on a collection of dust grains may be smaller, in magnitude, than that of an isolated grain. This report presents some of the plasma parameters that lead to that reduction.

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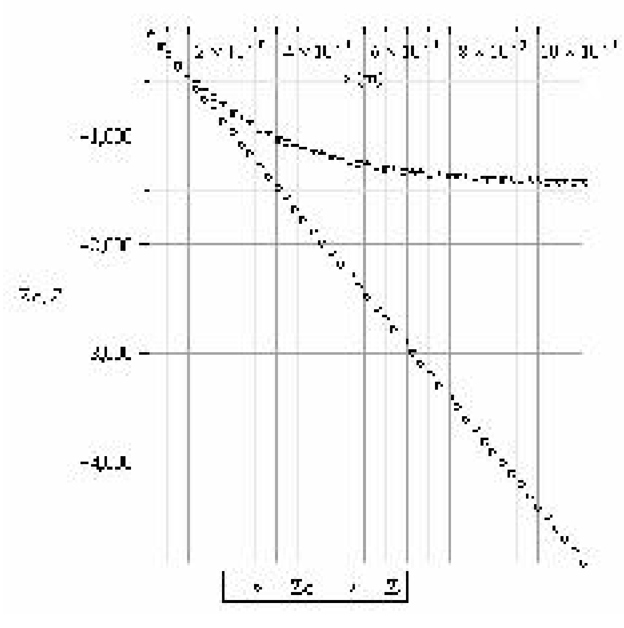
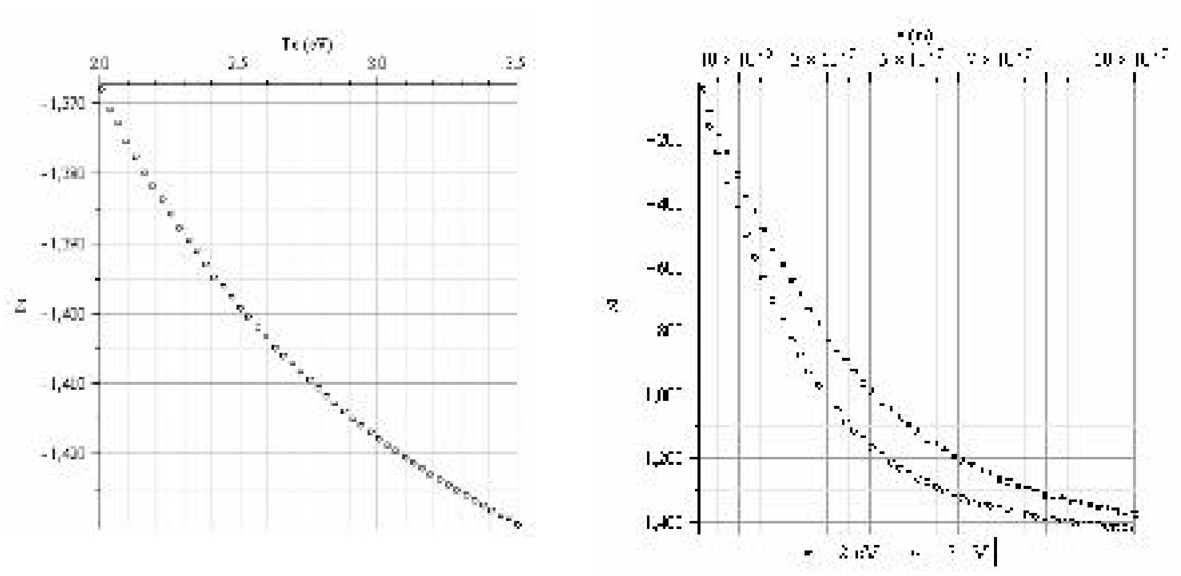
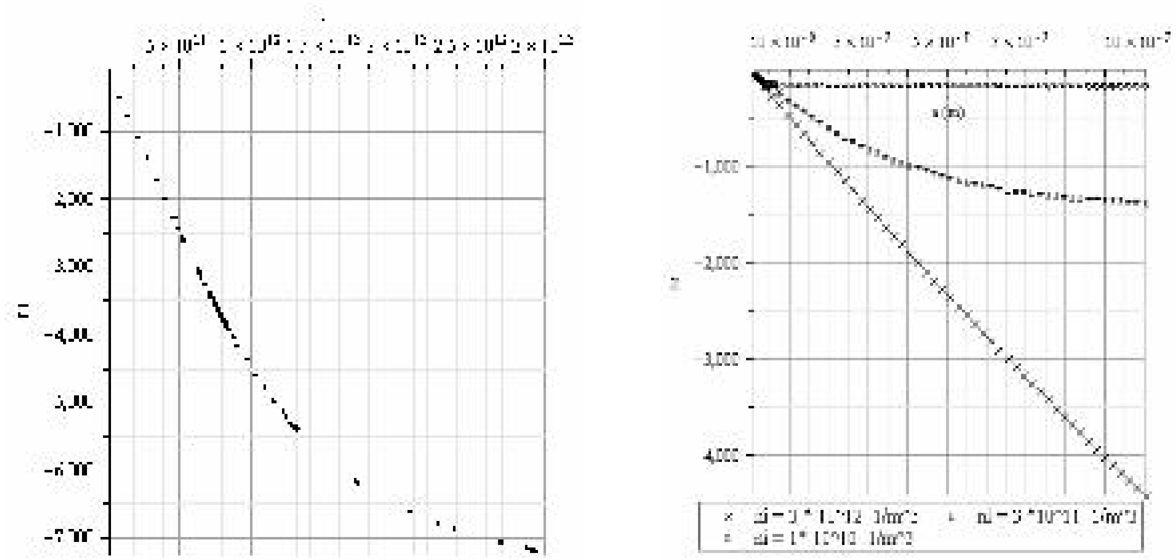


Fig. (1) Dust radii vs. charge number in Ar-plasma for isolated dust particle Z_o and considering the close-packed effect Z. For both two curves: $T_i = 0.025eV$, $T_e = 3eV$, $n_d = 2 \times 10^8 m^{-3}$, and $n_i = 3 \times 10^{11} m^{-3}$.



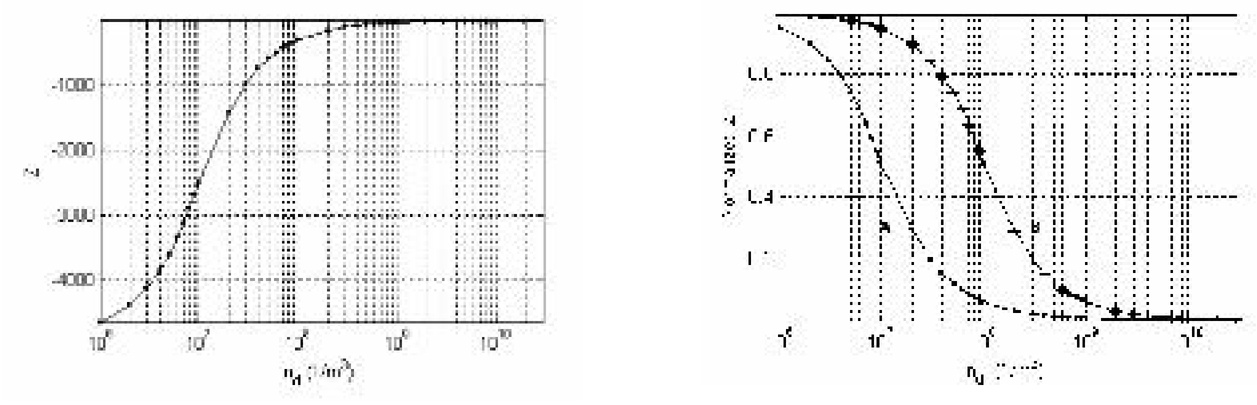
(A) (B)

Fig.(2) :(A) The variation of electron temperature vs. the charge number. (B) Plot of the dust radius vs. charge number in Ar-plasma for different electron temperatures. For both two diagrams: $T_i = 0.025\text{eV}$, $n_d = 2 \times 10^8 \text{m}^{-3}$, **and** $n_i = 3 \times 10^{11}\ \text{m}^{-3}$.



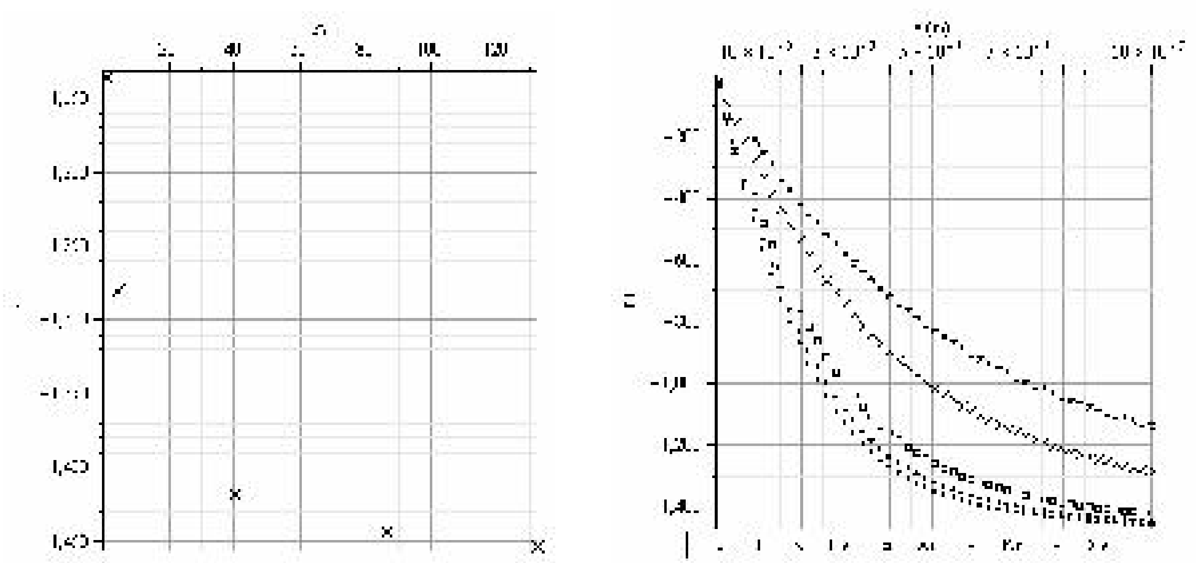
(A) (B)

Fig. (3): (A) The variation of ion density vs. charge number. (B) A plot of dust radius vs. charge number for various values of ion density. For both diagrams: Ar- plasma, $T_i = 0.025\text{eV}$, $T_e = 3\text{eV}$, $n_d = 2 \times 10^8 \text{m}^{-3}$.



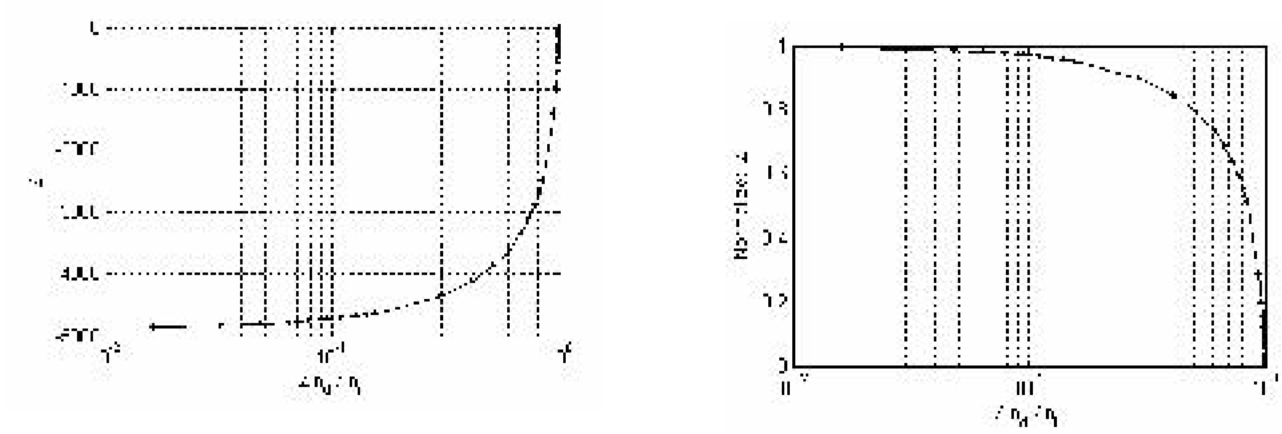
(A) (B)

Fig.(4):(A) The variation of charge number as a function of dust density in Ar-plasma. (B) The variation of dust density vs. normalized charge number for two values of grain radii (A) $1\mu m$ (B) $0.1\mu m$. In both two diagrams: $T_i = 0.025\text{eV}$, $T_e = 3\text{eV}$, $a = 1\times10^{-6}\text{m}$ and $n_i = 1\times10^{10}\text{m}^{-3}$.



(A) (B)

Fig.(5): (A) The variation of atomic number vs. charge number with $a = 1\times10^{-6}\text{m}$ for the atoms described in B. (B) plot of dust radius vs. charge number for various background plasma taking into account the close-packed effect . For all curves: $T_i = 0.025\text{eV}$, $T_e = 3\text{eV}$, $n_i = 3\times10^{11}\text{m}^{-3}$and $n_d = 2\times10^{8}\text{m}^{-3}$.



(A) (B)

Fig. (6): (A) The variation of Havnes parameter vs. charge number in Ar-plasma. (B) The Havnes parameter vs. normalized charge number. For both curves $T_i = 0.025\text{eV}$, $T_e = 3\text{eV}$, $a = 1 \times 10^{-6}\text{m}$ and $n_i = 1 \times 10^{10}\text{m}^{-3}$.

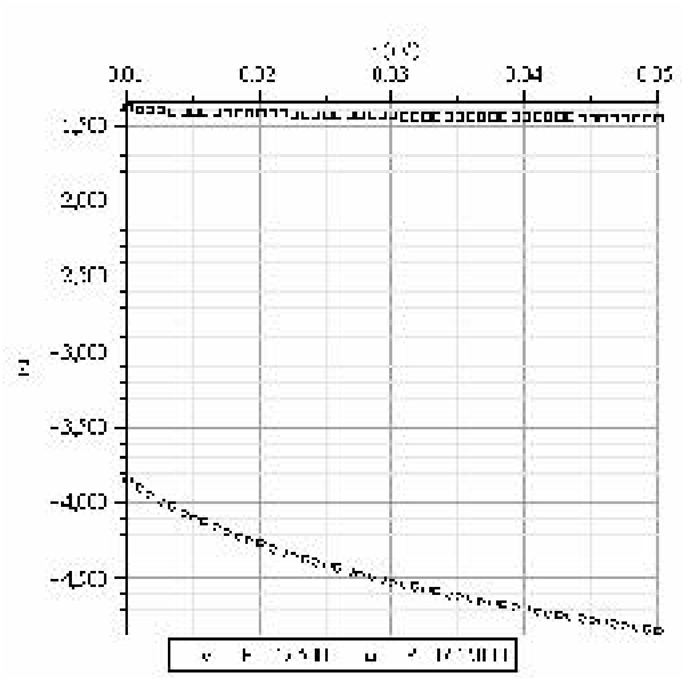


Fig. (7): The variation of ion temperature vs. charge number in Ar-plasma for two different value of P. For both curves, $T_e = 3\text{eV}$, and $a = 1 \times 10^{-6}\text{m}$.