Ionic Wind Phenomenon and Charge Carrier Mobility in Very High Density Argon Corona Discharge Plasma

M.Nur[1], N. Bonifaci[2] and A. Denat[2]

[1] Physics Department, Faculty of Sciences and Mathematic, Diponegoro University, Semarang 50275 Indonesia
[2] G2E.Laboratory, CNRS and Joseph Fourier University 25 rue des Martyrs, 38042 Grenoble, France
E-mail: m.nur@undip.ac.id

Abstract. Wind ions phenomenon has been observed in the high density argon corona discharge plasma. Corona discharge plasma was produced by point to plane electrodes and high voltage DC. Light emission from the recombination process was observed visually. The light emission proper follow the electric field lines that occur between point and plane electrodes. By using saturation current, the mobilities of non-thermal electrons and ions have been obtained in argon gas and liquid with variation of density from 2,5 10^{21} to 2 10^{22} cm^{-3}. In the case of ions, we found that the behaviour of the apparent mobility inversely proportional to the density or follow the Langevin variation law. For non-thermal electron, mobility decreases and approximately follows a variation of Langevin type until the density ≤ 0,25 the critical density of argon.

1. Introduction

Research on the plasma corona have been carried out both in theoretical , experimental and applicative purposes [1.2.3]. Corona plasma applications has entered every aspect of the field of food technology [4]. Effect of ions in the plasma corona wind generated by electrodes on the field of multi - point heat transfer technology that enables such as drying technology has been done for example by Kim [5]. Technology which produces winds corona corona is often also called "ionic wind" has been used to reduce dust and oil dirt on insulators, and it has been patented in the U.S. Patent by Gelfan [6]. In the case of plasma corona, the mobility of ions are very interesting to discuss. Theoretical approach has been publish by **Robinson** [7] and Choelo [8]. Plasma corona with point to plane electrodes system has been used to determine the non- thermal electron mobility in very pure and high density of argon and nitrogen gaseous [9]. In 1971 Choelo [8] performed an analysis of the relationship corona current, voltage, distance between electrodes of an electrode system which generates a field is not symmetric. Under conditions of corona discharge ion flow is one type of ion (unipolar). Unlike the arc discharge conditions can charge flowing positive ions, negative ions and electrons (bipolar). Unipolar ion current flowing to the mobility μ by charge density ρ (r,t) and current density j = ρv without experiencing diffusion in an electric field E (r,t) , changes in the charge density (ρ) along the flow is:

$$\frac{d\rho}{dt} = \frac{\partial \rho}{\partial t} + v.\nabla \rho \qquad (1)$$

Obtained from the continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla.(v\rho) = \frac{\partial \rho}{\partial t} + v.\nabla\rho + \rho\nabla.v = 0 \tag{2}$$

Then equation 1 can be written

$$\frac{d\rho}{dt} = \rho\nabla.v = -\mu\rho\nabla.E = \frac{-\mu\rho^2}{\varepsilon_0} \tag{3}$$

Equation (3) can be integrated to obtain the
(4)

$$\frac{1}{\rho(t)} - \frac{1}{\rho_0} = \frac{\mu}{\varepsilon_0}(t - t_0) \tag{4}$$

Assuming the ions are no space charge effect of the ion flow time (T) , then the equation (9) can be minimized

$$\frac{1}{\rho} - \frac{1}{\rho_0} = \frac{\rho - \rho_0}{\rho.\rho_0} = \frac{\mu}{\varepsilon_0}(t - t_0) = \mu T$$

$$\frac{\Delta\rho}{\rho} = -\frac{\rho_0 \mu T}{\varepsilon_0} = \frac{\rho_0}{\rho_s}$$

$$\rho_s \equiv \frac{\varepsilon_0}{\mu T} \tag{5}$$

and the meeting called unipolar ion saturation.

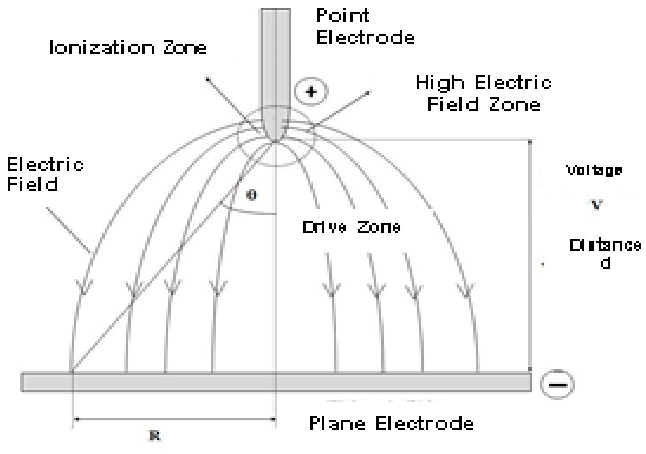

Figure 1. Sketch of a positive corona discharge electrode configuration hyperbolic (dot) - plane field .

If the ion flow distance (L) in the electric field (E) can be obtained flow time T = L / μE , it is known that the flow rate of the average ion v = μE = μV / L and ρs can be restated as ρs = ε0E / L in order to obtain the saturation current density

$$J_s = \mu\varepsilon_0 V^2 / L^3$$

$$j_s = \rho_s.\mu_s = \frac{\mu\varepsilon_0 E^2}{L} \quad (6)$$

Equation (6) is called the ion saturation current density .
If given voltage corona (V) the average speed along the field is v = μE = μV / L and flow time L / v minimum , then

$$\rho_L = \varepsilon_0 \overline{E} / L$$

$$j_L \approx \mu\overline{E}\sigma_L = \mu\varepsilon_0 \overline{E}^2 / L = j_s$$

or

$$J_s = \mu\varepsilon_0 V^2 / L^3 \quad (7)$$

Equation (7) is called the saturation current density corona . By taking hiperbolid - field geometry simplification , distribution and utilization of Warburg formulated , and the flow of ions along the distance between the point and the plane Choelo gain saturation current of

$$I_s \approx 2\mu\varepsilon_0 V^2 / d \quad (8)$$

In experiments, saturation current (I) can be measured for the operating voltage (V) of a certain corona discharge formed by the configuration of the field point distance between the point and the field of d . If the calculated threshold voltage corona Vi then the saturation current to voltage relationship is shown by the equation :

$$I_s = \frac{2\mu\varepsilon_0}{d}(V - V_i)^2 \quad (9)$$

Robinson approach [7] through a symmetrical field and Choelo [8] specifically for the hyperbolic plane electrodes (generally also produce a symmetrical field) produces the same equation. By using the experimental data the relationship between current and voltage, and using the formulation Robinson and Choelo the rate of charge carrier mobility (ion mobility) as well as velosity of ions can be determined**.**

2. **Experimental Set up**

The electrical measurements (current, pulse pause time) are performed by a device developed in the laboratory. The high voltage generator was provided by a stabilized DC voltage 0, ± 20 kV (Spellman RHSR/20PN60) connected to the point (tip) while the electrode plane was grounded. The intensity of the average current has been measured either by means of a galvanometer (Sefram Vérispot) a Keithley electrometer (Model 610C). The current pulses were visualized using a set preamplifier followed by a Tektronix oscilloscope (model 7633). In the field of pulse current, the pulses of light emitted were simultaneously detected using a photomultiplier tube (model DARIO 56AVP) with a spectral response of between 300 and 650 nm (maximum sensitivity at 400 nm) and the pulse current.. Our experimental set up is shown in the figure 2.

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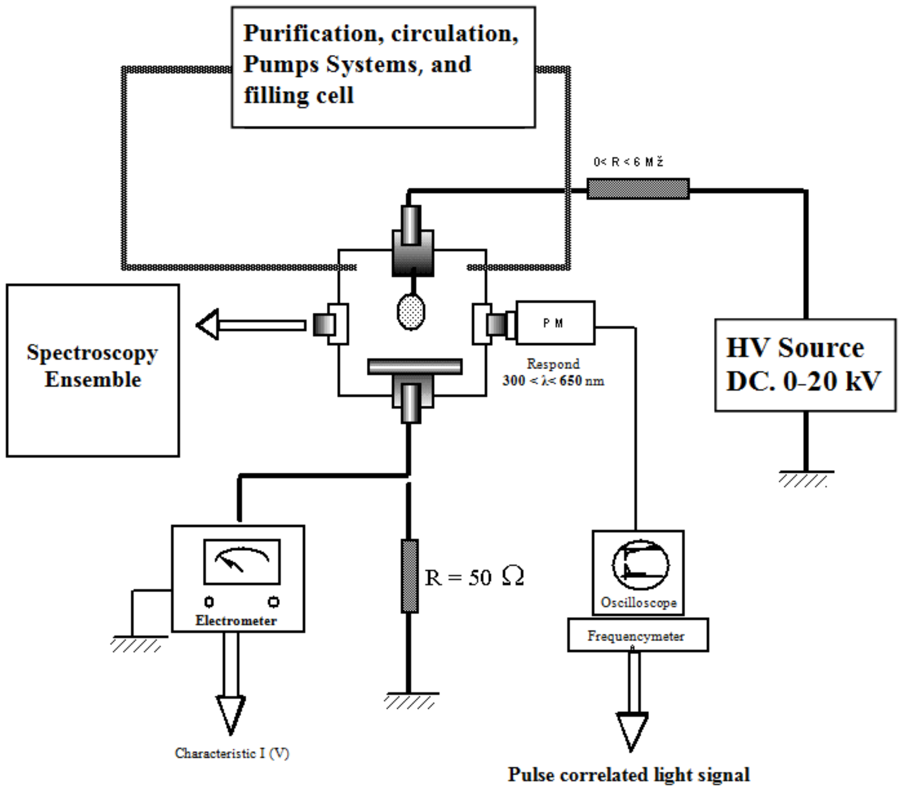

Figure 2. Sketch of experimental set up

3. **Result and Discussion**

The study of transport of charge carriers in a corona discharge in argon has been curried out from 0.5 MPa to 9,7 MPa. Before presenting the experimental results, we recall that the corona discharge, in our experimental conditions (ie very small radius of curvature of the tip and high density of the fluid) can be decomposed into two distinct regions: a region of ionization confined near the tip and a transport region. These two regions have the following characteristics. Region of ionization is very bright, its maximum length measured by visualization is about ten times smaller than the distance point-plan and the calculation shows that the entire charge is created in this region. The temperature Tp of the region similar to a plasma is unknown. By cons its pressure equals the pressure P_∞ gas or, in the case of a liquid, the hydrostatic pressure applied on it (for a stationary corona discharge, there is no pressure difference between the area ionization and the surrounding environment). The plasma density Np can be calculated after determining a value of Tp. The transport region shows no luminescence except in the case of argon gas to a point where a very small negative luminescence is observed. No measurable charge is created in this area. Under these conditions, temperature and pressure correspond to the temperature $T\ \infty$ and the pressure $P\ \infty$ of the test. The density $N_\infty = f\ (T_\infty,\ P_\infty)$ is known and calculable. The two regions of discharge and their conditions of temperature and pressure are presented in the figure 3. Discharge in argon gas, has been created in the range of pressure (P_∞) from 0.1 MPa to 10 MPa.

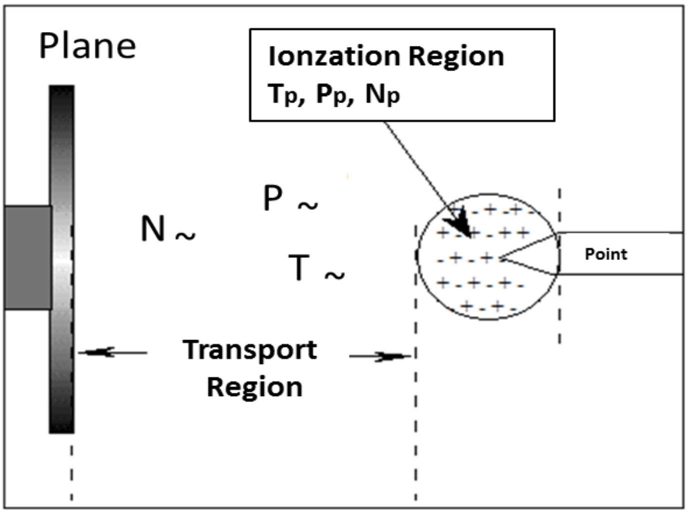

Figure 3. Sketch of region in the corona

3.1 Current-Voltage Characteristics

In all our experiments with purified gas well (= 20 successive passes through the purification system), a current is always observed beyond the threshold voltage Vs corresponding to the onset of corona discharge process. Indeed, for V = Vs, the current rises abruptly from a value not detectable ($<10^{-14}$ A), reaching about 10 μA. Ionic wind phenomenon has been cause of light emission from the recombination process between electron and ions. The light emission proper follow the electric field lines that occur between point and plane electrodes. To illustrate this phenomenon, we present patterns of events in figure 5 and the corresponding photographs in figures 4.

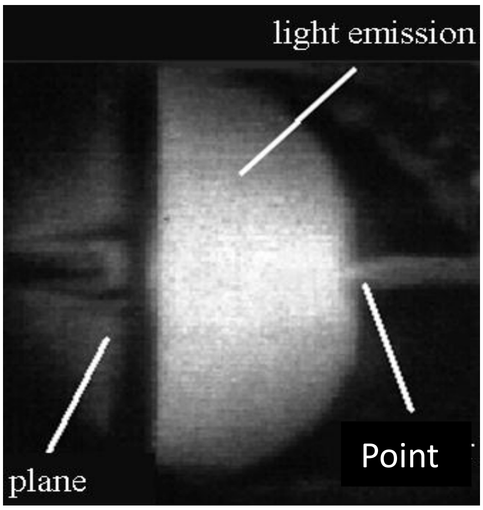

Figure 4. Photo of a negative corona discharge continues in pure argon. P = 1,2 MPa, T = 297 K, I = 110 uA and V = 2,5 kV. The black line is not visible in the photo.

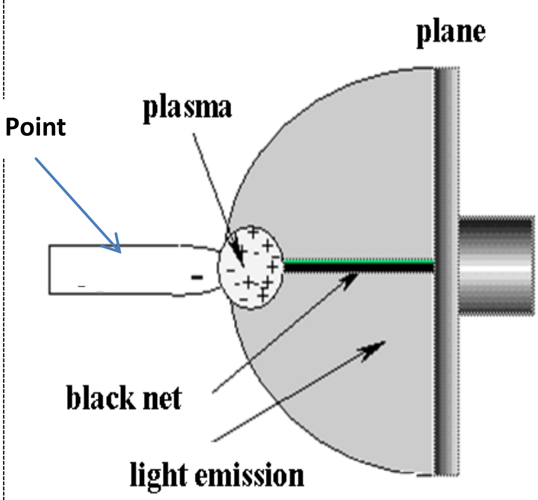

Figure 5. Detailed diagram of the corona of the photo in the figure 4

The typical shape of the current, depending on the voltage applied to tip, is shown in figure 6. The typical shape of the current-voltage curves in the argon gas is presented by scheth in the figure 7. In zone A, the measured current is always lower than the saturation current of Sigmond [10], so it is an unipolar current. After the transition in discharge region C, the current becomes bipolar and, in extreme cases, an arc current is directly detected. Since region A is that we can be analyzed according to the gas density, we will restrict the following presentation to the study of this part of the characteristics I(V). Firstly, the current increases steadily with V (area A) then becomes approximately constant (area B) and increas sharply (zone C). The value of current, there is the pseudo-saturation depends on the density of gas. In zone A, the very bright area is confined near the tip. When discharge condition with current in the area C, we found forms a bright discharge channel that completely crosses the space between the two electrodes (point and plane).

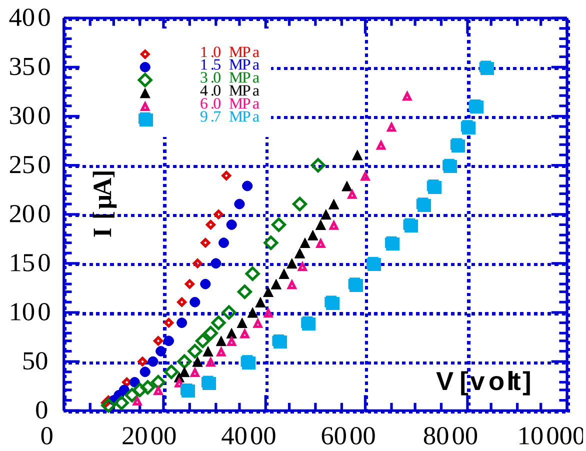

Figure 6. Characteristics I-V for argon gas at different pressures, limited to the region A. Negative polarity of the tip.

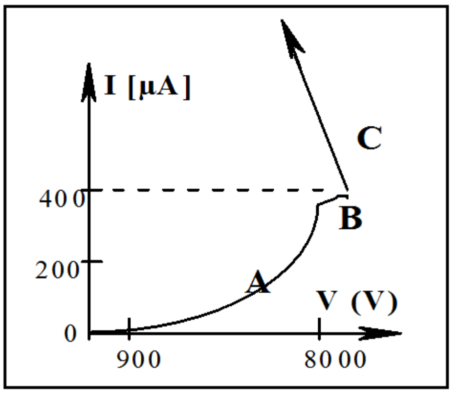

Figure 7. Typical shape of the current-voltage curves in the argon gas.

Another important aspect to consider is the role that impurities (N_2, O_2) in argon gaseous . Weislers observed a continuous glow discharge in contaminated by at least 0,3% nitrogen while it has obtained the same result with a content of 10% nitrogen in argon. In our case, we use a very pure gas whose nitrogen content is less than 0,3 ppm-volume before passing through the purification system. We have also used a titanium purifier that completely eliminates the residual nitrogen or desorbed from the walls . The glow discharge that we obtained in our experiments is therefore not the result of a residual nitrogen. In the presence of oxygen ($\geq$ 0,1%), Weislers got a pulse discharge rate Trichel type and also a very significant reduction of the current. We also obtained this result using a gas and its supply circuit unpurified. In figure 8, we show the variation of I/V versus V at different pressures. We can see that the voltage V (which is the value of V extrapolated to zero current) does not depend on the pressure. For all pressures studied, we note that Vo $\cong$ 400 volt. This value is low compared to the values of the corresponding threshold voltages. For example, a pressure of 1 MPa, $V_{threshold}$ $\cong$ 900 volt volt and at a pressure of 9,7 MPa, $V_{threshold}$ is equal to 2500 volt. In this case, the discharge rate is close to a current region limited by space charge [10].

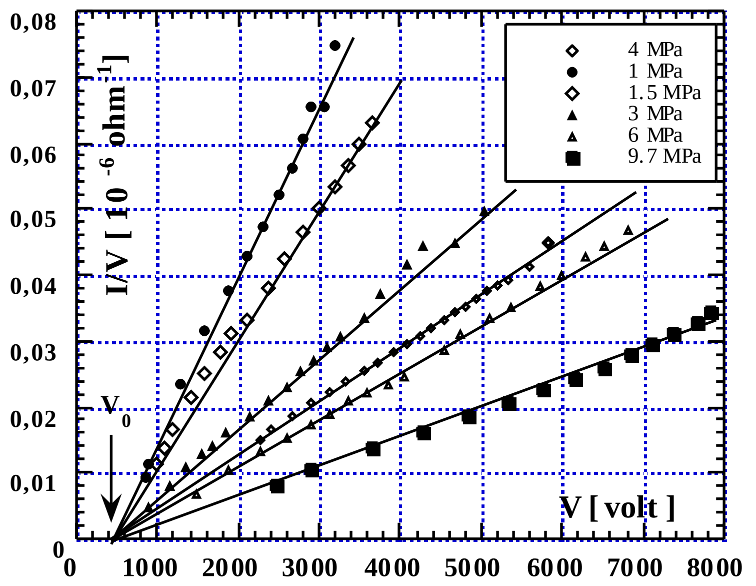

Figure 8. Curves I/V(V) to the argon gas in negative polarity at different pressures.

3.2 Nonthermal electronic Mobility

They are derived from tests where negative polarity of the voltage on the tip is applied (negative corona discharge). This corresponds to the creation and transport of electrons (or if the medium is impure to negative ion transport). Using spectral analysis, we measured the maximum length of the field glow discharge (ionization zone, excitement, creation of non-equilibrium plasma). It is at most 1,5 mm to the lowest pressures used. Under these conditions, the transport area and being close to the curves √I(V) are all straight , we can calculate the "apparent" mobility of charge carriers. They were calculated from the slope of the lines √I(V), using the model Sigmond. In Figure 9 we can observe the evolution of this "apparent" mobility with the gas density. Mobility decreases and approximately follows a variation of Langevin type until the density $N / Nc \leq 0,25$ (here Nc is the critical density of argon). Values mobility obviously can not be attributed to thermal electrons . Indeed, the reduced electric field (E/N) in our experiment was too high for it to strike a balance between the gas and electrons. For point-plane geometry, the actual field in the transport can be approximated by the value of the mean field V/d, and the reduced field can be written as E/N = V/ND. However, V may be varied between the threshold voltage (V_{th}) and the breakdown voltage (V_b) , and Vb and Vth as similarly depend on the density of the gas , wherein the field can vary the field is reduced very limited and it is practically independent of the density . For all ranges of density of our experiments, the reduced field varies only slightly between 0.5×10^{-17} and 3×10^{-17} Vcm^2. We note in figure 9 , our results are in good agreement with those obtained by a direct method and Prew Allen [12] and Dutton [14] for non- thermal electrons in the same field reduced field. Therefore, in our case, we can say that our charge carriers are non- thermal electrons . We also present the results obtained in argon using a cell placed in a cryostat [11] and where it was possible variation of density from $2{,}5\ 10^{21}$ to $2\ 10^{22}$ cm^{-3} (liquid state near the triple point) . It is noted that these results are far from those achieved when Dutton the highest densities. One suspects that, in our case, the low mobilities observed are the result of argon purification still insufficient. The higher impurity content should be low to achieve the same result at lower density .

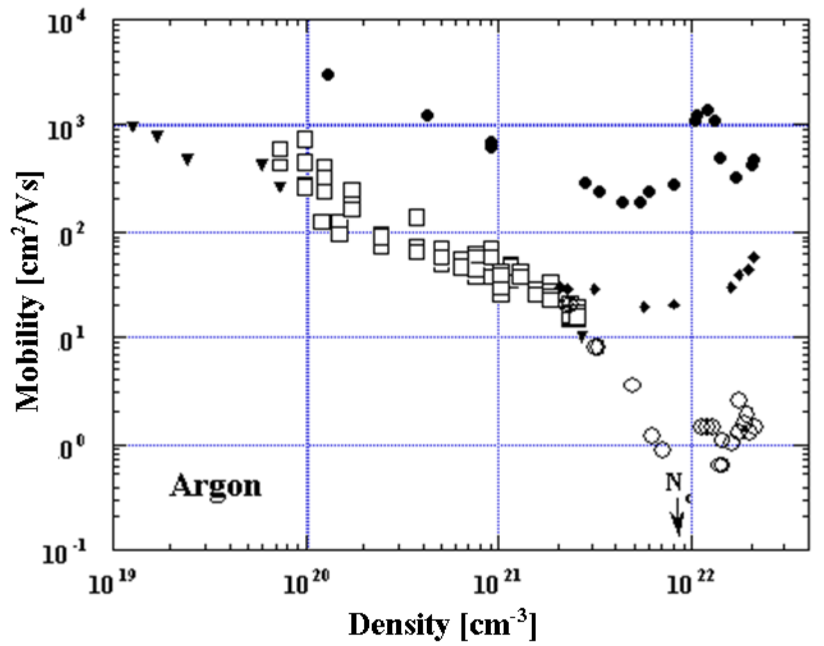

Figure 9. Mobilities depending on the density of negative charges.

¤ K_gas, our results.
○ K_app. gas and liquid [11]
▼ μ_e non-thermal electron in Ar gas [12].
• μ_e the thermal electron in Ar gas and ArL [13].
♦ μ_e non-thermal electron in Ar gas [14] and ArL [15].

3.3 Mobility of Ions

In the positive polarity, we studied positive corona discharge plasma which corresponds to a generation of positive ions. In argon, beyond the threshold voltage V_{th} a DC was recorded. The measured values of the current are very low compared with those obtained in negative polarity of the point (at least in the most pure gas). The threshold voltage increases with gas density. Characteristics I (V) being straight, the "apparent" mobility of the charge carriers was calculated from the measurement of their slope again using the model Sigmond [10]. In Figure 9, the behaviour of the apparent mobility with the gas density is presented. The apparent mobility inversely proportional to the density or follow the Langevin variation law [17]. On the same graph, we also present the results obtained by Freeman [13] and Hornbeck [15] . In both cases, these authors have performed a direct measurement (time of flight) of the speed of positive carriers between flat parallel electrodes.

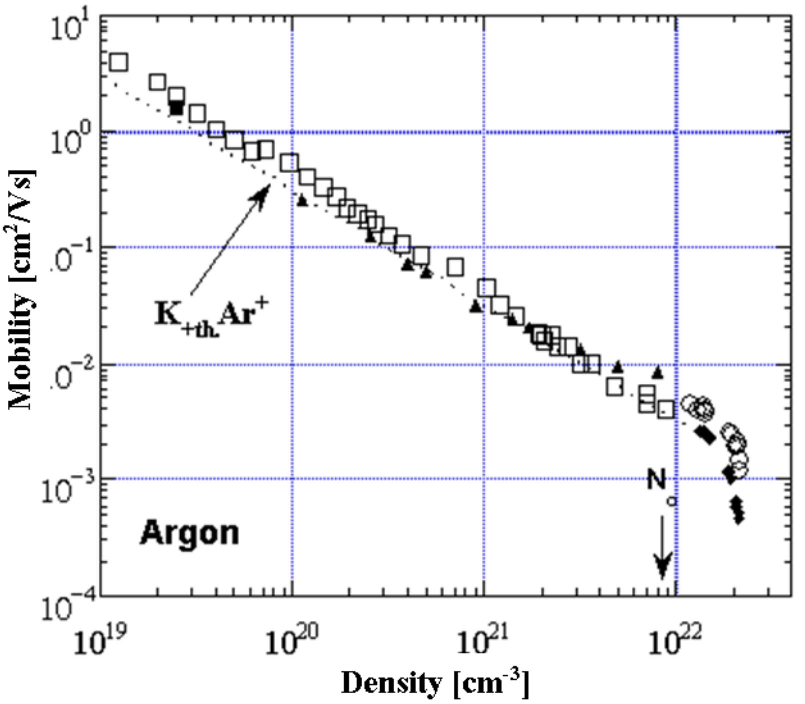

Figure 10. Mobility of positive ions depending on the density.
¤ K_{+app} gas, our results.
○ K_+ liquid [11]
♦ K_+ liquid [16].
▲ K_+ gas [13].
■ K_+ gas [15].
--- $K_{+th.Ar}^+$ theoretical curve according to the theory of Langevin corrected[17]

We can see that our values are in good agreement with measurements of others authors [13,15,16]. On the other hand if we consider that the charge carriers are ions Ar^+ and its evolved the Langevin model corrected [15,16], for the effect of charge transfer resonance is applied. We can see that the theoretical curve and the calculated mobility overlaps substantially all of our experimental values and those of Freeman and Hornbeck [13,15]. It seems that the charge carriers in these conditions are well Ar+ ions. The results obtained in the liquid argon are also shown in figure 10. These results show that when the density exceeds the critical density (Nc), the apparent mobility no longer follows the law of variation of Langevin. The same behavior is shown by the results of Davis [16].

4. Conclussion

In the very pure argon, corona discharge plasma can produce ionic wind phenomenon that has been shown by light emission from the recombination process. The light emission was observed visually and proper follow the electric field lines that occur between point and plane electrodes. Our results on mobility of charge carrier, we found that non-thermal electron, mobility decreases and approximately follows a variation of Langevin type until the density ≤ 0,25 the critical density of argon. In the case of ions, we found that the behaviour of the apparent mobility inversely proportional to the density or follow the Langevin variation law. Determination of mobility of charge carrier of corona discherge plasma can be done with variation of density from 2,5 10^{21} to 2 10^{22} cm^{-3}.

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References
[1] Jones, J.E. 2008 "On corona-induced gas motion and heating I:Field equations, modelling and vortex formation", *Journal of Electrostatics*, 66 84–93
[2] Nur, M. 1997 "Etude des décharges couronne dans l'argan et l'azote trés purs: transport des charges, spectroscopie et influence de la densité", *PhD. Thesis*, Joseph Fourier University, Grenoble, France.
[3] Coelho, R., Debeau, J. 1971,"Properties of the tip-plane configuration, *J. Phys. D: Appl. Phys*., 4, p. 1266
[4] Timothy I.J. Goodenough P., Goodenough, W., and Goodenough, S. M. 2007, "The efficiency of "corona wind" drying and its application to the food industry", *Journal of Food Engineering*, Volume 80, Issue 4, , Pages 1233-1238
[5] Kim, C. Park, D.. Noh, K.C. and Hwang J. 2010 "Velocity and energy conversion efficiency characteristics of ionic wind generator in a multistage configuration", *Journal of Electrostatics* 68, 36–41
[6] Gelfan, P.C., 1975 "Corona Wind Generating Device", U.S. Patent No. 3,896,347 (22 July 1975)
[7] Robinson, M. 1961, "Movement of air in the electric "wind" of the corona discharge", *AIEE Trans.* 80, pp. 143–150
[8] Coelho R. and Debeau J., "Properties of the Tip-Plane Configuration", *J. Phys. D : Appl. Phys.,* Vol. 4, pp. 1266-1280, 1971.
[9] H. Kalman, E. Sher,1997 Enhancement of heat transfer by means of a corona wind created by a wire electrode and confined wings assembly, *Applied Thermal Engineering* 21 (2001) 265±282
[10] Sigmond, R.S. (1982),"Simple approximate treatment of unipolar spacecharge-dominated coronas: the Warburg law and the saturation current", *J. Appl. Phys*. 53 (1982) 891–898.
[11]Bonifaci N., Denat A., and Malraison B., "Transport phenomena in point-plane geometry in dense argon", J. Electrostatic 40&41 pp.91-96, 1997
[12]Allen N. L. and Prew B. A., 1970 "Some measurements of electron drift velocities in compresed gases ", *J. Phys. B : Atom. Molec. Phys* , Vol **3** , pp. 1113-1126
[13] Gee N. , Floriano M. A., Wada T., Huang S. S. S. and Freeman G.R., 1985"Ion and electron mobilities in cryogenic liquids: Argon, Nitrogen, Methane and Ethane", *J. Appl. Phys.* Vol. 57, pp. 1097-1101
[14]Dutton J.,1975 "A survey of electron swarm data", *J. Phys. Chem*. Ref. Data, Vol. **4**, pp 577-857
[15]Hornbeck J. A.,1951 "The drift velocities of molecular and atomic ions in helium, neon and argon", Phys. Rev. Vol. 84, pp. 615-620
[16] Davis H.T. , Stuart A.R.and Mayer L. , *J. Chem. Phys*.,37 (1962) 947
[15] McDaniel E. W. and Mason E. A., 1964 "Collision phenomena in ionized gases", John Wiley & Sons, New York , chapter 7 and 9
[16] Reininger R., Asaf U., Steinberger I. T., Basak S.,1983 "Relationship between the energy V_0 of the quasi-free-electron and its mobility in fluid argon, kripton, and xenon", *Phys. Rev. B,* Vol. **28** (8), pp. 4426-4432
[17] McDaniel E. W. and Mason E. A.1973, "The mobility and diffusion of ions in gases", John Wiley & Sons, New York , chapter 5