The Role of Sodium Halide in Improving the Plasma Properties of Mercury-Sodium Mixture Under Atmospheric Pressure

Fatima Mohammed Hadi, Rafid Abbas Ali and Raad S.Sabry
Department of Physics, College of Science, Mustansiriyah University, 10052 Baghdad, Iraq
{fatima.m.h, rafidphy_1972, drraad_sci}@uomustansiriyah.edu.iq

Keywords: Arc Discharge, Current Density, Cathode Temperature, Electron Temperature, Energy Flux Density.

Abstract: The model used in this study includes theoretical calculations and numerical simulation data to determine the impact of cathode surface temperature (Tw) on the current densities in plasma (electrons, ions, and emitted electrons) in arc discharge plasma. The goal of the study is to improve lamp lighting, increase the brightness ratio, and enhance overall performance. The model employed in this study is computational and numerical, utilizing simulations to predict the effects of cathode surface temperature on various plasma parameters. The study assumes thermal equilibrium in the plasma. The temperature change of the electrons was studied according to the change in temperature of the cathode surface inside the plasma. A mixture of mercury and sodium (0.1, 0.01 and 0.001 mol.) was used in varying proportions, and the effect of changing the concentration and choosing the optimal temperature to increase lighting efficiency and brightness was examined. Plasma physics, especially arc discharge, forms a strong foundation for lighting technology in gas discharge lamps. The effect of ionization and excitation processes near the cathode surface was studied, and it was observed that as the temperature increases As a consequence, the current densities (j_i, j_e, and j_{em}) also increase, leading to a rise in the plasma current density (j). By using varying concentrations of sodium (Na) with mercury gas (Hg), a noticeable increase in ionization processes and electron emission is observed as the halide concentration in the mixture increases. Choosing 10 V and 40 V as a method to study the effects of both low and high voltages on plasma properties. When applying different voltages, 10 volts and 40 volts, it is noted that reducing the applied voltage to 10 volts reduces the electric field and the energy supplied to the electron to release it, which affects the rates of ionization, collision, and thermal emission in the plasma.

1 INTRODUCTION

In physics, plasma is a state of matter that contains an equal number of positively and negatively charged particles. Often referred to as the fourth state of matter, plasma consists of charged particles, typically produced by heating a gas to the point where electrons are separated from the atoms or molecules that make it up. Plasma is an ionized gas containing both electrons and ions. It is formed as a result of heating the gas[1].The phenomenon is called an electric arc, which Leads to a reduction in the breakdown voltage. During discharge, the arc is formed, and the electrons emitted from the cathode generate a thermal field [2]. Electric arcs typically require a high current, greater than that of glow discharge. The voltage in short arcs usually exceeds 20-30 V, although in some cases, it can drop to just a few volts [3]. Arc discharge technology has diverse applications across various fields, including optical fiber technology, welding, and material processing [4]. The electric arc discharge is capable of generating active particles and high temperatures, making it useful in a wide range of industrial processes [5] . Peter et al. studied the scattering of light to measure the speed and size of particles in order to understand the behavior of arc discharge in material processing [6].

M. Auger et al. developed advanced experimental setups using arc discharges. similar to those used in neutrino physics, as an alternative to photon detection systems in large particle detectors [7] . R. Abbas Ali et al. conducted a comprehensive theoretical investigation of He-Ne gas mixture. And its effect on electronic transactions in plasma. In low varying electric field and thermodynamic equilibrium. The diffusion coefficients and total collision frequency were studied by solving the Boltzmann equation using the binomial approximation [8] .The aim of research improving the lighting of the lamp by adding sodium halide, which improves the lighting and extends the life of the lamp. In this work, the cathode radius (0.001m) and the distance between the electrodes (0.01m) were determined at room temperature, and the work was conducted using (NCPL and Thermo cad) programs. It explores the theoretical aspects of the work, with the use of the programs NCPL and THERMOCAT. These modeling programs include tools for calculating various plasma parameters based on the temperature of the cathode and the plasma layers adjacent to the cathode. [9] [10]. The code calculates all of the following parameters Flux density of plasma at the cathode contact, $[q(T_w, U)]$ Electric current density as it passes through the plasma and reaches the cathode contact. $[j(T_w, U)]$. Temperature of the electron layer approaching the cathode, $[T_e(T_w, U)]$. Plasma pressure exerted on the cathode interface. $[P_{pl}(T_w, U)]$ .The database includes gases that produce plasma, such as mercury (Hg), cesium (Cs), xenon (Xe), copper (Cu), argon (Ar), sodium (Na), helium (He), air, and mixtures of cesium-mercury (Cs-Hg) and sodium-mercury (Na-Hg), as well as metal halides [11]. At heated cathodes in a high-pressure arc discharge, the imbalanced layer coefficients are evaluated as functions of the interface temperature T_w and the low voltage applied to the cathode surface. U is essential for accurate modeling of the high-pressure arc's behavior. The NCPL symbol is used for this evaluation [12]. When working with a pure monatomic gas producing plasma, we simply enter the chemical symbol for the gas in the "produced gas" field (e.g., He). It is important to pay attention to the case of the letters (uppercase and lowercase). The code calculates the plasma layer near the cathode using atomic parameters and other fixed data. Ionization of atoms occurs through electron collisions, and the momentum transfer cross-section is determined during elastic collisions (ion-atom interactions). The gas data is retrieved from the internal database, which includes elements such as Cu, He, Ar, Ne, Na, Hg, Xe, Cs, and Kr. Provided. The formatter will need to create these components, incorporating the applicable criteria that follow.

2 THEORETICAL PART

There are various forms of electric arcs, each with distinct characteristics arising from direct external connections involving alternating current and electric fields [12] . An arc discharge occurs in a gas-saturated medium between two conducting terminals the cathode and the anode at extremely high temperatures, which can vaporize or destroy most materials. An electric arc is characterized by an instantaneous discharge of electricity [13].

An electric arc is a continuous discharge, whereas an electric spark is an instantaneous discharge. Electrical discharge can occur with either direct or alternating current. An electric arc differs from a glow discharge in that it has a relatively high current density and a small voltage drop during arcing. At the cathode, the current density can reach up to one million amperes per cubic centimeter [14].

The two key equations for plasma and gas behavior are as Maxwell Distribution (Velocity Distribution) this describes the velocity distribution of particles in gases or plasmas, which is governed by the temperature and mass of the particles. The Maxwell distribution function is given by:

$$f(v_x) = N\left(\frac{T}{2\pi m}\right)^{1/2} \exp\left(-\frac{mv_x^2}{2T}\right). \quad (1)$$

Where v is the particle velocity, mmm is the particle mass, Tis the temperature, and n is the number density of particles. Saha Equation (Ionization Equilibrium) This equation relates the number densities of electrons Ne, ions Ni and atoms Na in a plasma under ionization equilibrium. The (2) is:

$$\frac{N_e N_i}{N_a} = \frac{g_e g_i}{g_a} = \left(\frac{m_e T_e}{2\pi\hbar^2}\right)^{3/2} exp\left(-\frac{J}{T_e}\right). \quad (2)$$

Where g_e - the electron statistical weights. g_i: Is the ion statistical weights. g_a: Is the atom statistical weights. m_e is the mass of electron، T_e: the temperature of the electron, J Is the ionization potential of an atom.

The Boltzmann distribution describes the spatial distribution function of atomic particles when equilibrium is established under the influence of a weak external environment. It is expressed as:

$$N(r) = N_0 \exp\left[-\frac{U(r)}{T}\right]. \quad (3)$$

Where N_0 - the particle number density at the position, $U = 0$, $U(r)$ - the particle interaction potential with an external field, T is the temperature.

In a high-pressure arc discharge, both the voltage drop (U) and the cathode surface temperature (T_x) influence the alternating current. This study focuses on examining the relationship between the cathode surface temperature (T_x) and voltage (U) with respect to the plasma layer near the cathode, specifically analyzing the current flow rate and current density (j) [15] .

$$j = j(T_w, U) \text{ , specifying for all } (T_w \geq \text{Tc}). \quad (4)$$

Where T_W - the cathode surface temperature, changes with changes in current density and applied voltage

Current flux density is described by the formula $q = q(T_w, u)$ all define is

$$(T_w \geq Tc). \quad (5)$$

Where q - Energy Flux Density, distribution of temperatures cathode structure determined by figuring out the heat conduction formula [16] .

$$\nabla(K\nabla T) = 0 . \quad (6)$$

Where ∇T - the cathode material's thermal conductivity K - a shift in temperature.

There is a boundary situation .The cathode body's surface temperature distribution can be determined by using the cathode body's thermal conductivity and it is represented by the equation in $q(T_w, u)$ function

$$k\frac{\partial T}{\partial n} = q\ (T_w, U\ ). \quad (7)$$

Where U - the low combined voltage. ,T_W - cathode surface temperature, q: Energy flux density.

The density of the plasma's energy flux can be expressed by the following[17] .

$$q_{\ p} = q_i + q_e - q_{em}. \quad (8)$$

Where, q_p - plasma's energy flux density. q_e - plasma electrons' energy flux density q_{em} - plasma energy flux density of electrons emitted from the cathode surface. The following form can be used to express the energy flux of ions, elections and energy flux elections Emitted

$$q_i = \ \mathrm{j_i}\ [\ \mathrm{Z_e U_D} + \mathrm{E} - \ \mathrm{ZA_{eff}} + \mathrm{k}(2\mathrm{T_h} + \ -2\ T_W), \quad (9)$$

$$q_e = J_e\left(2\mathrm{K}T_e + A_{eff}\right), \quad (10)$$

$$q_{em} = J_{em}\left(2\mathrm{k}T_W + A_{eff}\right). \quad (11)$$

Where, $j_i -$ ions current density, T_h - heavy particle temperature (ions, neutral particles), T_e- temperature electrons. Z - rate of ion charge accumulation, E - average ionization energy of the layer near the cathode , U_D - low voltage within space charge envelop, A_{eff} - effective work function (Schottky correction), $\mathrm{J_e} = \mathrm{e}\,\mathrm{J_e}$ - is the quantity of ions that provide a voltage to the cathode's electrical surface, J_{em} - the current density of electrons emitted from the cathode; $J_{em} = e\,J_{em}$, $J_i = Z_e\,j_i$ quantity ions that provide an electrical flow across the cathode's surface.

3 RESULTS AND DISCUSSION

3.1 Effect of Hg-Na Concentration on Plasma Properties

Different concentrations (0.001, 0.01, and 0.1, mol.) of Hg-Na, were chosen to determine the effect of changing the ratios in the mixture on the plasma properties. As the concentrations (0.001, 0.01, 0.1, mol.) increase, a proportional increase in emitted electrons is observed, indicating the impact of higher temperatures on the density of liberated electrons due to collisions with molecules, which in turn reduces the voltage barrier. In the case of applying higher voltage (U=40V), stronger electricity is generated with a shorter voltage barrier and increased electron emission due to the higher electric field. Additionally, increasing the concentrations (0.1 and 0.5 mol.) leads to a decrease in the voltage barrier due to increased ionization processes, which enhances collisions and increases electron emission .Hg pure has a lower ion concentration, and its plasma exhibits a less pronounced response to the increase in voltage, resulting in a smaller effect on ion energy flux density compared to (Hg-Na) max. With higher concentrations. The results indicate that pure mercury exhibits superior electrical and thermal properties compared to the mercury-sodium mixture, as it can withstand higher temperatures due to its lower melting point. Sodium, being an alkaline element, impacts plasma efficiency at elevated temperatures by influencing ionization processes and forming compounds that reduce performance. In contrast, pure mercury remains more stable, improving plasma density and efficiency at high temperatures. The results indicate that pure mercury exhibits superior electrical and thermal properties compared to the mercury-sodium mixture, as it can withstand higher temperatures due to its lower melting point. Sodium, being an alkaline element, impacts plasma efficiency at elevated temperatures by influencing ionization processes and forming compounds that reduce performance. In contrast, pure mercury remains more stable, improving plasma density and efficiency at high temperatures.

3.2 Electron Temperature

Figure 1 illustrates the relationship between electron temperature and cathode temperature. A balance and relative stability exist between the two. The emission of electrons increases with the surface temperature of the cathode due to the thermal effect. However, the temperature of the electrons rises more significantly than that of the cathode, often reaching thousands of degrees Celsius, while the cathode surface temperature remains much lower. This occurs because the energy gained by the electrons in the gas discharge increases their Velocity, which in turn raises their temperature.

Figure 1a and 1b which using a voltage barrier of 10 and 40 volts. In the case of pure mercury and for the mixture Hg-Na with different concentrations of Na (0.001, 0.005, 0.01, 0.05, 0.1and 0.5 mol.). We observe that the temperature effect becomes more pronounced at higher sodium concentrations. This is because sodium, being an alkali metal, increases the number of atoms interacting with mercury, which leads to a higher number of electrons being released into the plasma. These electrons absorb more energy from the cathode surface, causing the plasma temperature to rise [1].

The voltage barrier also plays a role in this effect. Increasing the voltage from 10 V to 40 V strengthens the relationship between cathode temperature and electron temperature. As the applied electrical voltage increases, the electrons gain more energy upon acceleration, raising their temperature. This, in turn, enhances the efficiency of the arc discharge [18].

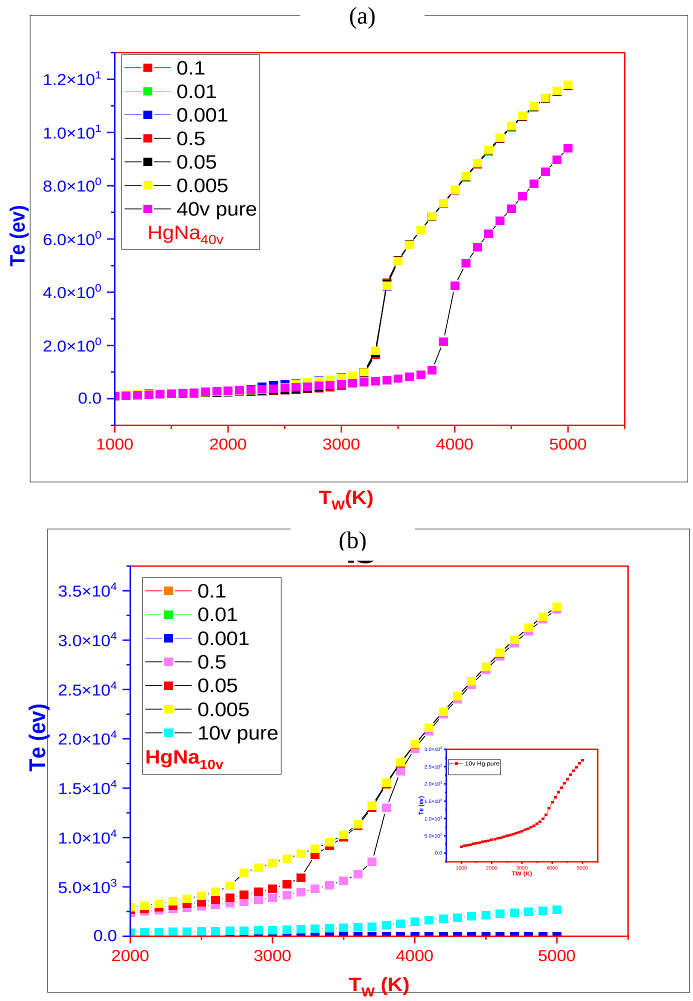
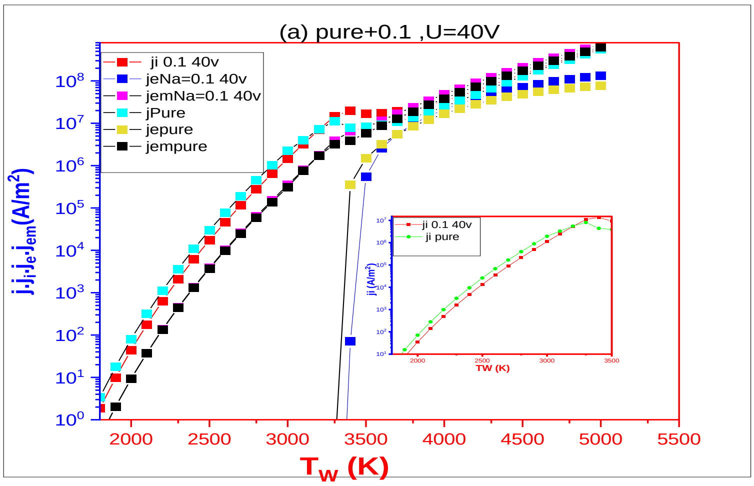


Figure 1: Electron temperature Te from the vs. cathode surface temperature TW for all concentrations a) U =40 V, b) U =10 V.

4 CURRENT DENSITY OF CONCENTRATION

Figure 2a and 2b, Figure 3a and 3b and Figure 4a and 4b shows the relationship between the current density (j, ji , je and jem) and the cathode surface temperature(TW) when using different voltages of 10 and 40 volts for pure mercury and for different concentrations of the mercury and sodium mixture (0.001,0.01 and 0.1mol) as the voltage barrier increases, the effect of TW on (*j*, *ji* , *je* and *jem*) increases. Increasing the current density of the electrons increases the degree of ionization of the gas .Increasing ji leads to plasma stability and reduced oscillations the density of the plasma affects the distribution of heat within the system The density of the electrons emitted from the cathode increases because the acceleration of the electrons in the cathode leads to secondary emissions, so the density of electrons in the plasma increases [19].



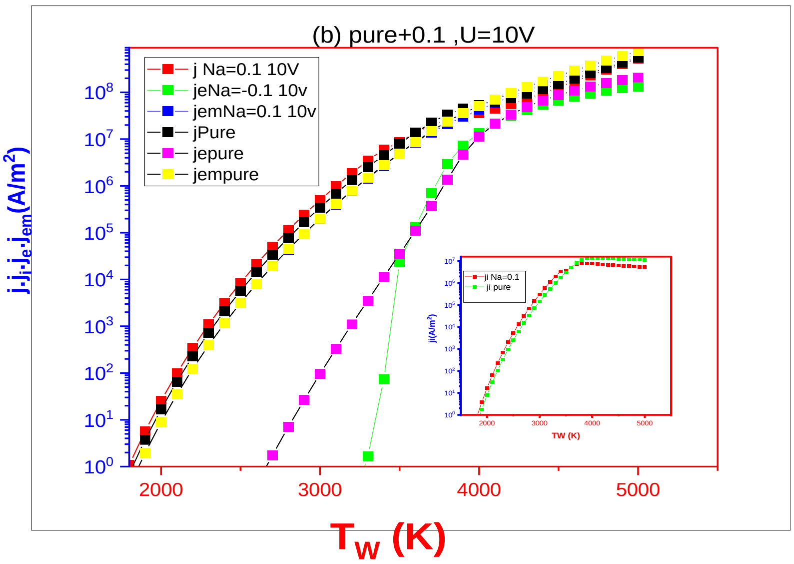


Figure 2: The current density (j, ji , je and jem) from the vs. cathode surface temperature (TW) at the concentration (0.1mol.): a) U=40V, b) U=10V.

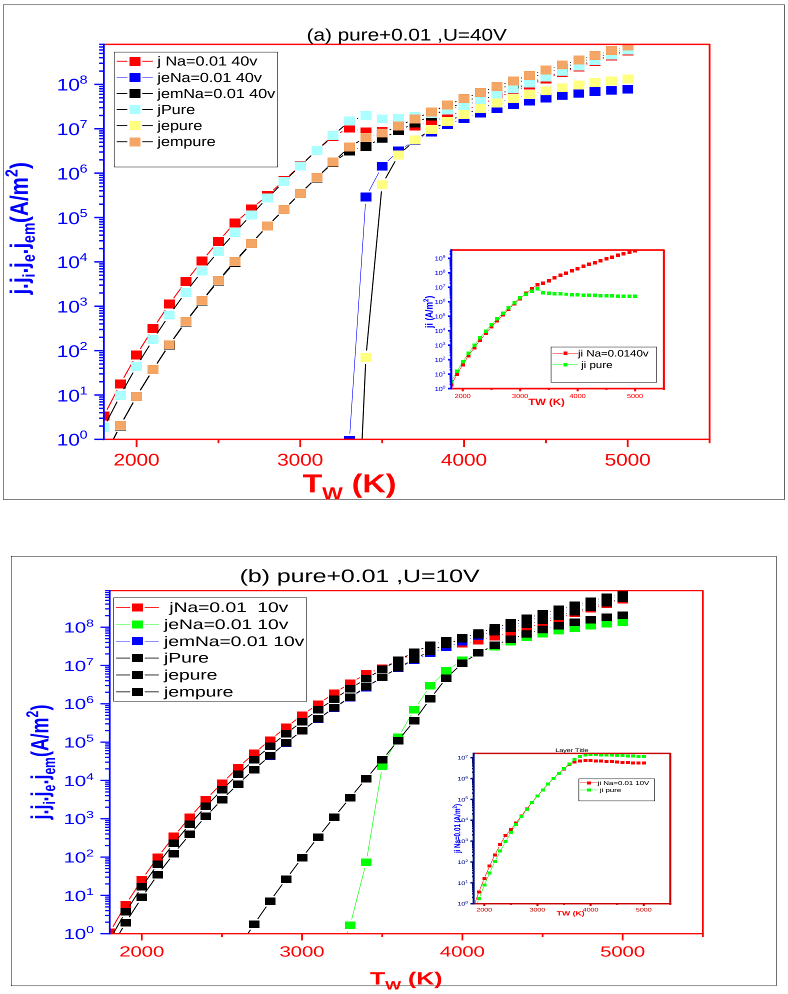


Figure 3: The current density (j, ji, je and jem) from the vs. cathode surface temperature TW at the concentration (0.01mol.): a) U=40V, b) U=10V.

When comparing the results obtained with a previous study (Tapark Abdlraheem Saber et al.) [20], which used a mixture of xenon and sodium, it is observed that both studies highlight the importance of cathode temperature and voltage in influencing plasma behavior and efficiency. However, our study places a greater emphasis on how varying sodium concentrations and cathode temperature directly affect plasma density, while the other study focuses on the role of the electric field in lowering the voltage barrier and enhancing ionization. The numerical simulations this Study are beneficial for optimizing arc discharge to improve lighting efficiency, while the thermodynamic insights from second Study are essential for understanding how electric fields and temperature variations interact to influence electron emission and plasma stability. As the cathode surface temperature (Tw) increases, the emitted electron current increases sharply, while the ion current decreases, especially at high voltages. Furthermore, high concentrations and voltages enhance current and power densities due to increased ion heating and higher electron temperatures this is consistent with the results obtained by H F Jassam [12].

The results indicate that pure mercury exhibits superior electrical and thermal properties compared to the mercury-sodium mixture, as it can withstand higher temperatures due to its lower melting point. Sodium, being an alkaline element, impacts plasma efficiency at elevated temperatures by influencing ionization processes and forming compounds that reduce performance. In contrast, pure mercury remains more stable, improving plasma density and efficiency at high temperatures.

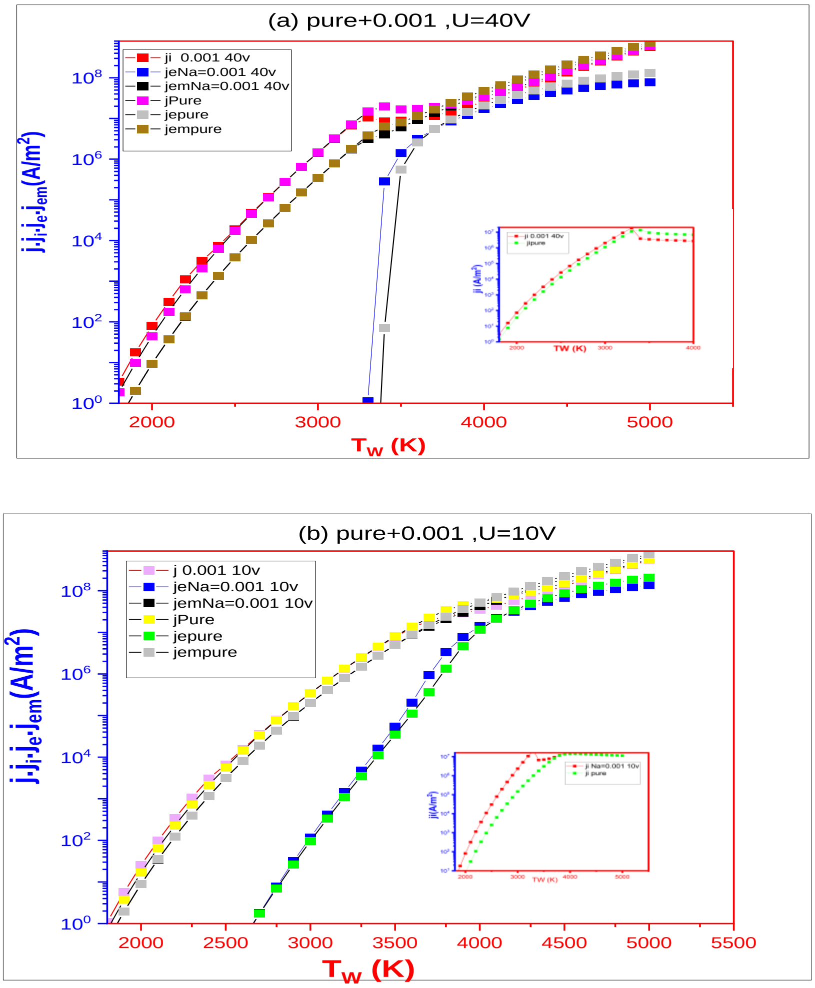


Figure 4: The current density (j, ji, je and jem) from the vs. cathode surface temperature TW at the concentration (0.001mol): a) U=40V, b) U=10V.

5 CONCLUSIONS

This paper provides computational analysis of the effect of sodium halide concentrations on the plasma characteristics of mercury-based arc discharges under atmospheric pressure. Simulations present that increasing the cathode surface temperature leads to a important improvement in current density and energy flux across all sodium concentrations and for pure mercury, highlighting the strong thermal coupling between cathode heating and plasma behavior. From the results, it is evident that as the surface temperature of the cathode increases, the density of the energy flux electrons and ions increases for all concentrations of sodium (Na), as well as for pure mercury. The plasma density also increases in general. Different concentrations of sodium affect the thermal behavior of the arc discharge system, which contributes to improving the lighting and efficiency of the generated plasma. Additionally, the effect of varying the voltage barrier from 10 V to 40 V enhances the influence of the cathode surface temperature on elastic and inelastic collisions, ionization processes, and the release of high-energy electrons. This leads to a significant increase in electron temperature compared to lower voltage conditions.

ACKNOWLEDGMENTS

Authors would like to thank Mustansiriyah University Baghdad-Iraq for its support in the present work.

REFERENCES

[1] M. T. Al-Obaidi, R. A. Ali and B. Hamed, "Modelling of Reduced Electric Field and Concentration Influence on Electron Transport Coefficients of He-Ne Plasma," Acta Phys. Pol. A, vol. 140, no. 4, 2021.

[2] N. N. Misra, O. Schlüter and P. J. Cullen, Cold Plasma in Food and Agriculture: Fundamentals and Applications. Academic Press, 2016.

[3] F. M. Hadi, R. A. Ali and A. A. Al-Rubaiee, "Mathematical Model of the Electronic Coefficients for Different Concentrations of Argon and Mercury Mixture," IOP Conf. Ser. Mater. Sci. Eng., vol. 928, no. 7, 2020, [Online]. Available: https://doi.org/10.1088/1757-899X/928/7/072072.

[4] M. S. Benilov, M. D. Cunha and G. V. Naidis, "Modelling interaction of multispecies plasmas with thermionic cathodes," Plasma Sources Sci. Technol., vol. 14, no. 3, p. 517, 2005.

[5] A. A. Temur, A. F. Ahmed and R. A. Ali, "Determination of the Mathematical Model for Plasma Electronic Coefficients of the Earth's Ionosphere," Iraqi J. Sci., pp. 1508-1517, 2023.

[6] A. Gleizes, "Perspectives on thermal plasma modelling," Plasma Chem. Plasma Process., vol. 35, pp. 455-469, 2015.

[7] M. Auger, et al., "ArCLight-A compact dielectric large-area photon detector," Instruments, vol. 2, no. 1, p. 3, 2018.

[8] R. Abbas Ali, B. Hamed, M. T. Al-Obaidi and A. M. Abbas, "Estimation of a Mathematical Model for Theoretical Measuring of Plasma Electrons Mobility at Different Concentrations of He-Cu Mixture," J. Phys. Conf. Ser., vol. 1999, no. 1, 2021, [Online]. Available: https://doi.org/10.1088/1742-6596/1999/1/012132.

[9] M. S. Benilov and A. Marotta, "A model of the cathode region of atmospheric pressure arcs," J. Phys. D. Appl. Phys., vol. 28, no. 9, p. 1869, 1995.

[10] M. S. Benilov and M. D. Cunha, "Heating of refractory cathodes by high-pressure arc plasmas: II," J. Phys. D. Appl. Phys., vol. 36, no. 6, p. 603, 2003.

[11] M. S. Benilov and M. D. Cunha, "Bifurcation points in the theory of axially symmetric arc cathodes," Phys. Rev. E, vol. 68, no. 5, p. 56407, 2003.

[12] H. F. Jassam and R. A. Ali, "Interaction of near-cathode plasma layers with thermionic electrodes under high pressure arc plasma," J. Phys. Conf. Ser., vol. 2322, no. 1, 2022, [Online]. Available: https://doi.org/10.1088/1742-6596/2322/1/012076.

[13] O. A. Hamadi, M. K. Khalaf, F. J. Kadhim and B. T. Chiad, "Operation Characteristics of a Closed-Field Unbalanced Dual-Magnetrons Plasma Sputtering System," Bulg. J. Phys., vol. 41, no. 1, 2014.

[14] N. V. D. Long, et al., "Catalytic Ammonia Formation in a Microreaction Chamber with Electrically Intensified Arc Plasma," ChemCatChem, vol. 16, 2024.

[15] A. I. Saifutdinov, "Numerical study of various scenarios for the formation of atmospheric pressure DC discharge characteristics in argon: From glow to arc discharge," Plasma Sources Sci. Technol., vol. 31, no. 9, p. 94008, 2022.

[16] A. S. Noori, K. A. Aadim and A. H. Hussein, "Investigate and Prepare silver Nano Particles Using Jet Plasma," Iraqi J. Sci., pp. 2461-2469, 2022.

[17] B. M. Smirnov and D. V. Tereshonok, "Stepwise ionization in a glow discharge cathode layer in argon," High Temp., vol. 52, no. 6, pp. 781-786, 2014.

[18] F. M. Hadi, R. A. Ali and A. A. Al-Rubaiee, "Simulation analyses and investigation of the induced electric field and Ar-Hg mixture on the gas discharge processes," Al-Mustansiriyah J. Sci., vol. 31, no. 3, pp. 126-136, 2020.

[19] V. I. Kolobov and R. R. Arslanbekov, "Simulation of electron kinetics in gas discharges," IEEE Trans. Plasma Sci., vol. 34, no. 3, pp. 895-909, 2006.

[20] T. A. Saber, R. A. Ali and H. M. Jawad, "The Role of Cathode Heat in the Schottky Correction in the Ionization Layers of Arc Plasma," Adv. Sci. Technol. Res. J., vol. 18, no. 4, pp. 265-272, 2024, [Online]. Available: https://doi.org/10.12913/22998624/189290