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The Influence of Thallium Halide on Improving Arc Discharge Properties under Atmospheric Pressure

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Abstract

In this work, a comprehensive numerical analysis was conducted to investigate the effect of cathode surface temperature (T_w) on several key plasma parameters. These include the electron energy flux density(q_e), the emitted electron energy flux density (q_{em}), the total plasma current density (j), and its individual components: electron current density (j_e), ion current density (j_i), and thermionically emitted electron current density (j_{em}). The relationship between the electron temperature in the plasma (T_e) and the cathode surface temperature (T_w) was also examined, as this interaction plays a crucial role in defining surface reactions and overall plasma behavior. The simulations were carried out using pure xenon and a xenon–thallium gas mixture at different thallium concentrations (0.001, 0.01, and 0.1 mol.) under two applied voltages: 20 V and 40 V. Results indicated that the optimal performance was achieved with pure xenon at an applied voltage of 20 V. This is attributed to the higher ionization energy of xenon, which leads to greater electron energy and current densities compared to the Xe-Tl mixtures. Additionally, plasma operation at the lower voltage of 20 V was found to be more efficient than at 40 V, as it promotes greater stability in both electron energy and current density. This, in turn, enhances the overall plasma performance and energy efficiency of the system. These findings underscore the importance of carefully selecting the gas composition, applied voltage, and cathode temperature to optimize the discharge process, particularly in applications requiring stable plasma operation and high efficiency output, such as advanced lighting systems.

Keywords: Arc discharge, current density of electron, current density of ion, ion flux energy, electron energy flux, plasma ionization degree.

دور هاليد الثاليوم في تحسين خصائص البلازما لتفريغ القوس تحت تاثير الضغط الجوي

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الخلاصة

في في هذا العمل، تم إجراء تحليل عددي شامل لدراسة تأثير درجة حرارة سطح الكاثود T_wعلى عدد من المعلمات الأساسية للبلازما. وتشمل هذه المعلمات: كثافة فيض طاقة الإلكترونات q_e، وكثافة فيض طاقة

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الإلكترونات المنبعثة q_{em}، والكثافة الكلية للتيار في البلازما j، ومكوناته الفردية، وهي: كثافة تيار الإلكترونات j_e، وكثافة تيار الأيونات j_i، وكثافة تيار الإلكترونات المنبعثة حرارياً j_{em}. كما تم أيضًا فحص العلاقة بين درجة حرارة الإلكترونات في البلازما T_e ودرجة حرارة سطح الكاثود T_w، حيث تلعب هذه العلاقة دورًا حاسمًا في تحديد التفاعلات السطحية وسلوك البلازما بشكل عام. وقد أُجريت المحاكاة باستخدام مزيج من غازي الزينون والثاليوم بتركيزات مختلفة من الثاليوم (0.001، 0.01، و0.1 مول) تحت تطبيق فولتيتين: 20 فولت و40 فولت. وأظهرت النتائج أن الأداء الأمثل تحقق عند استخدام الزينون النقي مع تطبيق جهد مقداره 20 فولت. ويُعزى ذلك إلى طاقة التأين العالية للزينون، مما يؤدي إلى طاقات وكثافات تيار إلكتروني أكبر مقارنةً بخليط الزينون–الثاليوم. بالإضافة إلى ذلك، وُجد أن تشغيل البلازما عند الجهد المنخفض 20 فولت أكثر كفاءة من التشغيل عند 40 فولت، حيث يعزز ذلك الاستقرار في طاقة الإلكترونات وكثافة التيار، مما يحسن أداء البلازما العام وكفاءة الطاقة للنظام. وتؤكد هذه النتائج على أهمية الاختيار الدقيق لتركيب الغاز والجهد المطبق ودرجة حرارة الكاثود من أجل تحسين عملية التفريغ الكهربائي، لا سيما في التطبيقات التي تتطلب تشغيلًا مستقرًا للبلازما وإنتاجية عالية مثل أنظمة الإضاءة المتقدمة.

1. Introduction

Matter has four states: gas, liquid, solid, and plasma [1]. Each has different physical characteristics. Plasma may produce light and interact with magnetic and electric fields [2]. As is known, plasma consists of electrons and ions, depending on the specific plasma conditions. Plasma is present in the sun, stars, neon lights, and electrical discharge devices. It is also utilized in laser cutting, microprocessor manufacturing, power generation, and medical applications. Gas discharge is a plasma formed by ionizing a gas in a partly evacuated chamber with a high voltage [3]. Several forms of gas discharge are employed in numerous applications: glow discharge, a type of low-current arc discharge, is used in electroplating and surface cleaning, a high-current arc discharge is utilised in welding, and corona and spark discharge are used in electrical discharge devices for illumination. Arc discharge is the process of passing a high-density electric current between two electrodes to form plasma. Creating a high voltage difference between two electrodes ionizes the gas, which then generates very high heat and converts the gas into plasma [4]. Arc discharge has numerous applications in various fields, including the production of thin films [5]. Lamp arc discharge produces light by sending an electric current through a gas [6]. The principle of this process is the electric discharge. When the gas inside the lamp is ionized, light is emitted. In arc discharge lamps, noble gases are usually used, sometimes mercury, which gives a distinctive color, with the addition of halogens, which play a major role in maintaining the lamp's long life and improving the plasma properties [7-9].

The aim of this research is to improve the plasma properties and their role in enhancing the luminosity of arc discharge lamps. In this work, the effect of cathode surface temperature on arc discharge parameters, including electron energy flux density, emitted electron energy flux density, total plasma current density, electron current density, ion current density, emitted electron current density and electron temperature was investigated. Simulations were performed using a xenon–thallium gas mixture at different thallium concentrations (0.001, 0.01, and 0.1 mol.) (Tl-I) under specific operating conditions, such as a cathode radius of 0.001 m, a 0.01 m cathode-anode gap distance, a gas temperature of 300 K, and a gas pressure of 1 atm, providing a realistic and controlled environment for evaluating cathode-plasma interactions.

2. Theoretical part

Figure 1 represents a radiant cathode used in electric arc glow under intense pressure. As shown, the cathode consists of two sections [10]. The first section of the exterior is in direct contact with the plasma arc. Ionization processes in the discharge region increase current during arc discharge, leading to heating by the electric arc glowing under high pressure. The second part is in contact with the gas [11]. It is necessary to separate the first part from the second to ensure optimal performance [12]. Thermic accessibility for cathode k depends on temperature T; it is a formula temperature dependent (k=k(T)). Generated energy is transferred to the cathode surface, where part of it is concentrated within a slim plasma layer surrounding the cathode. The electric current moves in one direction through the plasma layers to the cathode surface [13]. It mainly depends on the voltage drop and the temperature variation of the cathode surface. The properties of the plasma layer near the cathode, including power flow density and electric current flow density, are functions of variable voltage and surface temperature [14]. As the heat degree T_w changes, the cathode's heat transfer fluctuates according to a specific function, affecting its thermal and electrical performance [15]:

$$q = q(Tw, U) \tag{1}$$

This function determines the surface heating at low temperatures ($T_W \geq Tc$), Also:

$$j = j(Tw, U) \tag{2}$$

This function determines the current transfer to the receiving surface [16], where the function is known when ($T_W \geq T_C$)and vanishes at low temperatures $q(T_w, U)$. Once defined, it is easy to describe the heat degree allocation on the surface of the cathode and inside it using heat conduction equation [7] :

$$\nabla.(k\nabla T) = 0 \tag{3}$$

Under border conditions [7]:

$$\kappa\left(\frac{\partial T}{\partial n}\right) = q(Tw, U) \tag{4}$$

n is the direction perpendicular to the cathode surface that points outward with the condition: $Tw = Tc$

The energy flux density generated near the cathode surface is transferred to the cathode surface and plays an important role in thermionic emission. It is calculated based on the basic contributions reaching the cathode, which include ion energy, electron energy, and thermal radiation [17]. The general formula for its calculation is [18]:

$$q_p = q_i + q_e - q_{em} \tag{5}$$

Where q_p is the thermal energy flow of plasma, q_e is the energy flow of electrons, and q_{em} is the energy flow from the cathode surface.

This formula expresses energy transferred to the surface of the cathode by plasma, and affected by Equations (1) and (2), where [13]:

$$q_i = j_i[Z_e\, U_D + E - ZA_{eff} + K(2T_h + \frac{ZT_e}{2} - 2T_w)] \tag{6}$$

$$q_e = J_e(2KT_e + A_{eff}) \tag{7}$$

$$q_{em} = j_{em}(2kT_w + A_{eff}) \tag{8}$$

Where T_h is the temperature of heavy particles, including (impartial particles,ions), T_e is the electron temperature in the cathode surrounding region, Z is the mean number of charged ions, E is the average total ionization energy in the region surrounding the cathode, $U_D$is the low electrical potential inside space charge wrapper, A_{eff} is the work function (Schottky correction), w_i is the low voltage in the layer of ionization, j_{is} the ion current density; it represents the current carried by positive or negative ions within the plasma [4].

$$j_i = ZeJi \quad (9)$$
$$j_e = eJ_e \quad (10)$$
$$j_{em} = eJ_{em} \quad (11)$$

where j_e is the electron current density; it represents the current carried by free electrons within the plasma, j_{em} is the current density of emitted electrons which is the current resulting from the thermionic or critical emission of electrons from the electrode, which usually results from thermal effects or the existence of a high electric field [4].

$$j = j_i + j_{em} - j_e \quad (12)$$

Where j is the total current density in the plasma, which represents the sum of the densities of electrons, ions, and thermionic electrons [10]. The importance of each component depends on the arc discharge conditions, such as pressure, temperature, and the type of material used in the electrodes [17]. Studying these values is essential for understanding the dynamics of arc discharge in applications, such as carbon nanotube manufacturing or in electric spark cutting processes.

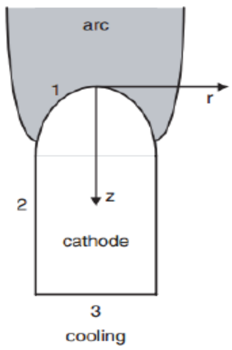
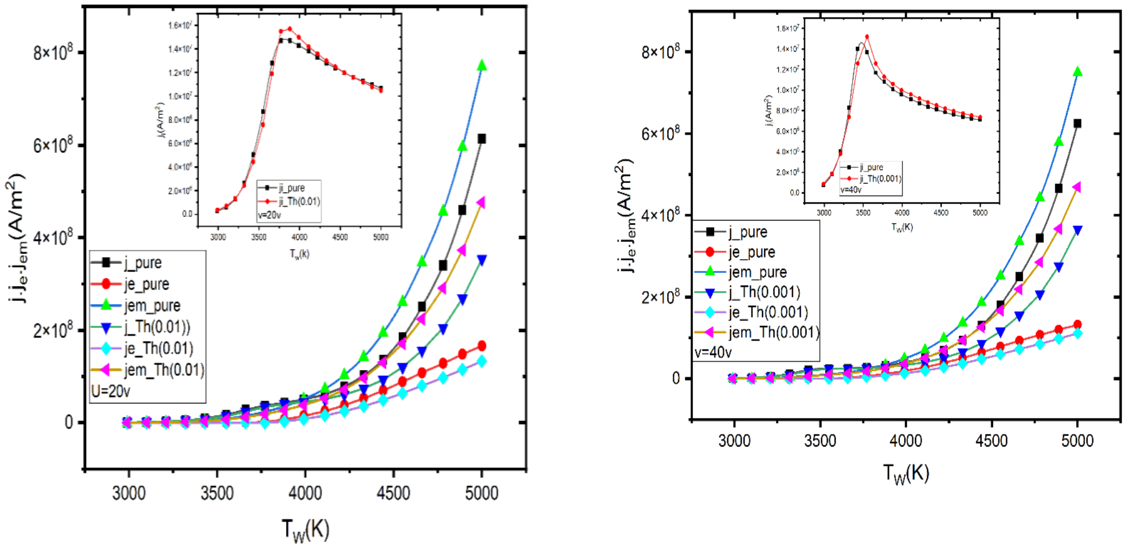


Figure 1: High-pressure arc plasma heating system for heat-resistant cathodes [4].

3. Results and discussion:

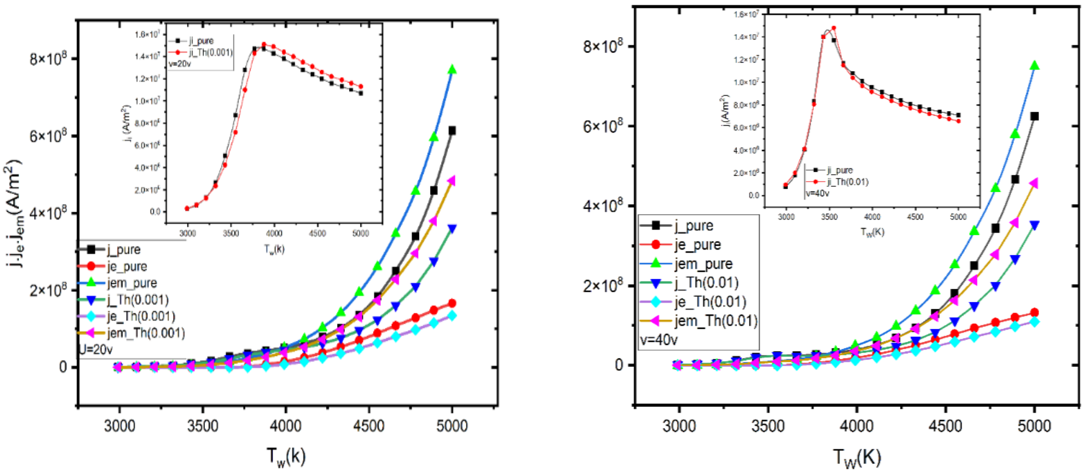
Current density

j, j_i, j_e, and j_{em}, were calculated using pure xenon and xenon–thallium gas mixture at different thallium concentrations (0.001, 0.01, and 0.1 mol.), as shown in Figures 2, 3, and 4. It was observed that at low temperatures (3000-3700 K), the current densities, j, j_i, j_e, and j_{em}, were relatively low. This is attributed to the fact that electrons do not possess sufficient energy to initiate ionization processes. However, as the temperature increased (3700-5000 K), electrons gained sufficient energy to induce ionization, resulting in a noticeable rise in current density values. These values were higher when using pure xenon compared to the mixture (xenon-thallium). This is because the ionization energy of thallium is reduced compared to xenon, thus reducing the density of high-energy ions in the plasma, resulting in a lower value of (j_i). Additionally, the presence of thallium lowers the overall temperature of the plasma, thereby reducing the electron density (n_e) and weakening the thermal emissions (j_{em}). Thallium also increases the dispersion of electrons and reduces their kinetic energy, leading to a decrease in the density of different currents. As for the effect of the potential difference, the values of (j_i and j_e) at a potential difference of 20 V were higher compared to 40 V, this is due to the fact that the plasma is more stable at a low voltage 20 V, which allows for a balanced generation of electrons and ions, and thus increasing the density of the currents in return. The plasma current density (j) and cathode electron emission current density (j_{em}) increased with an increase in voltage from 20 V to 40 V, and this increase improves both ionization and electron emission through thermal, electrical and field mechanisms. At high voltage 40 V, there was a variation in plasma density and turbulence that led to a reduction in electrical conductivity and current density. These factors contribute to reducing current density at high voltage. As for the effect of thallium on (j, j_i, j_e and j_{em}), the current density decreased with increasing thallium concentration in the xenon-thallium mixture due to the decrease in the efficiency of ionization processes [7].



(a) (b)

Figure 2: Current density j, j_e, j_i and j_{em} vs. cathode temperature for pure xenon and xenon–thallium gas mixture at 0.001mol thallium concentration at (a): U=20 V and (b): U= 40 V.



(a) (b)

Figure 3: Current density j, j_e, j_i and j_{em} vs. cathode temperature for pure xenon and xenon–thallium gas mixture at 0.01mol thallium concentration at (a): U=20 V and (b): U= 40 V

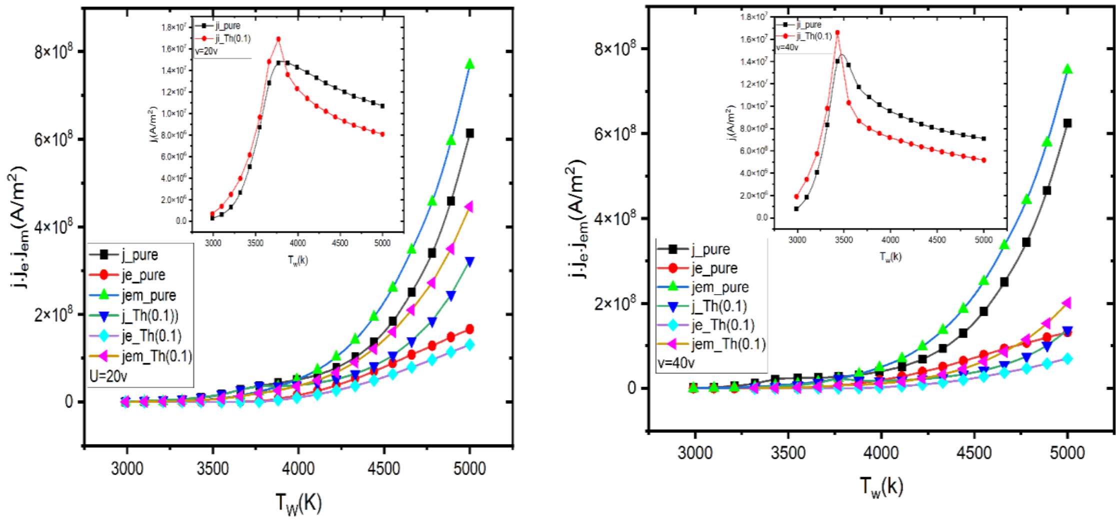


Figure 4: Current density $j, j_e, j_i$and j_{em} vs. cathode temperature for pure xenon and xenon–thallium gas mixture at 0.1mol thallium concentration at (a): U=20 V and (b): U= 40 V

4. Energy Flux Density

Figures (5) and (6) show the changes in electron energy flux (q_e) and emitted electron energy flux (q_{em}) with the cathode surface temperature (T_w) using pure xenon and xenon–thallium gas mixture at different thallium concentrations (0.001, 0.01, and 0.1 mol.) at two applied voltages of 20 V and 40 V. The study revealed that pure xenon has significantly higher qe values than the xenon-thallium mixture, even at low thallium concentrations (0.001, 0.01 and 0.1 mol.). Xenon's high ionization energy and heavy noble gas properties enable electrons to retain higher energy levels within plasma. It undergoes numerous elastic and inelastic collisions with free electrons, enhancing the electron heating process and increasing electron energy density [14]. Thallium significantly absorbs electron energy when added to xenon plasma due to its low excitation and ionization energies. Atoms are excited and return to their ground state by emitting electromagnetic radiation, reducing energy transfer from electrons to the cathode surface and decreasing q_e. As thallium concentration increased, radiative emission became more prominent, resulting in less electron kinetic energy retention. qe decreased when thallium was introduced into plasma, as additional electron energy, particularly at higher voltages, was redistributed among energy loss mechanisms, such as excitation, ionization, and radiation. The energy available for thermionic or secondary electron emission processes was limited. In pure xenon, the difference in (q_{em}) between 20 V and 40 V was small, suggesting that high voltage leads to more frequent collisions but does not significantly increase emitted electron energy flux, as much energy is consumed in other inelastic processes [14].

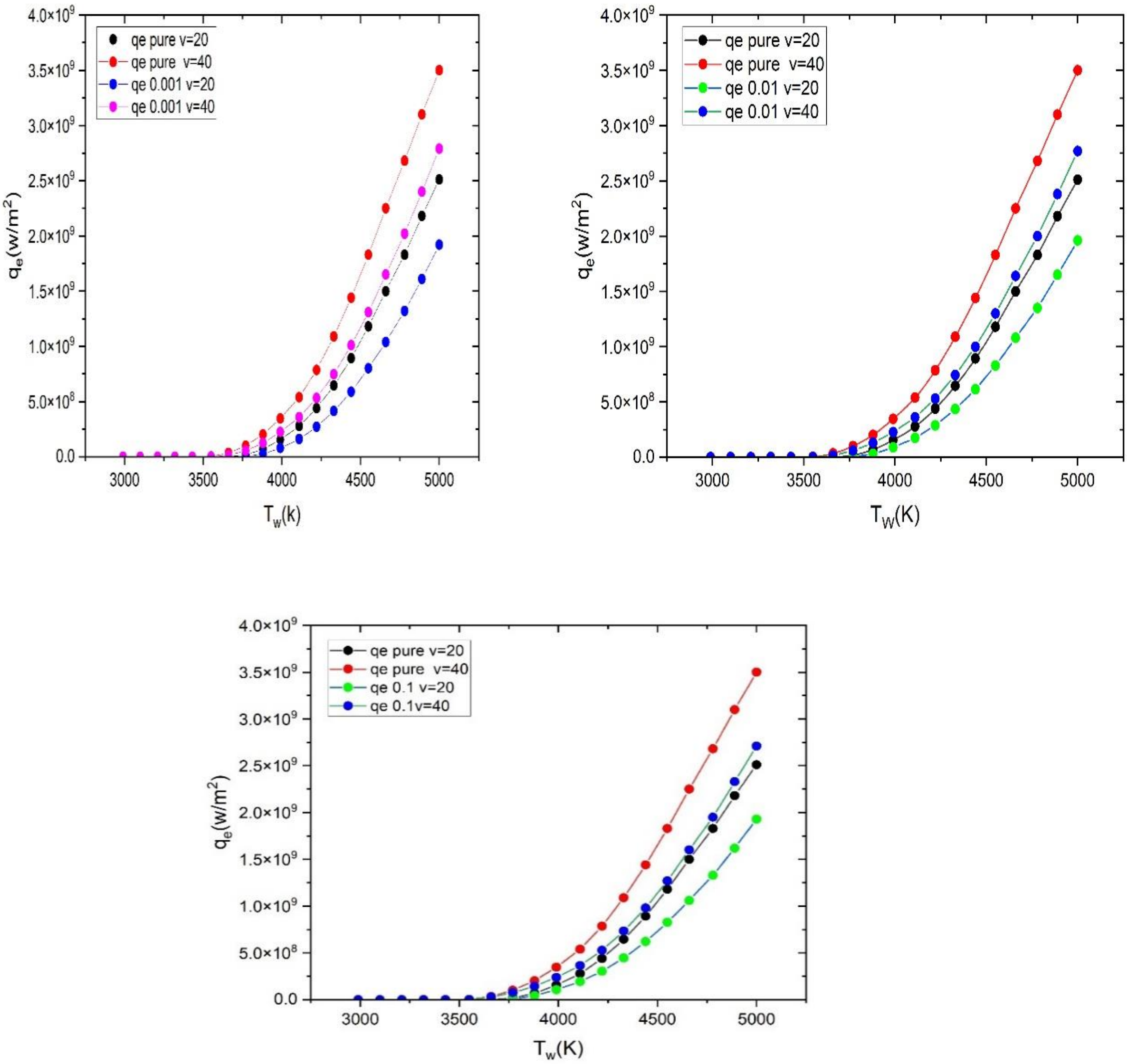


Figure 5: The electron energy flux (q_e) using pure xenon and xenon–thallium gas mixture at thallium concentrations of (0.001, 0.01 and 0.1 mol.) vs. the cathode surface temperature T_w at U= 20 V and 40V.

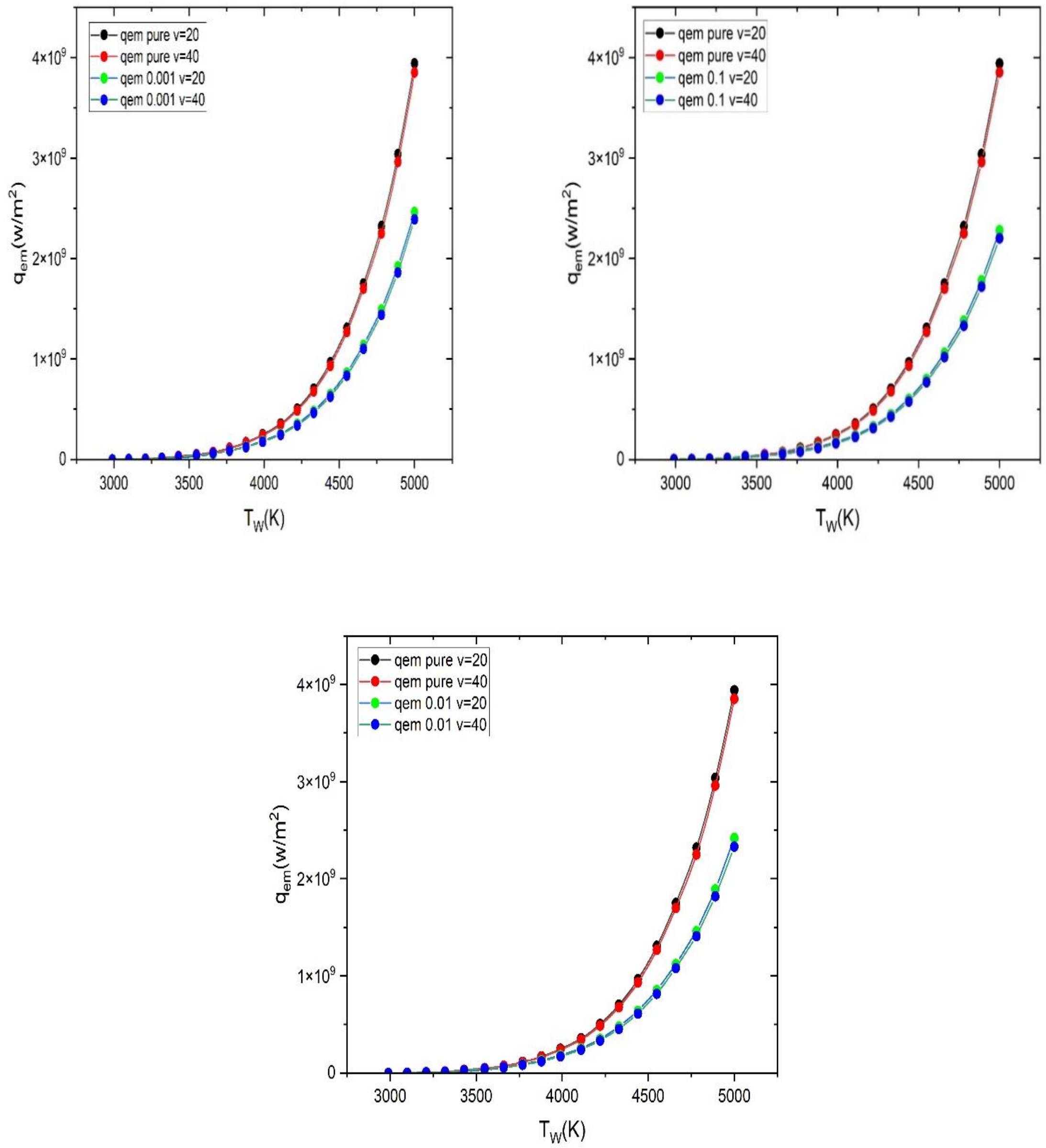


Figure 6: The electron energy emitted from cathode surface (q_{em}) using pure xenon and xenon–thallium gas mixture at thallium concentrations of (0.001, 0.01 and 0.1 mol.) vs. the cathode surface temperature T_w at U= 20 V and 40 V.

5. Electron Temperature

Figure (7) shows the relationship between electron temperatures (T_e) calculated using Equation (3) and cathode temperature (T_w) for both pure xenon and xenon-thallium mixture at different thallium concentrations of (0.5, 0.1, 0.05, 0.01, 0.005, and 0.001 mol.). It was observed that the effect of cathode temperature became more pronounced with increasing thallium concentration. This is because high thallium concentration enhances the effect of cathode temperature by increasing the thermal interactions and changes within the plasma, making the relationship between electron temperature and cathode temperature more pronounced [19]. The voltage barrier also plays an important role in this effect; the produced voltage increase from 20 V to 40 V strengthened the relationship between cathode temperature and electron temperature. As the applied voltage increased, the electrons gained more energy as they accelerated, which increased their temperature. This temperature increase significantly enhanced the efficiency of the arc discharge process.

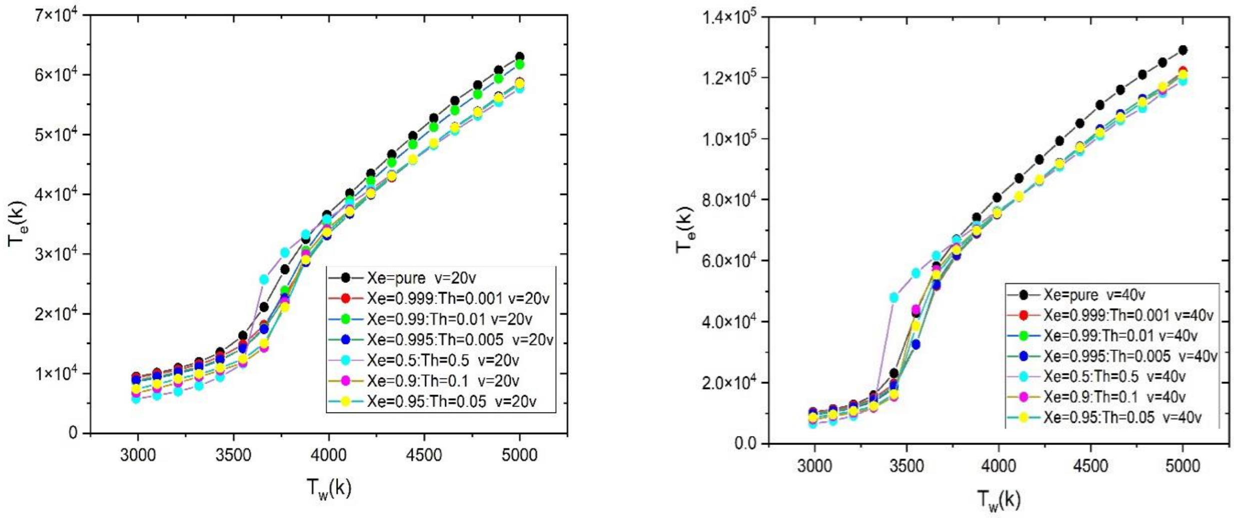


Figure 7: The relationship between electron temperature (T_e) and cathode temperature (T_w) using pure xenon and xenon–thallium gas mixture at thallium concentrations of (0.5, 0.1, 0.05, 0.01, 0.005, and 0.001 mol.) at U= 20 V and 40 V..

6. Conclusions

This work found that increasing the cathode surface temperature significantly improved electron and ion flow in all tested conditions, including pure xenon and xenon mixed with varying thallium concentrations of 0.001, 0.01, and 0.1 mol. This thermal enhancement led to a notable increase in plasma number density due to increased ionization and excitation processes. Its presence influenced the thermal behaviour of the arc discharge system by enhancing radiative emission and improving plasma efficiency, particularly with an increase in thallium concentration. The electrical characteristics of the current densities, including (j, j_i, j_e, and j_{em}), consistently increased with rising cathode surface temperature due to enhanced ionization processes triggered by elevated thermal energy, and the inclusion of thallium reducing the ionization energy threshold. The increase in discharge voltage from 20 V to 40 V, combined with higher cathode temperatures, led to more significant physical phenomena like elastic and inelastic collisions, excitation, ionization, and high-energy electron emission, resulting in a rise in electron temperature and plasma activity. When the cathode surface temperature is below 3500 K, electrons cannot gain sufficient energy for ionization and excitation processes. However, when the temperature exceeded 3500 K, current densities, ion energy, electron energy, and energy transferred to the cathode surface increased. Higher temperatures enable plasma particles to acquire sufficient thermal energy for excitation and ionization, enhancing the overall energy exchange and efficiency of the arc discharge system.

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