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Using Schottky Arc-plasma for Modelling the Cathode Temperatures of Various Materials at High Pressure

Zainab Majeed Mohamed, Rafid Abbas Ali *
Department of physics, College science, Mustansiriyah University Baghdad, Iraq

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Abstract

Theoretical investigation for cathodes of different metals, including hafnium (Hf), niobium (Nb), tungsten (W), and molybdenum (Mo) were used. It was noticed that the plasma energy at the cathode (Hf) has a higher value than that at the cathode metal because the energy losses of electrons for (Hf) are less due to inelastic collisions. As for the energy of electrons, their value for the metal (Hf) is also higher than of the other metals, and the reason is that the energy is proportional to the temperature according to the equation: (E = 3/2 KT). It was also noted that the energy of ions for all metals is almost equal at temperature (Tw≅4000K) due to energy losses due to elastic and inelastic collisions, this leads to a state of saturation. There is a large decrease in the voltage barrier accompanied by an increase in the current density, differences occur in the values of the voltage barrier due to the difference in the work function which varies according to the metal.

Keywords: Arc discharge, Current flux density, Energy flux density, Voltage barrier, Electron temperature

استخدام بلازما القوس لشوتكي لنمذجة درجات الحرارة الكاثود لمعادن مختلفة عند الضغوط العالية

زينب مجيد محمد, رافد عباس علي*
قسم الفيزياء, كلية العلوم, الجامعة المستنصرية, بغداد, العراق

الخلاصة

تمت دراسة كيفية تأثير الجهد ودرجة حرارة سطح الكاثود على كثافة تدفق الطاقة. تم استخدام كاثودات مختلفة مثل الهافنيوم (Hf) والنيوبيوم (Nb) والتنغستن (W) والموليبدينوم (Mo). لاحظنا أن طاقة البلازما عند (Hf) لها قيمة أعلى من المعادن الأخرى لأن فقدان الطاقة لمعدن (Hf) أقل من المعادن الأخرى بسبب الاصطدامات غير المرنة. أما بالنسبة لطاقة الإلكترونات ، فإن قيمة المعدن (Hf) أعلى أيضًا من المعادن الأخرى ، والسبب في ذلك أن الطاقة تتناسب طرديًا مع درجة الحرارة وفقًا للمعادلة التالية (E = 3 / 2 KT) ، ونلاحظ أن طاقة الأيونات لجميع المعادن تكاد تكون متساوية عند قيمة درجة الحرارة (Tw≅4000K). بسبب فقدان الطاقة نتيجة التصادمات المرنة وغير المرنة التي تحدث هذه القيمة . بالنسبة لتأثير درجة حرارة الإلكترونات على حاجز الجهد ، نلاحظ عندما يكون هناك انخفاض كبير في حاجز الجهد تزداد كثافة التيار ، ومع وجود حاجز عالي الجهد عند درجات الحرارة المرتفعة نتيجة الاصطدامات بين الإلكترونات ، وهذا يؤدي إلى حالة من التشبع. فضلًا عن الفروق التي حدثت في قيم حاجز الجهد بسبب الاختلاف في دالة الشغل والتي تختلف باختلاف المعدن.

*Email: rafidphy_1972@uomustansiriyah.edu.iq

1. Introduction

Plasma can easily be generated via gas discharge. Arc discharges are created when an electric current passes through a gas, creating an electric field. Gas discharge plasma is formed where the electric current is present[1][2]. Typical examples of gas discharge include flare and arc discharge in a cylindrical tube exposed to a constant electric field. The difference between a glow and an arc discharge is how electrons are created near the cathode[3][4]. A glow discharge occurs when the cathode emits electrons as secondary electrons as ions hit the cathode. Electrons are due to thermal emission mechanisms and spontaneous electron emission on the cathode during an arc discharge[5][6]. In 2018, Choquet et al. checked modeling assumptions, emphasizing important yet unexplored modeling issues[7]. While in 2020, Golubovskii et al. explained the fundamental differences between helium contraction and the contraction of other inert gases (argon and neon)[8]. In 2022, Saifutdinov et al. described the electrodes for two-dimensional geometry and gas discharge gap[9].

The model used in this paper is based on non-linear surface heating. It is used to simulate the interaction between high-pressure arc plasma and thermal cathode metals under pre-determined conditions, including temperature, pressure, the distance between the electrodes, radius, and cathode quality. Also the included model of the near-cathode plasma layer investigates how the cathode temperature is affected by the different metals of the cathode. The cathode metals investigated were hafnium (Hf), niobium (Nb), tungsten (W), and molybdenum (Mo). Argon gas, with an electrode spacing of r=0.01m and a cathode diameter of D=0.001, was used to accomplish this and under a pressure of 1 bar.

2. Theoretical part:

The thermal cathode is used in high-pressure arc discharge. It is made up of two regions: first region is current-collecting part of the cathode surface, which warms the arc plasma by high pressure arc discharge and is connected to the arc plasma and collects electricity through the arc discharge, the second region is that which is in contact with the cold gas and may exchange heat with the gas or lose energy by radiation. It is well known that the cathode material's thermal conductivity *(k)* depends on temperature($k = k(T)$). It is necessary to distinguish between the first region, the surface of the cathode, associated with the plasma arc and the gas connected to the second region. The thin plasma layer near the cathode collects energy flux density generated by the plasma arc on its surface. Both the voltage drop (U) and cathode surface temperature (T_w) in this layer affect the one-dimensional current that is transferred through it. In this study, the relationship between temperature (T_w) and voltage (U) on the modulus of the plasma layer close to the cathode (the density of the current flux, as well as the energy transfer from the plasma to the cathode surface) was examined. At each point of the surface current, the surface layer near the cathode has a low voltage across it. When the cathode's surface temperature T_w changes, similarly does the radiation lost from the surface area in contact with the gas or the cathode's exchange temperature[10].

The first and second portions' current flux density (j) and energy flux density (q) is described by equations (1) and (2):

$$q = q(T_w, u) \text{ when } (T_w \geq Tc). \quad (1)$$

$$j = j(T_w, u) \text{ when } (T_w \geq \text{Tc}). \quad (2)$$

The cathode body's surface temperature distribution can be determined using the cathode body's thermal conductivity which is represented by the equation in $q(T_w, u)$ function[11]:

$$\nabla \cdot (\kappa \nabla T) = 0 \quad (3)$$

$$\kappa \frac{\partial T}{\partial n} = q(T_w, U) \quad (4)$$

Where; k is Boltzmann's constant, T_w is the temperature of cathode, Tc is the temperature of the base of the cathode, U is the near-cathode voltage drop and n is a direction locally orthogonal to the cathode surface and directed outside the cathode.
Under boundary conditions, the cathode surface's portion designated as both the arc plasma and the cold gas are in touch with n [12]:

$$T = T_c \quad (5)$$

Where Tc: Temperature of the base of the cathode
The plasma is close to the cathode layer, which comprises the area where currents gather on the surface and the area where the energy flow is created (both the ionization layer and the charge sheath that are close to the cathode's surface). The ions that are produced near the ionization layer heat the surface with the fast plasma electrons and pass through the cathode's surface. Then, they are accelerated and heated by the ions. There are no ion collisions in the space charge shell[13]:

$$q_p = q_i + q_e - q_{em} \quad (6)$$

Where
q_p: The density of the plasma's energy flux.
q_e: Plasma electrons' energy flow density.
Energy flux density from electron emission is known as:q_{em}.
q_i: The density of ion energy flux.
The following relations can be used to express the energy flux in Equation (1) [14]:

$$q_i = j_i[z_e U_D + E - ZA_{eff} + k(2T_h + ZT_e/2 - 2T_w)] \quad (7)$$

$$q_e = j_e(2kT_e + A_{eff}) \quad (8)$$

$$q_{em} = j_{em}(2kT_w + A_{eff}) \quad (9)$$

Where: U is the near-cathode voltage drop, E is the electric field, A_{eff} is the effective work function, $and\ T_h$ is the temperature of heavy particles
The following form can be used to express Equation (5)[15]:

$$q_i = j_i(ZeU_D + E - ZA_{eff}) + w_i + [j_i k\left(2T_h + \frac{ZT_e}{2}\right) - (j_i 2kT_w + w_i)] \quad (10)$$

Where:
Z: The average charge number of ions
e: Charge of electron
j_e: Plasma electron current density.
j_{em}: The density of electrons emitted from the cathode surface at any given time.
j_i: The ion current density
T_h And T_e represent the temperatures of heavy particles (non-charged atoms and ions) and temperatures of electrons, respectively, E: ionization energy, w_i: work of the electric field and the low voltage in the space charge envelope is given by the constant U_D.
The last part on the right-hand side should be eliminated from equation (10) and this equation assumes the form[16]:

$$q_i = j_i(z_e U_D + E - ZA_{eff}) + w_i \quad (11)$$

The balance of the electron energy product in the ionization energy is given by the following:

$$j_e\left(\frac{2kTe}{2} + U_D\right) + 3.2j\frac{kTe}{e} + j_i E = j_{em}\left(\frac{2kTw}{e} + U_D\right) + w_e \quad (12)$$

The density of the net electric current from the surface of cathode to the plasma is seen in Equation (13) [17]:

$$j = j_i + j_{em} - j_e \quad (13)$$

The energy flow from the plasma to the cathode surface is given by the following equation:

$$q_p = ju - \frac{j}{e}(A_{eff} + 3.2kT_e) \tag{14}$$

Which represents the difference between the electrical energy of photons and the electrical energy of electron deposition per unit area at the cathode layer and the current from this layer to the majority of the plasma. By causing a potential difference on both sides of the junction, the barrier voltage prevents more electrons from entering to fill the gaps and struggle to get past the barrier. The following equation gives the voltage barrier's height[18]:

$$\phi_B = kT/q \ln\left(\frac{A^*T^2}{J_s}\right) \tag{15}$$

Where: k is Boltzmann constant, T is the temperature, and J_s is the saturation current density.

3. Results and discussion:

Figure (1) shows that the density of the plasma's energy flux. (q_p) for the cathode made up of (Hf) is higher than that of the other cathode metals and it is obtained at temperatures (T_w) lower than that needed for the other cathode metals. The plasma energy values (q_p) of the cathode made up of (Nb) are higher than those for cathodes made of (W) and (Mo), because energy (E) is directly proportional to temperature (T_w) according to the equation ($E = \frac{3}{2}KT$). As the temperature increases, the kinetic energy of electrons increases. At temperatures beyond 3500 K, a decrease in the plasma energy was observed due to the collisions between electrons resulting in the loss of energy.

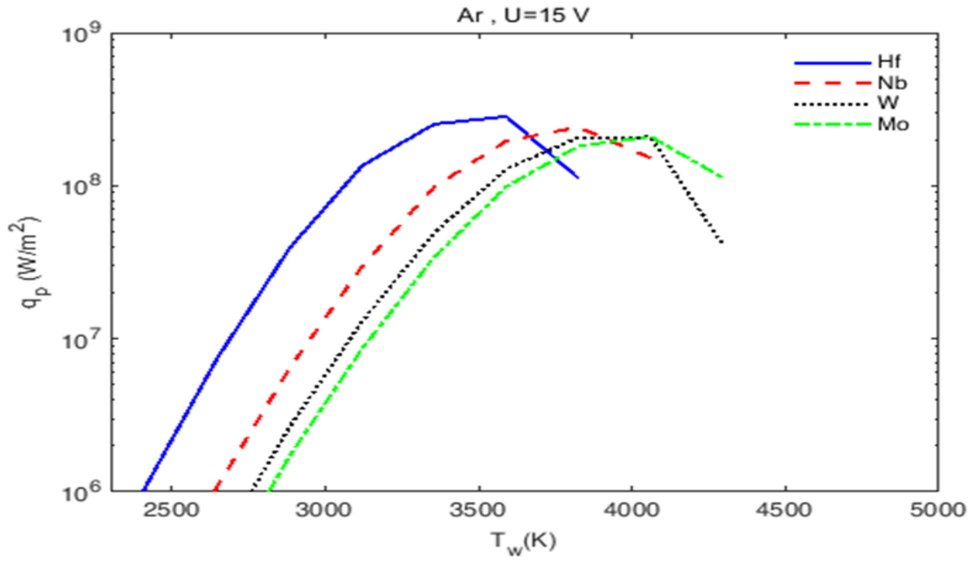

Figure 1: Plasma energy vs. cathode surface temperature

Figure (2) shows the relation between the electron energy (q_e) and the cathode surface temperature. It can be noted that the cathode metal (Hf) has a greater electron energy (q_e) value than the other metals. The electron energy (q_e) of the cathode metal (Nb) is higher than that of the metal (W) and the electron energy of this metal (W) is higher than (Mo). The reason for this is that energy is proportional to temperature according to the equation ($E = \frac{3}{2}KT$) because increase of electrons kinetic energy. In the temperature range of (4000-5000 K), the energy of the electrons of the four elements is in a stable state (saturated state).

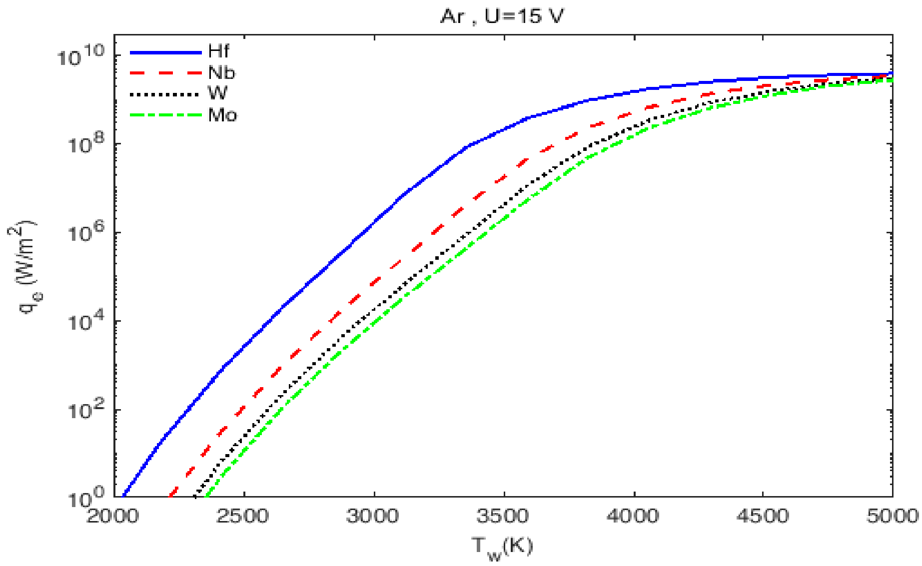

Figure 2: Energy of electrons (q_e) vs. cathode surface temperature

Figure 3 shows that the cathode metal (Hf) emits electrons with an energy that is higher than that of the electrons emitted by the other metals. This is because the energy lost by the electrons in collisions with (Hf) is lower than that of the collisions in the other metals due to elastic and inelastic forces.

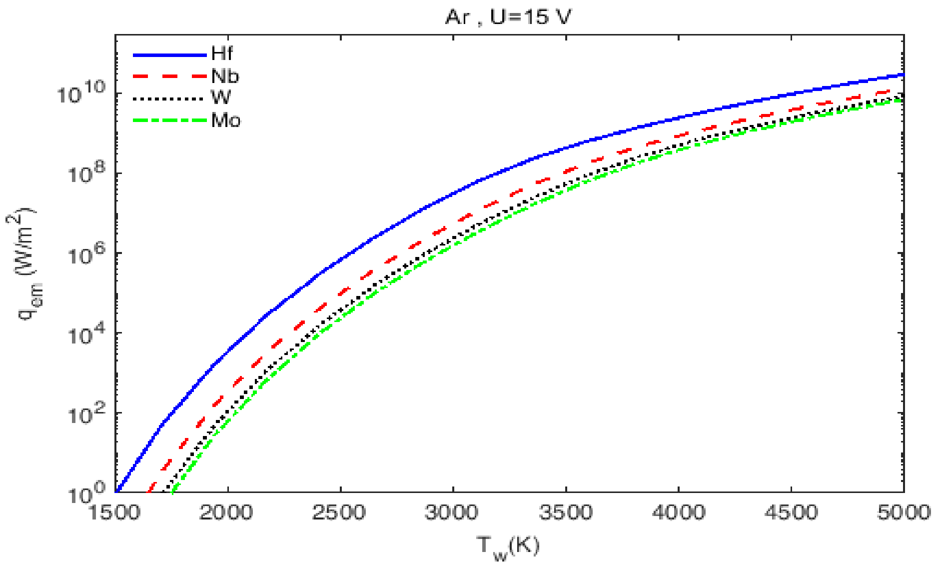

Figure 3: Energy of the emitted electrons vs. cathode surface temperature

Figure (4) shows that the energy of the ions for all cathode metals is approximately the same at (4000 K), the collision-induced energy loss is the cause of this occurrence. In the temperature range of 4000 K and above, where the ionic energy of the four elements is in a steady state (saturated state).

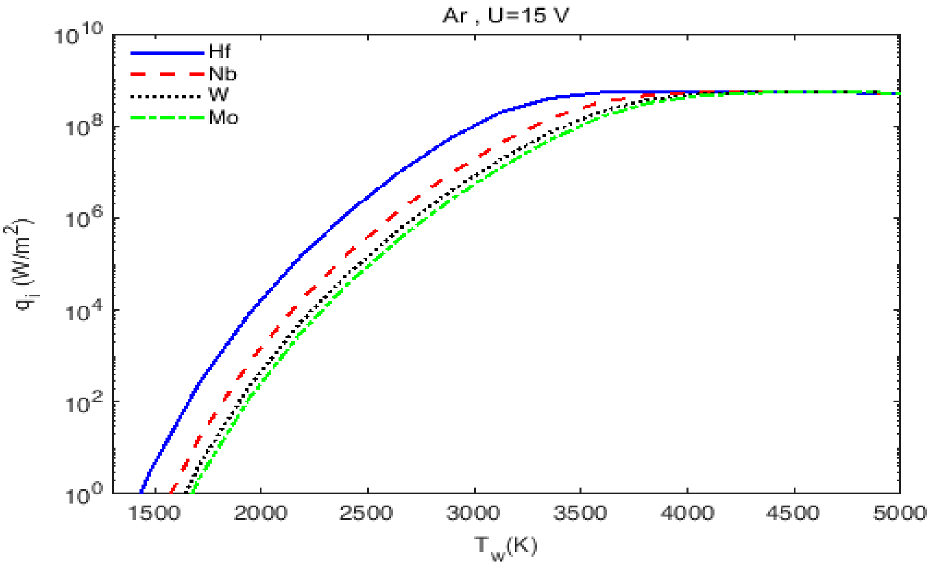

Figure 4: Energy of the ions vs. cathode surface temperature

Figure (5) shows how the different cathode metals and the electrons temperature affect the voltage barrier and the current density of the plasma. It is noted that the effect of the electrons' temperature on the current density is almost the same for all metals. The current density values increases gradually at low electrons temperature. The effect of the electrons' temperature is stabilized at temperatures of $(0.8 \times 10^4 K)$ and above. The reason for this is the increase of collisions between electrons at high temperatures as well as the different work functions of the different metals. As for the effect of temperature on the voltage barrier, note that the voltage barrier starts to increase sharply and the current density increases gradually. The reason for this is the collision of electrons. At high temperatures, saturation of the current density will occur due to the processes of ionization and recombination.

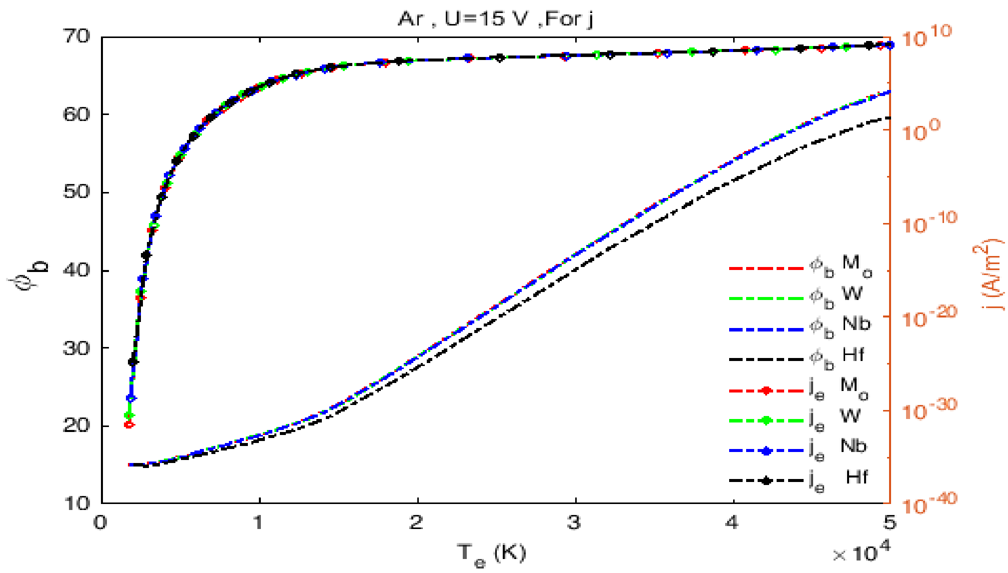

Figure 5: Voltage barrier and the current density of plasma vs. temperature of electrons

According to the metal of the cathode, Figure (6) depicts how the temperature of the electrons affects the voltage barrier and the current density of the electrons. It was noted that the effect of the electrons' temperature on the voltage barrier and the current density is almost equal for all metals. The current density values increased sharply at low electrons' temperature, then at temperatures of $(0.9 \times 10^4 K)$ and above the effect was stabilized; this is due to the increase in collisions between electrons at high temperatures and different work functions of metals. As for the effect of temperature on the voltage barrier, it was noted as the voltage barrier increases significantly, after temperature $Te > 1.5 \times 10^4\ K$ it becomes constant, and the current density increases, while the increase in the voltage barrier at high temperatures leads to saturation of the electron current density due to ionization and recombination processes.

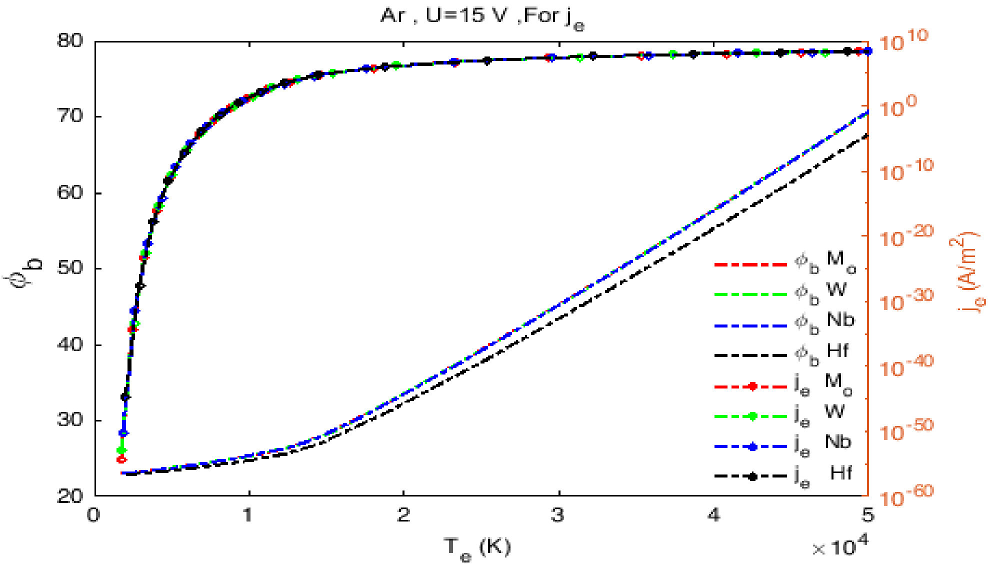

Figure 6: Voltage barrier that affects the current density of plasma vs. electrons' temperature.

Figure (7) shows, for the different cathode metals, how the electrons' temperature affects the voltage barrier and the current density of the electrons emitted from the cathode surface. It was noticed that at a temperature of less than 1 K, the effect of the electrons' temperature on the voltage barrier and the current density is almost equal for all metals. The current density increases rapidly when the $Te < 1.5 \times 10^4\ K.$ The reason for this is the increase in collisions between electrons at high temperatures as well as different work function of metals. Regarding the voltage barrier's relationship to the electrons' temperature, it was observed that the voltage barrier increases sharply while the current density increases gradually due to electron collisions increase. As a result, the current density of the upstream electrons eventually reaches saturation.

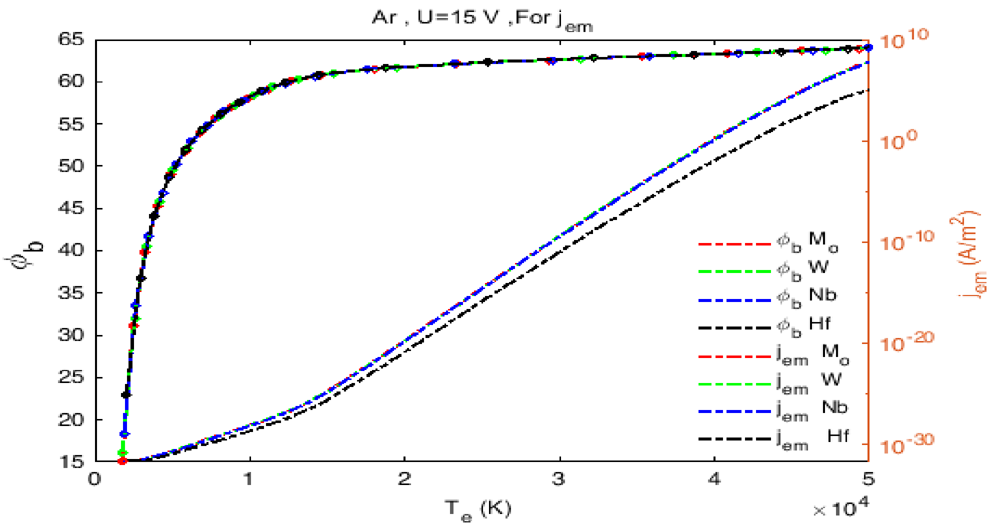

Figure 7: Voltage barrier and emitted electrons current from cathode surface vs. electrons' temperature.

From Figure (8), the effect of the electrons' temperature on the voltage barrier and the current density of ions according to the types of metals is studied. The effect of the electrons' temperature on the voltage barrier and the current density of ions is almost equal for all metals. The current density of the ions increased sharply at low electrons temperatures, then the effect of the electrons' temperature stabilized at the temperature of (1.5×10^4 K) and above; this is due to the increase in collisions between electrons at high temperatures as well as the different work functions of the different metals. Also a high voltage barrier at high temperatures was observed as a result of the collision between electrons; this led to a state of saturation of the current density of ions.

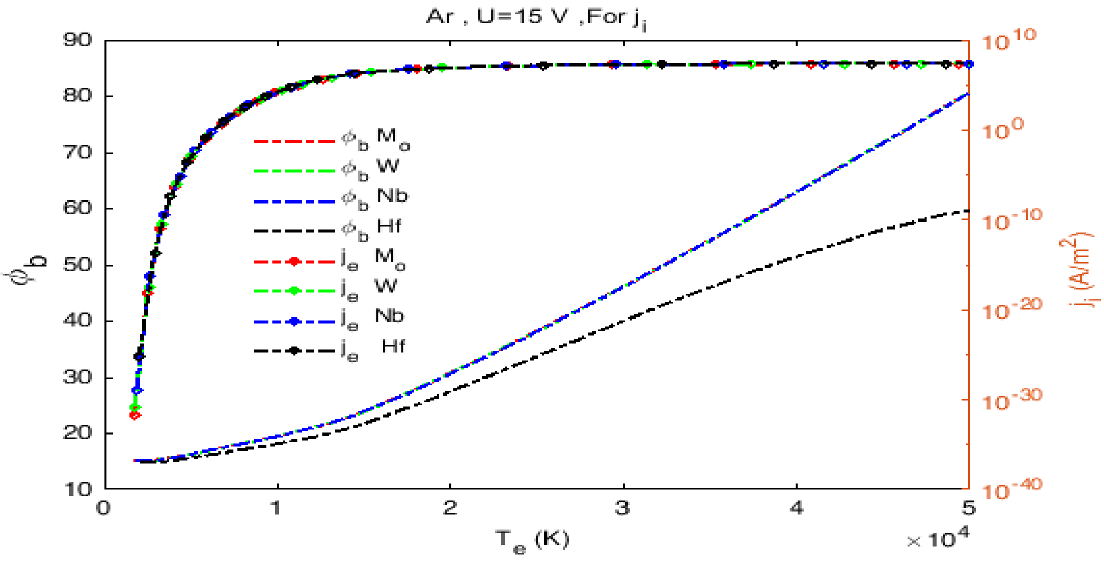

Figure 8: Voltage barrier and current density of ions vs. electrons' temperature.

4. Conclusions:

The energy loss of electrons for the cathode metal (Hf) is less than that of other metals due to elastic and inelastic collisions, and the energies (q_p, q_i, q_e and q_{em}) of metal (Hf) are higher than that of the other metals used, because the energy is proportional to the temperature according to relationship $E = \frac{3}{2}KT$, which led to the conclusion that metal (Hf) has a higher plasma energy than the other metals.

Regarding how the temperature of the electrons affects the voltage barrier, it was observed that the observed stability in the voltage barrier was accompanied by a rise in the current density. As a result of collisions between electrons.

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