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Comparative Study on Electron Beam Characteristics of a Thermionic Electron Gun for Different Shapes of Wehnelt Cup

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Abstract

This research paper presents a comparative study on the effect of the geometric design of a thermionic electron gun on the quality of the electron beam. Although several studies have been conducted on the thermionic electron gun design. However, the effect of the geometry of the Wehnelt electrode on the performance of the electron gun needs to be investigated through accurate and comparative analysis. Simulations were performed to test three different shapes of Wehnelt electrodes and their effect on electron gun performance behavior of the electron gun in which the characteristics of electron beams for different designs were analyzed with the aid of computer aided simulations. The results showed that the conical shape is the most efficient, producing low emittance (ε) and a small crossover diameter (R) of the electron beam. Based on these results, the performance of the electron gun can be improved by selecting an appropriate shape for the Wehnelt electrode, which produces high-quality electron beams.

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1. Introduction

Electron guns are essential components in many electronic devices, scientific instruments, and industrial facilities. Advancements in the design of electron guns are critical to improving electron beam control. The well-designed electron gun determines the quality of the electron beam in terms of efficient electron emission and precise focusing [1]. The Wehnelt cup is one of the main parts of the thermionic electron gun, acting as a converging electrostatic lens, it's importance lies in the ability to control the characteristics of an electron beam at its beginning by controlling the distribution of the electric field while reducing secondary emissions. The shape of the Wehnelt cap is an influential factor in determining the behavior of the electron beam..Although its effect on the kinetic energy of electrons is minimal [2,3]. Recent studies were focused on obtaining a highly efficient electron beam through using different cathode materials and different Wehnelt cup configurations [4]. In the electron microscope, the parameters of an electron beam depend on the electron gun [5]. In recent times, the importance of the electron gun has surged in wide applications such as accelerators, computer monitors and many scientific studies [6]. This reduction in the emittance value is influenced by the electrode geometry, which ensures the generated electron beam with the highest laminar flow [7]. In addition, one of the components that help the electron gun is magnetic or electrostatic electron lenses, which works to direct and focus the electron beam [8]. The electron gun consists of several parts, and the quality of the electronic beam can be controlled by changing the design of these parts according to the requirements of the designer and the type of use [9]. The electron beam source must be carefully and expertly designed, in addition to the initial operating conditions of the electron beam [10]. A significant challenge in electron gun design technology is to reduce electron beam emittance [11,12]. It is worth noting that emittance is defined as the area within phase space that contains the particles [13]. Particle dynamics obey a conservation law of phase space called Liouville's theorem. Liouville's theorem describes the motions of the particles under the influence of an external magnetic field or in a general field, in particular, states that volumes in phase space are invariant [14]. The flexibility provided by numerical simulations by CAD programs in making the required modifications to geometric shapes has made them a fundamental pillar of engineering innovation, as confirmed by recent studies [15]. This article performed the design and simulation of the electron gun by studying the effect of different Wehnelt cup shapes on its performance and focusing on optimizing the geometry and dimensions of the Wehnelt cup to achieve an electron beam with low emittance and high brightness. The characteristics of an electron gun were investigated for three different designs using the SIMION 8.0 program [16]. Several designs for electron guns were studied to perform this simulation. Three different shapes were made for the Wehnelt cup geometry. In addition, a study of the electron gun characteristics was carried out for three Wehnelt cup shapes under two cases, the first involved changing the distance d between the Wehnelt cup and the anode electrode, and the second involved changing the outer diameter r_2 of the anode electrode. The results were analyzed for both cases independently, with a comparison to illustrate their effect on the electron gun performance.

2. Optimization

The electron gun simulation has been performed using a personal computer running SIMION 8.0 software, a program specialized in simulating ion optics and particle paths. This program was used to calculate the electric field, potential distribution, equipotential lines, and trajectory of charged particles. Furthermore, the LUA code was used to search for the optimum electron beam emittance and electron beam diameter; the computations were made for three different shapes of the Wehnelt cup. The computations were achieved for two cases, the first by changing the distance between the anode electrode and the Wehnelt cup for each shape of the Wehnelt cup, and the second by changing the outer diameter of the anode electrode for each shape of the Wehnelt cup too. In the present calculations, the electron gun is designed to produce electrons at different exit angles but with similar energy ranges. For more clarification, the emitting electron beam from the cathode is generated (using the SIMION8.0 program), depending on the elevation angle, using 21 electrons. Similarly, the beam current value is maintained constant for all the computations and is equal to $(1 \times 10^{-12}$ A). The cathode material for thermionic emission is tungsten (of work function equal to 4.5 eV and of melting point 3410 °C). The cathode filament must be heated to a temperature of roughly 2500 °C [17]. The electron beam is formed and accelerated using the applied voltages given in Table 1. These values were selected based on common criteria in the simulation of electron guns to ensure that the results are realistic and comparable.

3. Geometry

The simulation of designing an electron gun was started by defining the components of the electron gun which include three shapes of the Wehnelt cup; flat, hemispherical and conical. An optimal design of the Wehnelt cup configuration ensures the efficiency of the electron gun. The simulation geometry of electron gun electrodes was designed using the SIMION 8.0 program. The anode electrode has a conventional disc shape. Figure 1 shows the Three-dimensional plot of the three different final designs of the electron gun. It is worth noting that a comparative analysis of these three shapes determines the best electron gun design. In this article, the comparisons between three different geometric shapes of the Wehnelt cup with the same geometrical dimensions and the same operating conditions are made for each of them.

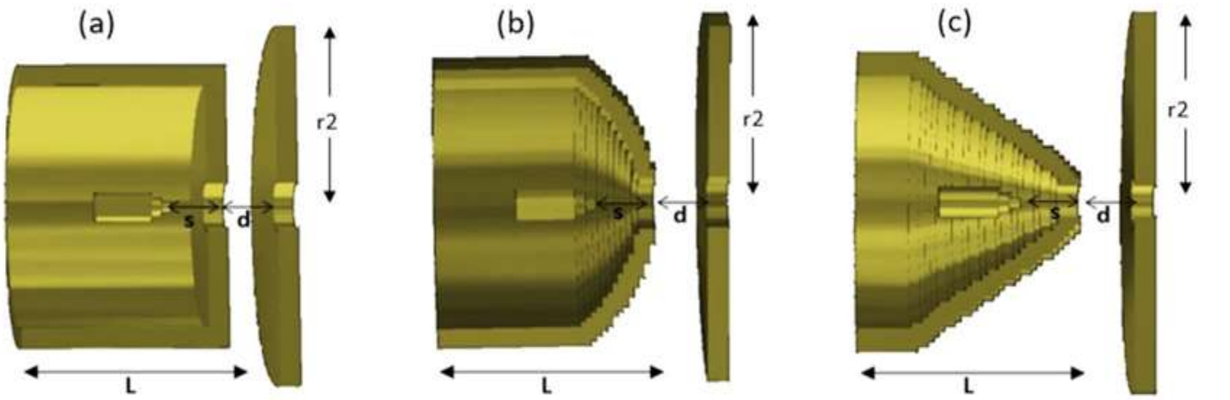


Figure 1. Three-dimensional plot of the three electron gun designs for different Wehnelt cup shapes: (a) flat, (b) hemispherical and (c) conical.

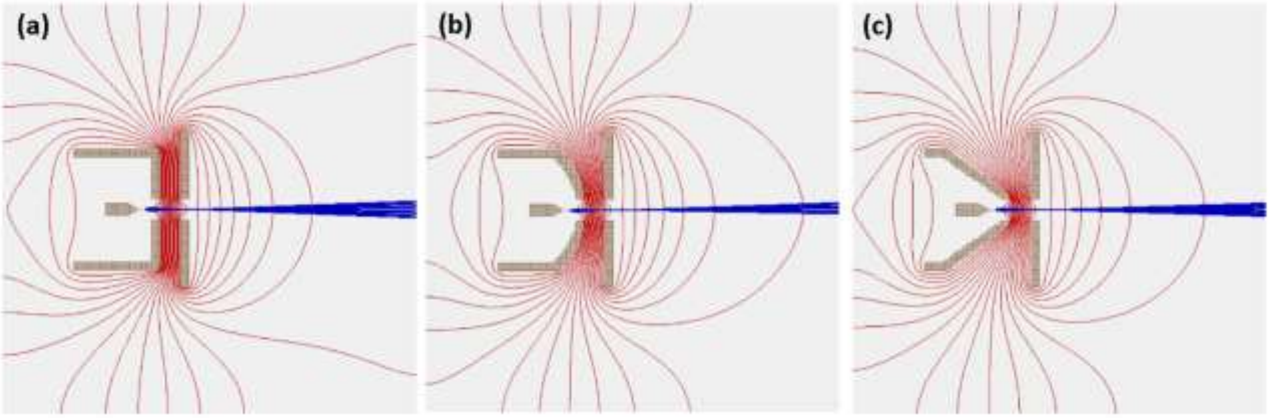


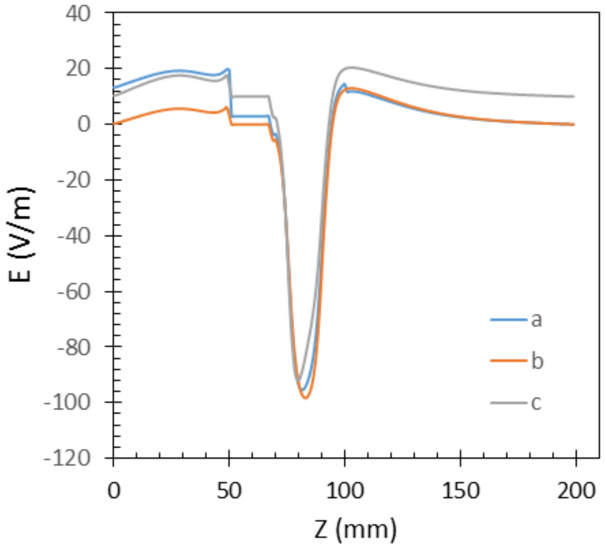
Figure 2. Comparison of variation of the equipotential lines contours and electron beam trajectories of the three electron gun designs with different shapes of Wehnelt cup: (a) flat, (b) hemispherical and (c) conical.

Table 1. Fixed parameter values of an electron gun geometry.

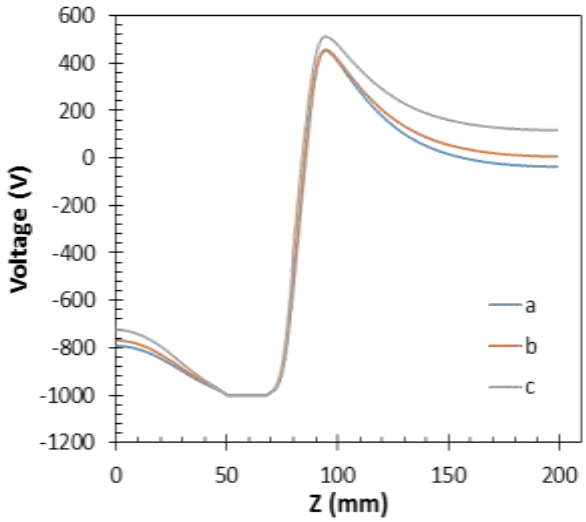
Parameter	Value
Cathode-Wehnelt spacing (S)	5 mm
Inner Radius of the Wehnelt (rw)	2 mm
Inner Radius of anode (r1)	4 mm
Thickness of Wehnelt (t1)	5 mm
Thickness of anode (t2)	5 mm
Length of Wehnelt (L)	20 mm
Cathode and Wehnelt Voltage	-120 V
Anode voltage	1000 V

4. Results and Discussion

The systematic procedures for the optimal design of the electron gun were implemented by selecting three different shapes of the Wehnelt cup, including the flat, hemispherical and conical, with the same dimensions and operating conditions. The geometrical parameters dimensions and the applied voltage value on the electrodes of the electron gun are listed in Table 1. In an electron gun, the configuration of equipotential lines is affected by the potential difference between the electrodes of the electron gun, as well as their geometry. Figure 2 illustrates the distribution of equipotential lines and electron beam trajectory for three different shapes of the Wehnelt cup at a constant value for both the distance between the Wehnelt cup and anode electrode, which was chosen equal to d=12mm as well as the value of the outer radius of the anode r_2 = 28 mm. Moreover, the figure illustrates that the equipotential lines are densely packed and highly concentrated between the Wehnelt cup and the anode electrodes. This indicates the strength of the electric field in this region, which is necessary to ensure effective acceleration of electrons and increase the concentration of the electron beam. Furthermore, one can notice from Figure 2 that the electron beam generated by an electron gun with a conical Wehnelt cup shape is more collimated and focused.



(a)



(b)

Figure 3. The variation of the: (a) electric field E(V/m) and (b) axial potential distributions V(volts) for three different shapes of Wehnelt cup at constant d=12mm.

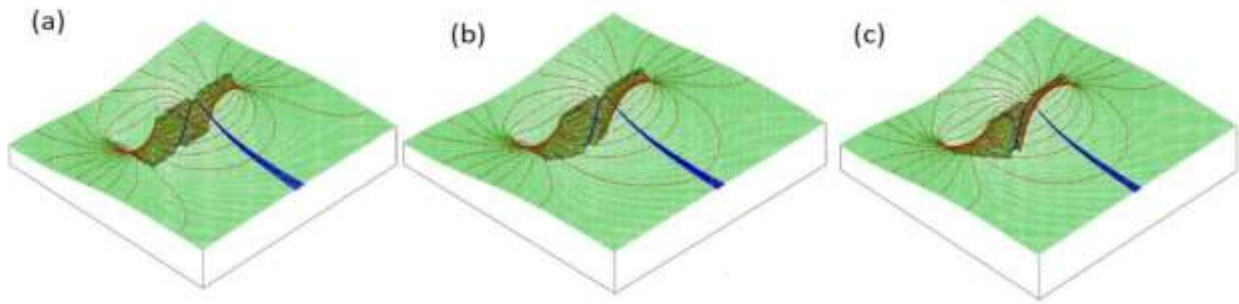


Figure 4. The potential array in 3D view of the equipotential lines and the trajectory of the electron beam for three shapes of the Wehnelt cup (a) flat, (b) hemispherical and (c) conical.

The distribution of electric potential V (in volts) and the axial electric field E(V/m) for three different shapes of Wehnelt cup are calculated and illustrated in Figure 3. Consequently, the calculations were performed with a fixed distance of d = 12 mm between the Wehnelt cup and the anode electrode for all three shapes, with the outer radius of the anode set to r_2 = 28 mm. The figure also illustrates that both the electric field and the axial potential decrease to nearly zero in the region behind the anode, which is part of a common design strategy aimed at enhancing the efficiency of the electron gun. Despite the general similarity in the shapes shown in Figure 4, which is attributed to the geometric symmetry of the three electron gun designs and the same operating conditions. However there are small differences in the intensity of the fields centered around the electron gun electrodes. These small differences lead to clear differences in the quality and stability of the electronic beam.

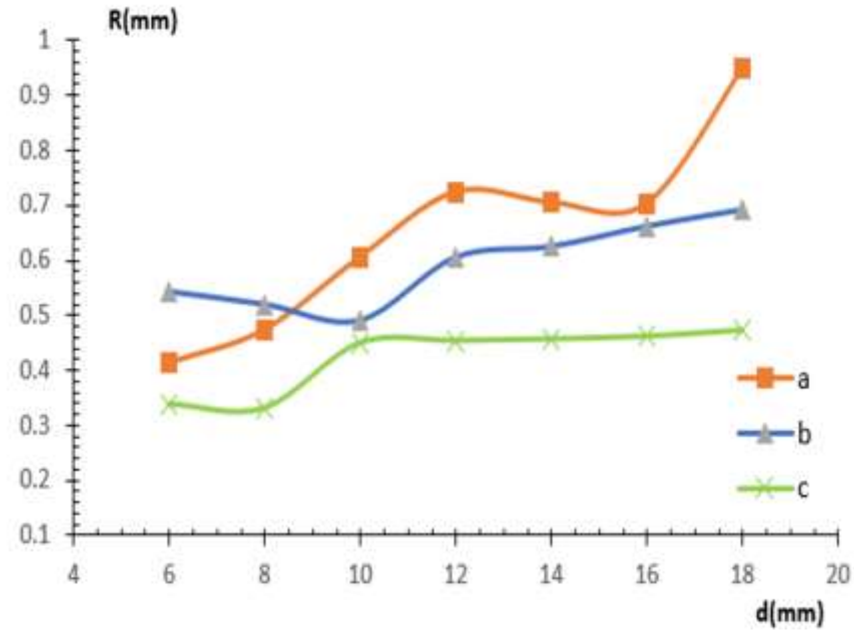


Figure 5. Variation of the crossover diameter values of the electron beam with the distance d for three different shapes of the Wehnelt cup.

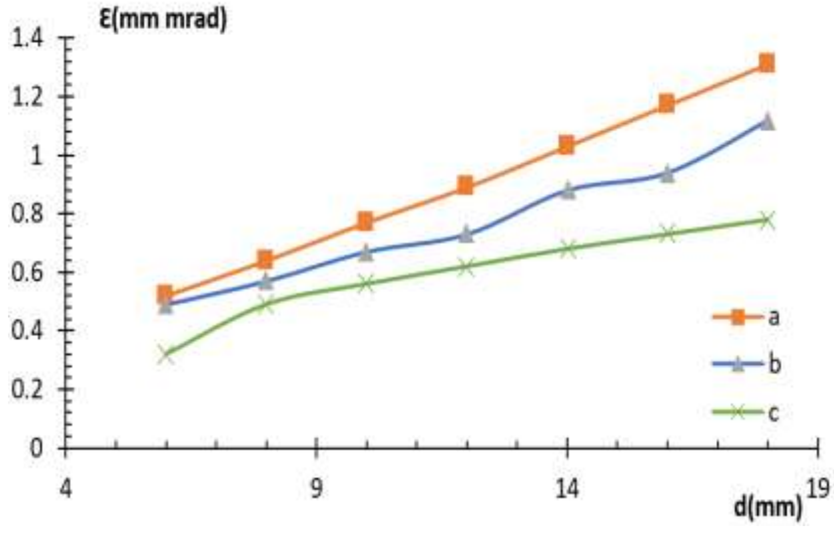


Figure 6. Variation of the emittance values of the electron beam with the distance d for three different shapes of the Wehnelt cup.

The comparison of the dependence of the crossover diameter of an electron beam on the Wehnelt cup shape is shown in figure 5. These comparisons specifically considered the effect of variation values of d which was chosen equal to (6,8,10,12,14,16 and 18 mm) with a constant value of the outer radius of the anode r_2 = 28 mm. The results show that as the distance d between the Wehnelt cup and the anode electrode decreases, the crossover diameter of the electron beam decreases as well, because the electric field increases, accelerating more electrons and reducing the spacing between them. The results show that the conical Wehnelt cup shape produces a small crossover diameter of the electron beam as compared with the other shapes. Figure 6 shows the comparison of the effect of the Wehnelt cup shapes on the emittance value of the electron beam. The comparison happened with the impact of variation of the value of the d, which was chosen equals to (6,8,10,12,14,16 and 18) and at a constant value of the outer radius of the anode electrode r_2 = 28 mm. The calculations show that the values of the beam emittance improve as the value of the distance d decreases. For more clarification, the smaller the distance between the Wehnelt cup and the anode electrode, the greater control of the electrons passing from the Wehnelt cup into the anode electrode and minimizing dispersion, which is due to the strength of the electric field between the electrodes. The conclusions are as follows, First, choosing the optimal shape for the Wehnelt cup can enhance the gun's efficiency, and second, improving the performance of the electron gun in precision applications while keeping the geometrical dimension of the electron gun unchanged.

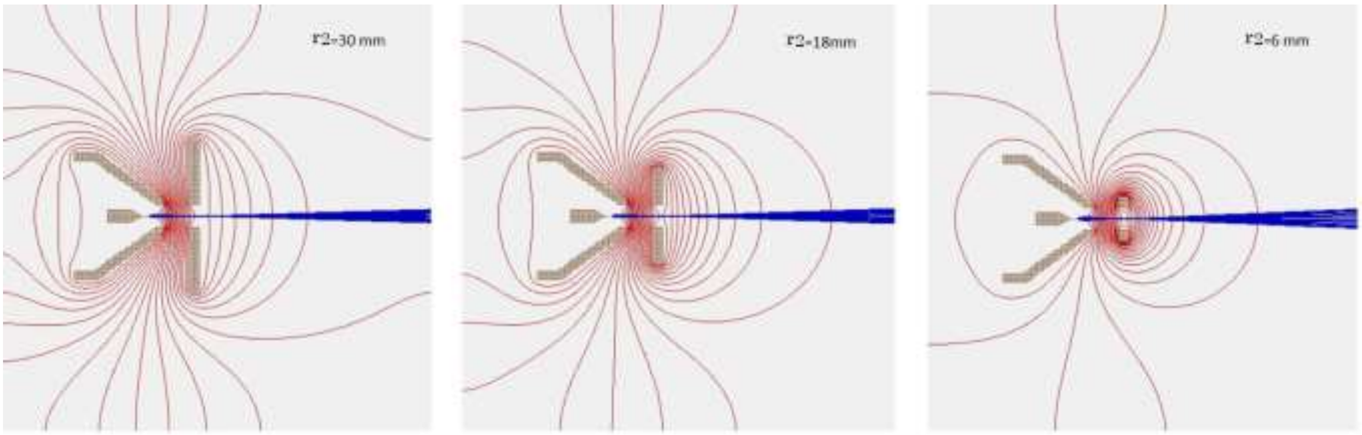


Figure 7. Comparison of variation of the equipotential lines contours and electron beam trajectories for the conical shape of the Wehnelt cup for different values of r_2 at a constant value of d=12mm.

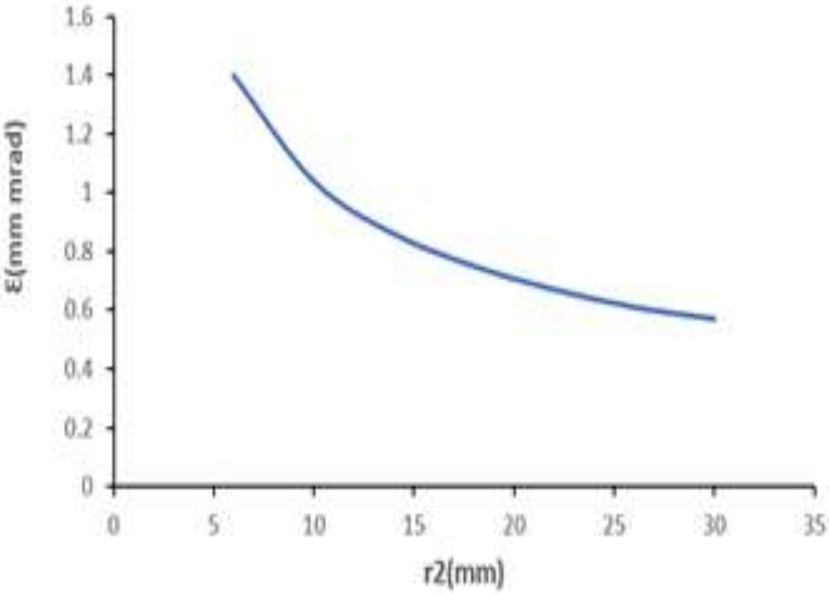


Figure 8. Variation of the emittance of the electron beam for different values of r_2 of the conical shape of the Wehnelt cup.

Figure 7 illustrates the distribution of equipotential lines and electron beam of the conical shape of the Wehnelt cup at different values of the outer radius of the anode r_2, which was chosen equal to (6, 18 and 30 mm) with a constant value of d=12mm. Figure 7 also shows the importance of equipotential lines, the principles behind their formation and their relationship to the path of the electronic beam.

Moreover, this figure shows that the potential distribution between the electrodes is well balanced and the potential is not concentrated on one of the electrodes, which reduces the risk of damage to the electronic parts and increases the efficiency of the electron gun. Figure 8, presents a comparison of the dependence of electron beam emittance on the Wehnelt cup shape, alongside the effects resulting from variations in the anode outer radius r_2. The comparison occurred with the variation of the value of r_2, which was chosen equal to (6,10,14,18,22,26 and 30mm) and a constant value of the distance between Wehnelt cup and anode electrode, d = 12 mm. Obviously, there is an inverse proportion between the outer diameter of the anode and the emittance. This indicates that a longer anode creates a more extended and stable electric field along the electron beam path, as a result, it reduces abrupt changes in the field lines, enhances electron alignment, minimizes angular scattering, improves beam focusing, and decreases irregular acceleration. In other words, increasing the outer diameter of the anode contributes to better control of the electron beam, leading to a more uniform and lower-emittance output. The results obtained in this study fall within the acceptable limits for thermal electron gun designs, as compared to the values adopted in the scientific literatures, in which the emittance values range from 0.1-10 mm mrad, and the radius of the electron beam in simple acceleration systems is from 10 to 100 µm or more. In the present study, the calculated values of the emittance ranged between 0.2-1.4 mm mrad, and the radius of the electronic beam ranged between 0.3-0.9 mm, which are within the acceptable range in the approved thermal models. These results enhance the reliability and efficiency of the model used in this study, with the simulation results showed that the conical shape of the Wehnelt cup gives better results compared to other shapes in terms of beam concentration and emittance reduction. To date, no previous studies have compared the different forms of the Wehnelt cup in the electron gun and this highlights the importance of current research as it fills an important research gap in scientific studies that can be considered in future studies.

5. Conclusion

This work is characterized by its simultaneous study of two basic parameters. The geometry of the Wehnelt electrode and the distance between the electrodes using a comparative simulation. Relatively it was found that the shape of the Wehnelt cup is an important factor for improving the performance of the electron gun, by controlling how the electric field lines are distributed, which affects the behavior of the electron beam in terms of direction and stability. The electron gun designed with a conical shape of the Wehnelt cup produces a beam with lower emittance, compared with the flat and hemispherical shapes, as well as when reducing the distance d between it and the anode electrode. More specifically, when the distance decreases, the effect of the electric field on the electron beam increases, which reduces the dispersion and spacing of the electron beam. This is beneficial for the final shape of the electron gun which will be relatively smaller. Conclusively, the effects of the space charge or the properties of the cathode material were not taken into account in this work. Future studies could include experimental verification of simulation results, study of space charge interactions, and the effect of different cathode materials on beam properties.

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