

Jordan Journal of Physics

ARTICLE

The Influence of Electrode Angle on the Minimization of the Aberration Coefficients of the Two Electrodes Electrostatic Immersion Lens

M.A. Al-Khashab and A.A. Ahmad

Physics Department, College of Science, Mosul University, Mosul, Iraq.

Received on: 30/4/2011; Accepted on: 26/2/2012

Abstract: This paper deals with the electron optical properties of a set of asymmetrical electrostatic immersion lenses with two electrodes which have been designed using different angles (θ) of the outer lens electrodes as well as air gaps (S) between the electrodes of each lens. It was found that the angle of the outer electrode and the air gap have a clear effect on the electron optical performance of such lenses. In addition to that, it was noticed that the better electron optical properties occurred when the angle of the outer electrode equals ($\theta = 0^\circ$) and the air gap equals ($S = 11$ mm). The results of the preferable design of the present work were compared with those in published papers in terms of the optical properties. It was found that the results are in good agreement with each other.

Keywords: Asymmetrical electrostatic immersion lens; Angle of the outer electrode; Air gap.

Introduction

A wide variety of electrostatic lenses has been used for focusing charged particles [1, 2]. The appearance and physical properties of lenses which were previously designed for different applications are totally different in geometrical shape. It is difficult to develop a general optimal lens design for all applications. A systematic investigation on a suitable lens is possible only if we are able to identify the most characteristic parameters and investigate their influence on the optical properties of different lenses. It is also evident that one can only hope to find such simple geometrical parameters in terms of the axial potential distribution [3].

Two-element electrostatic lenses have been used in low energy electron spectrometers in order to increase sensitivity and resolution [4]. Coaxial cylinder electrostatic lenses are mainly used for accelerating or decelerating the electron or ion beams. Firestein and Vine gave in 1963 useful design criteria for overlapping two cylindrical lenses [5]. This configuration gives the least spherical aberration in which the

cylinder at high potential has the smallest diameter. Details of the optical properties for several types of two-element coaxial cylinder electrostatic lenses were found in many references such as [3, 6]. It is well known that a two-element lens system cannot keep the image position constant while varying the ratio of final to initial electron energy. Details of the properties of several types of electrostatic lenses can be found in [7]. The focal properties of multi-electrode electrostatic lenses have been obtained by [8] using electrostatic immersion lenses and by [9] using unipotential electrostatic lenses. Moreover, (Abd-Hujazie, 2006), (Frosien et al., 2009), (Al-Jumayli, 2010), (Al-Khashab and Hujazie, 2010) and (Al-Khashab and Hujazie, 2011) [10-14] used two electrodes electrostatic immersion lenses for different geometry and distance between two electrodes.

The imaging properties of electrostatic lenses and their aberration are less well known. The properties of the lens approximation have been much less systematically studied, partly because

of premature loss of interest in electrostatic optics. Electrostatic lenses are difficult to characterize. Even for a simple lens, there are several geometrical parameters involved (thickness of electrodes, electrode air gap distances and diameters and the electrode shapes) that affect the potential distribution. For the above reasons, the production of the universal curves for the electrostatic lenses is not of similar manner like the universal curves of magnetic lenses [15]. The final design would usually be based on trial and error, different electrode geometries and voltages are tried until acceptable results are achieved.

The aim of this paper is to achieve an improved design for the electrostatic immersion lens suitable for an objective lens. The work tackles the influence of the outer electrode angle as well as the influence of the electrodes air gap on the performance of these lenses which have been investigated under the same optical conditions.

The Consideration of Asymmetrical Electrostatic Lens Design

Intensive studies on asymmetrical electrostatic immersion lenses have been carried out on a family of identical lenses which are designed to consist of two coaxial electrodes overlapping each other. The inner electrode I(in) is in the form of a cylinder, while the outer electrode II(out) is in the form of a conical shape. The studies have been carried out through two principal parts:

In the first part, a set of the asymmetrical electrostatic lenses are designed with a constant

geometry of the inner electrode while different angles of the outer electrode have been changed to find the preferred lens design.

In the second part, the effect of the air gap between the two electrodes on the electron optical properties has been studied for the lenses which possess a preferred design of outer electrode angle obtained from the former part.

The cross-section of the lens geometry and the design parameters are shown in Fig. 1. The lens model is asymmetrical in shape; namely (two coaxial cylinders) and consists of two electrodes in the form of an overlapping system. Therefore, the geometry of the inner electrode I(in) in the form of a cylinder remains constant, and the outer electrode II(out) like a conical shape makes an angle θ with the horizontal direction. The air gap (S) between the electrodes is chosen to be (7mm).

The investigation has required extensive calculation based on several physical and mathematical concepts. The design work and calculation are accordingly handled with the aid of a personal computer, so that several computer programs are being employed in order to understand the behavior of electrostatic lens system. A technique for calculating the equipotential lines due to the effect of the outer electrode angle as well as the electrodes air gap on the electrostatic lens is also presented. Each shape is illustrated by a typical computer result on graphical screen. It should be born in mind that the optical properties of the lenses have been investigated under zero magnification conditions.

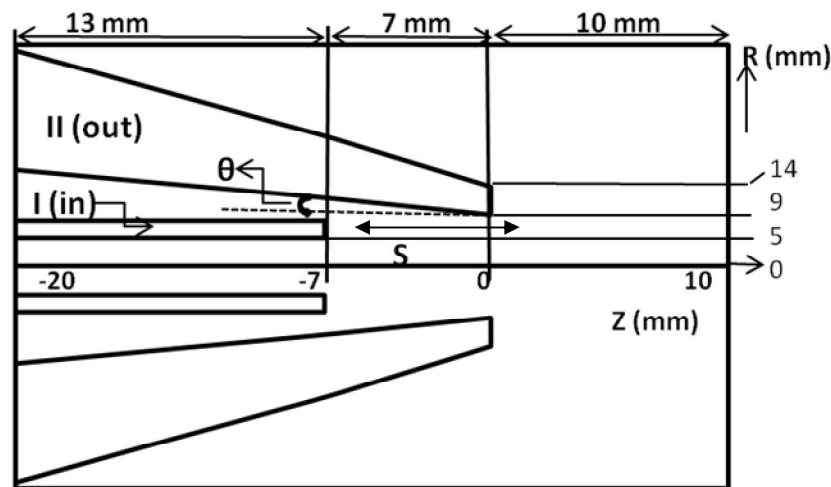


FIG. 1. Schematic diagram of the cross-section of the asymmetrical two-coaxial electrodes electrostatic lens design, showing the inner I(in) and outer II(out) electrodes.

The Effect of Outer Electrode Angle Design

In order to investigate the effect of the outer electrode angle on the two-electrode electrostatic lens designed, the inner electrode represented by $I_{(in)}$ was chosen of a constant geometry at a voltage of ($V_{I(in)} = 8000$ V). However, the outer electrode like a conical shape represented by $II_{(out)}$ was chosen with different angles θ ($0^\circ - 40^\circ$) and at a constant voltage of ($V_{II(out)} = 100$ V). These lenses have been studied under zero magnification conditions.

In order to investigate the performance of the electrostatic lens with the variation of the outer electrode angle, five configurations of the lens model of an identical geometry are chosen. Different angles in the range ($0^\circ - 40^\circ$) and a constant air gap which equals (7mm) were selected. The calculation of the properties of any electrostatic lens requires knowing the axial potential distribution V_z along the optical axis Z . The values of V_z for the electrostatic lenses are computed with the aid of program E11 [16], using the finite element method. The analysis is based on dividing the upper half of the cross-section for each of the lenses into quadrilateral areas so as to make the lens geometry correctly specified. The total number of the meshes was chosen to be constant for all lenses designed with a size which is equal to (15 radial x 20 axial). Fig. 2 shows the axial potential distribution V_z as a function of Z for the previous lenses of angles ($0^\circ - 40^\circ$), where the voltages of

the inner and outer electrodes equal ($V_{I(in)} = 8000$ V) and ($V_{II(out)} = 100$ V), respectively. Therefore, the region from ($Z = -20$ mm to -6 mm) is given in the above figure and is called a divergent region. In this region, the longitudinal component of the electric field accelerates the electrons. Thus, the diverging power diminishes as the divergence action lasts for a shorter time, while the region from ($Z = -2$ mm to 10 mm) is called a converging region. The longitudinal component of electric field retards the electrons, and the converging power increases. Consequently, the converging effect exceeds the diverging effect and the whole lens becomes convergent [17].

In order to demonstrate the performance of the previous lenses at different outer electrode angles, the trajectory ray $R(z)$ inside the lenses has been computed by program E21 [16] for calculating the optical properties of these lenses by solving the paraxial ray equation, using the fourth order-Runge-Kutta formula [18]. Figure 3 indicates the trajectories of the electrons inside the lenses at constant inner and outer electrode voltages as mentioned above and at a constant air gap ($S = 7$ mm). This figure shows that the lens that possesses the outer electrode of ($\theta = 0^\circ$) has acquired a minimum value of the working distance (W.D.) in the image plane at ($Z_i = 7.2$ mm), which in turn, gives an acceptable performance in comparison with other electrostatic lenses.

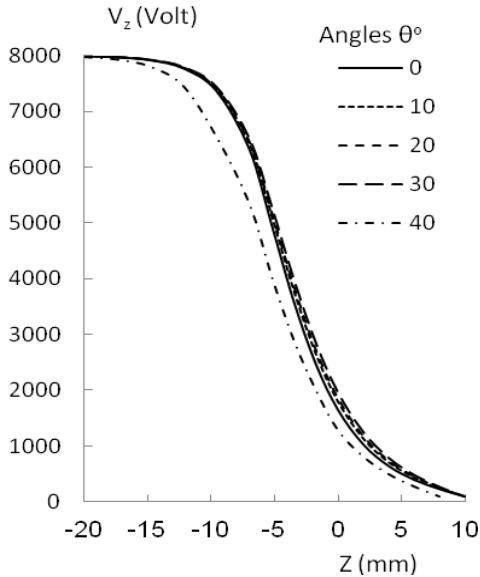


FIG. 2. The axial potential distribution of the electrostatic lenses of different angles (θ) at voltages $V_{I(in)}=8000$ and $V_{II(out)}=100$ V.

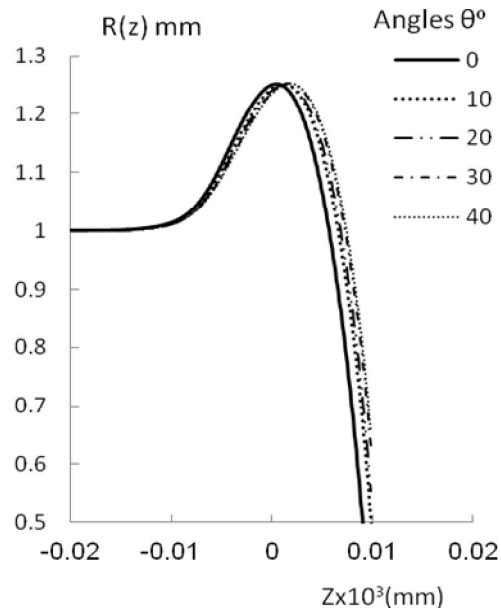


FIG. 3. The trajectories of the electrons inside the electrostatic lenses of different angles (θ) at constant voltages $V_{I(in)}=8000$ and $V_{II(out)}=100$ V.

In order to study the effect of the outer electrode angles $\theta(0^\circ - 40^\circ)$ on the above lenses, it is important to compute the equipotential lines of the electrons inside the structure of these lenses. The trajectory of equipotential lines of the electrons of the previous lenses has been calculated by using program E31 [16] and modified by [10]. Fig. 4 illustrates the trajectories of equipotential lines for the above lenses at constant mentioned conditions. It is noticed that the equipotential lines are more

converging toward the optical axis as in the lens of $(\theta = 0^\circ)$ compared to those in the other lenses whose equipotential lines are more diverging away from the optical axis. Therefore, the focusing of the electrons is displacing away from the specimen position. This behavior is important for reducing the beam voltage reaching the specimen surface. This is one of the important parameters to protect the specimen from damage.

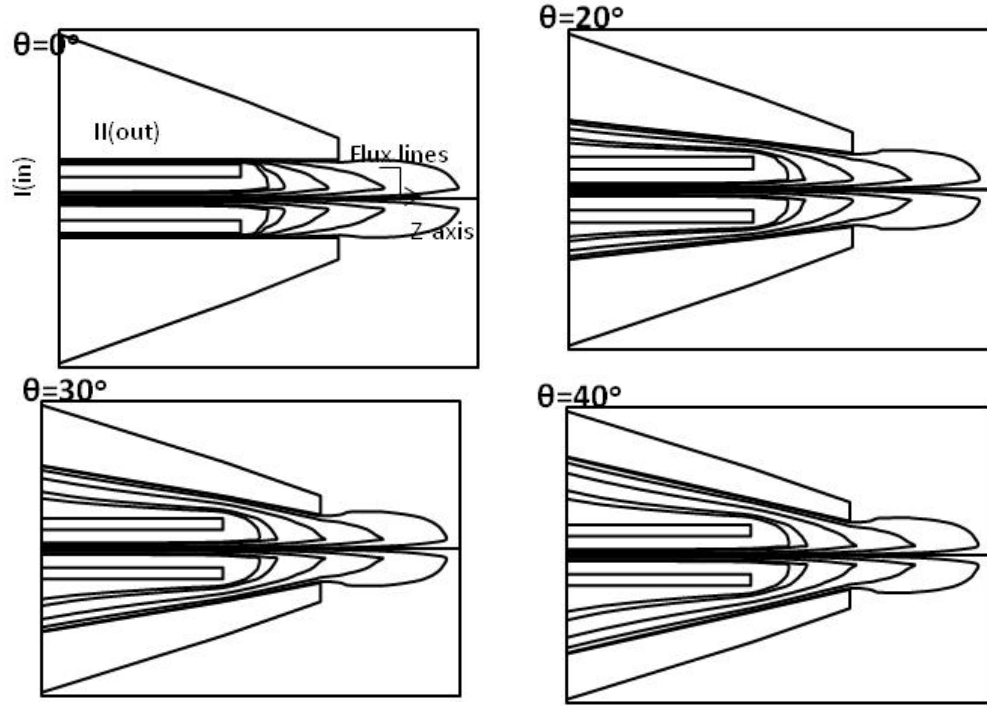


FIG. 4. The equipotential lines of the electrostatic lenses of different angles, at constant voltages ($V_{l(in)} = 8000$ V) and $V_{l(out)} = 100$ V). The air gap between the two electrodes ($S = 7$ mm).

Before a commitment is made as to which angle of the lenses is the most suitable, the objective focal properties must be investigated.

In order to evaluate the effect of outer electrode angle on the electron optical properties of the previous lenses, the objective focal properties have been calculated by program E21 [16].

The most important optical properties of an objective lens are: the objective focal length f_e , spherical and chromatic aberration coefficients C_s and C_c , respectively. When the relative aberration coefficients are considered, the results will be independent of any scaling factor. The variation of the relative spherical and chromatic

aberration coefficients (C_s/f_e , C_c/f_e) of the electrostatic lenses as a function of the outer electrode angle is shown in Fig. 5. It is noticeable that both curves are similar in shape and their values increase slowly with increasing the angle in the region where $\theta(0^\circ - 20^\circ)$, but the rate of the values increases a little bit more in the region where $\theta > 20^\circ$. It is clear from the above mentioned figure that the lenses of outer electrode angles $(\theta = 0^\circ)$ and $(\theta = 20^\circ)$ have relatively lower aberration coefficients than other lenses of higher angles. So, the above angles $(0^\circ, 20^\circ)$ can be regarded to present the best design adopted in the next part of the investigations.

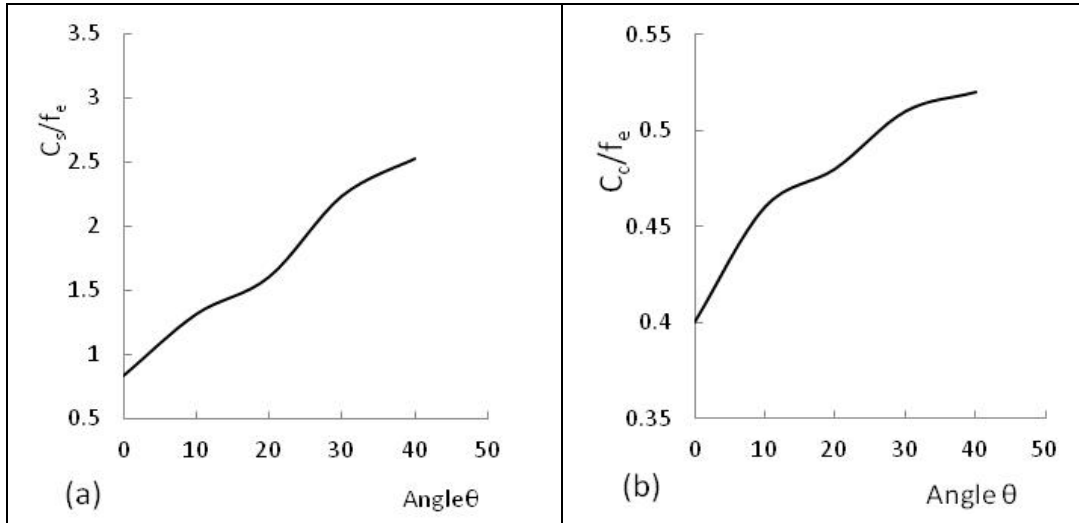


FIG. 5. Variation of the:(a)relative spherical aberration coefficient (C_s/f_e) and (b)relative chromatic aberration coefficient (C_c/f_e) of the lenses as a function of the angle at ($V_{I(in)} = 8000V$ and $V_{II(out)} = 100V$).

The Effect of Air Gap Electrodes Design

Research work has been conducted on the influence of air gap electrodes distance on the other set of electrostatic lenses. The principles in the above section can be applied to the different air gap lenses at the preferred angles (0° and 20°), respectively. This involves operating the lenses at the same optical conditions ($V_{I(in)} = 8000V$, $V_{II(out)} = 100V$) and at zero magnification conditions.

In order to calculate the variation in the electron optical properties of the two types of lenses having angles (0° and 20°) with the air gap, six different kinds of asymmetrical electrostatic lenses are chosen for the performance of detailed calculation. The corresponding values of the air gap distance are taken [$S = (0, 3, 5, 7, 10, 11 \text{ \& } 15) \text{ mm}$], respectively for the two types of lenses (0° and 20°). These lenses are identical in all dimensions.

The variations of the axial potential distribution of the previous lenses for different air gaps are calculated at constant electrode voltages ($V_{I(in)} = 8000V$ and $V_{II(out)} = 100V$) as demonstrated in Fig. 6 for the angles (a) $\theta = 0^\circ$ and (b) $\theta = 20^\circ$. It is noticed from this figure that the half-width of the potential distribution in both angles decreases as the distance of air gap increases; see Fig. 6(a and b), (i.e. when the inner electrode I(in) becomes far from the specimen). Other tests for the air gap distance were performed and yielded the fact that the preferred electrode angles (0° and 20°) produce the best optical performance. It is worthy to

calculate the trajectories of electrons inside the previous electrostatic lenses in order to compare their optical performances. The trajectories of electrons $R(z)$ of these lenses as a function of Z are calculated at the same optical conditions as mentioned before for different air gaps of the two values of angles (0° and 20°) as illustrated in Fig. 7. When the air gap value increases, the working distance decreases. It is clear that there is a linear relation between them as given in Fig. 7(a and b). This in turn will give good results in relation to the optical performance of these lenses.

Systematic investigations have been carried out on the effect of the air gap on equipotential lines of electrostatic lenses for both angles ($\theta = 0^\circ$) and ($\theta = 20^\circ$) at the same optical conditions as mentioned before in order to compare the trajectories of equipotential lines in the structures of these lenses. The equipotential lines of the previous lenses for different air gaps are calculated at the same voltages as represented by graphical results shown in Fig. 8. It is noticeable that for the lens of the air gap ($S = 0$), the equipotential lines emerge in the circular paths from the outer electrode region compared with the lens of ($S = 15\text{mm}$). The equipotential lines are converging toward the optical axis and do not exceed the outer electrode region in both angles ($\theta = 0^\circ$ and $\theta = 20^\circ$); therefore, the air gap of ($S = 15 \text{ mm}$) can be considered a preferred gap for these lenses. It should be mentioned that the air gap distance has a great effect on the electron optical properties of the asymmetrical electrostatic lenses.

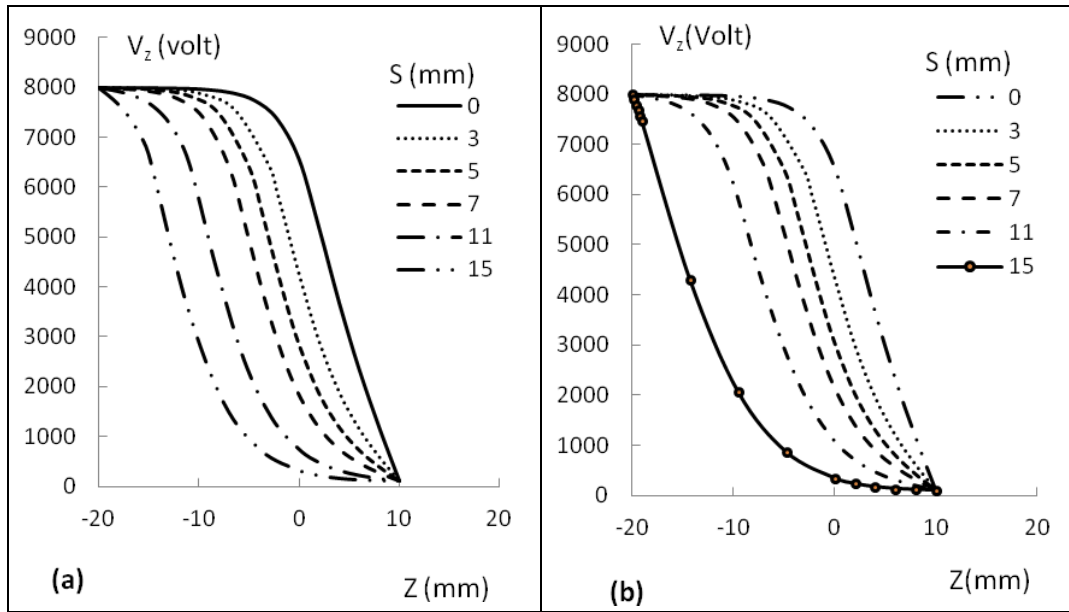


FIG. 6. The axial potential distribution of the electrostatic lenses of different air gaps (S) at voltages ($V_{I(in)}=8000\text{V}$ and $V_{II(out)}=100\text{V}$) of the two values of angle (a) $\theta = 0^\circ$ and (b) $\theta = 20^\circ$.

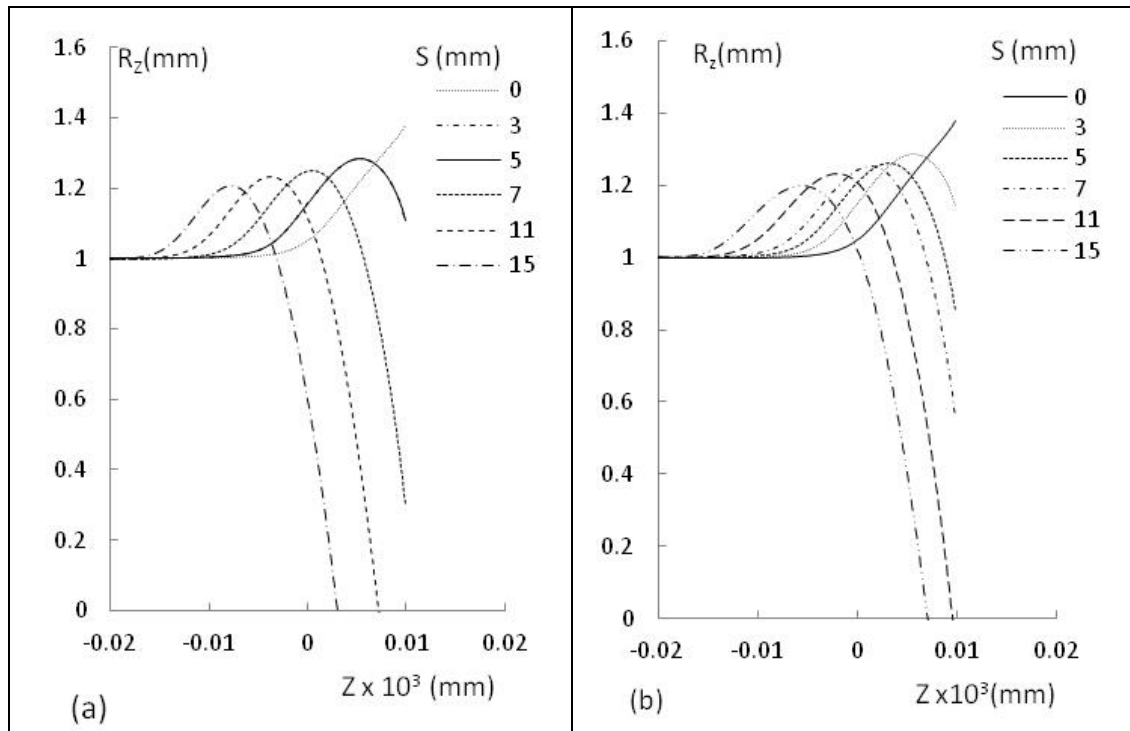


FIG. 7. The trajectories of the electrons inside the electrostatic lenses of different air gaps (S) at voltages ($V_{I(in)} = 8000\text{ V}$ and $V_{II(out)} = 100\text{ V}$) of the two values of angle (a) $\theta = 0^\circ$ and (b) $\theta = 20^\circ$.

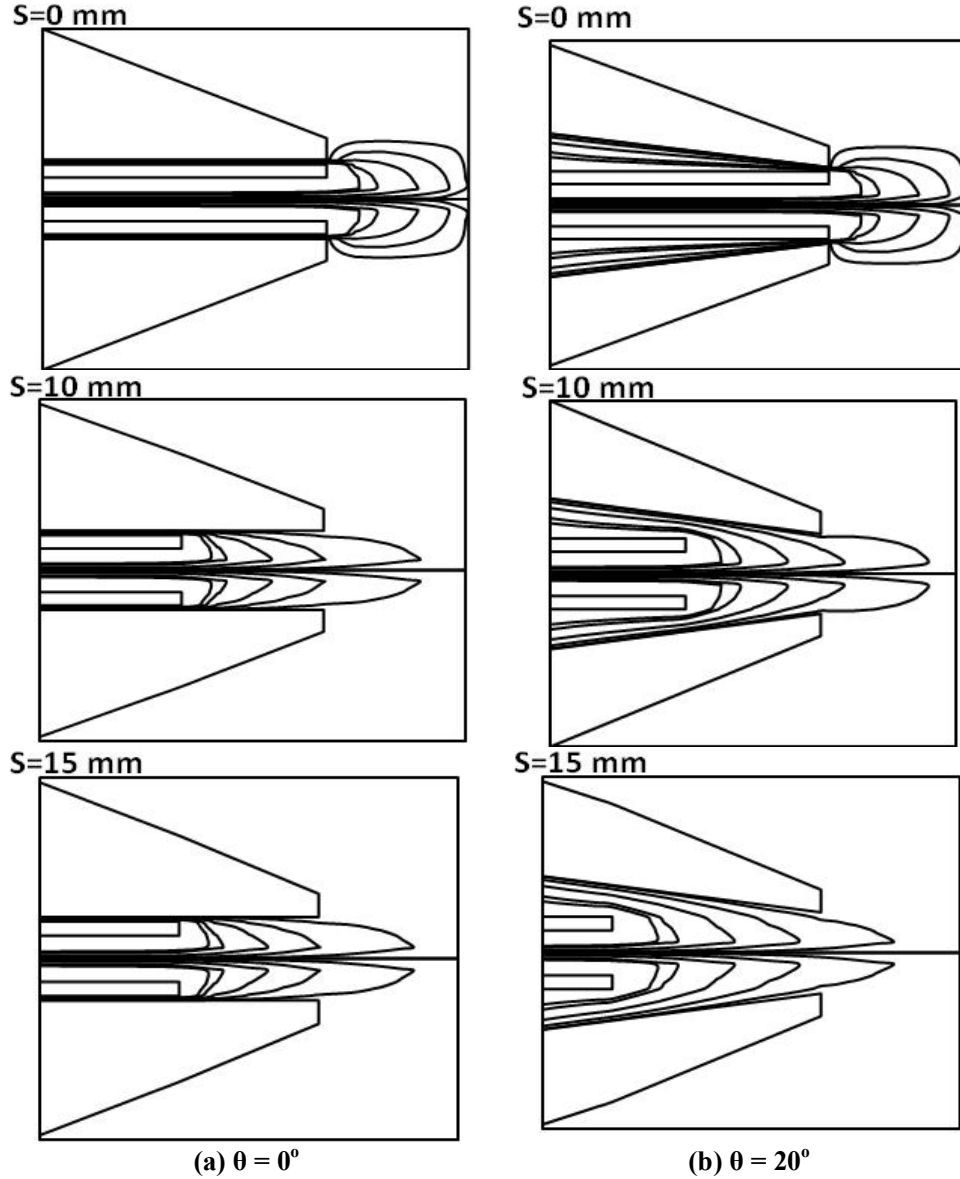


FIG. 8. The equipotential lines of electrostatic lenses of different air gaps $S = (0, 10, 15)$ mm at voltages ($V_{I(in)} = 8000$ V and $V_{II(out)} = 100$ V) of the two values of angle: (a) $\theta = 0^\circ$ and (b) $\theta = 20^\circ$.

This paper studies the impact of both parameters, the air gap (S) and the outer electrode angle (θ), on the improvement of the electron optical properties of the electrostatic lenses. A systematic investigation has been carried out on the effect of the above parameters (S and θ) on the optical properties in order to obtain the performance of these lenses. The spherical and chromatic aberration coefficients of these lenses were calculated as mentioned in the previous section at the same optical conditions. Fig. 9 shows a comparison between the relative spherical aberration coefficient (C_s/f_c) of the above lenses of angles ($\theta = 0^\circ$ and $\theta = 20^\circ$) as a function of the air gap at the same

inner and outer electrode voltages ($V_{I(in)} = 8000$ V) and ($V_{II(out)} = 100$ V) respectively. It is noticed from Fig. 9 that both curves for ($\theta = 0^\circ, \theta = 20^\circ$) intersect and acquire their lowest values of the relative spherical aberration coefficient at ($S = 11$ mm). Fig. 10 also shows a comparison between the relative chromatic aberration coefficient (C_c/f_c) of the two types of electrostatic lenses of angles (0° and 20°) as a function of air gap at constant voltages as mentioned above. From the previous figure, it can be noticed that the curve of ($\theta = 0^\circ$) has acquired the lowest value of (C_c/f_c) at ($S = 13$ mm) in comparison with the other curve of ($\theta = 20^\circ$), and their values decrease irregularly.

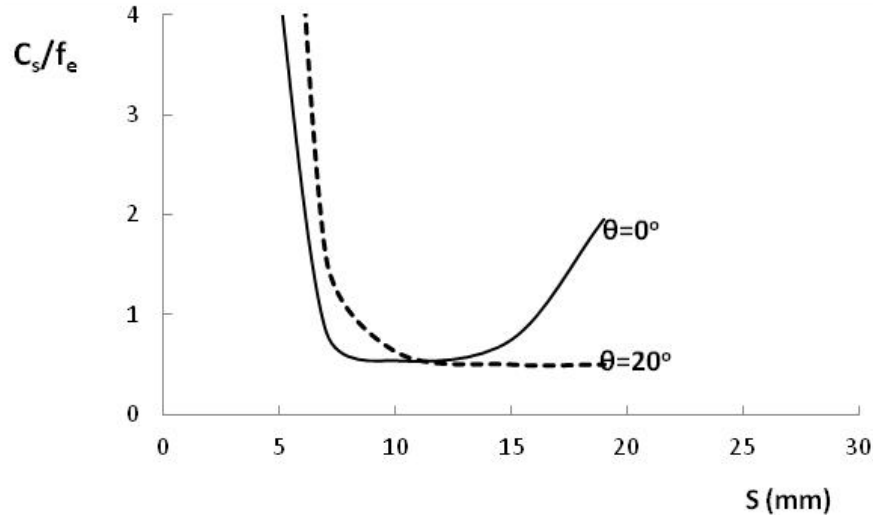


FIG. 9. Comparison between the relative spherical aberration coefficient (C_s/f_e) of the two types of electrostatic lenses of angles (0° and 20°) as a function of the air gap at constant voltages ($V_{I(in)} = 8000$ V and $V_{II(out)} = 100$ V).

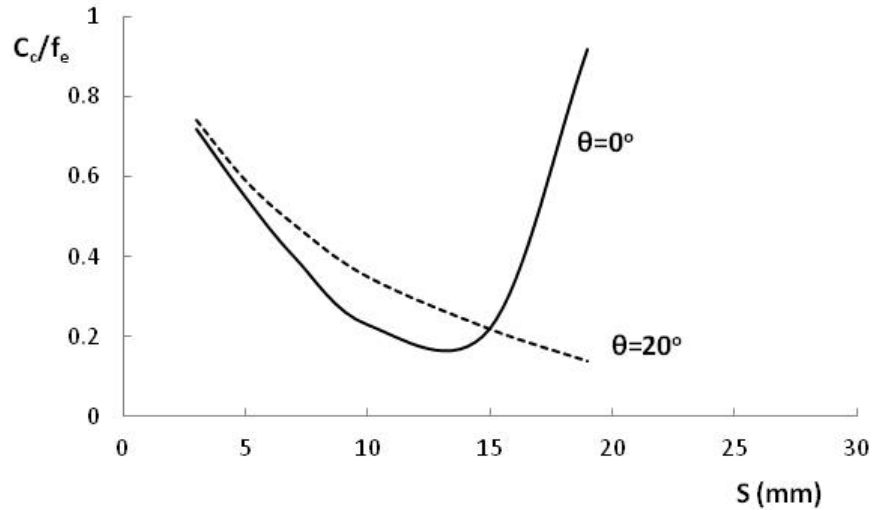


FIG. 10. Comparison between the relative chromatic aberration coefficient (C_c/f_e) of the two types of electrostatic lenses of angles (0° and 20°) as a function of the air gap at constant voltages ($V_{I(in)} = 8000$ V and $V_{II(out)} = 100$ V).

From the above investigation, it is interesting to point out that there are progressive developments in the electron optical properties of the electrostatic lenses concerning the above discussed parameters.

Comparison with Earlier Published Results

In this section, a comparison between the electron optical performance of the preferred asymmetrical electrostatic lenses designed and presented at this work with that of other

electrostatic lenses studied earlier by other researchers as indicated in Table 1. It can be noticed that the lowest values of the relative spherical and chromatic aberration coefficients occur corresponding to the present work in comparison with those of recently published results by other researchers which in turn gives a better resolution in comparison with other lenses. However, these lenses have verified higher resolution in the image formation of the electron microscope.

TABLE 1. Comparison between the relative spherical and chromatic aberration coefficients (C_s/f_e and C_c/f_e) for the asymmetrical electrostatic lenses of the present work with those of published results.

Lenses of published results	C_s/f_e	C_c/f_e	$V_{II(out)}$ (Volt)
Al- Meshhadany (2002) [19]	3.60	0.79	-----
Abd- Hujazie (2006) [10]	0.53	0.26	100
Al-Khashab and Al-Shamma (2009a) [8]	4.85	4.20	100
Al-Khashab and Al-Shamma (2009b) [9]	2.68	0.60	100
Present work ($\theta = 0^\circ$, $S = 11$ mm)	0.53	0.19	100
Present work ($\theta = 0^\circ$, $S = 13$ mm)	0.59	0.16	100

Conclusions

It is found out from the foregoing analysis that the plots of equipotential lines can be very essential in the early design stages of the real system, since they can often explain the apparently unusual behavior of the lens in comparison with the design expectations based on axial potential distribution only.

In the present investigation, it has been observed that the outer electrode angle together with the air gap of the electrodes have a very important effect on the design characteristics of the asymmetrical electrostatic lenses and consequently on their objective focal properties. This lens design of ($\theta = 0^\circ$ and $S = 11$ mm) probably represents the best performance that can be obtained with the present technology.

References

- [1] Hanszen, K.J. and Lauer, R., in: Focusing of Charged Particles, A.Septies, Ed. (Academic, New York, 1967) Ch.2.2.
- [2] Mulvey, T. and Wallington, M.J., Rep. Prog. Phys. 36 (1973) 347.
- [3] Szilagyi, M., J. Vac. Sci. Technol. A5 (1987) 273.
- [4] Kuyatt, C.J. and Simpson, J.A., Rev. Sci. Instrum. 38 (1967) 103.
- [5] Firestein, F. and Vine, J., Br. J. Appl. Phys. 14 (1963) 449.
- [6] Hawkes, P.W. and Kasper, E., Principle of Electron Optics, (Academic Press, London, 1996).
- [7] Al-Shamma, M.T.M., M.Sc. Thesis, Mosul University, Mosul, Iraq, (2007).
- [8] Al-Khashab, M.A. and Al-Shamma, M.T.M., Dirasat, Pure Sciences, 37(2) (2009a) 171.
- [9] Al-Khashab, M.A. and Al-Shamma, M.T.M., Dirasat, Pure Sciences, 37(2) (2009b) 183.
- [10] Abd-Hujazie, N.S., Ph.D. Thesis, The University of Mosul, Iraq, (2006).
- [11] Frosien, J., Plies, E. and Anger, K., Journal of Vacuum Science and Technology, 7(6) (2009) 1071.
- [12] Al-Jumayli, F.A.M., Ph.D. Thesis, The University of Mosul, Iraq, (2010).
- [13] Al-Khashab, M.A. and Hujazie, N.S., Dirasat, Pure Sciences, 37(2) (2010) 85.
- [14] Al-Khashab, M.A. and Hujazie, N.S., Dirasat, Pure Sciences, 38(1) (2011) 52.
- [15] Lencova', B., Nuclear Instruments and Methods in Phys. Research, Section A (1995) 1.
- [16] Munro, E., A Set of Computer Programs for Calculating the Properties of Electron Lenses, Report CUED/B-ELECT/TR 45, Cambridge University, Eng. Dept., (1975).
- [17] Grivet, P., Electron Optics, Part 1 Translated by Hawkes, P.W., (Pergamon Press Oxford, 2nd English Edition, 1972).
- [18] Lencova', B. and Lenc, M., Optik, 97(3) (1994) 121.
- [19] Al-Meshhadany, I.A.M., M.Sc. Thesis, Baghdad University, Iraq, (2002).