# A Novel Design and Development of Thermionic Emission Microscope

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***Abstract*:**

*Thermionic emission microscope (THEM) is an important analytical research tool for studying the electron emission uniformity of a thermionic cathode. The criticality of its design and development stems from the inhomogeneous emission nature of impregnated cathode surface. In this paper, a design approach of lens and deflection plate is described. The analytical equation for focal length, refractive index and condition for beam convergence of the microscope is derived using electron-optical phenomena. Finally, all the parameters are optimized using TRAK simulation software. The microscope has been developed and tested in UHV chamber. The emission image of cathode shows the performance of the microscope.*

## 1. Introduction:

Thermionic emission microscope (THEM) comprises of subsystems: *viz.* (a) electrostatic lens, (b) deflection plate and (c) Faraday cage as shown in figure-1. Electrostatic lens magnifies the emission image of the object. The deflection plate is used for scanning the image beam and the Faraday cage is used to extract element-by-element data from which the image is obtained. The image is formed at the screen due to the electrons emitted from the object (cathode surface) itself [1]. Here object is a part of the lens system. This type of lens is called immersion lens. This kind of microscope is simpler than the other conventional microscope as no illuminating system is required.

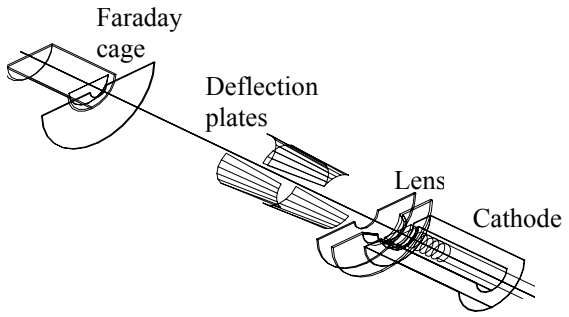


Figure-1: Schematic diagram of Thermionic Emission Microscope (THEM)

In this paper, we propose a procedure of designing THEM. The electrostatic lens and deflection plates are theoretically designed and finally optimized using TRAK simulation software [2]. TRAK has widely been used for the study of charged particle optics. Using the optimized parameter the THEM is developed. The testing is carried out in an ultra high vacuum chamber to obtain image of the object. The image picture of thermionic cathode surface could be seen under two modes, *viz.* (1) visual mode and (2) data acquisition mode. The visual mode is necessary to focus the image by adjusting the lens spacing and voltage. After optimization, the output signal is switched over to data acquisition mode in which Faraday cage signal is fed to the computer through a data acquisition card for storing the data so that the emission distribution of cathode is quantified. The emission picture of thermionic cathode surface could be seen on the fluorescent screen or the image data could be stored element by element in both horizontal and vertical directions by controlling the deflection signal step by step through a computer. The ramp signals (-10V to +10V) are generated either by electronic circuit or by computer through data acquisition card. These are amplified using DC amplifier and are fed to the horizontal and vertical deflection plates for deflecting the electron beam. The signal from the output of Faraday cage is amplified using a transconductance amplifier. The following sections elaborate a novel approach of designing the lens and deflection plate of THEM alongwith the results.

## 2. Design Approach

### 2.1. Design of Electrostatic lens

The simplest immersion lens may consist only of a single aperture at positive potential for accelerating the electrons. The necessary convex curvature can be given to the equipotentials by introducing a second electrode at higher potential. This electrode is often, but not necessarily, kept at negative potential relative to the cathode (C) and is known as the beam-focusing electrode (BFE). The other one, known as anode (A), is kept at positive potential in order to accelerate the electrons. The essential requirement is that the potential of the anode (A) be high enough to create a greater field between anode and the BFE than that of BFE and the cathode. Here the object (cathode) is deeply immersed in the field, and thus, electrons enter the lens with almost zero velocity. These electrons are extracted from the cathode under the influence of the applied potentials, and have initially only the velocity of thermal emission [3].

The critical electrostatic lens parameter such as refractive index, focal length and condition for beam convergent can be explained from simple optical phenomena shown in figure-2. An electron starting from cathode 'O' (with zero velocity) is given a velocity $v_1$ in the direction of OP. The point 'P' is on the boundary layer AB of the two media, such that the electric force to the right of AB is increasing and is normal to AB. The electron is thus accelerated only in the direction of the normal and changes to a velocity $v_2$ to the right of AB, and hence suffers no tangential displacement while it crosses from one layer to another. The refractive index of the layer of field can be expressed as in optics by

$$\mu = \frac{Sin\ (i)}{Sin\,(r)} = \frac{Tangential\ component\ of\ velocity}{incident\ velocity\,(v_1)} \Big/ \frac{Tangential\ component\ of\ velocity}{velocity\ after\ refraction\,(v_2)}$$

$$= \frac{v_2}{v_1} = \sqrt{2V_2\frac{e}{m}} \Big/ \sqrt{2V_1\frac{e}{m}} = \sqrt{\frac{V_2}{V_1}} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (1)$$

The electron path through the field would thus coincide exactly with the path of a light ray OP, incident at the angle '$i$' on the boundary AB. Also, from equation (1), the refractive index of the separating medium AB is expressed as the square root of the ratio of $V_2$ and $V_1$. This property of the path is of fundamental importance [4,5]. Now the condition for beam convergent and focal length can be established by replacing the interface boundary layer to a convex lens as follows.

Let us consider a ray at height '$r$' entering the field parallel to the axis. This will be refracted to an axial point 'F'. Now from figure-3 we can write

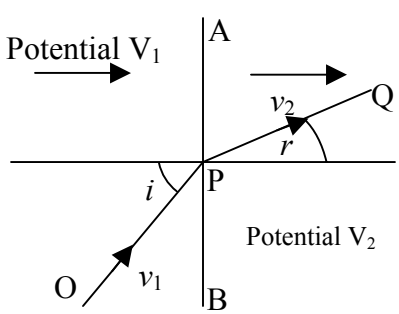


Figure-2: Optical analogy of electron beam

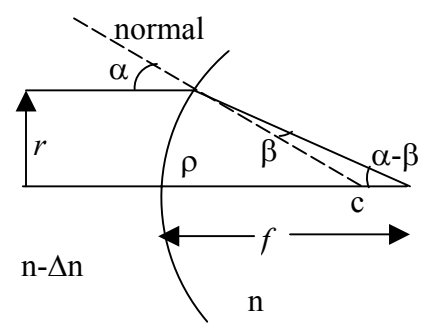


Figure-3: Path of electron beam through a lens

$$\frac{r}{f} = \tan(\alpha-\beta) = (\alpha-\beta),\ \text{Or,}\ \frac{1}{f} = \frac{\alpha-\beta}{r},\ Also, \frac{Sin\,\alpha}{Sin\,\beta} = \frac{\alpha}{\beta} = \frac{n}{n-\Delta n},\ or, \frac{\alpha-\beta}{\alpha} = \frac{\Delta n}{n}$$

Therefore, $\frac{1}{f} = \frac{\alpha\Delta n}{rn} = \frac{\alpha\Delta n}{\rho\alpha n} = \frac{\Delta n}{n\rho}$, Hence for the whole lens, $\frac{1}{f} = \frac{1}{n_e}\sum\frac{\Delta n}{\rho}$ ... ... ... ... (2)

In the limit,

$$\frac{1}{f}=\frac{1}{n_e}\int_{n_i}^{n_e}\frac{dn}{\rho}=\frac{1}{n_e}\int_{Z_1}^{Z_2}\frac{1}{\rho}\frac{dn}{dz}dz \text{ Or, } \frac{1}{f}=\frac{1}{4\sqrt{V_2}}\int_{Z_1}^{Z_2}\frac{V^{//}}{\sqrt{V}}dz \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (3)$$

where $n_e$ is the refractive index on the emergent side. Replace '$n$' by $\sqrt{V}$ and '$\rho$' by $2(\frac{V^{/}}{V^{//}})$

Thus, knowing the axial potential distribution and its derivatives, it is possible to determine the focal length. Above equation (3) shows that $V^{//}$ has to be positive to make '$f$' positive. This is the condition that the lens should be a converging [6,7].

**2.2 Design of Deflection Plate**

By providing two sets of deflecting systems at right angles to each other, it is thus possible to scan any desired area of the screen. The requirements of the deflecting system are (i) Deflection should be proportional to the deflecting voltage and (ii) Deflecting field should introduce no distortion of the spot. When the deflection exceeds a certain value, neither of these two requirements are fulfilled in practice. For small deflections, the proportionality is fairly strict as the following shows.

Let an electron of velocity $v_1$ enters a homogeneous field 'E' of length '$l$' between the parallel plates spaced at distance '$s$' apart as shown in figure-4.

Time of electron in the field is $t = l/v_1$ and acceleration in the direction of the field= $Ee/m$, therefore velocity in the direction of the field= $Eet/m$. Also angle of deflection=tanα=velocity in field direction/velocity in axial direction = $Eet/mv_1 = Eel/mv_1^2 = El/2v_1$, therefore the total deflection $D = 2EV_1/l$. These expressions show that the deflection varies with the deflecting field E. Since $E = V/s$, where V is the voltage on the plates, the deflection sensitivity then becomes $D/V = lL/2sV_1$ mm/volt.

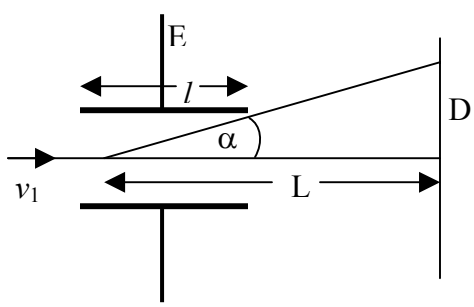


Figure-4: Deflection path of electron beam

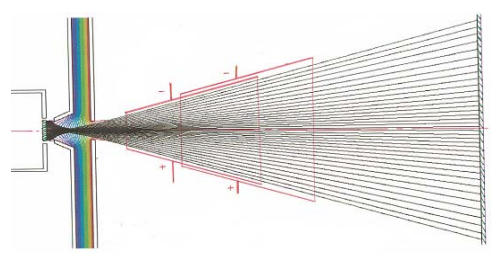

Figure-5: Simulated electron trajectory using TRAK software

Once the theoretical values of the design parameters are established, a complete 3D model of an emission microscope is simulated using Omni-TRAK software. The simulation in this paper is carried out in two stages by: (a) TRAK (2-D model), and (b) OmniTrak (3-D model). The 2-D model has been used for simulation of lens system and for obtaining electron trajectories; while, the 3-D model has been adopted to optimize deflection plates to find out the extent of image deflection. A simulated picture of electron beam trajectories in an emission microscope is shown in figure-5.

**3. Results:**

The optical photograph of emission microscope is shown in figure-6. This devise has been installed in a vacuum chamber and tested using a thermionic cathode of diameter 3.1 mm. The pressure inside chamber has been maintained $1.10\times10^{-9}$ torr. The center of cathode has been coated to enhance the emission. The emission picture obtained in fluorescent screen is shown in figure-7. The lens voltage and the distance between cathode and BFE are adjusted for proper focusing. Thereafter, the element-by-element data from Faraday cage is stored in computer using Kiethley data acquisition card. The emission picture obtained from computer is shown in figure-8. Figure-9 shows the enlarged image of a small region of the emission surface. The bright spots in figure-7 and high amplitude regions in figure-8 represent the good emission region of the thermionic cathode while the dark spots in figure-7 and lower amplitude regions in figure-8 indicate the poor emission of the cathode.

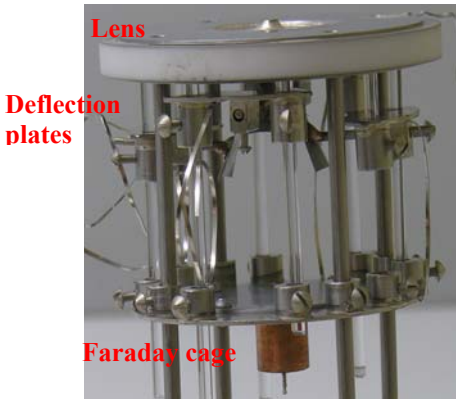


Figure-6: Photograph of THEM

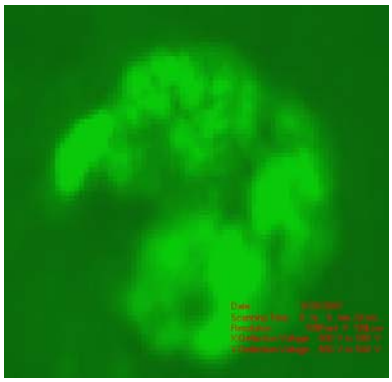

Figure-7: Image from florescent screen

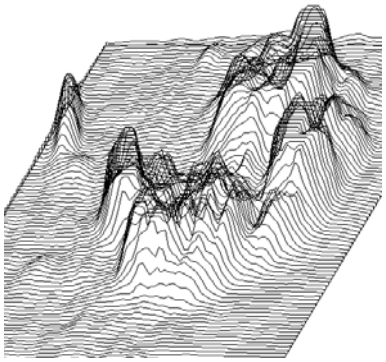

Figure-8: Image obtained from computer

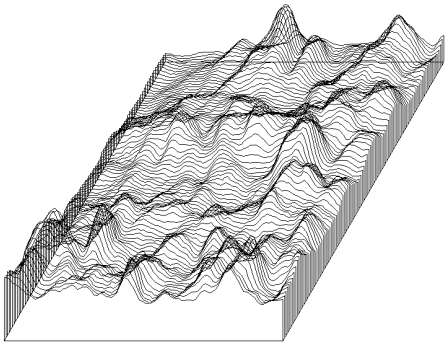

Figure-9: Emission picture of cathode

4. **Conclusion:**

In this work, theoretical values of the design parameters are calculated using analytical formula derived in section-2. All the parameters are also optimized using TRAK simulation software. Finally the THEM is developed and tested in an ultra high vacuum chamber. The emission picture obtained from fluorescent screen and computer are quite satisfactory. These pictures represent the spatial emission distribution of the thermionic cathode. Introducing magnetic deflection system, instead of electrostatic deflection, can increase spatial resolution of the microscope further. Presently resolution of the microscope is 30 μm. In near future, resolution will be increased up to sub-micron level.

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