A theoretical study on solar thermionic (thermo electronic) power conversion with a parabolic concentrator

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***Abstract*: In this paper Part I we consider the detailed energy dynamics of a thermionic converter heated by solar energy concentrated by a parabolic mirror and compute the total output power for different solar insolation, height of emitter, reflectivity of parabolic mirror, assuming no space charge effect initially. Our theoretical investigation gives for the first time the dependence of the output electric power on height h of the emitter from the base of the parabolic concentrator. The investigation discusses many novel ways the space-charge problem can be tackled and shows method of calculation of efficiencies which is also found to be dependent on solar insolation. Part II of the paper considers in details the effect of space charge on above calculations and the extent of space charge reduction following the novel ways such as gate, magnetic field etc..**

Keywords— Thermionic power conversion, solar parabolic concentrator, modified Thermionic equation, space charge, magnetic field, gate, efficiency.

I. INTRODUCCTION

Solar concentrators are finding increasing applications in (i) Photovoltaic power generation [1-4]; (ii) Steam turbine power generation [5-7]; (iii) energy storage systems[8] etc. There is also possibility of future applications of solar concentrators in thermionic power generation [9] [using concentrated solar energy focused on thermionic emitter to make it very hot so as to emit electrons profusely]; the latter being much easier, simpler and environmentally friendlier and more energy efficient than power generation through other means such as steam turbines (with heat from coal, fuel, nuclear power), photovoltaic systems etc..

Thermionic emission has the potential to enhance the solar or coal based power generation replacing the steam turbine, if the space charge limitation could be overcome. Recently efficiencies as high as 42% have been predicted for thermionic emitter devoid of space charge [10] compares well with those reported earlier [11-13] such as PV solar cells [14] and thermoelectric materials [15-16]. The major problem with thermionic power generation is that it requires high temperature. So far nuclear reactors [17] have been used as the thermal source for thermionic power systems. This has limited the use of thermionic systems for power generation. Because the space-charge cloud suppresses the emission current for emitter-collector distances of $d_{ec} > 3-5$ micron, practical fabrication of emitter-collector assemblies that operate with the required close tolerances at a temperature difference $T_e - T_c$ of many hundred Kelvin's was found to be challenging [18-20]. The space-charge problem so far has been tackled by introduction of Cs+ ions in to the space charge [13, 20]. This however reduces the output current by $\sim 50\ \%$ [10]. Reference [10] recently investigated the space-charge problem using a novel technique by introducing a +ve gate in between the cathode and the anode and a magnetic field perpendicular to the cathode and anode parallel surfaces. They found considerable increase in measured output current with increase in gate voltage and with introduction of magnetic field (B = 200 mT = 2000 G). They had used resistively heated emitter barium oxide (BaO). In many places on earth the normal solar energy availability is about 6.67kWhr/(m^2.day) [26].With solar concentrators (specially parabolic mirror type) high temperatures of the emitter surface can easily be attained. The black body temperature T attainable can be obtained from: $\sigma T^4 = xI_0$, x is the sun-factor of solar concentrator and Io is the solar insolation. With $x = 1000$, and $I_0 = 700\frac{W}{m^2}$W/m^2, $T = 1874\ K$. However, when thermo-electron emission takes place temperature would be lowered considerably from such values.

Considerable thermionic emission current from such emitter (cesium or rare-earth oxide coated tungsten plates) can take place even with the corrected Richardson-Dushman Equation [23]. Solar concentrators have potential not only to make the thermionic power systems a clean source of power but also to widen its application significantly because of abundance of sunshine on earth. Additional advantage of use of solar energy for thermionic power generation over nuclear energy is that the photon-enhanced thermionic emission where both photo-emission of electrons(photo-electric electric effect) by sun light and thermionic emission of electrons by the heat of the concentrated light can be exploited simultaneously in specially constructed devices for greater efficiency gains [22] (through photon-enhanced thermo-electron emission). In this paper we carry out theoretical studies on the thermionic power generation using a parabolic concentrator using the Richardson-Dushman Equation modified by [23] including the cooling effect of thermionic emitter as a result of electron

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emission but neglecting the photon-enhanced effect and the space charge effect. Since we are neglecting addition of positive ions to neutralize the space charge, the system may also be called thermo electronic rather than the conventional thermionic.

II. THEORETICAL CONSIDERATIONS

Even though the normal power output from a single solar thermionic converter is said to be limited to 3 kW, advances in large scale cost effective solar concentrators may push this limit much higher. Moreover, cascading power output from several such units can boost the power output significantly. With this view in this paper we carry out theoretical studies on the solar thermionic power generation using a parabolic concentrator. We consider the thermionic converter to consist of cathode and anode separated by spacing of the order of 1.5-2 mm instead of very low spacing of the order of a small fraction of a mm as used in earlier devices. Major reason for much smaller separation between the cathode (emitter) and the anode (collector) has been the fact that for $d_{ec} > 3-5$ micron, the space-charge cloud suppresses the emission current. The space charge problem has recently been elegantly handled both theoretically and with some experiments [10]. In this analysis we assume no space charge initially. The space charge problem can be minimized by taking some simple steps as follows:

The cathode emitter surface facing the anode is specially built with fine nano-tipped hills of height around ½ mm. The tip diameter should be a few nano meter. There is a gate with holes of diameter about 1-1.5 mm in front of the emitter at a distance about 0.75 mm to 1 mm from the emitter; The hole diameter can be kept at values twice the cyclotron radius, r_c of the emitted electron, $mv_m = BeR$. The mean velocity v_m of the emitted electrons can be obtained as shown in Paper II. The hole diameter should not be large enough to disturb the gate electric field at the emitter. The idea of +ve gate and magnetic field was introduced to tackle the space charge [10]. Along with that the idea of fine tipped hills at the emitter surface may completely obviate the need of introduction of positive charges into the space charge region. To keep the gate collection minimum the holes are to be made such that the ratio of total hole surface area to the gate area should be close to unity while still maintaining an effective electric field with parallel field lines at the emitter.

This separation is realistic enough for a thin gate to be easily placed before the emitter. Through the gate holes the electrons will pass on to the anode kept at a higher potential than the gate, being guided by both gate field and the applied magnetic field. This is expected to minimize the formation of the space charge.

Because of the fine tips at the emitter surface there will exist much high electric field near the tip which will ward off accumulation of electrons (space charge) near the emitter. The gate being at positive potential will attract the warded off electrons towards the anode kept at higher positive potential. The tipped hills at the emitter surface will also aid thermionic emission from the tips which will have a lowered effective work function through Schottky effect. The cathode should be made of porous tungsten impregnated with aluminates of barium and calcium. This would ensure lower work function and further lowering can be achieved with a low vapour pressure cesium sealed in between the space of cathode and the anode. Converter performance can be improved significantly (i) by addition of oxygen to the caesium vapor, [23] and oxygen containing electrodes [24] (ii) suppression of electron reflection at the collector electrode surfaces [25] and by hybrid mode operation. Caesium-Rydberg matter cluster that are formed through excited Cs atoms [26] yield a decrease of collector emitting work function from 1.5 eV to 1.0 – 0.7 eV. Due to long-lived nature of Rydberg matter this low work function [27] remains low for a long time which essentially increases the low-temperature converter's efficiency. The work function of the cathode must however be greater than that of the anode the net power conversion [10]. Since there exists a barrier of $W = \phi_e - \phi_c$ volt across the cathode-anode the net power P (assuming no space charge and no gate current) delivered on the external load will be $P = Js(\phi_e - \phi_c) = JsW$, J being the thermionic emission current density. The space charge problem can be further reduced in line with recent work [10, 22] by placing the emitter-collector combination near the centre of a Helmholtz coil. This heat extraction has advantage and disadvantages. The advantage is that we want to keep the collector temperature low enough to prevent thermionic emission from the collector and at the same time the collector temperature (heat sink) should not be too low to increase the heat radiation from the emitter surface 2 to the collector surface 1. The latter will have a cooling effect on emitter. There has to be a compromise with the temperature of the collector. We also need to note that the thermionic emission of electrons has a cooling effect on the emitter, which is different from the cooling due to radiation and conduction losses.

We assume the emitter-collector combination to be placed with its centre on the axis of a parabolic mirror and plane perpendicular to it (Fig.1) and solar energy(from the sun) falls on the parabolic mirror in the direction of its axis and thus normal to the thermionic emitter surface (Fig.1). The emitter surface 1(Fig.2) receiving the concentrated energy is blackened and coated with fine bone charcoal dust to minimize the reflection and maximize the absorption of the concentrated solar energy.

With thermionic emission current (based on the modified RD equation [23]) we then consider the total energy balance equation.

This analysis enables us to correctly predict the output power as a function of height h from a given parabolic mirror base and hence the efficiency. The formulations of correct energy balance equations help design the parabolic mirror and the emitter-Collector assembly.

A. Considerations to Minimize Space-Charge

We assume in this theoretical modeling that the space-charge can be minimized with steps similar to that of [10]. In addition to their steps we add the following considerations. (i) the cathode (emitter) surface should be tipped with micro hills. When electrons are emitted the electrons would be accelerated by the high electric field that can exist near the tipped surface; (ii) the radius R of the gate hole should be such that it is just equal to the cyclotron radius of the electron around the magnetic field B that is perpendicular to the gate. R is given by:

$$mv_m = BeR \tag{1}$$

The mean velocity of the emitted electrons:

$$V_m = \frac{1}{n}\int_{\sqrt{\frac{2E_F}{m}}}^{\infty} v dn(v) =$$

$$\frac{1}{n}\int_{\sqrt{\frac{2E_F}{m}}}^{\infty} v dn = \frac{1}{n}\int_{\sqrt{\frac{2E_F}{m}}}^{\infty} \sqrt{\frac{2E}{m}}\, dn(E) \tag{2}$$

$$E = \frac{1}{2}mv^2 \tag{3}$$

$$dn(E) = CE^{\frac{1}{2}}\frac{dE}{1+\exp\frac{(E-E_F)}{\mathrm{KT}}} \tag{4}$$

$$n = \int_{E_F}^{\infty} CE^{\frac{1}{2}}\frac{dE}{1+\exp\frac{(E-E_F)}{\mathrm{KT}}} \tag{5}$$

$$C = \left(\frac{m}{\hbar^2}\right)^{\frac{3}{2}} 2^{\frac{1}{2}}\pi^2 \tag{6}$$

The radius R should be such that the electric field lines from the emitter to the collector is directed in near straight lines to the gate holes. The emitted electrons that are still deviated from this path will be captured by the applied magnetic field (consider the component of velocities of such electrons perpendicular to B) in helical spirals that would be directed towards the anode.

The emitter-collector configuration is assumed to be similar to the design of [10]. The gate will be placed midway between the emitter and collector.

III. The Energy dynamics of solar thermionic converter

In thermionic power conversion the work function of the emitter (W_e) must be greater than that (W_c) of the collector, if we want output power from the thermally emitted electrons. This is because for deriving the power output the emitter and collector has to be externally connected. This connection makes the Fermi-levels of the two metals equal. Now if the emitter has higher work function compared to the collector, the thermally emitted electrons at emitter will be at lower potential (or higher energy) compared to the thermally emitted electrons at the collector with lower work function. The electrons at the emitter can then be received by the collector. Opposite is not possible. This however means that the collector has to be at considerable lower temperature T3 than the emitter to minimize back emission from the collector. This temperature difference $T_2 - T_3$again causes heat radiation from the emitter to the collector, which reduces the efficiency of the thermos-electronic power conversion process. Maximum output power for a given concentrated solar power is then a complicated function of the temperatures T_2 ,T_3 and the work functions W_e and W_c . The best options is to look for metals with proper rare earth oxides coatings so as to obtain low W_e and W_c but $W_e > W_c$. Since the space charge is dependent on $J_e - J_c$, it also depends on the temperature difference between the cathode and the anode. In the absence of space charge, the output power is then $P_{out} = s(J_e - J_c)(\phi_e - \phi_c)$. Such detailed accurate modelling of the solar thermos electronic power conversion is left for our next publication. Radiation heat from surface 1 of the emitter is $\sigma\varepsilon_e(T_1^4 - T_a^4)$to environment and the radiation heat from the emitter surface 2 to the anode surface 1: $\sigma\varepsilon_e(T_2^4 - T_3^4)$
The energy dynamic equation (Assuming both emitter & collector to have same surface area) then is given by

$$\mathrm{I}_0(S - s)r_m = s(J_e - J_c)(W_e - W_c) + \sigma\varepsilon_e s(T_2^4 - T_3^4) + \sigma\varepsilon_e s(T_1^4 - T_a^4) \tag{7}$$

Where

$$J_e = \mathrm{A}_\mathrm{e}^* T_2^4 \exp\left(-\frac{\mathrm{W}_e}{\mathrm{kT}_2}\right) \tag{8}$$

$$J_c = A_c^* T_3^4 \exp\left(-\frac{W_c}{kT_3}\right) \tag{9}$$

$$A^* = \mathrm{A}_\mathrm{c}^* T_3^4 \exp\left(\frac{-\mathrm{r}\alpha\mathrm{E}_{\mathrm{F0}}}{\mathrm{kT}_2}\right) \tag{10}$$

$A_0 = 120 \times 10^4 \frac{A}{m^2K^2}$. r_m is the reflection coefficient of the parabolic mirror. A^*= is the actual thermionic constant for tungsten, which is calculated to be $60 \times 10^4 \frac{A}{m^2}$ [24].

Assuming that thermionic emission takes place surface 2 of the emitter only. A_c is the collector surface area. We can see latter that there is an advantage in keeping the collector area larger than the emitter area. To prevent the thermionic emission from surface 1 of emitter we suggest that the surface 1 be covered by a thin quartz sheet (that can withstand high temperature) and at the same time transparent to most of the solar radiations. This surface not being quoted with caesium will have work function 4.5 eV and consequently the emission from emitter surface 1(Fig.2) will be insignificant. The energy balance on equation on emitter further requires:

$$\frac{k_e(T_1 - T_2)}{x_1} = (J_e - J_c)(W_e - W_c) + \sigma\varepsilon_e(T_2^4 - T_3^4) \tag{11}$$

x_1 is the thickness of the emitter. In the solar thermionic power conversion the thickness is going to be an important factor.

Thus from anode surface 2 to the environment

$$= \sigma\varepsilon_c A_c (T_4^4 - T_a^4)$$

Energy balance on anode gives:

$$\sigma\varepsilon_e (T_2^4 - T_3^4) - J_c (W_e - W_c) = \frac{k_c(T_3 - T_4)}{x_2}$$

$$= \sigma\varepsilon_c (T_4^4 - T_a^4) \quad (12)$$

T_a= Surrounding temperature$\sim 300K$

K_e and K_c are thermal conductivities of the emitter and the collector. All the above energy balances refer to the equilibrium conditions, yet with thermionic emissions taking place. In this energy balance equation we assume that the electrons (from emitter surface 2) collected at the surface 1 of the collector does not produce any heat on the collector surface. The space-charge problem can be tackled by considering a factor f such that $P_{out} = (J_e - J_c) f (W_e - W_c) s$ where $0 < f \leq 1$. Higher f means lower space charge problem. We have suggested possible ways above how f close to 1 can be achieved.

The goal is to have maximum $P_{out} = (J_e - J_c) \times (W_e - W_c)s$ subject to equations (7)-(10) and that $J_e \gg J_c$. This requires optimization of $T_2 - T_3$ for which P_{out} will be maximum. This optimization also depends on W_e *and* W_c. The temperature depends on s which again depends on h (Fig.1). As such efforts are very time consuming, we have adopted below a simpler approach to estimate the thermionic power output using a parabolic solar concentrator.

IV. RESULTS AND DISCUSSION

We assume that x_1 and x_2 are quite low (i.e., the emitter and collector are quite thin) so that $T_1 = T_2$ and $T_3 = T_4$. We also assume that J_c is negligible (this is the biggest challenge in a real thermionic power converter where $W_e > W_c$) in line with above arguments). Under these conditions maximum and minimum power output, for a given solar insolation I_0 can be approximately given by

$$I_0(S_0 - s)r_m = fJ_e(W_e - W_c)s + \sigma\varepsilon_e T_2^4 \quad (13)$$

And

$$I_0(S_0 - s)r_m = fJ_e(W_e - W_c)s + 2\sigma\varepsilon_e T_2^4 \quad (14)$$

r_m is the reflection coefficient of the parabolic mirror and $fJ_e(W_e - W_c)s$ is the output power.

A. Efficiency of the device:

Efficiency of the solar thermo-electronic power conversion

$$\eta = \frac{P_{out}}{P_{in}} \quad (15)$$

$$P_{in} = I_0(S_0 - s) \quad (16)$$

For a given s, η depends on T_1. As s varies both P_{in} will vary only slightly but P_{out} will vary drastically and hence η. The detailed quantitative theoretical studies of the solar thermionic power converter efficiency will be presented in our next paper. For high efficiency it is critical that the emitter area should just be equal to the focused area at a height h (Fig.1). If it is smaller, focused energy will be wasted. If it is larger, then temperature will be lowered, reducing J_e, while radiation loss will be high.

B. Parabolic Concentrator Parameters and the Thermionic Power Output

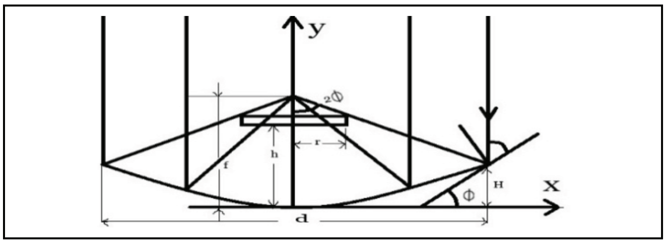

Fig. 1. Schematic diagram with relevant parameters of the thermionic power converter with a parabolic concentrator. The emitter is placed at a height h from the base centre.

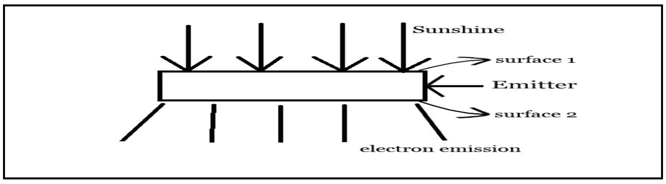

Fig. 2. Showing the two surfaces 1 & 2 of a thermionic emitter. It is the surface 2 that is cesiated to lower the work function and not the surface 1.

The collector (not shown) is placed close to the emitter. Referred to Fig. 1.0, our plan is to achieve an optimal temperature of the metal emitter surface when sunshine is concentrated by a parabolic mirror on to it. Geometrically (see Fig. 2) this depends on many factors such as: Incident solar insolation, I_0 (Watts/m^2) at the place; parabolic mirror radius R; Mirror height H at the edge from the bottom; surface area of the emitter s. and on a safety side the emitter temperature should be kept within 0.5-0.6T_m. For example, Tungsten has a melting point of 3695 K [23]. Therefore emitter operating temperature (T_2) can be kept very safely around 1900 K.

$s = \pi r^2$ The relation of h with s [Fig.3] can be calculated from the following equations. Referred to Fig.1

$$tan\emptyset = \frac{H}{2R} \quad (17)$$

$$r = (f - h)tan2\emptyset \quad (18)$$

$$f = \frac{R^2}{4H} \quad (19)$$

Using (13) Fig.4 represents the variation of emitter temperature as function of s for three different solar intensities concentrated by a parabolic mirror of radius 1 m with R=1. We see from Fig.5 that the output power for different solar insolation I_o increases with s. The minimum efficiency computed turns out to be 38.3 and 43.8% for $s = 0.001m^2$with $I_0 = 1000$ and $1250\frac{W}{m^2}$ respectively. Thus the emitter efficiency is expected to be higher in places with higher insolation. In space where solar insolation is maximum the solar thermionic converter should be a cost effective efficient way to generate electric power.

C. The intensity of the concentrated solar beam at the emitter and its black body temperature

The intensity of the concentrated solar radiation at the emitter surface is (assuming perfectly reflecting mirror surface and no absorption of solar energy by the mirror)

$$I = I_0 \frac{(S_0 - s)}{s} \quad (20)$$

$$S_o = \pi R^2 \quad (21)$$

D. Parabolic mirror and emitter surface areas:

Mirror surface area S_0 is calculated by

And R is the diameter of the parabolic surface which is 1 meter in this investigation.

H is the height of the paraboloid edge from its base. In this investigation H is kept constant at 0.5 meter and 0.2 m.

E. Computation of available output power

To compute P_{out} we proceed as follows. We assume the following: $W_0 = 1.5eV; W = \varphi_e - \varphi_c = 0.5V; R = 1m;$
Using Eqs.7-16 we compute the temperature of the emitter surface, the thermo-electronic power output, for various solar intensities, emitter surface areas s, neglecting conduction & convection heat losses. We also show the computation of s vs. h (Fig.3) for two values of H using Eqs. 7-9. All the computations are shown in Figs. 3-10. We notice that for smaller values of s the temperature T_{1op} is higher and also the P_{out} . This temperature T_{1op} should be chosen such that it is between $0.5T_m$ and $0.6T_m$ where T_m is the melting point of the emitter metal. For tungsten $T_m = 3422 + 273 = 3695K$ The plot of temperature T_1

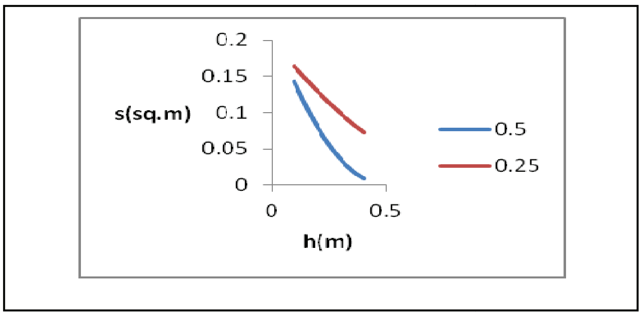

Fig. 3. Variation of s with h for a parabolic concentrator of radius R=1 m for H=0.5 m and 0.25 m.

(Considering thermionic emission) of the surface 1 of the emitter (Fig.2) for different concentrated power onto the emitter surface is shown in Fig.4. As expected the smaller the focused area s is the higher the temperature. T vs h can be also computed by noting Fig. 3. In Fig.5 the minimum output power (assuming radiation from surface 1 of emitter and surface 2 of collector-see text) as function of solar insolation is shown for four values of s (Fig.1). To prevent oxidation of the emitter surface 1, the surface is covered with a layer of quartz. The effect of space charge and its control by +Ve gate and magnetic field will be discussed in our next paper II. We see that the efficiency of solar thermionic power conversion depends also on solar insolation.

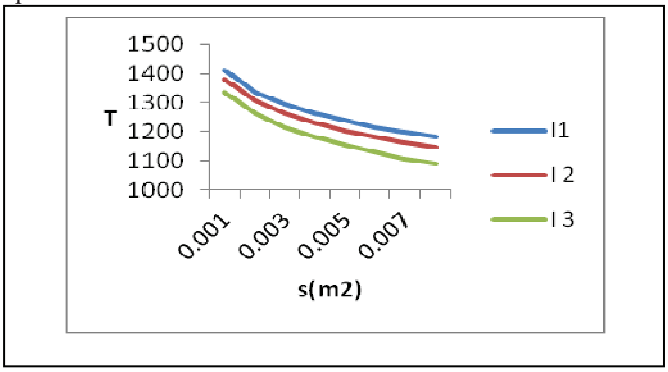

Fig. 4. Thermionic emitter temperature (K) (with thermionic emission taking place) for different areas of the emitter surface (Fig.1) when solar energy of different intensities I1-I3(1000,750&500 W/m^2) are focused by a parabolic mirror of radius R=1 m.

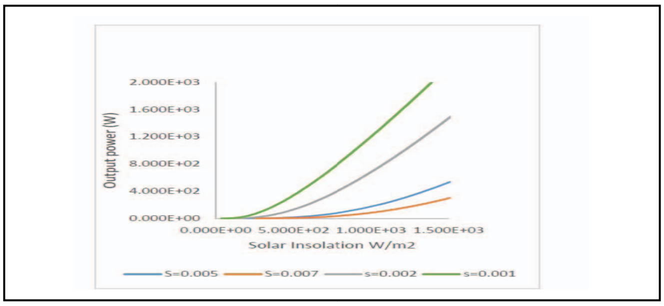

Fig. 5. The expected minimum output power vs solar insolation when solar energy concentrated by a parabolic mirror on to an emitter of different surface area s (in units of m^2). The parabolic concentrator has an aperture area = 3.14 m^2. We have neglected space charge, assuming that the effect is minimized by steps suggested in the text. The efficiency for surface area s=0.001 m^2 is 38.2% and 43.8% respectively for solar insolation I_o = 1000 and 1250 W/m^2.

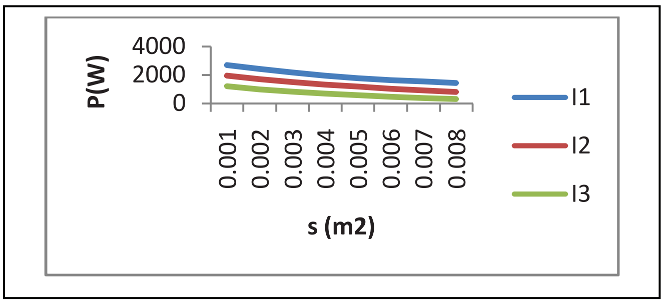

Fig. 6. Solar thermo-electronic power output against focused areas for different solar insolation:I1=1000, I2=750; I3=500 W/m^2. We have also

the effect of reflection coefficients, rm of the mirror surface of the parabolic concentrator (Fig.1) on the thermionic power output (Fig. 7) by replacing I_0 by $I_0 r_m$ in the Eq15.

We have also the effect of reflection coefficients, rm of the mirror surface of the parabolic concentrator(Fig.1) on the thermionic power output(Fig. 7) by replacing I_o by $I_o$rm in the Eq15.

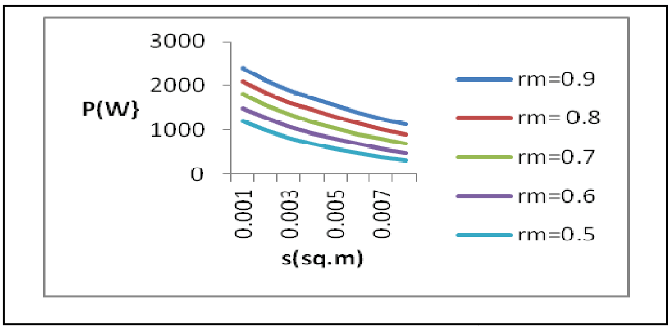

Fig. 7. Simulated thermionic power output vs thermionic emitter of surface area s(see Fig.1) where solar energy of intensity I_0=1000 W/m^2 are focused by a parabolic mirror R=1m of different reflection coefficients rm of the mirror.

CONCLUSION

For the first time we have shown methods of computations of thermo-electronic emitter temperature, and the power output from thermo-electronic emitter irradiated by solar energy concentrated by a parabolic mirror, as functions of various parameters such as focused emitter surface area s, emitter height h, solar insolation, reflection coefficient of the mirror, mirror parameters R & H etc, even though neglecting space charge effect, which can be minimized by methods suggested in the paper. We have discussed methods of minimizing, if not eliminating completely the space charge problem. Even though in the simulations presented we have neglected space charge effect, we have discussed that it can be taken care of through a factor f which depends on the emitter-collector configuration and the temperature, presence of magnetic field, gate, gate voltage etc. We shall present our detailed studies on the latter aspect in future publications. Our present studies show that solar thermionic power conversion can be achievable. We believe that these computations and the methodologies stated will be of immense use for the realistic design and practical exploitation of solar thermionic power conversion.

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