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MAXIMUM CONVERSION EFFICIENCY OF THERMIONIC HEAT TO ELECTRICITY CONVERTERS USING MOLYBDENUM AS THE EMITTER

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ABSTRACT

An analysis of Thermionic converters of heat to electricity is made in terms of the potential difference between the top of the potential barrier in the inter electrode space and the Fermi level of the emitter, the potential drop across a load impedance connected in series to the converter, and the potential drop to the necessary electrical connection to the collector. This analysis is carried out by developing an expression with respect to the potential drops. The expression yields optimum values of load impedance, collector lead geometry and emitter work function in terms of collector voltage, emitter temperature, effective emmissivity of the emitter for both thetheoretical and practically obtain Richardson Dushman constant (usually denoted by A) for a Molybdenum metal surface. The expression developed is worked out numerically and the out come shows that (1) a low value of collector voltage is required for a high efficiency (2) a low radiation heat loss is required for a high conversion efficiency and (3) relatively low values of emitter work function are required for maximum conversion efficiency at ordinary emitter temperature.

Key words: Thermionic converters, emitter, potential drop, Richardson Constant

Nomenclature

The following symbols will be adopted in the various formulae to be used in the efficiency computation and the data analysis for the study.

A = the Richardson Dushman constant appears in eq. (2.7) with value 120 A/(cm^{2}k^2)
A_E = Emitter area used for calculation of current density, m^2
A_l = Area of the leads, m^2
E = energy levels higher than the Fermi level
E_F = Fermi level energy as in 2.1
e = electron charge as in eqn. 2.2 value is 1.602×10^{-19} Coulomb.
i = electric current, A
j_o = out put current density of emissive surface, A/m^2
j_n = saturation current density of emissive surface, A/m^2
j_E = Emitter current density, A/m^2
j_C = Collector current density, A/m^2
k_B = Boltzmann's constant, = 1.381×10^{-23} J/K
K_l = thermal conductivity of the leads
l = length of the connecting leads, m
m = effective mass of an electron as in eqn. (2.3) with value 9.110×10^{-31} Kg
P_{out} = power out put, W/cm^2
P_{in} = power in put, W/cm^2

P_e = electron emission power loss, W/cm^2
P_r = radiation power loss, W/cm^2
P_K = Power loss due to conduction, W/cm^2
P_j = power loss due to joule heating, W/cm^2
ρ_l = resistivity of the lead, Ωm^{-1}
R = resistance in circuit from surface of collector to surface of emitter, Ω
R_L = Load resistance, Ω
R_l = leads resistance, Ω
T = absolute temperature on Kelvin scale
T_E = Emitter temperature, K
T_C = Collector temperature, K
V_L = Voltage across the load, (V)
V_l = Voltage across the leads, (V)
V_E = Emitter Voltage, (V)
V_C = Collector Voltage, (V)
V_C = Collector Voltage , (V)
V_{CB} = Collector Barrier index, (V)
V_{EB} = Emitter Barrier index, (V)
V_{out} = Out put voltage across both the load and the leads between the Emitter and the collector (V)
v = velocity of an electron as in eq. (2.2), ms^{-1}
ϕ_E = Emitter work function, (eV)
ϕ_C = Collector work function, (eV)
ε_E = Emitter emissivity
ε_C = Collector emissivity
σ = Stefan-Boltzmann constant with value 5.67×10^{-8}, W/ (K^4 m^2)
h = Planck's constant, with value 6.626×10^{-34}Js
η = Thermal efficiency of the converter in %
η_{max} = maximum conversion efficiency in %

INTRODUCTION

Since the early 1950s, there had been serious desires for lightweight, portable and quiet power supplies, interest in utilizing solar energy and realization of more electrical energy from atomic reactors. A lightweight electronic generator for space vehicles has also been sought for this long. Efforts has therefore been intensified to develop a means of generating electricity directly from heat, because it was observed that this would avoid the uses of rotating machineries, Wilson 1960[1].

Metals, as demonstrated by their ability to conduct an electric current, contain mobile electrons. Most electrons in metals, particularly the "core" electrons close to the nucleus, are tightly bound to individual atoms; it is only the outermost valence electrons that are somewhat free. These free electrons are generally confined to the bulk of the metal. An electron attempting to leave a conductor experiences a strong force attracting it back towards the conductor due to an image charge given as

$$F = -\frac{e^2}{4\pi\varepsilon_0 (2x)^2} \qquad (1)$$

where$x$ is the distance of the electron from the interface and e is the absolute value of the charge on an electron. Of course, inside the metal the electric field is zero so an electron there experiences zero (average) force. if we increase the temperature of the metal, the electrons will be moving faster and some will have enough energy to overcome the image-charge force (which after all become infinitesimally small at large distances from the interface) and escape. This temperature induced electron flow is called thermionic emission, Baragiola and Bringa 2006[2].

The process of converting thermal energy (heat) to a useful electrical work by the phenomenon of thermionic emission is the fundamental concept applied to a cylindrical version of the planner converter, considered the building block for space nuclear power system (SNPS) at any power level. Space nuclear reactors based on this process can produce electrical power ranging 5KWh to 5MWh. This spectrum serves the need of current users such as National Aeronautic and Space Administration (NASA),Ramalingam and Young 1993[3]. Moreover electrical power in this range is currently being considered for commercial telecommunications satellites, navigation, propulsion and planetary exploration mission to mention a few,Mysore 1993[4].

The history of thermionic emission dates back to the mid 1700s when Charles Dufay observed that electricity is conducted in the space near a red-hot body. Although Thomas Edison requested a patent in the late 1800s indicating that he had observed thermionic emission while perfecting his electric light system, it was not until 1960s that the phenomenon of thermionic energy conversion was adequately described theoretically and experimentally, Hatsopoulos et al 1979[5].

A Thermionic Converter is a static device that converts heat into electricity by boiling electrons from the hot emitter surface (at a temperature of about 1800^{o}K) across a small inter-electrode gap (< 0.5mm) to a cooler collector surface (at a temperature of 1000^{o}K) ,Mysore 1993. It is a form of electron tube that has been designed to function as an electrical generator rather than to control the flow of electric currents. It has a hot metal plate (the cathode or emitter), closely spaced from a colder metal plate (the anode or collector) (Fomenco, V. 1966, Culp 1991[6]. The heat supplied to the emitter can be from any source such as thermionic reactors that incorporate thermionic cells into the reactor fuel element, burning fossil fuels, burning hydrogen and oxygen in the exact proportions to produce an exhaust of pure water. Like the electron tube, either a high vacuum or low pressure gas or vapor is provided in the inter-electrode space of a thermionic converter, but unlike the electron tube, which has an electron emissive coating on the cathode only, both the emitter and the collector of a thermionic converter are coated to enhance the flow of electric current. Again in the operation of the electron tube an external voltage in applied to force the anode to become positive and the cathode negative, while in the converter, the natural polarity is not interfered with: the hot emitter takes on positive polarity and the colder, but still very hot, collector is negative. To produce useful quantities of electricity the converter’s collector is maintained in the same range of temperature as a collector of the electron tube at 800K to 1000K, while the emitter is heated to twice that temperature (1600K to 2000K). Therefore there are some common components in electron tubes and thermionic converters. However there are significant differences in both function and design ,Eguchi et al 1994[7].

The Operations of the Thermionic Converters

In the operation of the thermionic converter electrons "boil-off" from the emitter material surface, a refractory metal such as tungsten, when heated to high temperatures (1600K-2000K). The electrons then traverse the small inter electrode gap, to a colder (800K-1000K) collector where they condense, producing an output voltage that drives the current through the electrical load and back to the emitter, (figure 1). The flow of electrons through the electrical load is sustained by the temperature difference and the difference in surface work functions ϕ of the electrodes,Gyftopoulos 1997[8].

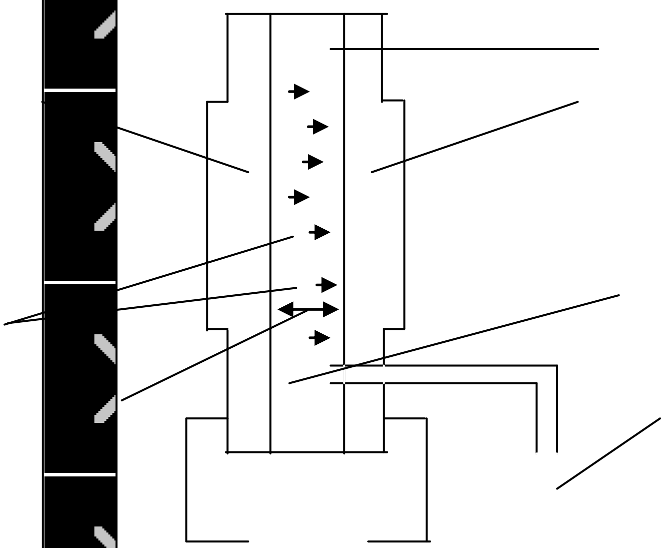


Fig. 1: Schematic diagram of an elementary thermionic converter

Operating Regime

Emitter temperature (1500K – 2000K)	Emitter material: Molybdenum metal
Collector temperature (800K – 1000K)	Collector material: various metals
Electrode efficiency up to 20%	Insulator Al_2O_3, Al_2O_3/Nb
Power density 1-10 W/cm^2	Electrode atmosphere:Cs at 1Torr

Several analyses of the direct conversion of heat to electricity have been published ,Houston 1959[9], Rasor 1960[10], Xuan et al 2003[11], Humphrey et al 2005). But all of these analyses employ the use of the theoretically assumed Richardson Dushmaan Constant, A. The analyses in the existing workuses both the practically obtained A value (Culp 1991)Presented in the table below, as well as the theoretical A value giving practical results and hence the expected efficiency of the thermionic converters.

Methodology

The converter output voltage

If we designate the work function of the emitter (cathode) as ϕ_E and that for the collector (anode) as ϕ_C, then the total output voltage is

$$V_{out} = \phi_E - \phi_C \quad (2)$$

where V_{out} is the voltage across the load and the leads applied between the emitter and the collector.

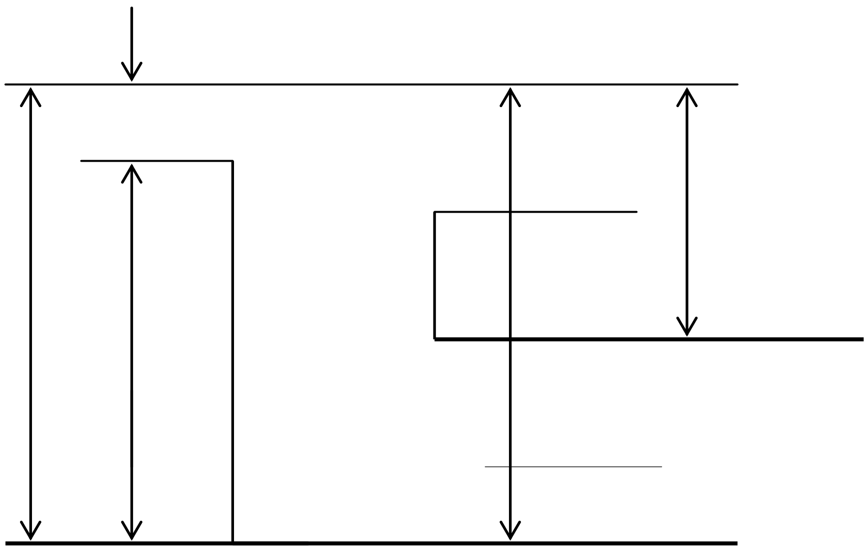


Figure 2: Potential diagram of a thermionic vacuum diode

Note that as long as $V_{out}+\phi_C<\phi_E$, the barrier to electron flow is ϕ_E and the current is independent of the thermionic device voltage and is called saturation current.

$$j = AT_E^2 \exp\left(-\frac{\phi_E}{k_B T_E}\right) \quad (3)$$

However, when $V_{out}+\phi_C>\phi_E$, then the barrier is $V_{out}+\phi_C$ and any increase in V_{out} will reduce j.

Figure 2 above shows the potential diagram used in this project subscripts E and C denote emitter and collector respectively. And ϕ denotes work function, V_E the potential difference but the top of the potential barrier and the Fermi level of the emitter is seen to be equal to $\Delta V_c + \Delta V_L + \Delta V_l$ which is the voltage across the collector, load and the leads. The net current density in the system is equal to $j_E - j_C$, which gets over the potential barrier. j_E and j_C are given by the Richardson-Dushman equation as

$$j_E = AT_E^2 \exp\left[-\left(\frac{e\Delta V_E}{k_B T_E}\right)\right] \tag{4}$$

$$j_C = AT_C^2 \exp\left[-\left(\frac{e\Delta V_C}{k_B T_C}\right)\right] \tag{5}$$

The effect of space charge

Once the electron cloud builds up between the electrodes, the flow of the electrons from the emitter is retarded by an additional potential, ΔV_{EB}. Adding in the voltage loss across the leads ΔV_l and the voltage loss across the load, ΔV_L as in fig. 1 above gives

$$j_n = AT_E^2 \exp\left[-\left(\frac{\phi_C + \Delta V_{CB} + \Delta V_l + \Delta V_L}{k_B T_E}\right)\right] \tag{6}$$

Note that in Thermionics, large current requires small work function, and large ΔV_{EB} voltage ($V_{out}=\phi_E - \phi_C$) requires large work function.

Efficiency computation

Efficiency is defined as the useful electrical power output per unit area of the emitter divided by the power input per unit area of the emitter.

$$\eta = \frac{power\ output / unit\ area\ of\ emitter}{power\ input / unit\ area\ of\ emitter} \times 100\% \tag{7}$$

The useful electrical power output is given by $(j_E - j_C)V_L = jv_L$. The case of practical interest, of course is that for $j_C << j_{E;}$ otherwise there would be negligible power output from the device. This project would be restricted to the case for which j_C is very small compared to j_E. Consider equations (2) and (3), when $j_C << j_E$ then

$$\left({}^{\theta_C}\!/_{\theta_E}\right)^2 \exp\left[\left({}^{\Delta V_E}\!/_{\theta_E}\right) - \left({}^{\Delta V_C}\!/_{\theta_C}\right)\right] \langle\langle\ 1 \tag{8}$$

where $\theta_i \equiv k_B T_i/e$. For practical purposes therefore, the neglect of j_C in comparison with j_E in the following analysis is justified.

In the steady state, the heat input to the emitter is expected to be equal the heat loss from the emitter.

Heat input = Heat output (9)

The heat loss from the emitter consists of mainly three terms, which are as follows: -

1). Electron emission cooling term, P_e (W/cm^2) which is the sum of the potential energy, P.E imparted to the electrons and the Kinetic energy, K.E at the emitter temperature.
2). Radiation heat losses, P_r (W/cm^2) radiated from the hot emitter, and
3). Heat conduction and I^2 R losses, P_l (W/cm^2) conducted away from the emitter through the electrical connection. In case of the gas-filled converter there is an additional loss p_g due to the conduction of heat in the gas. However, this term is probably very small and it has been neglected in this analysis.

(a) Electron emission cooling term, P_e

Only those electrons emitted from the emitter with an x- component of velocity greater than $\left[2\left(e/m\right)(\Delta V_E - \phi_E)\right]^{\frac{1}{2}}$ can get over the potential barrier (ΔV_E -ϕ_E)to the anode, and each such electron takes away from the cathode (emitter) an energy equal to eϕ +m/2 (u^2 +v^2 + w^2) where u, v and w are the x, y and z components of velocity, respectively. Then if U is the total number of electrons per unit volume just outside the emitter the total energy taken away from the emitter per unit area is given as

$$P_e = \int_a^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} nu\left[e\phi + \frac{m}{2}\bigcup^2\right]\left(\frac{m}{2\pi k_B T_E}\right)\times \exp\left(-\frac{m}{2k_B T_E}\bigcup^2\right)dudvdw \quad (10)$$

where $a^2 \equiv 2\left(e/m\right)(\Delta V_E - \phi_E)$; $\bigcup^2 \equiv u^2 + v^2 + w^2$

Thus, the electron emission cooling term is

$$\Rightarrow P_e = j_n\left(\Delta V_E + \frac{2k_B T_E}{e}\right) \quad (11)$$

But from figure1, $\Delta V_E = \Delta V_L + \Delta V_l + \Delta V_C$, and $\Delta V_l = j_n A_E R_l$

$$\therefore P_e = j_n\left(\Delta V_L + j_n A_E R_l + \Delta V_C + \frac{2k_B T_E}{e}\right) \quad (12)$$

There is another term in (12) whichaccounts for the energy received by the cathode from the electrons emitted from the anode which gets over the potential barrier, but for $j_C << j_E$ this term is negligible.

(b) Radiation loss term, P_r

This term is given by

$$P_r = \left(\frac{\sigma\left[T_E^4 - T_C^4\right]}{\left\{\left(\frac{1}{\varepsilon_E}\right) + \left(\frac{1}{\varepsilon_C}\right) - 1\right\}}\right) \quad (13)$$

The above equation shows that using materials with low emissivities can reduce heat loss.

(c) Heat conduction and thermal losses, P_l

i) Conduction Loss; P_k

Heat loss due to conduction is given by

$$P_K = \frac{K_l A_l}{A_E}\left(\frac{T_E - T_L}{l}\right) \quad (14)$$

From the definition of resistivity, ρ the length of the lead, l is given by

$$l = \frac{R_l A_l}{\rho_l} \quad (15)$$

$$\therefore P_K = \frac{K_l \rho_l}{A_E}\left(\frac{T_E - T_L}{R_l}\right) \quad (16)$$

But from the Wideman – Franz law

$$\rho_l K_l = \left(\frac{\pi^2}{6}\right)\left(\frac{K_B}{e}\right)^2 (T_E + T_L) \text{ , where } T_l = \left(\frac{T_E + T_L}{2}\right)$$

$$\Rightarrow P_K = \left[\frac{1}{A_E}\right]\left(\frac{\pi^2}{6}\right)\left(\frac{K_B}{e}\right)^2 (T_E^2 - T_L^2) \quad (17)$$

ii) Thermal Loss; P_j (Joule heating):
This is given by:

$$P_j = \left[\frac{1}{A_E}\right](j_n A_E)^2 R_l \quad (18)$$

Assuming that half of the loss flows towards the cathode, then

$$P_j = \frac{1}{2}\left[\frac{1}{A_E}\right](j_n A_E)^2 R_l \quad (19)$$

The combined loss ($P_k + P_j$)

The combined loss for the (a) and (b) above is

$$P_l = P_{Kj} = \left\{\frac{1}{A_E}\right\}\sum\left[\frac{\pi^2\left(\frac{K_B}{e}\right)^2 (T_E^2 - T_L^2)}{6 A_E R_l} - \frac{(j_n A_E)^2 R_l}{2}\right] \quad (20)$$

The efficiency of the diode η is therefore

$$\eta = \frac{P_L}{P_e + P_r + P_l} \times 100\% \quad (21)$$

where $P_L = j_n \Delta V_L$ (useful load/unit area of emitter).

Substituting the results for P_e, P_r and P_l into (21) gives

$$\eta = \frac{j_n \Delta V_L}{j_n(\Delta V_C + \Delta V_L + \Delta V_l) + 2 j_n \theta_E + P_r + P_l} \qquad (22)$$

where $\theta_i \equiv k_B T_i/e$ has been used.

Dividing the numerator and the denominator of the right hand side of the above equation by $j_n\theta_E$ and noting that $V_l = j_n A_E R_l$ we can write for efficiency

$$\eta = \frac{\psi_L}{\psi_L + \psi_C + 2 + \left(P_r \big/ j_n\theta_E\right) + \left(\pi^2 \big/ 3\psi_l\right)\frac{1}{2}\psi_l} \qquad (23)$$

where $\psi_i = V_i/\theta_E$, θ_C^2 has been neglected compared with θ_E^2 and j_n is given by

$$j_n = j_o \exp(-\psi_C - \psi_L - \psi_l) \qquad (24)$$

where $j_o \equiv A(e/K_B)^2\theta_E^2$.

According to (23) the efficiency can be interpreted as the ratio of power delivered to the load to the sum of powers delivered to the load and the anode (collector).

In optimizing ψ_L and ψ_l (i.e. V_L and V_l) , it is convenient to work with the reciprocal of the efficiency, which from (23) is

$$\frac{1}{\eta} = 1 + \frac{1}{\psi_L}\left[\psi_C + 2 + \frac{P_r}{j_n\theta_E} + \frac{\pi^2}{3\psi_l} + \frac{1}{2}\psi_l\right] \qquad (25)$$

where ψ_C, θ_E and P_r are constant parameters.

For η to be maximum (i.e. $1/\eta$ to be minimum) it is required that:

Maximizing

$$\frac{\partial\left(\frac{1}{\eta}\right)}{\partial\psi_l} = -\frac{P_r}{j_n^2\theta_E}\frac{\partial j_n}{\partial\psi_l} - \frac{\pi^2}{3\psi_l^2} + \frac{1}{2} = 0 \qquad (26)$$

$$\frac{\partial\left(\frac{1}{\eta}\right)}{\partial\psi_L} = -\frac{1}{\psi_L}\frac{P_r}{j_n^2\theta_E}\frac{\partial j_n}{\partial\psi_L} - \frac{1}{\psi_l^2}\left(\psi_C + 2 + \frac{P_r}{j_n\theta_E} + \frac{\pi^2}{3\psi_l} + \frac{1}{2}\psi_l\right) = 0 \qquad (27)$$

from (24)

$$\frac{\partial j_n}{\partial\psi_l} = \frac{\partial j_n}{\partial\psi_L} = -j_n \qquad (28)$$

Therefore, from (26) and (27) one gets

$$\psi_l = \frac{\pi\left(\frac{2}{3}\right)^{\frac{1}{2}}}{\left[1 + 2\left(\frac{P_r}{j_n\theta_E}\right)\right]^{\frac{1}{2}}} \qquad (29)$$

$$\psi_L = \frac{\psi_C + 2 + \left(\frac{P_r}{j_n\theta_E}\right) + \psi_L\left[1 + \left(\frac{P_r}{j_n\theta_E}\right)\right]}{\frac{P_r}{j_n\theta_E}} \qquad (30)$$

Equation (29) and (30) are not explicit solutions for the optimum values of ψ_l and ψ_L because j_n depends exponentially on these two parameters. Instead one has two equations, which must be solved simultaneously for the optimum values of ψ_l and ψ_L. It turns out however, that first working with j_n alone can do this indirectly. Substituting equations (29) and (30) into (24) taking the logarithm of each side, and then simplifying gives

$$\frac{P_r}{j_n\theta_E} = \frac{\psi_C + 2 + \pi\left(\frac{2}{3}\right)^{\frac{1}{2}}\left[1 + 2\left(\frac{P_r}{j_n\theta_E}\right)\right]^{\frac{1}{2}}}{\ln\left(\frac{j_0\theta_E}{P_r}\right) + \ln\left(\frac{P_r}{j_n\theta_E}\right) - (\psi_C + 1)},$$

With $P_r/j_n\theta_E = \xi$, we therefore get

$$\xi = \frac{\left(\frac{e\Delta V_C}{K_B T_E}\right) + 2 + \pi\left[\frac{2(1 + 2\xi)}{3}\right]^{\frac{1}{2}}}{\ln\left(\frac{AK_B T_E^3}{eP_r}\right) + \ln\xi - \left(\frac{e\Delta V_C}{K_B T_E}\right) - 1} \qquad (31)$$

Equation (31) is the condition on j_n and hence on ψ_l and ψ_L for which η is a maximum.

Substituting (29) and (30) into (31) and simplifying the results gives maximum efficiency in terms of the optimum value of $P_r/j_n\theta_E$ obtained from (31) as

$$\eta_{\max} = \frac{1}{1 + \left(\frac{P_r}{j_n\theta_E}\right)_{opt}} \quad \text{or} \quad \eta_{\max} = \frac{1}{1 + \xi} \qquad (32)$$

where $\xi = P_r/j_n\theta_E = ep_r/j_nK_BT_E$

Thus the maximum efficiency for particular values of V_c and T_E depends on the ratio of the radiation loss, P_r to the optimum value of $2j_n\theta_E$, which is the K.E. of the electrons that reach the anode (collector) from the cathode (emitter).

The optimum values of cathode lead resistance R_l and load impedance R_L can be obtained in terms of Γ from (29) and (30) by using the relation $R_i = (\theta_E/j_n A_E)\psi_i$ as

$$\left(R_l\right)_{opt} = \pi\left(\frac{2}{3}\right)^{1/2} \frac{\left(K_B T_E\right)^2}{e^2 P_r A_E} \frac{\xi}{\left(1+2\xi\right)^{1/2}} \tag{33}$$

and

$$\left(R_L\right)_{opt} = \frac{\left(\frac{K_B T_E}{e}\right)^2}{P_r A_E}\left[\frac{e\Delta V_C}{K_B T_E} + \left(2+\xi\right) + \pi\left(\frac{2}{3}\right)^{1/2} \frac{1+\xi}{\left(1+2\xi\right)^{1/2}}\right] \tag{34}$$

For the maximum efficiency, the following interrelated conditions must be satisfied.

(a) The current in the circuit must satisfy equation (31)
(b) The cathode or emitter lead resistance and the load impedance must satisfy equations (33) and (34) respectively.
(c) The optimum cathode lead geometry l/A_E can be obtained directly from equation (20)

Data Generation

The data was generated by first solving equation (31) iteratively for different values of T_E and V_C. The results were used in connection with equation (32) to obtain the maximum conversion efficiency. Since to produce useful quantities of electricity the temperature of the collector has to be maintained in the same range as that of electron tube i.e. 800K to 1000K, while the emitter is to be heated to about twice that temperature i.e. 1500 to 2000K therefore, the Emitter temperature, T_E was varied from 1500K to 5000K in steps of 500K and the collector voltage, V_C was varied from 1.0V to 3.0V in steps of 0.5V. This was done for the metal considered (Molybdenum, Ta) with experimental Richardson Dushman constant, $A = 55$ A/cm^{2}K^2 (determined by Culp 1991), as well as with the theoretical A value i.e. ($A = 120$ A/cm^{2}K^2). Tables of values are then computed based both the theoretical and experimental A.

RESULTS

The results of the computations using both the theoretical and experimental A values were recorded. Maximum conversion efficiencies, η_{max} are plotted against emitter temperatures, T_E for the various collector voltages, V_C.

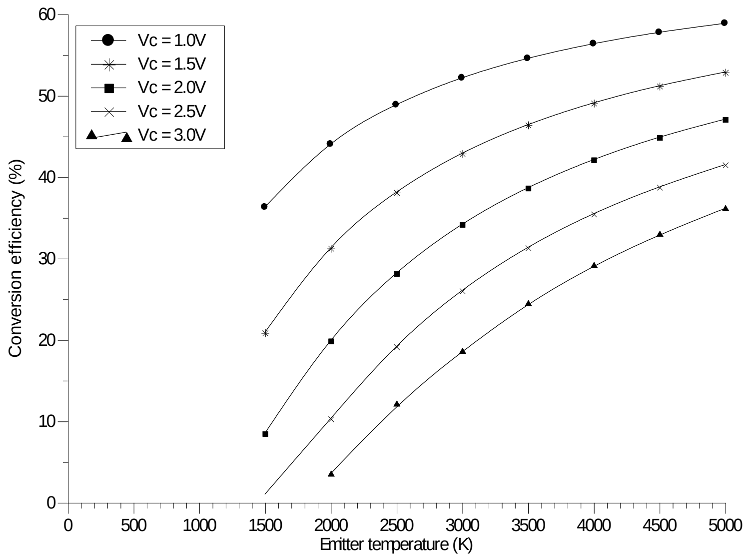
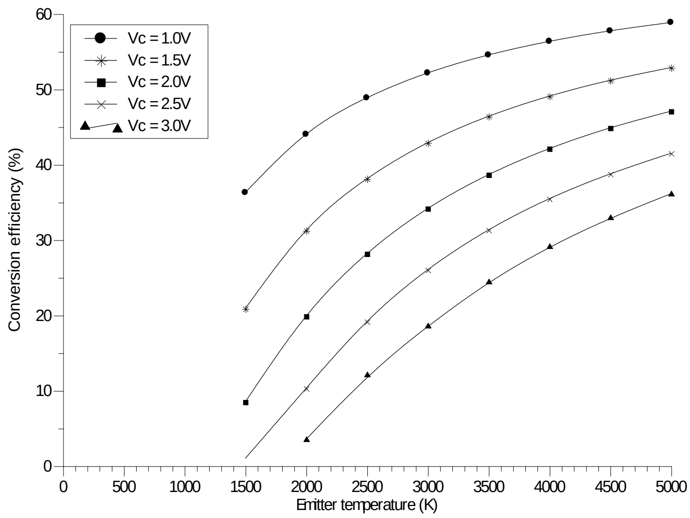


Fig. 3: Conversion efficiency versus emitter temperature at different V_C for Molybdenum using theoretical Richardson-



Du shman constant (A)

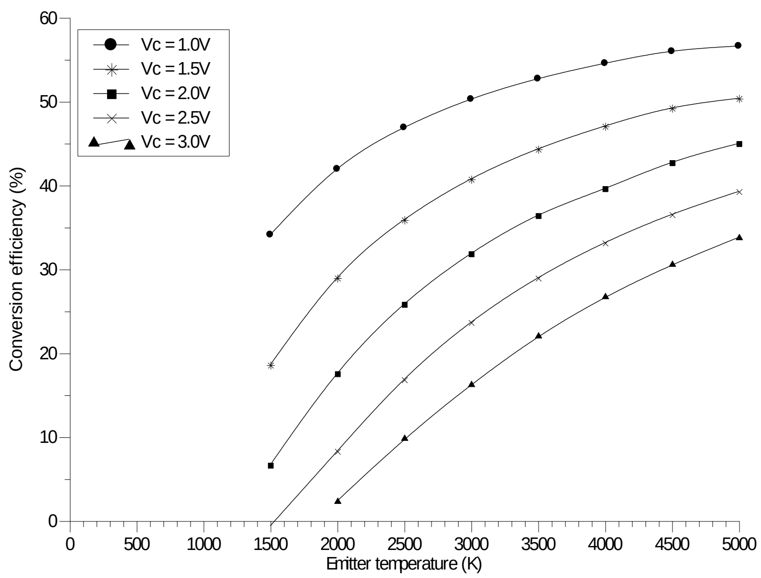


Fig. 4: Conversion efficiency versus emitter temperature at different V_C for Molybdenum using experimental Richardson-Dushman constant (A)

Analysis and Discussions

Analyses were drawn from both the tables and the graphs. From the tables it was observed that:- (1) The values for the efficiencies increases as the Γ decreases. (2) The values of the efficiencies decrease along the row as the V_C increases. (3) The values of the efficiencies increase along the column as the temperature increases. (4) There were no values for the efficiencies at V_C = 2.5 V and 3.0 V for T_E = 1500K.

From the graphs it was observed that:- (1) the curves for the efficiency becomes linear as the V_C increases. (2) the curves for the theoretical A is higher than that for the experimental A.

CONCLUSION

In summary, it is clear that variation in the Richardson Dushman constant A affects the conversion efficiencies. In essence all the results of the thermionic converters of heat to electricity obtained by assuming A to be 120 A/cm^2 has this much deviation from the observed A value on a particular converter. To resolve this discrepancy, the following has to be considered (1) the effect of the reflection coefficient (2) the effect of the emitter work function (3) the surface ruggedness and (4) the effect of the external electric field all of which brings about the deviation of the Dushman constant from its theoretical value. In conclusion, using the observed A value in computing the efficiency of the thermionic converter yields more reliable results than just assuming A to be 120 A/cm^2.

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