Effect of Vacuum Condition on Thermionic Emission of Tungsten Filaments with Low Voltage DC

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Abstract: ***The photon source (proton) for cyclotron is using electrons to ionize hydrogen gas to release proton particle. The main aim of this research is to produce electrons that have sufficient energy to ionize hydrogen gas to form proton for small scale cyclotron. There are several methods to generate electrons, (i) Thermionic emission (ii) Photoelectric emission (iii) Secondary emission, and (iv) Field emission. In this research, thermionic emission was used to generate electrons. To achieve thermionic emission for this research, the filament temperature must be approximately 1000 K and this temperature was achieved when approximately DC 10 volts was applied across the filament. In this paper, variation of vacuum pressure on thermionic emission of the filament was studied. Testing the filament for thermionic emission, firstly, glass vacuum tube with electrical feed throughs and outlet terminal for vacuum pump and vacuum gauge, the length of the glass tube is 16 cm, bottom end of the glass tube diameter is 8 cm and 0.3 cm thickness and the other small end is 2.6 cm diameter in which silicon rubber gasket was constructed. Vacuum chamber can be consistently pumped down to approximately 2×10^{-3} mmHg. Vacuum chamber must be withstanding the pressure and completely seal is important so vacuum test for vacuum chamber is the important first step for entire research. Results show the suitable vacuum condition was achieved approximately about -746 mmHg to -752mmHg. The temperature is enough to reach good thermionic emission and emission current from filament is about (73 to 99.67 mA). However, some impurities due to tungsten filament and housing materials are the challenges to get stable vacuum condition.***

Keywords: thermionic, vacuum, tungsten, emission

1. Introduction

In today's world, radio isotopes applications are more popular than ever because of their great advantages. Radioisotopes are used in many fields of research, healthcare, industrial, agriculture and archaeology. More than 1600 radioisotopes have been identified which can be produced either in a research reactor or in a cyclotron [3]. Actually, research reactors are not necessary at all for the production of isotopes. Radioisotopes production with cyclotrons offers many advantages over a nuclear reactor. Firstly, the volume of radioactive waste produced by cyclotrons is far less and much less hazardous than the radioactive waste of research reactors. Secondly, the production is decentralized. Cyclotrons are located hospital-based, by which the delivery of pharmaceuticals to patients is much more secured. In addition the risk of transport accidents is practically zero. Thirdly, there are no risks due to nuclear-power accidents, because there is no need for controlled chain reactions. Fourthly, there is no nuclear proliferation risk. Cyclotrons are a clean nuclear technology and create very little radioactive waste as a result of their operation [5].

The basic operating principle of a cyclotron is shown in figure 1. The particles to be accelerated are formed in the centre of the dees, typically with a device that ionizes a gas. Particles are accelerated in spiral paths inside two semicircular, flat metallic electrodes called dees (D's). The dees are connected to an RF generator and are placed in a nearly uniform magnetic field. Charged particles are produced by an ion source located at the centre of the cyclotron between the dees and extracted by a puller electrode at the same potential as the dee. The magnetic field causes the particles to move in a plane called median plane in approximately circular orbits inside the dee and across the gap between them. At each gap, particles are accelerated and, therefore, they follow a spiral path as they gain energy. This is because the radius of orbit, being a function of the particle velocity, increases with time. At the edge of the magnet, full energy particle beam is pulled out (extracted) as an external beam by an electrostatic deflector. The dees, deflector, ion source etc are enclosed in a flat vacuum chamber where a low pressure of the order of $\sim10^{-6}$ torr is maintained. High vacuum is essential to generate high voltages on dee and deflector as well as to avoid the beam loss by scattering during acceleration. In practice, it is possible to achieve the same effect with a single dee and a "dummy dee" that is simply a grounded piece of metal with an opening of the correct size. The single electrode is driven by the oscillating potential and repeatedly pushes and pulls the particles being accelerated across the gap between the dee and the dummy dee. As there is no electric field inside of the dee, the acceleration only takes place via the electric field in the gap [4].

The key components of the cyclotron are vacuum chamber, Dee electrodes, RF system, photon source, electro magnet, particle detector. The photon source (proton), using electrons to ionize hydrogen gas, thereby generating protons. In this experiment, the production of electrons to produce proton particles was studied. There are multiple methods available to produce electrons. In which, Field emission: uses strong fields to remove electrons from cold surfaces. Secondary emission: is the result of high energy electrons or ions colliding with a surface, essentially knocking electrons off of the surface. Photoelectric emission: involves the use of high-energy light waves that supply energy to knock electrons

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from the surface of a metal. Thermionic emission: occurs when electrons on the surface of a hot conductor (on the order of 1000 – 3000K) have enough kinetic energy to overcome the electrostatic forces binding them to the surface. The method in which this experiment uses is thermionic emission. The number of electrons emitted depends upon the temperature. The higher the temperature and vacuum condition the greater the emission of electrons.

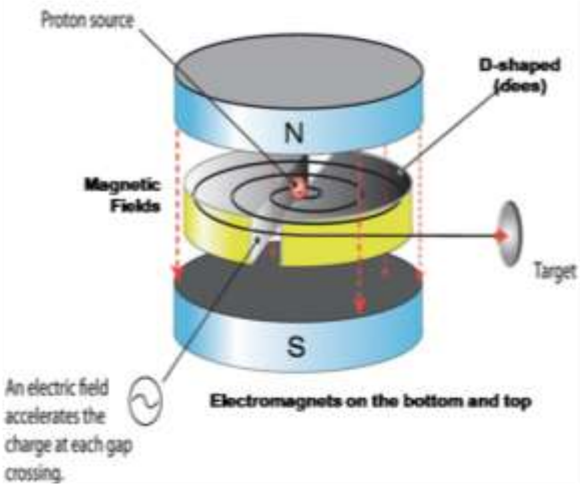

Figure 1: Schematic layout of a cyclotron [4]

This type of emission is employed in vacuum tubes. The effect of vacuum condition is also important to determine thermionic emission of materials. In this paper, we only emphasize the thermionic emission of tungsten varies with vacuum condition of the vacuum tube. The common factor among all methods is that energy is given to the electrons of the metal in hope of removing them from the metal [1], [2].

2. Principle of Thermionic Electron Emitter

The energy distribution of electrons inside a solid metal is governed by Fermi–Dirac distribution, which allows the only one conduction electron to occupy a given wave function and spin polarity inside the metal. The electron density n(E) in a small energy range dE is given by –

$$n(E)dE = \left[\frac{4\pi\pi(2_{e})^{3/2}}{h^3}\right]\sqrt{E}\left[1+\exp\left(\frac{E-E_{Fermi}}{kT}\right)\right]^{-1} dE \quad (1)$$

Where, m_e is the electron mass, h and k are the Planck and Boltzmann constants and T is the temperature. E_{Fermi} is then the highest energy level filled for T = 0 K. As the temperature of the metal is increased, the electrons move to higher energy states, where some are above the metal's work function. Approximately integrating the density of electrons above the work-function yields the Richardson–Dushman equation, which gives the current density of electrons available to be extracted from the metal, i.e.

$$J = A \times T^2 \exp\left(\frac{-e\phi_{work}}{kT}\right) \quad (2)$$

Where,

$$A = \frac{4\pi em_c k^2}{h^3} \approx 1.2\times10^6 Am^{-2}K^{-2} \quad (3)$$

Hence the current available is a strong function of the temperature of the material, with the highest emission from a material with a low work-function. In addition, the factor A is usually below the theoretical value, and is fixed for a material but is not a function of temperature. Emission from pure metal such as tungsten follows the Richardson – Dushman equation as closely as can be determined experimentally. The principle of thermionic electron emitter is shown in figure 2.

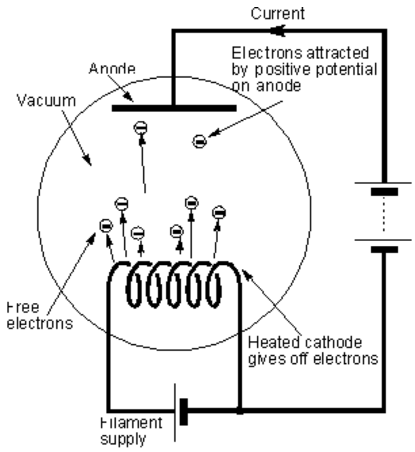

Figure 2: Principle of thermionic electron emitter [6].

3. Experimental Works of Vacuum Tube Thermionic Electron Emitter

3.1 Materials and Equipments

The material and equipments for the thermionic vacuum tube are listed in table 1.

Table 1: Materials and equipments

No	*Materials*	*Quantity*
1	Glass bottle	1
2	Copper electrode for feed	5
3	Vacuum pump (8cfm)	1
4	Variable DC power supply	2
5	Digital multimeter	1
6	Connection wire (5m)	1
7	K-type thermocouple (1m)	1
8	Digital vacuum gauge	1
9	Digital temperature display	1
10	Tungsten wires (0.25mm diameter, 4m length)	1
11	Acrylic (1inch thickness) plate (8" x 8")	1
12	Stainless steel collector	1
13	Inner sealed silicon rubber	1
14	Machining copper flange with tube pipe connector	1
15	Vacuum tube pipes (diameter = 8mm, length = 4m)	1

3.2 Experimental Procedure for Thermionic Emission

3.2.1 Constructing the Vacuum Glass Tube

The main component for emitting electrons from metal by using thermionic emission method is vacuum glass tube. In this research, glass tube with cylinder shape was constructed by cutting bottom edge of the glass bottle. The length of the glass tube is 16 cm, bottom end of the glass tube diameter is 8 cm with 0.3 cm thickness and the other small end is 2.6 cm diameter. The vacuum glass tube needs only be large enough

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to contain the bias collector plate (stainless steel), four terminals for filament and temperature sensor. The filament is situated face to face with collector plate. Outside back end of the glass tube is closed with 1 inch thickness acrylic circular shape flange and it was used in order to make good insulation and clean view also easy to machining for desire shape. It has four terminals for electrical feed through and opposite small end is closed with copper stopper which is also directly connected with vacuum pump and collector plate. So (+) bias voltage is applied to copper end or one of three reinforce frame of the glass tube which are also directly contact with copper stopper. Both side ends of the glass tube are sealed with silicon rubber gasket to obtain required vacuum condition. Constructions steps of the vacuum glass tube are shown in Figure 3. The overall construction was done at workshop in our department.

Figure 3: Construction of vacuum glass tube (a) Machining glass bottle (b) Side view of after cutting glass bottle (c) Back end view of the glass bottle (d) Machining acrylic flange (e) Internal terminals with acrylic flange (f) External terminals with acrylic flange (g) Machining copper stopper (h) Copper with silicon rubber gasket (i) Acrylic flange with silicon rubber gasket and copper stopper (j) Collector plate spot weld with screw rod (k) Assembly of collector plate and copper stopper (l) Complete assembly of vacuum glass tube for thermionic emitter

3.2.2 Experimental Setup

The experimental set up requires a filament (tungsten) and bias plate to be in vacuum. This necessitates the use of electrical feed throughs from atmosphere to vacuum. This experiment used a five port electrical feed through. Two ports for DC power supply and another two ports for positive and negative terminal for thermocouple to determine temperature. The other one is copper stopper itself or any one of three reinforcement rods are bias supply and fastening device for cylinder shape glass tube to maintain vacuum. The filament assembly is then screwed to two electrical feed through. A collector steel circular shape plate is 6.2 cm in diameter and 0.1 cm thickness. The collector plate is spot weld together with screw rod which is support for collector plate and screwed to copper stopper. This collector plate will be used as the bias plate. The plate will be positioned face to face with the filament and will be attached to steel rod and copper stopper which will be used to positively bias the plate and additional physical support.

When general assembly is completed with the bias plate, filament and glass tube are checked to ensure there is no electrical contact between them. Once this is accomplished, the chamber is evacuated. The quality of data increases as the pressure drops. First, vacuum condition of the chamber must be tested. In this paper, the vacuum pumped down to approximately -746 mmHg in 10 minutes. Several vacuum tests were done to ensure no leakage of air. Vacuum chamber must be withstanding the pressure and completely seal is important and so vacuum test for vacuum glass tube is the important first step for entire research. To get absolute seal, silicon rubber gasket with high pressure grease was used.

In this experiment, two DC power supply are needed - one for filaments power supply which has variable 1 to 100 V, 50 Amp and other for positive bias supply which has four variable voltages (150V, 300V, 450V and 600V) with one ampere. Filament power supply is available at laboratory and bias supply is made by us. The complete assembly for this experiment is shown in Figure 4 and bias supply circuit is shown in Figure 5. An ammeter with milliampere range is placed in series between the bias plates to the bias plate's DC power supply. When thermionic emission is occurred the electron from filament are escaped and strike to the nearest surface of positive bias supply plate or collector plate. This ammeter allows the collection of electron emission current data. The experimental setups are shown in Table 2.

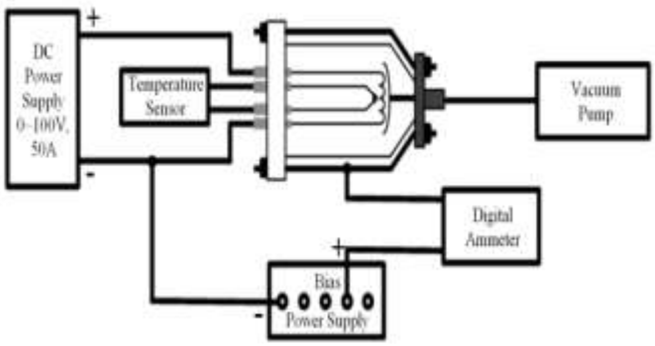

Figure 4: Diagram of experimental setup

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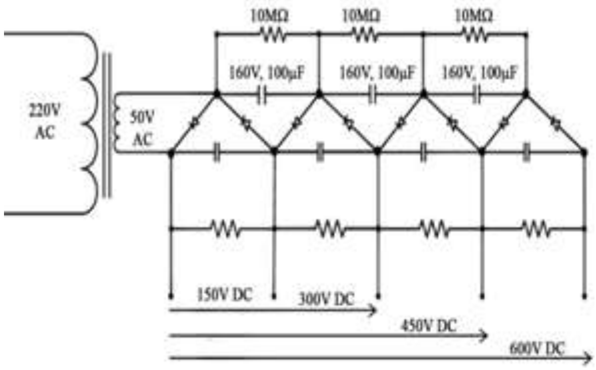

Figure 5: Circuit diagram of bias power supply

Table 2: Experimental setup

No. of Experiment	*Conditions*	
	Vacuum Condition	*Filament*
1	-746 mmHg	0.25 mm wire diameter single straight, length 40 mm
2	-750 mmHg	0.25 mm wire diameter single straight, length 40 mm
3	-752 mmHg	0.25 mm wire diameter single straight, length 40 mm

3.3.3 Experiments

First, tungsten wire with 0.25 mm diameter, single straight and length is 40 mm was used as filament. In this test, when vacuum pressure reached at (-746 mmHg or -746 torr) and the voltage for emission test was 1 to 10 volts DC . The bias voltage was +450 volts DC. During the test, small amount of emission current were occurred at 2 volt and when voltage reached to 10 volt the emission current was obtained some suitable amount of 73.3 mA.

Second, same tungsten wire was used as filament. The voltage feed to filament was same in all experiment 1 to 10 volts DC. The bias voltage is also +450 volt DC. The vacuum pressure in this experiment was (-750 mmHg or -750 torr). At that vacuum pressure, the emission was occurred at 2 volt but the amount is more than the first experiment is about 2.67 mA. When the voltage reached to 10 volt the emission current was obtained some good amount of 94.56 mA. It was seen that the variation in this experiments were only vacuum condition so the vacuum condition and emission current are inversely proportional when the vacuum was decreased the emission current was increased. It must be sure so we took another third experiment.

Third, same filament and same shape was used as filaments. The other facts such as supplied voltages and bias voltage were same but vacuum pressure was (-752 mmHg or -752 torr) that was the maximum vacuum obtained for this experiments. There were no emission current in 1 volt. At 2 volt 2.77 mA were occurred and then after increasing the voltage the emission current were gradually increased and at 10 volt 99.67 mA were obtained and it was the highest emission current at 10 volt of all experiments. After 10 volt, filament was too bright and glass tube chamber became very hot. Bias voltage was also decrease when emission current increase because the constructed bias voltage supply was no enough ampere for over 10 volts of main filament supply. All experiments are operated without measuring the temperature of the filaments because emission current depends on temperature were achieved previous research papers where vacuum pressure was constant.

4. Results and Discussions

Vacuum test result of the glass tube was shown in Table 3. Vacuum pump using in this experiment is 220V, 50Hz, 550W pumping rate 14.4 m^3/hr made by China. Vacuum pressure (-746, -750, -752 mmHg) were applied in this research work. After attaining 752mmHg, there was no change in pressure gauge even though pumping was continued for one hour. Vacuum pressure at -752 mmHg is the optimum pressure for experiment because longer the pumping time will result more heat in the pump.

In some literature review, oxide coated tungsten or throated tungsten is used as filament to get good thermionic emission since it has high melting point and low electrical resistance. In this experiment, throated tungsten is not available in our country and so pure tungsten was used as filament. Although the best condition for thermionic emission for generation of electrons was not obtained, the experiment gave some experiences and ideas for further research work.

Table 3: Vacuum test result of the glass tube

Time (minute)	*Vacuum Pressure (mmHg)*
1	-720
3	-730
5	-736
7	-740
9	-744
10	-746
15	-750
20	-752

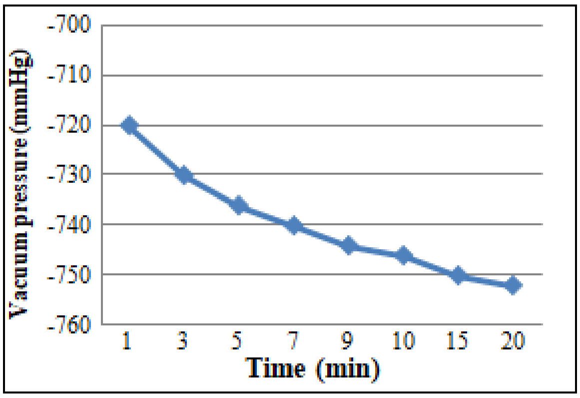

Figure 6: Vacuum condition change with the pumping time

Figure 6 shows the vacuum conditions is changed with the pumping time. Moreover, the changes in vacuum pressure can also control the emission of current. The results of the experiments were mentioned in Table 4 and it can be found that supply voltage is main source for current emission. So the primary DC power supply (100V, 50A) could give enough voltage and ampere to filament. Also bias power supply must be modified to get stable constant bias voltage. It was also noticed that the resistance of the filament is not very important for this experiment. In theory, it is mentioned that the resistance across the feed through leads is 22 ohms.

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Based on the results obtained from the experiment, third experiment could give the highest emission current up to (99.67) mA. If vacuum tube's vacuum condition is good and strong enough to withstand the heat, the higher emission current would be collected. Complete setup picture of during the experiment three of vacuum pressure at (-752 mmHg) were shown in Figure 7. Figure 8 shows the variation of emission current with vacuum pressures. It can be seen that the relationship of supply voltage and emission current graph gives similar trend so this experiment were according to the theoretical background.

Table 4: Result of thermionic emission tests on tungsten filaments

Experiments	Voltage Supply (V)	Bias Voltage (V)	Vacuum Pressure (mmHg)	Emission Current (mA)
1	1	+450	-746	0
	2	+450	-746	0.0218
	3	+450	-746	0.9390
	4	+450	-746	2.1350
	5	+450	-746	5.5800
	6	+450	-746	6.3400
	7	+450	-746	19.920
	8	+450	-746	41.750
	9	+450	-746	59.370
	10	+450	-746	73.300
2	1	+450	-750	0
	2	+450	-750	2.6700
	3	+450	-750	8.4500
	4	+450	-750	12.630
	5	+450	-750	19.423
	6	+450	-750	23.680
	7	+450	-750	45.210
	8	+450	-750	71.231
	9	+450	-750	85.643
	10	+450	-750	94.560
3	1	+450	-752	0
	2	+450	-752	2.7700
	3	+450	-752	9.5500
	4	+450	-752	15.430
	5	+450	-752	23.560
	6	+450	-752	28.470
	7	+450	-752	50.583
	8	+450	-752	78.691
	9	+450	-752	89.343
	10	+450	-752	99.670

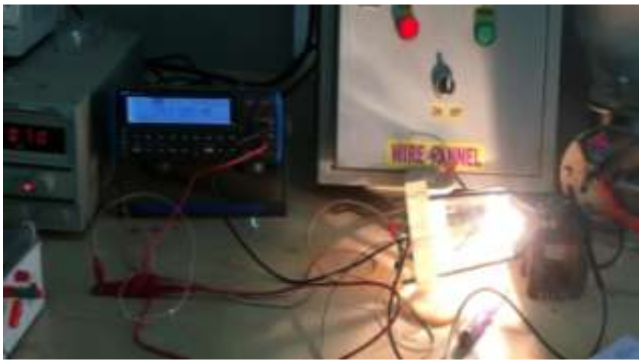

Figure 7: Picture of during the experiment of vacuum pressure at (-752 mmHg)

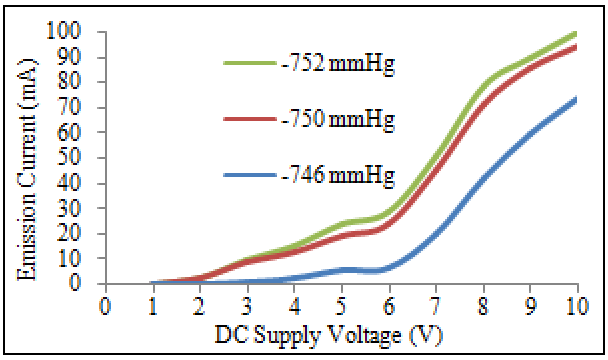

Figure 8: Emission current change with vacuum pressure

5. Conclusions

The constructed vacuum glass tube can give required vacuum condition for thermionic emission. It was achieved suitable vacuum condition of (-746, -750 and -752 mmHg) respectively and emission current from filament is (73.3, 94.56 and 99.67 mA). But it still needs high performance vacuum pump for better vacuum condition because better vacuum gives better emission current. Some research papers were using a Varian M-4 diffusion pump backed by a roughing pump. The diffusion pump is theoretically capable of reaching an ultimate vacuum of 10^{-9} torr and pumping a volume of 1000 liters/second.

Moreover, some of the vacuum glass tube design errors were found during experiments and current design should be modified for better vacuum condition and resistance of the heat. Finally, the research is first step and it can give for modified thermionic electron emitter.

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