CHAPTER 3

DESIGN, DEVELOPMENT AND EVALUATION OF CATHODE HEATER ASSEMBLY OF A 42GHZ 200KW GYROTRON*

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3.1 Introduction

The electrical and mechanical design of MIG has already been described in Chapter 2. In the present Chapter 3, the cathode-heater assembly which is used in an electron beam source of the gyrotron, MIG will be developed. The heater is used for heating the cathode and this cathode act as the warehouse of electrons and is basically electrons emitter. The cathode of a gyrotron is typically a conical ring shaped structure, which helps in the formation of the hollow or annular electron beam and works under the temperature limited condition. The most common thermionic emitters are tungsten, LaB_6 cathode, oxide cathode, dispenser cathode, scandate cathode and thorium-based cathode [Singh *et al*. (2012)**].** Dispenser cathode is preferably used in the present gyrotrons due to better life and performance of cathode. The annular ring shaped cathode is made of the tungsten pellet impregnated with suitable active material for electron emission and is backed by a toroidal shaped heater to supply thermal energy for the electron emission. The heater is usually made up of wire of tungsten-(3%) rhenium material.

Cathode-heater assembly is employed in a gyrotron electron beam source, that is, in magnetron injection gun (MIG) which is an important subassembly of the gyrotron and used to provide the proper annular electron beam as required for the electron beam and RF wave interaction. The MIG consists of two major subassemblies; (i) cathode-heater subassembly for obtaining the electron beam emission and (ii) anode-cathode system for accelerating the emitted electron beam towards the interaction region.

The functioning of MIG mainly depends upon the good uniform emission of the electrons which further depends upon the cathode heater subassembly. The design study of cathode-heater subassembly is carried out in detail and elaborated in this Chapter 3 as Section 3.2. The developed cathode-heater subassembly is described in Section 3.3. Further, the developed cathode-heater subassembly is tested to determine the cathode surface temperature independently in a bell jar system and also in the complete magnetron injection gun (MIG) assembly (Section 3.4). In MIG system, the cathode-heater subassembly is characterized under two situations, namely, (i) MIG processing (Sub-section 3.4.1) and (iii) MIG testing (Sub-section 3.4.2), respectively.

3.2 Design of the Cathode-Heater Assembly

Cathode-heater assembly consists of a cathode pellet backed by a suitable heater. With the application of the electrical power to filament heater, the cathode pellet is heated and electrons gain sufficient thermal energy to overcome the work function barrier. The emitted electrons are immediately accelerated towards the cavity with the desired beam properties due to negative biasing of the emitting cathode with respect to the hollow anode. The filament current and cathode surface temperature can be adjusted by varying the potential of heater power supply. The cathode dimensions for a 42 GHz gyrotron, particularly, cathode radius, cathode width (slant length) and cathode angle, are designed during the design of the MIG (Chapter 2). The designed values of cathode radius, cathode width and cathode angle are found as 22.5 mm, 07 mm and 28^o, respectively (Table 2.2). Obviously for the support of cathode the upper and lower supports were used on special shaped cathode with the inserted filament heater. Fig. 3.1 shows a schematic of cathode-heater assembly with all the relevant piece-parts.

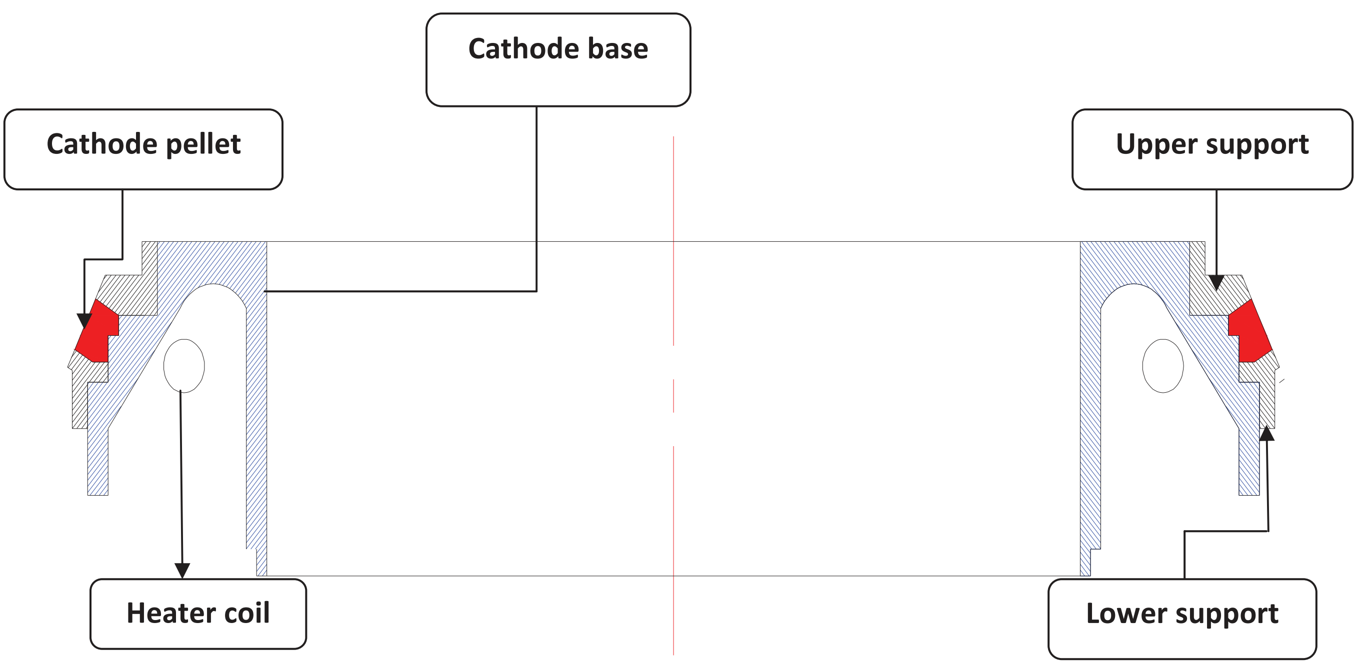

Fig. 3.1: Schematic of the cathode-heater assembly of a 42 GHz gyrotron.

3.2.1 Design optimization through thermal simulation

The heater inserted inside the cathode base is normally potted, that is, fixed with the alumina powder for the sake of rigidity of heater filament through a heating process known as sintering. The assembly dimensions including thickness and material are optimized through thermal analysis with the help of the commercial software ANSYS.

Design optimization is a process of reaching the best output whilst minimizing the use of resources and performance may vary by changing one of many input parameters. Thus, in design optimization, first step is to correlate input and output parameters by performing sensitivity analysis to determine key parameters which greatly influence performance. Next step is to understand a particular response of the system due to variation of key variables.

The input AC voltage is applied across the heater to optimize the design. The simulations are carried out for cathode heater assembly at different input voltage, heater turn diameter, heater wire diameter, number of turns, etc. as well as heater materials. On the basis of simulation results, tungsten is selected as the heater material due higher melting point and better thermal conductivity, The cathode made of tungsten pellet is indirectly heated by heater, whereas the cathode upper support and cathode lower support are directly in contact with the cathode. The heater is made up of tungsten wire whereas the rest of the parts are made up of molybdenum. List of piece-part materials used in cathode-heater assembly is given in Table 3.1. Table 3.2 shows the material properties of piece-part materials used during the thermal analysis.

Table 3.1: Type of materials used in cathode heater

Parts	**Toroidal heater**	**Cathode base**	**Upper support**	**Lower support**	**Cathode pellet**	**Potting material**
Material	Tungsten	Molybdenum	Molybdenum	Molybdenum	Tungsten	Alumina

Table 3.2: Properties of material at 300 K

Material with melting temperature	**Density (Kg/m^3)**	**Thermal conductivity (W/mK)**	**Specific heat (J/KgK)**	**Thermal expansion coefficient (1/K)**	**Young's modulus (Pa)**	**Poisson's ratio**	**Electric resistivity (x m)**
Molybdenum (2,623°C)	10,200	100	251	4.8 x10^{-6}	2.26x10^{12}	0.31	5.34 x10^{-8}
Tungsten (3,422°C)	19,300	173	133	4.5 x10^{-6}	2.80x10^{12}	0.28	5.68 x10^{-8}
Alumina 96% (2,073°C)	3,890	25	880	8.2 x10^{-6}	2.08 x10^{12}	0.21	1.00x10^{-16}

The annular shape M-Type Dispenser cathode pellet is used in the cathode heater assembly and toroidal shaped helix type heater filament for uniform heating of gyrotron cathode for a 42 GHz, 200 kW gyrotron, is shown in Fig. 3.2 [Kumar *et al*. (2012)]. The cathode pellet is made of porous tungsten impregnated with Ba-Ca-Aluminates. The cathode pellet surface is coated with Os-Ru to minimize the work function. The heater coil is made of tungsten and of toroidal shape having negligible inductance value. The heater is potted with alumina for good thermal efficiency and mechanical strength. The cathode-heater assembly based upon indigenous design is procured from M/s Semicon, US and is used in the MIG assembly.

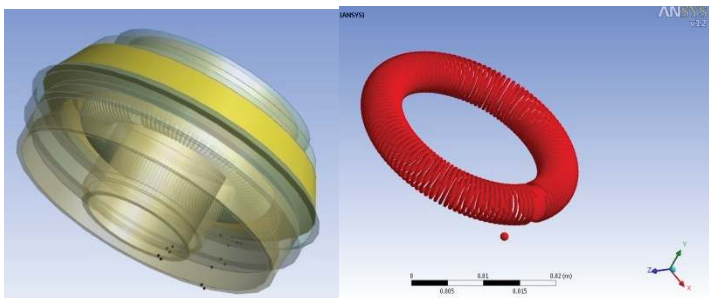

Fig. 3.2: Annular shape M- Type dispenser cathode pellet used in cathode heater assembly and toroidal shaped helix type heater filament for 42 GHz, 200 kW gyrotron.

The heater filament voltage is given as input for tungsten and molybdenum as heater material, respectively, during the thermal analysis carried-out for cathode-heater assembly using ANSYS code. The heater current for a heater voltage depends upon the load, that is, heater filament diameter (cross section), number of turns, thickness, material, etc. The effect of heater turns number, diameter, etc. are also carried out. Some of the typical results obtained from thermal analysis are presented in Figs. 3.3-3.6. The simulated results for tungsten and molybdenum filaments are shown in Figs. 3.3 and 3.4, respectively. The filament heater temperature (THF), the cathode surface temperature (TC) and the filament heater current (IHF) are found to increase with the increase of the heater voltage for both tungsten and molybdenum filaments (Figs. 3.3 and 3.4). The linear increase of filament heater current (IHF) increases the filament power yielding the increase of heat flux and thus increase of filament heater temperature (THF), cathode surface temperature (TC). From Figs. 3.3-3.4, it is clear that the cathode temperature above 1000^{o}C is possible only with the filament power equal to 220W and 180W for tungsten and molybdenum filaments, respectively. The low input power for molybdenum filament is due to low resistivity value of molybdenum compared with that of tungsten.

Figs. 3.5 and 3.6 present the variation of the filament heater temperature (THF), the cathode surface temperature (TC) and the filament heater current (IHF) for tungsten as filament heater, with respect to the number of turns and filament heater diameter (cross section), respectively. Fig. 3.5 clearly shows that the filament heater power decreases with the increase in number of turns at the applied filament voltage, 12V and thus the cathode surface temperature is also reduced. Similarly, the cathode surface temperature reduces with increase in each turn diameter of the toroidal shape filament heater at 12V (Fig. 3.6). This is due to fact that the increase in number of turns and turn diameter increase the effective length and resistance of the filament heater. Thus, the cathode surface temperature is reduced as the increase in resistance decreases the current flowing through the filament heater at the given applied voltage yielding reduced filament heater power.

The toroidal shaped heater made of tungsten is finally optimized for the best performance. The optimized dimensions of filament heater are heater wire diameter, heater helix diameter, heater helix pitch, toroidal heater position diameter are 0.75mm, 4.00mm, 1.5mm and 33mm, respectively. The toroid heater position diameter is the diameter of a circle around which the filament heater is supposed to be positioned so that the filament heater is in contact with the cathode base.

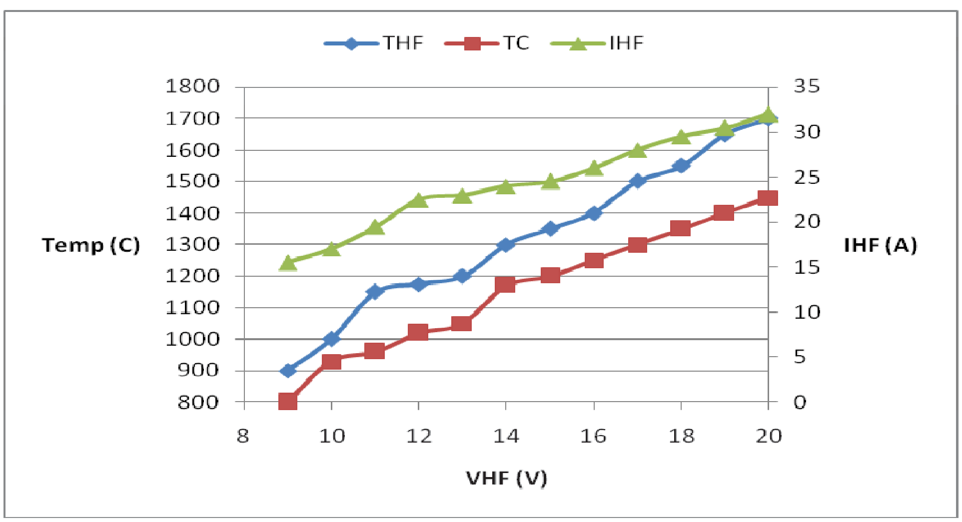

Fig. 3.3 : Heater (THF) and cathode (TC) temperature (deg C) with respect to heater voltage (VHF) and heater current (IHF) for tungsten as filament heater material [number of turns= 140, filament diameter = 6 mm, wire diameter = 0.5 mm].

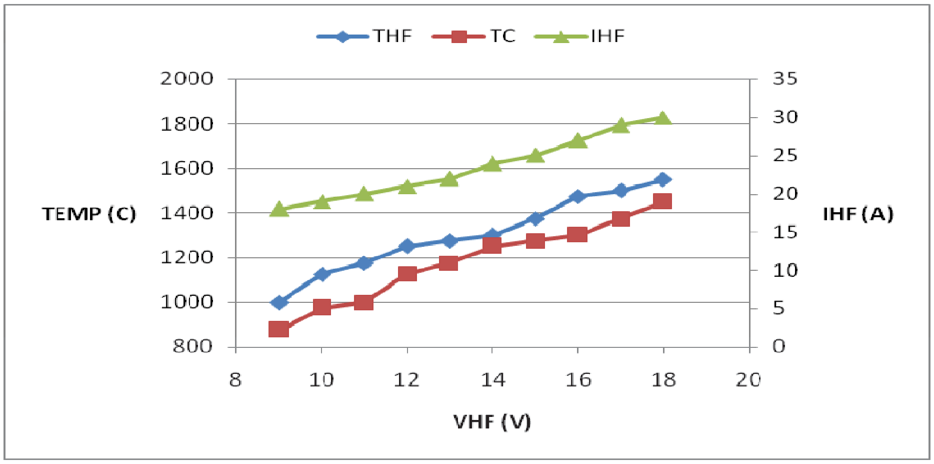

Fig. 3.4: Heater (THF) and cathode (TC) temperature (°C) with respect to heater voltage (VHF) and heater current (IHF) for molybdenum as filament heater material [number of turns = 140, filament diameter = 6 mm, wire diameter = 0.5 mm].

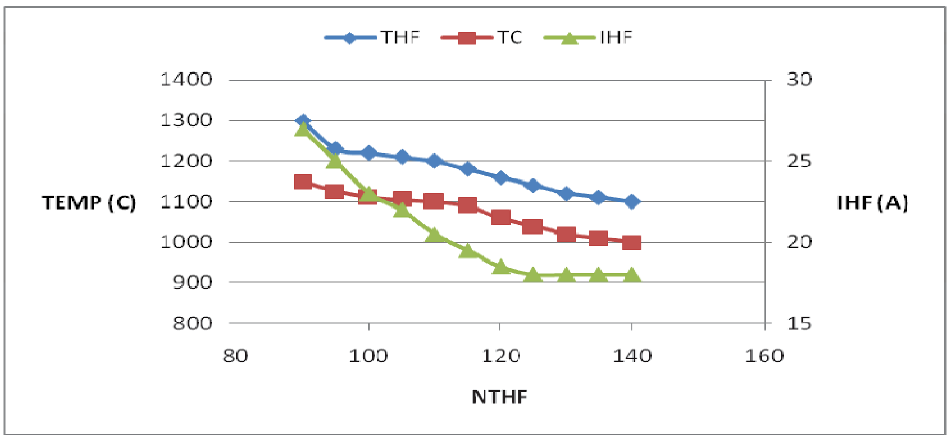

Fig. 3.5: Heater (THF) and cathode (TC) temperature (°C) with respect to number of turns (NTHF) and heater current (IHF) for tungsten as filament heater material.

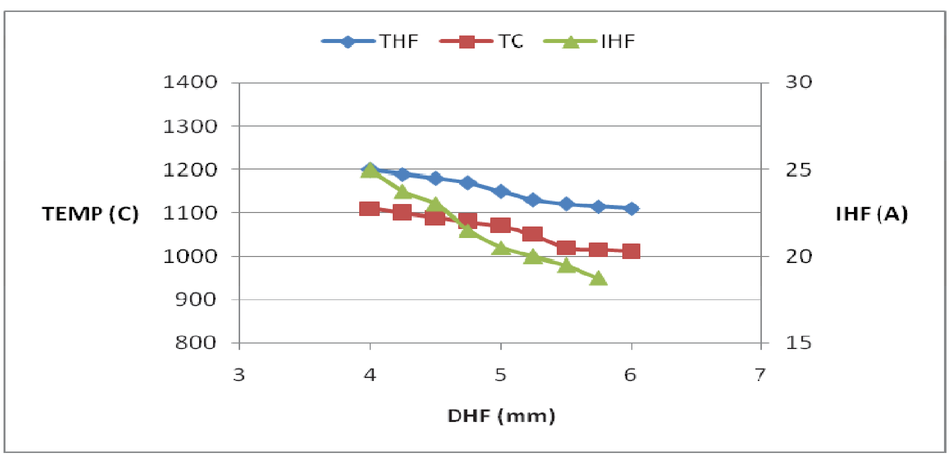

Fig. 3.6 : Heater (THF) and cathode (TC) temperature (°C) with respect to diameter of heater filament (DHF) and heater current (IHF) for tungsten as filament heater material [number of turns = 140, wire diameter = 0.5 mm, filament heater voltage =12 V].

3.2.2 Development of cathode-heater assembly

The functioning of MIG mainly depends upon the good uniform emission of the electrons which further depends upon the cathode heater assembly. The successful design of the cathode-heater assembly is carried out for use in magnetron injection gun for a 42 GHz, 200 kW gyrotron. For the sake of confidence and time constraint, the designed cathode-heater assembly developed by M/S Semicon, US as per design carried out at CEERI and then supplied to CSIR-CEERI. The cathode-heater assembly is used and found as per design; and thus properly used to make the gun-collector module. It is of interest to mention here that cathode pellet is also procured from M/S Semicon for the sake of study (Fig. 3.7). Cathode pellet can also be clearly seen in a cathode-modulating assembly (Fig. 2.10).

Fig. 3.7: Cathode pellet procured from M/S Semicon, US.

Table 3.3: Some typical measured data of procured cathode pellet

[A: inner diameter on top surface, B: outer diameter on top surface, C: inner diameter on bottom surface, D: outer diameter on bottom surface and E: Height of the cathode pellet]

Angular position (deg)	Value of A (mm)	Value of B (mm)	Value of C (mm)	Value of D (mm)	Value of E (mm)
0	36.347	41.810	38.989	48.365	7.233
45	36.331	41.800	38.986	48.372	7.220
90	36.322	41.806	38.993	48.365	7.228
135	36.327	41.795	38.980	48.379	7.230
180	36.337	41.816	38.987	48.343	7.223
225	36.326	41.819	38.984	48.356	7.195
270	36.330	41.814	39.000	48.365	7.238
315	36.328	41.795	38.985	48.371	7.230
360	36.328	41.817	38.985	48.374	7.220
Average	36.331	41.808	38.998	48.365	7.224
Design Value	36.30 ± 0.05	41.80 ± 0.05	39.00 ± 0.05	48.40 ± 0.05	7.20 ± 0.05

Various dimensions of cathode pellet has been measured with the help of a microscope having least count equal to 1micron, that is, 0.001mm. Some typical data are presented in Table 3.of the cathode pellet is fabricated as per design values of CEERI and, the cathode-heater assembly is also dimensional checked and found satisfactory.

3.3 Characterization of Cathode-Heater Assembly in Bell-Jar System

The procured cathode-heater assembly is tested independently at CSIR-CEERI, Pilani, in a bell-jar system to ensure the required rise of cathode surface temperature for the pre-set heater power (Fig. 3.8). For this purpose, the mounting jigs and fixture are designed and fabricated for mounting of cathode-heater assembly in the bell-jar system. The system has a turbo pump which brings the vacuum down to 1×10^{-6} Torr after baking for 30min. using a internal heater. The system is fitted with argon injection facility with a fine leak valve. A partial argon atmosphere is used to ensure that the cathode is not poisoned when heated. After mounting the assembly in vacuum bell-jar, at first, low heater voltage equal to 2.5V is applied and cathode surface temperature is observed with the help of thermal pyrometer. Fig. 3.9 shows a typical temperature measurement of cathode in the bell-jar system. For thermionic cathodes, the uniformity of the beam is determined by the uniformity of the cathode surface temperature. The disappearance filament type pyrometer is used to measure the temperature of cathode all around 360^{o}. Then, the heater voltage is increased slowly in steps upto 9V (Fig. 3.10). At each step of heater voltage increment, vacuum of the chamber is observed and found in 10^{-4} Torr in presence of argon. Besides, a sufficient time is provided at each step to reach temperature stability. It is found that the cathode temperature equal to 1080^{o}C is achieved with the heater power < 350W.

3.4 Characterization of Cathode-Heater Assembly in Gun-Collector Module

The complete gun-collector module is developed (Chapter 6). In this system, the same cathode-heater assembly procured from M/S Semicon, US is successfully used in the actual magnetron injection gun (MIG) assembly designed for the 42GHz, 200kW gyrotron (Chapter 6). The gun-collector module is required to be vacuum processed and then tested for electron beam emission. Thus, to see the performance of the cathode, in particular, cathode-heater assembly is also characterized in the complete gun-collector module in two stages during vacuum processing (Section 3.4.1) and MIG testing (Section 3.4.2), respectively.

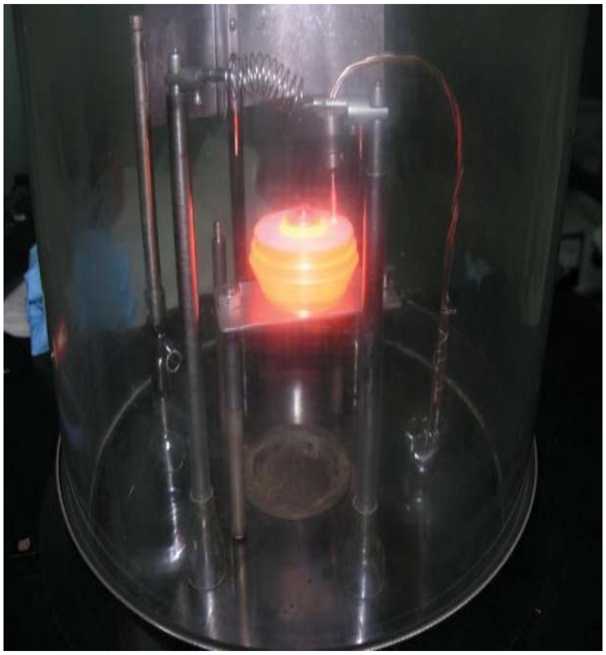

Fig. 3.8: V-I Characterization set-up for cathode heater assembly in bell-jar system.

Fig. 3.9: Temperature measurement of cathode in the bell-jar system.

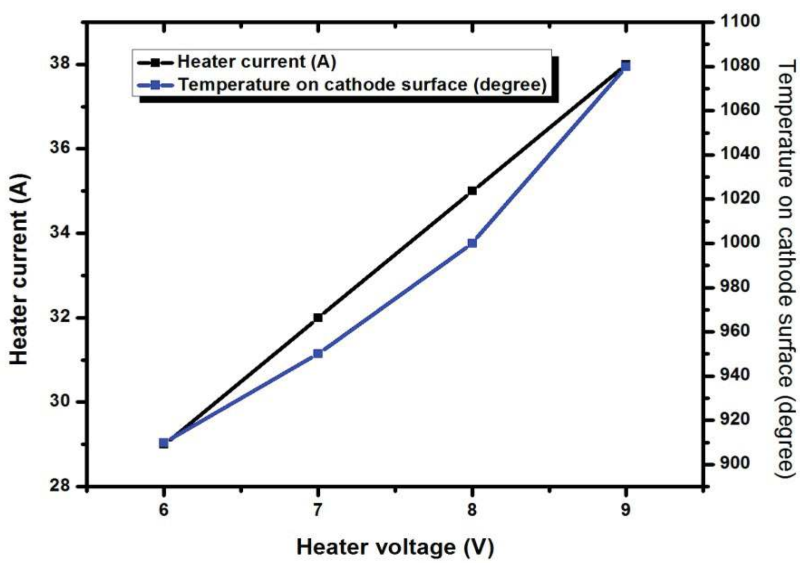

Fig. 3.10: V-I characteristics of heater along with cathode surface temperature in the argon gas atmosphere of pressure $4.35X10^{-04}$ Torr.

3.4.1 Characterization during vacuum processing

The gun-collector module, that is, MIG with test collector got fabricated by using the cathode-heater assembly and other piece-parts through various joining techniques, like, brazing, welding, etc. (Section 6.2). The gun-collector module, that is, the magnetron injection gun

MIG assembly is vacuum processed in the baking system to achieve the good vacuum. The cathode-heater activation is carried out during vacuum processing of MIG (Fig. 3.11). During cathode activation, filament heater voltage is applied and the vacuum inside the device is observed. Normally, with the increase of filament heater voltage, the vacuum of the device gets disturbed to some extent. During this process, the filament heater current is also measured. The filament heater voltage is not increased till the maintenance of vacuum. Here, the heater voltage is also increased slowly in steps upto 9V as carried out during characterization of the cathode-heater assembly in the bell-jar system. At each step of heater voltage increment, vacuum of the MIG is observed and found in the pressure range of 10^{-5} -10^{-4} Torr. The V-I characteristics of heater are shown in Fig. 3.12 which clearly shows that the V-I characteristics during cathode activation are almost the same with those obtained in the bell jar system. Thus, it is concluded that the temperature on cathode surface is above 1000^{o}C.

Fig. 3.11: Vacuum processing of MIG at BEL, Bangalore.

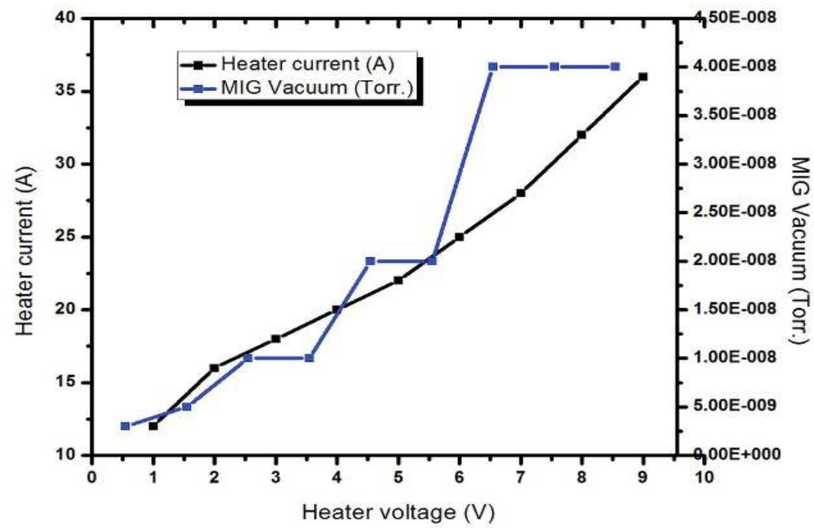

Fig. 3.12: V-I characteristics of heater along with MIG vacuum during cathode activation.

3.4.2: Characterization during MIG testing

The MIG is tested for electron beam generation performance after vacuum processing (Fig. 3.13). During MIG testing, the heater-voltage (V) and heater current (I) characteristics estimates the cathode performance too with respect to the cathode temperature as discussed in previous Sub-section 3.4.1. The V-I characteristics of heater along with tube vacuum is shown in Fig. 3.14. The results are approximately same in three different conditions and the heater wattage is within the design range (< 350 watt).

It is of interest to mention here that the required temperature, that is, above 1000^{o}C is achieved with the heater wattage less than 350W to achieve the beam current 10A in each of three different conditions, namely, (i) in bell-jar system, (ii) during vacuum processing station and (iii) during MIG test, respectively. It was found that the experiments carried out in different situations reproduce almost the same results after several repeated characterizations. Table 3.4 presents a comparative study of heater characteristics in different systems for a typical heater voltage equal to 8V and the results clearly show almost the same value.

Fig. 3.13: Vacuum processed MIG.

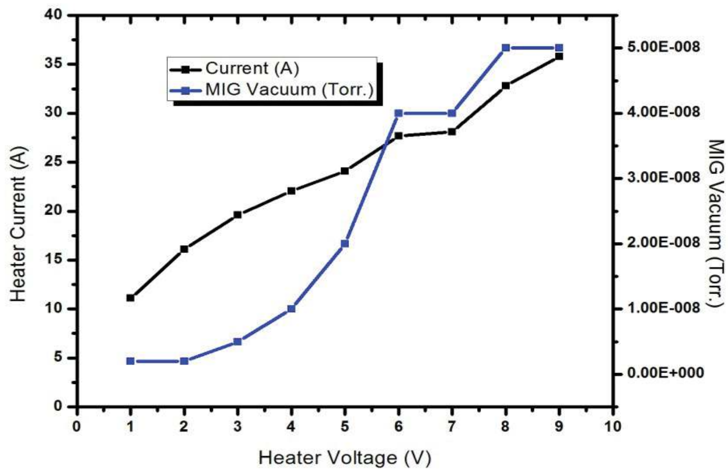

Fig. 3.14: V-I characteristics of heater during MIG testing.

Table 3.4: Comparison of the heater characteristics in different systems.

Particular	Heater Voltage (V)	Heater Current (A)
Bell Jar system	8	35.00
MIG vacuum processing system	8	30.00
MIG testing system	8	30.80

3.5 Conclusion

The cathode-heater assembly has been designed and developed in-house as well as also procured from a reliable global vendor M/S Semicon, US. Afterwards, the cathode-heater assembly has been subjected to evaluations, particularly to see that the evaluation of cathode parameter on the basis of heater power. The evaluations have been carried out in two situation, namely, cathode-heater assembly independently in a bell-jar system and also in gun-collector module, in which the same cathode heater assembly has been integrated. In the gun-collector module which is basically gun-collector module, that is, MIG attached with a test collector for keeping vacuum inside the device. Then, cathode evaluations inside MIG have been carried in two situations, namely, during vacuum processing and also during electron beam emission testing stages. It has been found that in all these situations, cathode performance is almost the same.