Thermal and Structural Analysis of Electron Gun Assembly for a C-band 60W Space TWT

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Abstract—Thermal and structural analysis of the electron gun assembly for an in-house designed C-band 60W space Traveling Wave Tube (TWT) has been carried out for optimizing the design of cathode support structure and cathode heat shield. M-type tungsten dispenser cathode of disc diameter 3.20mm has been used. Thermally efficient cathode support structure with heat shield has been designed in order to achieve the required cathode operating brightness temperature (\(\sim 9500\, \text{C}_\text{b}\)) at heater power around 3.5W. Dimensional deformations in the gun assembly due to thermal expansion of various parts of the cathode assembly have been estimated under hot operating conditions. Also, cathode support assembly and heat shield have been designed for their lowest modal frequency more than 1000 Hz, as specified for the space application. Performance of the gun assembly, designed and developed with due considerations for thermal and structural requirements, has been evaluated experimentally. This paper presents thermal and structural analysis of the electron gun assembly for the C-band 60W space TWT

Index Terms- Electron gun, Traveling wave tubes, Thermal and structural analysis.

I. INTRODUCTION

C-band 60W space TWT has been designed, as shown in Fig.1, at CEERI, Pilani and developed successfully jointly with Bharat Electronics, Bangalore. The TWT is used as a high frequency high gain microwave amplifier in a satellite communication transponder. Long life, high efficiency, high linearity and high reliability, are essential requirements for a space TWT. Enhanced life and reliability of a space TWT are achieved through necessary thermal and structural management [1-7]. This includes selection of suitable materials, determination of stable shape and size of the individual components and their integration in a TWT to meet the thermal and structural requirement.

Electron gun assembly as being the hottest component of a TWT, require due considerations for the thermal and structural management in meeting the stringent requirements of a space TWT. Electron gun assembly (Fig.2) has been used to produce a beam of electrons with desired parameters. It consists of a number of components like cathode, cathode heater assembly, and beam forming electrode, heat shield, and anode. The electron gun assembly of the C-band 60W space TWT is thermally and structurally analyzed using code ANSYS [8].

M-type tungsten dispenser cathode of diameter 3.20 mm operating at the lowest possible cathode operating brightness temperature (950\(^\circ\text{C}\)) with lower heater loading (\(\sim 3.5\text{W}\)) has been used in
the C-band TWT for long life [2], [9]. Cathode support structure with heat shield has been designed for thermally efficient cathode and structural ruggedness maintaining the accuracy of the axial and radial dimensions of all electrodes under operating conditions of a TWT [2-3].

Also, the structure with heat shield is designed to have minimum mechanical resonance frequency greater than 1000Hz in order to avoid mechanical failure of the gun assembly due to external vibrations as experienced by a space TWT. Details of thermal and structural analysis of the electron gun assembly are presented for thermally efficient and structurally rugged cathode support structure.

![Fig. 2. Schematic diagram of electron-gun assembly of C-band 60W space TWT showing different parts and their materials.](image-url)

After modeling the gun geometry, the material properties, as shown in Table 1 [10-12], are assigned for each component, then these geometries are converted into meshed geometry (FEM model) [8]. Quadrilateral shaped mesh has been used because of its good accuracy. Localized fine meshing has been chosen in cathode and BFE regions. After creating FEM model, the necessary boundary conditions, i.e., the heater power (3.5W) and ambient temperature (25°C) are applied and all free surfaces are defined as radiation surfaces. The analysis results are reviewed through post processing and temperature distributions have been found at different locations of the electron gun assembly.

II. THERMAL AND STRUCTURAL ANALYSIS OF ELECTRON GUN ASSEMBLY

Thermal and structural analysis of the electron gun assembly for the C-band 60W space TWT has been carried out using code ANSYS and the process flow given in Fig.3. The gun assembly has been modeled on ANSYS with actual dimension.

![Fig. 3. Process flow for thermal and structural analysis of electron gun.](image-url)
Table 1: Material properties used in thermal and structural analysis [11-13]

<table>
<thead>
<tr>
<th>Material</th>
<th>D (Kg/m³)</th>
<th>K (W/m.K)</th>
<th>C (J/Kg.K)</th>
<th>ε</th>
<th>Y (Pa×10⁹)</th>
<th>α (10⁻⁶/C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>19300</td>
<td>173</td>
<td>133</td>
<td>0.52</td>
<td>411.0</td>
<td>4.5</td>
</tr>
<tr>
<td>Mo</td>
<td>10220</td>
<td>138</td>
<td>251</td>
<td>0.20</td>
<td>324.8</td>
<td>5.1</td>
</tr>
<tr>
<td>Fe</td>
<td>7870</td>
<td>80.4</td>
<td>444</td>
<td>0.07</td>
<td>211.4</td>
<td>12.1</td>
</tr>
<tr>
<td>Ko</td>
<td>8360</td>
<td>24.5</td>
<td>649</td>
<td>0.15</td>
<td>14.1</td>
<td>4.81</td>
</tr>
<tr>
<td>Cu-Ni</td>
<td>8900</td>
<td>19.5</td>
<td>400</td>
<td>0.43</td>
<td>162.0</td>
<td>14.9</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>3690</td>
<td>18.0</td>
<td>880</td>
<td>0.9</td>
<td>300</td>
<td>8.1</td>
</tr>
</tbody>
</table>

D =Density (Kg/m³), K=Thermal conductivity (W/m.K), C=Specific heat (J/Kg.K), ε=Emmissivity, α=Thermal expansion co-efficient (10⁻⁶/C), Y=Young’s modulus ((Pa×10⁹)), W=Tungsten, Mo=Molybdenum, Fe=Soft iron, Ko=Kovar, Cu-Ni=Monel, Al₂O₃=Alumina (94%)

Cathode support structure and heat shield have been made of molybdenum and designed to provide minimum thermal drain from the cathode and to hold cathode and heat shield firmly for first mechanical resonance frequency more than 1000Hz [2], [9]. Thin metallic molybdenum cylinder of thickness 0.05mm has been used as cathode heat shield to shield the heat energy in cathode region [3-4]. Beam forming electrode (BFE) has also been thermally isolated from the cathode to reduce thermal drain from the cathode through conduction. The temperature distribution in different locations of the gun assembly has been obtained by steady state thermal analysis.

Fig.4(a) shows axi-symmetric ANSYS model for the gun assembly of C-band 60W Space TWT. In this assembly, cathode is held from the cathode base, as also shown in Fig.2. For comparison, another gun assembly in which cathode is held from the cathode sleeve (Fig.4(b)) has also been analysed. The temperature distributions at different locations in both the cases are compared in Table 2. It has been found that, for the rated heater power (3.5W) and ambient temperature (25°C), cathode temperature is obtained only 965°C for the gun configuration holding cathode from top (Fig.4(b)), while the cathode temperature has gone to 1020°C for the gun configuration holding cathode from bottom(Fig.4(a)). Therefore, the gun configuration of holding cathode from bottom (Fig. 2) has been used in the TWT as this configuration found to be relatively more thermally efficient.

The effect of heat shield thickness has been studied by analyzing the steady state cathode temperature for different thickness of the heat shield made of molybdenum. As shown in Fig. 5, the cathode temperature decreases with the increase of the heat shield thickness. It shows that the thermal drain is increased with the increase in the heat shield thickness [4-5]. Therefore, heat shield of 0.05mm thickness found optimum and finally used. To ascertain the effectiveness of the heat shield, transient analysis of the gun structure has been carried out with and

![Fig.4. Axi-symmetric view of electron gun configuration (a) holding cathode from the bottom, (b) holding cathode from the top (A: Cathode surface, B: Heat shield, C: BFE, D: anode, E: cathode support, F: Cathode support base).](image-url)
without the use of heat shield for the same heater power and the sink temperature. The cathode temperature for these two cases at different point of time is shown in Fig. 6. It can be seen that with the use of heat shield, cathode temperature 1020 °C level is reached within 180 seconds while without heat shield the required cathode temperature could not be reached even after 300 seconds.

Fig. 5. Effect of heat shield thickness on cathode thermal loading.

Structural analysis has been used to estimate the dimensional deformation of the electrodes due to thermal expansion in radial as well as axial directions. The changes in inter-electrode distances in hot operating conditions are summarized in Table 3. The margins for the expansions of parts have been kept in the cold design of assembly so that desired inter-electrode distances can be achieved under the actual operating conditions.

The modal analysis has been done to find out the natural frequencies of the electron gun assembly. Results of modal analysis for the first five modes of vibration are given in Table 4. The lowest resonance frequency of the gun corresponding to cathode along with its support structure found to be 2760Hz. Therefore, gun structure is sustainable to external mechanical shocks for space applications, as first frequency is much greater than 1000Hz [9].

Table 3: Inter-electrode distances in non-operating & operating conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>Axial cathode-anode distance</th>
<th>Radial gap between cathode-BFE</th>
<th>Axial cathode-BFE distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>cold</td>
<td>3.850</td>
<td>0.100</td>
<td>0.150</td>
</tr>
<tr>
<td>hot</td>
<td>3.796</td>
<td>0.096</td>
<td>0.122</td>
</tr>
</tbody>
</table>

Table 4: Modal frequencies of electron gun assembly

<table>
<thead>
<tr>
<th>Mode</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (kHz)</td>
<td>2.7</td>
<td>3.8</td>
<td>8.8</td>
<td>20.7</td>
<td>21.4</td>
</tr>
</tbody>
</table>

III. EXPERIMENTAL EVALUATION OF THE ELECTRON GUN ASSEMBLY

Electron gun assembly for the C-band 60W space TWT has been experimentally characterized in a test diode for cathode temperature and cathode emission characteristics. The complete gun assembly with and without OFHC copper collector was mounted on the UHV pump station and it was baked up to 450°C for 20 hours for getting ultimate vacuum of the order of 10^-9 Torr. The gun assembly without collector was used for measuring the cathode brightness temperature by the optical pyrometer thorough vacuum glass window. Actual cathode temperature has been...
calculated using the following correction formula [12]:

\[
\frac{1}{T} = \frac{1}{S_\lambda} + \frac{\lambda \ast 2.303 \ast \log \varepsilon_\lambda}{C}
\]

Where,

- \( T \) = True temperature \(^0K\)
- \( S_\lambda \) = Brightness temperature in \(^0K\)
- \( C = 14360 \mu \text{deg.} \)
- \( \varepsilon_\lambda \) = Spectral emissivity corresponding to wavelength \( \lambda \), for un-impregnated tungsten pellet (\( \varepsilon_\lambda = 0.52 \)) for \( \lambda = 0.64 \mu \text{m} \)

It is evident from cathode temperature characteristics (Fig. 7), the desired cathode temperature \( \sim 1000^0C \) (corrected) attained at \( \sim 3.5W \) heater power. A comparison of experimental and simulated values of cathode temperature versus heater power is presented in Fig. 7. This endorses the optimum design of cathode support structure and heat shield.

Cathode dip test has also been carried out to examine the cathode emission characteristics of the electron gun assembly. For the dip test, emission drawn at fixed anode potential (e.g. 1.0 kV and 2.0 kV in this case) and heater power brought down in steps from the level typically 50\% more than the rated heater power. The emission current remains almost constant (at the fixed beam voltage) on reducing the heater power before it sharply goes down at certain lower value. The dip-test on this gun (Fig. 8) also confirmed the operation capability of its cathode under space charge conditions at a heater power of 3.5 Watt corresponding to 20\% above the knee of the dip-test curve. The results (Figs. 7 and 8) have thus approved the cathode support design of the electron gun, which is supposed to operate at a lower cathode temperature and heater power from the standpoint of the life of the space-qualified TWT. Finally, the experimental beam voltage (\( V_0 \)) versus beam current (\( I_0 \)) characteristics of electron gun have agreed fairly well with those obtained by simulation [13] (Fig. 9). Also the desired beam current (\( I_0 \sim 75 \text{ mA} \)) has been obtained experimentally at the rated anode voltage (\( V_0 \sim 3.0 \text{ kV} \)).
IV. CONCLUSION

ANSYS software has been used for thermal and structural analysis of the complete electron gun assembly of a C-band 60W space TWT. Thermally efficient cathode-heater support is designed to ensure long life and high reliability of the electron gun and hence the TWT. Operating temperature of 3.20mm diameter cathode is achieved (≈1000°C) with heater wattage 3.5Watts and using suitably designed cathode heat shield. The modal analysis of the structure, has ensured suitability of the designed gun configuration from the standpoint of the avoidance of resonant vibration of the structure below 1000Hz and hence its employment in the space. Temperature and emission characteristics of the electron gun assembly have been evaluated experimentally and the design of the same found to be optimum for the C-band 60W TWT. The desired emission current (75mA) has been obtained at the rated heater power and the beam voltage (3.0 kV). C-band 60W space TWT has been developed successfully jointly with BEL, Bangalore, using the designed electron gun assembly. The developed TWT has met all the electrical and environmental specifications for space applications.

ACKNOWLEDGEMENT

The authors are thankful to the Director, CEERI, for granting permission for publication of this work, to ISAC/ISRO, Bangalore for funding the space TWT project(s), and to BEL, Bangalore for joint development of C-band 60W space TWT. Thanks are also due to their colleagues at CEERI and BEL for helpful interactions and comments.

REFERENCES