Effect of ceramic material on heat dissipation from multi-stage depressed collector used in high efficiency traveling-wave tubes

Vishant Gahlaut1*, R K Sharma1, V Srivastava1, P A Alvi2 & S K Ghosh1

1Microwave Tubes Division, CSIR-Central Electronics Engineering Research Institute, Pilani 333 031, Rajasthan, India
2Department of Physics, Banasthali University, Banasthali, Rajasthan, India

*E-mail: vgceeri@gmail.com, skghosh@ceeri.ernet.in

Received 26 November 2012; revised 19 February 2013; accepted 19 June 2013

To increase reliability, the thermal and structural integrity of a multi-stage depressed collector (MDC) used in traveling wave tubes (TWTs) has been improved. Highly reliable TWTs can be achieved by careful consideration of design requirements and constraints, material selection, weight reduction and cost effectiveness. In a TWT, maximum heat generated in MDC is due to maximum power dissipation and, hence, needs for proper thermal management. In the present paper, the thermal characteristics of MDC for different ceramic insulator materials have been studied.

Keywords: Thermal analysis, MDC collector, Traveling-wave tube

1 Introduction

The increasing need of high power, high efficiency, light weight and highly reliable TWTs for communication system demand better performance from the device. Essentially high power TWTs demand larger amount of input power and, hence, higher amount of power dissipation, mainly, in collector electrodes. In a TWT, high energy electron beam and RF wave interaction takes place under synchronous condition in the interaction region and the former delivers its energy to the latter and the spent electron beam is collected at different electrodes at different depressed potentials, commonly known as multi-stage depressed collector (MDC), to recover spent beam energy for efficiency enhancement. Higher power dissipation in the collector electrodes demands very good packaging for heat dissipation which in turn enhances weight of the TWT. Proper heat dissipation from TWT, mainly from MDC, enhances life and reliability of the TWT. Thus, MDC geometry and temperature-dependent material properties lead to the performance improvement, reduction of weight and longer life of the TWT. In the practical TWT, the multiple electrodes are brazed with ceramic insulators individually and finally brazed into a cylindrical metal envelop1,2 (Fig. 1). Heat generated in collector electrodes due to power loss is drained out through ceramic insulators by conduction mainly due to very high vacuum inside the TWT. However, from outer face of collector envelope, heat dissipation takes place through conduction, convection and radiation and, hence for effective cooling surrounding temperature is also important. If surrounding temperature varies from −20°C to +80°C, heat dissipation from electrodes is affected and these are criterion for space applications. Thus, material property of the ceramic insulators plays an important role in dissipating heat from collector electrodes3-5. A MDC, used in high efficiency TWT, is a complicated engineering structure and temperature distribution of such geometry is of considerable referential importance.

At the present time, methods for thermal analysis are, generally, numerical simulations with commercially available software, like, ANSYS, COSMOS finite element method, etc. With software packages, temperature distribution among the electrodes can be modeled but measurement is not possible, thus, it is very difficult to determine the key parameters of the model. Due to very high vacuum3-7 inside the TWT, thermal dissipation from electrodes occurs to cooling fins and or to base plate by conduction through ceramic insulators. Environment temperature or base plate temperature also affects heat dissipation from MDC as it enhances the thermal resistance between MDC and base plate.

In the present paper, authors have presented temperature distribution at different electrodes under different surrounding base plate temperature conditions, typically, −20°C, +20°C and +80°C for
different electrode and insulator materials. Expansion of individual electrodes and stresses at different joints have been studied and presented. Simulation of MDC has been carried out in COSMOS.

2 Model

In the four stage depressed collector model (Fig. 1) and its thermal model (Fig. 2), it has been considered that the contact between each electrode-ceramic-metal joints is uniform, i.e., thermal contact resistance is negligible. Thermal conductivities of different materials, for each electrode, are in parallel. Finite element algorithm COSMOS is used to simulate the model. Number of mesh points has been increased and mesh size has been optimized to achieve more accurate results. Power loss (W) in each electrode is taken from the output file of EGUN. In simulation, different electrodes materials, like, copper and graphite and different material of ceramic insulators, namely, 94% and 99% alumina have been used.

3 Results and Discussion

Inputs boundary conditions to the thermal model (Fig. 2) for modeling is taken as the spent beam power in different electrodes as 13.5 W, 23.1 W, 19.3 W and 25.9 W in RF condition, respectively, and under dc condition as 2 W, 3.1 W, 2.5 W and 136.4 W, respectively, which are obtained from EGUN design software at an ambient temperature +25°C. Moreover, for simulation it is assumed that braze joints (metal to ceramic) are uniform and have negligible thermal contact resistance as 4.0e-5 K-m²/W and different material properties used are given in Table 1.

It can be seen from Fig. 3, that the ceramic support material has very good effect on heat dissipation from collector electrodes (solid line) and in itself (broken line). With the increase in percentage composition of alumina, thermal conductivity increases and hence heat dissipation from copper electrodes is more. Temperature of electrodes and ceramic insulators is less if it is supported with 99% alumina than 94%. Thus, 99% alumina ceramic is a better choice for better thermal management, however, it is cost effective. Electrode materials commonly used for collector are copper and graphite for very good thermal conductivity and low secondary electron emission coefficient. However, graphite may have low secondary electron emission coefficient than the former but it is very difficult to machine to get required dimensions and also to braze with the metal. For copper electrodes, heat dissipation is faster than graphite (Fig. 4). Moreover, copper can easily be machined and can be brazed easily. Hence, copper electrode is chosen and the MDC is developed for typical applications. Thus, for further simulation copper electrode and 99% alumina are used.

Power loss in each electrode under RF and dc conditions rises temperature of the electrodes and dissipated through fins via ceramic supports (Fig. 5).
Table 1 — Properties of different materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg/m³)</th>
<th>Thermal Conductivity (W/m·K)</th>
<th>Specific Heat (J/kg·K)</th>
<th>Emissivity</th>
<th>Young’s Modulus (N/mm²) × 10¹¹</th>
<th>Thermal expansion (10⁻⁶/°C)</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>8960</td>
<td>401</td>
<td>385</td>
<td>0.25</td>
<td>129.8</td>
<td>17.0</td>
<td>0.343</td>
</tr>
<tr>
<td>Graphite</td>
<td>1800</td>
<td>85</td>
<td>830</td>
<td>0.45</td>
<td>154</td>
<td>11.9</td>
<td>0.17</td>
</tr>
<tr>
<td>Monel</td>
<td>8840</td>
<td>26.04</td>
<td>546</td>
<td>0.06</td>
<td>114</td>
<td>137</td>
<td>0.25</td>
</tr>
<tr>
<td>Nickel</td>
<td>8900</td>
<td>76.2</td>
<td>594</td>
<td>0.19</td>
<td>199.5</td>
<td>13.3</td>
<td>0.312</td>
</tr>
<tr>
<td>Alumina 94%</td>
<td>3690</td>
<td>18</td>
<td>880</td>
<td>0.4</td>
<td>300</td>
<td>8.2</td>
<td>0.21</td>
</tr>
<tr>
<td>Alumina 99%</td>
<td>3900</td>
<td>25-30</td>
<td>880</td>
<td>0.4</td>
<td>350</td>
<td>8.0</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Fig. 3 — Effect of ceramic support material on heat dissipation from copper electrodes (solid lines) and in ceramic insulators (broken line)

Fig. 4 — Effect of electrode material on heat dissipation from itself (copper (solid line) and graphite (line with symbol)) through 99% alumina ceramic supported

Under dc condition, maximum power loss occurs in the 4th electrode and hence temperature increases to a maximum value. It can be seen from Fig. 5 that under stable RF condition, temperature of 4th electrode is less. This may be due to larger contact area with the insulators as compared to other three electrodes. Under stable conditions, maximum temperature measured on the cooling fin is ~ 85°C (RF condition) and ~ 115°C (dc condition). Thus, due to the temperature gradient, stress develops at different joints (Fig. 6) and also expansion of electrodes occurs (Fig. 7). Stresses developed at ceramics to collector
Cylinder joints are more compared to that of ceramic to electrode joints. Collector cylinder is brazed at both ends and made of hard material, namely, monel and it do not have any axial expansion margin and this may be the reason for more stress. But, copper being a soft material expands axially and releases stress (Fig. 7). It can be seen from Fig. 7 that expansion of 4th electrode is maximum and does not cause any inter electrode short-circuit as the inter electrode axial distance is 1.0 mm. Thermal characteristics of MDC have also been studied with different environment temperature conditions under RF, namely, −25°C and +80°C (Fig. 8). However, under the extreme conditions, say, at + 80°C, the temperature in all the collector electrodes is much more as compared to other two conditions i.e., drainage of heat to the surrounding is less.

4 Conclusions

Role of material of collector electrode, ceramic insulator and ambient temperature has been studied with reference to thermal and structural analysis of a MDC used in high efficiency TWT. It has been observed that although 99% alumina is better for efficient thermal management. However, 94% alumina ceramic insulator is found suitable as it is cost effective and also does not affect heat dissipation significantly. Similarly, graphite may be a suitable choice for electrodes due to its low secondary electron emission coefficient and light weight. But copper is selected due to high thermal conductivity and fabrication and brazing simplicity. Due to non-uniform temperature distribution, expansion of electrodes has been studied to avoid internal short-circuit and it has been found that no voltage breakdown or short-circuit occurs. Under extreme operating conditions, the stresses developed at different joints (electrode-ceramic-collector cylinder) do not cause any damage or destruction.

Acknowledgement

Authors are thankful to the Director, CEERI, Pilani, for allowing to publish this work. They are also thankful to Dr S N Joshi and other colleagues for support.

References