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An Analytical Approach for Quick Temperature Prediction of Helix Traveling-Wave Tubes

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Abstract

An analytical approach has been presented in this paper to predict the helix temperature for slow-wave structure (SWS) to analysis the effective heat dissipation relative to helix. On the basis of this model, helix temperature is evaluated with comparison of analytically estimated helix temperature has been compared by ANSYS simulation results. Temperature of helix has been obtained at different power loss on helix.

Keywords; *Thermal analysis, slow-wave structure, traveling-wave tube, thermal contact resistance*

I. INTRODUCTION

In process of TWT, RF signal and the electron beam interacts in the helix SWS and amplified the RF energy. The beam of electron is confined toward the centre of the helix by the focusing structure of PPM. Whereas RF signal becomes amplified inside the beam-wave interaction, the beam of electron comes out unfocused and intercept along the helix. This interception current including the several losses like, circuit loss, loss of resistive, etc, leads loss of power through helix and that will arise the helix temperature [1-7] and causing break down of the TWT. For the average power handling capability of TWT, informal thermal management of helix limits also. The pitch of helix may become twisted and that induces to the disintegration of impedance and efficiency of the device as well as increment in the temperature of helix. Due to oscillation, the characteristic of impedance assists dissemblance of the helix with the coupler and obtained enhanced heat in the SWS and finally destroying the TWT. However, proper heat dissipation is evaluated through helix. Thermal contact resistances (TCRs) must be very lesser at various joints and that should have heat sink (base plate) to dissipate heat properly. According to space application, thermal management problem for TWT became assistant, where reliability, weight and size are analytical concern. For space application, demands efficient heat dissipation without disintegration of its ability over a long period through helix.

The temperature of helix is exhausted through the dielectric support rods. Support rods are fixed symmetrically throughout the helix (Fig. 1(a)), and other side with outer envelope (barrel) [1-7].For both analysis and simulation for heat is dissipated through helix to APBN support rods and this support rods to outside of envelope, the temperature of helix is dissipated in the radial direction only through conduction method and no flow of heat axially has been studied. The TWT has behaved like a high power device in which the provided power is dissipated by conduction appearances while the heat is dissipated and can be neglected through radiation of electromagnetic waves in travelling wave tube device. The Conduction of heat from helix to outside

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of envelope depends on a thermal resistance model of the slow wave structure (Fig. 1(b))[8-9]. The model of thermal resistance consists of parallel and series arrangement of thermal contact resistances (TCRs) of helix to three support rods and support rods to metal envelope [10].

In this analytical approach, helix temperature has been investigated heuristically through sections of effective resistances of the various joining materials is presented. Thermal contact resistance of individual materials, for helix, APBN support rod and metal envelope are calculated using material properties given in table-1. The contacts among the helix and support rods are separate cause of the periodicity of the helix SWS. However, the contacts are continuous through support rods to metal envelope. According to the efficient thermal heat dissipation, the contact resistance is very less due to demands of the less contact area in middle of helix and support-rod. Practically, since force fitting (cold stuffing) the support rods in the bundle and the bundle of helix support-rod into envelope of metal are properly sized to obtain 10 µm more outside diameter than inner diameter of barrel.

II. THERMAL ANALYSIS

A. Analysis

Heat transfer by conduction:

In addition to particular properties and different joints, the path of conduction heat consists of several materials. Thus, the path of thermal resistive consists of thermal contact resistance (R_{h-i}) and thermal resistance of the helix (R_h) at joint in middle of helix and support rod, thermal resistance of support rod (R_i), thermal contact resistance (R_{i-e}) at joint through the ceramic and external envelope, thermal resistance of the external envelope (R_e), and thermal resistance of the base-plate (R_b). The temperature (T_o) external base-plate can be evaluated by estimating above thermal resistances in conditions of the electrode temperature (T_i):

Thermal resistance of the helix (R_h) can be given by:

$$R_h = \frac{\ln\left(\frac{r_{ho}}{r_{hi}}\right)}{2\pi L_h k_h} \qquad (1)$$

Where, r_{ho} and r_{hi} are the outer and inner helix radii, respectively, L_h exhibits the axial length of the helix and k_e exhibits the thermal conductivity of helix material.

R_{h-i} exhibits the thermal contact resistance by cause of brazing through helix and support rod and is can be obtained as:

$$R_{h-i} = \frac{1}{h_{h-i} A_{h-i}} \qquad (2)$$

Where, A_{h-i} exhibits the cross-sectional contact area between electrode and ceramic and h_{h-i} exhibits the electrode – ceramic contact coefficient and can be calculated as [12]:

$$h_{h-i} = \frac{1}{L_{h-i}}\left(\frac{A_c}{A}\frac{2k_h k_i}{k_h + k_i} + \frac{A_v}{A}k_v\right) \qquad (3)$$

where, L_{h-i} exhibits the axial contact length through helix and support rod, A_c exhibits the perfect contact area in middle of helix and support rod, A exhibits the contact cross-sectional area through helix and support rod, A_v exhibits the void space area, k_i exhibits the thermal conductivity of support rod (APBN) and k_v exhibits the thermal conductivity of vacuum. As A_c/A increases, the joint comes to be more close to perfect by decreasing the thermal contact resistance at the join. As the ratio of the total cross-sectional area of the contact to the perfect contact area (A_c/A) increases as well as decreases the external temperature of the support rod.

Similarly, thermal resistance of the support rod (R_i), the thermal contact resistance (R_{i-e}) at the interface in middle of ceramic and envelope, thermal resistance of the external cylinder (R_e) and thermal resistance of the base plate (R_b), can be given by:

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$$R_i = \frac{\ln\left(r_{io}/r_{ii}\right)}{2\pi L_i k_i} \quad (4)$$

$$R_{i-e} = \frac{1}{h_{i-e} A_{i-e}} \quad (5)$$

$$R_e = \frac{\ln\left(r_{eo}/r_{ei}\right)}{2\pi L_e k_e} \quad (6)$$

$$R_b = \frac{\ln\left(r_{bo}/r_{bi}\right)}{2\pi L_b k_b} \quad (7)$$

with

$$h_{i-e} = \frac{1}{L_{i-e}}\left(\frac{A_e}{A}\frac{2k_i k_e}{k_i + k_e} + \frac{A_v}{A} k_v\right) \quad (8)$$

Here, r_{io} and r_{ii} are the outer and inner radii of the support rod, respectively and L_i exhibits the axial length of the ceramic, k_c exhibits the thermal conductivity of support rod. A_{i-e} exhibits the cross-sectional contact area in middle of support rod and outside of envelope, and h_{i-e} exhibits the ceramic to envelope contact coefficient. r_{eo} and r_{ei} are the outer and inner envelope radii, respectively, L_e exhibits the axial length of the outer envelope and k_e exhibits the thermal conductivity of outer envelope. r_{bo} and r_{bi} are the outer and inner base plate radii, respectively, L_b exhibits the axial length of the base-plate, k_b exhibits the thermal conductivity of envelope, and L_{i-e} exhibits the contact length between support rod and outer envelope [11].

The individual thermal resistances have series arrangement through the thermal resistive path (Fig. 2). However, the total resistance can be determined as:

$$R_T = R_h + R_{h-i} + R_i + R_{i-e} + R_e + R_b \quad (9)$$

The equation of conduction heat transfer , determined through Fourier's law is as follows:

$$q_{cond} = \frac{\Delta T}{R_T} \quad (10)$$

From the above equations (4)-(13), this temperature is reduced by the convection and losses of radiation. However, the heat conducted to the outer-most surface of base-plate can be determined.

Heat transfer by radiation:

The equation for radiation heat transfer is given by,

$$q_{rad} = \sigma A_o \varepsilon (T_o - T_s)^4 \quad (11)$$

Here, s– Stefen Boltzmann's constant, Ao exhibits same as considered in convection, and e exhibits the emissivity of the base-plate. This equation assumes a large open environment where free-radiation could occur.

The equation of the energy balance at the external surface of the base-plate is given as,

$$P = q_{cond} + q_{rad} \quad (12)$$

Substituting (13),(20) and (21) in (22), and rearranging for To yields a fourth order polynomial in T0, as,

$$T_0^4 + AT_0^3 + BT_0^2 + CT_0 + D = 0 \quad (13)$$

Where,

$$A = -4T_{env}$$

$$B = 6T_{env}^2$$

$$C = -4T_{env}^3 + \frac{h}{\sigma\varepsilon} + \frac{1}{R_T \sigma A_0 \varepsilon} \quad (14)$$

$$D = T_{env}^4 - \frac{h}{\sigma\varepsilon} T_{env} + \frac{T_i}{R_T \sigma A_0 \varepsilon} - \frac{P}{\sigma A_0 \varepsilon} \quad (15)$$

Using Newton-Raphson method, equation (23) has to be solved to evaluate the values of T_0, which gives,

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$$T_{0,n+1} = T_{0,n} - \left(\frac{T_{0,n}^4 + AT_{0,n}^3 + BT_{0,n}^2 + CT_{0,n} + D}{4T_{0,n}^3 + 3AT_{0,n}^2 + 2BT_{0,n} + C} \right) \quad (16)$$

$T_{0,n} - T_0$ at time '*n*', $T_{0,n+1} - T_0$ at time '*n+1*'.

B. Simulation

To simulate the slow wave structure of TWT, FEM based code; ANSYS [12] has been used. All boundary conditions have been applied that suits the actual operation (Fig. 2), also, the external environment is provided for vacuum to suit with the operating condition. The distribution of temperature and the thermal quantities under loading conditions has been predicted by using the steady-state analysis. In the process of analytical model, the three different materials like as tungsten, pyrolytic boron nitride and Monel are used for design the helix, support-rod and outer envelope respectively (Table 1). Input boundary conditions have been applied according to the operating conditions and power loss on helix in 12 watts and ambient temperature is 250C. The Simulation has been obtained by many times for different helix power. In heat flow condition of steady-state analysis, the temperature of helix has been determined due to loss of power in helix SWS.

III. RESULTS AND DISCUSSION

Temperature of helix can be predicted using Temperature of helix can be predicted using analytical approach quickly. Relevant resistances have been evaluated by using these equations (1)–(16) with structure parameters. Commercial code ANSYS has been used to authenticate the temperature distributions on helix, support rods, barrel and base-plate for analytical results.

The steady-state temperature distributions in slow wave structure are acquired beyond using steady-state thermal solver and presented in fig. 2, after apply in gall the input and boundary conditions. The Comparative study of the analytical modeled and software simulated results are shown in figure 3.

Analytical model doesn't consider axial variations because this model is not 3D. However, the dimensions of structure are described as the value of pitch =0.75 mm, helix thickness = 0.175 mm, helix tape width = 0.375 mm and outer helix radius=1.32mm. Two rectangular rods are obtained by broken of tapered geometry support rods and have width and height of first step are = 0.4 mm and 0.8 mm, respectively, and width and height of second step are 0.8 mm and 1.0 mm, respectively. Some dimensions are also described as barrel inner radius = 3.1mm with thickness of Monel spacer = 1.95 mm and length = 100.0 mm. According to table-1 and with the help of equation (2-7), one can gets R_h, R_i and R_e for single helix turn as: 35.7WK^{-1}m^{-1}, 144.5WK^{-1}m^{-1} and 49.1WK^{-1}m^{-1}, respectively. From figure 2, it can be seen that temperature of helix 850 ^{0}C is obtained even at lower R_{h-i} if values of R_{i-e} are expanded.

IV. CONCLUSION

A quick analytical model has been established because of the poorest-case thermal performance of helix. An analytical model evaluates the thermal contact resistances at several joints (conduction) and also losses of radiation only. The results of temperature distributions are obtained along closely agreement of analytical model throughout the results of simulation. Therefore, quick prediction of the helix thermal behavior can take by using that analytical model.

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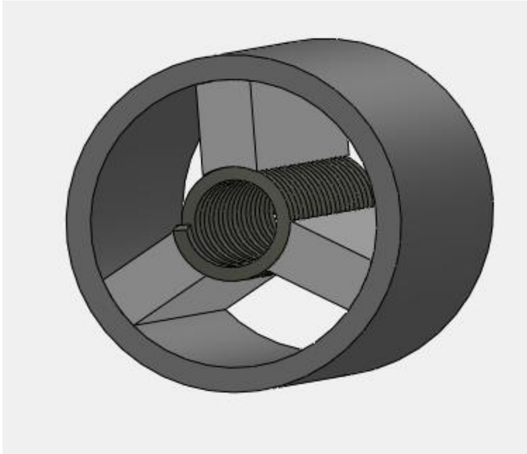

Fig. 1(a)3-D model of Helix support rod assembly

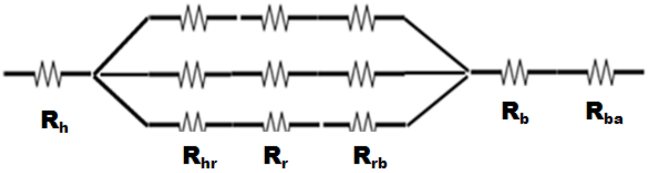

Fig. 1(b)Equivalent thermal resistance model for helix support rod assembly

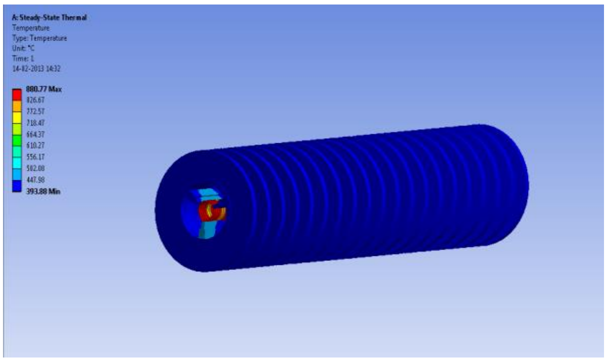

Fig. 2. Temperature distribution in helix-helix support rod assembly

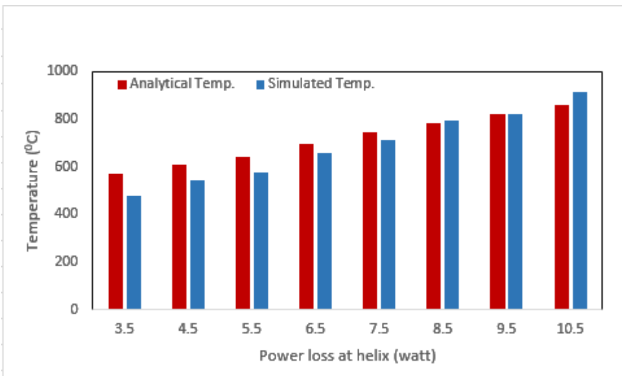

Fig. helix temperature at different power loss at helix

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Table 1:Properties of different materials

Material	Density (Kg/m^3)	Thermal Conductivity (W/m^0K)	Specific Heat (J/Kg^0K)	Emis-sivity	Young's Modulus (N/mm^2) $*10^{11}$	Thermal expansion ($10^{-6}/^0C$)	Poison's ratio
Tungsten	19300	173	133	0.25	411	4.5	0.28
APBN	2150	60	850	0.45	22	11.9	0.25
Monel	8900	19.5	400	0.43	4.11	13.5	0.30

Table-2: Comparison of analytical and simulated helix temperature

Power (W)	Analytical results. (^0C)	Simulated temp. (^0C) in vacuum
3.5	570	480.54
4.5	610	541.64
5.5	640	575.86
6.5	695	659.24
7.5	745	713.85
8.5	785	782
9.5	820	821.79
10.5	860	913.65

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