Experimental approach to validation of an analytical and numerical thermal analysis of a travelling wave tube

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Abstract. Travelling Wave Tube (TWT) is an electronic vacuum microwave device, which is used as a high power microwave amplifier, mainly in telecommunication purposes, e.g. radar systems. TWT's is an alternative solution in comparison to semiconductor devices in case of high power and high frequency applications. Thermal behaviour of TWT is one of the key aspects influencing its reliability and working parameters. The main goal of the research was to perform analytical, experimental and numerical analysis of a temperature distribution of a low band TWT in case of a typical working condition. Because the theoretical analysis seems to be very complex thus it was decided to compare the experimental results with the numerical simulations as well as with the simplified analytical formulas. As a first step of the presented research, the analytical analysis and numerical modelling of the helix TWT was carried out. The objective of the thermal analysis was to assess the temperature distribution in different parts of the helix TWT assembly during the extreme standard and working conditions. As a second stage of the research the numerical results were validated by the experimental measurements, which were carried out using a specially designed TWT test samples and corresponding experimental measurement tools.

1. Introduction
Travelling Wave Tube (TWT) is an electronic vacuum microwave device, which is used as a high power microwave amplifier, mainly in telecommunication purposes, as a driver or output tube in advanced radar systems and electronic test equipment. TWT seem to be an alternative and more reliable solution in comparison to semiconductor devices in case of high power and high frequency applications. The typical operating frequency range of TWT would be from 1 to 5GHz and each tube delivers a peak output power in frequency range without adjustment. There are a number of different construction of TWT devices of which the so-called helix TWT are the most popular. The main components of a helix TWT are: electron gun, helix slow wave structure (SWS), input and output coupler and collector. Additionally, a ceramic-metal construction provides exceptional mechanical strength. Electron beam is focused by periodic permanent magnet (PPM) structure.
Thermal behaviour of TWT is one of the key aspects influencing its reliability and working parameters. In fact the standard TWT is treated as a high power device and the supplied power is dissipated mainly through conduction and convection phenomena while the heat dissipation through the radiation can be neglected. In practical applications, depending on a type of TWT, they can be cooled either by a forced liquid or air circulation. Additionally, in some special TWT types, they would require mixed air-liquid cooling or specially designed heat conduction to the device base [1].

The main goal of the research was to perform experimental validation of the analytical and numerical analysis of a temperature distribution of a low band TWT in case of a typical working conditions. Because the theoretical analysis seems to be very complex thus it was decided to compare the experimental results with the numerical simulations as well as with the simplified analytical formulas. One of the advantages of numerical simulations over the analytical formulas is the ability to include real geometry and boundary conditions without a need of any physical phenomena simplification or neglecting any geometrical details. On the other hand the numerical analysis in comparison to experimental one, allows for application of an advanced numerical optimization algorithms, which makes it a very practical engineering tool during the prototyping stage. As a first step of the presented research, the analytical analysis and numerical modelling of the helix TWT was carried out. As a final stage of the research the achieved results were validated by the experimental measurements, which were carried out using a specially designed TWT test samples and corresponding experimental measurement setup [2].

2. Travelling Wave Tube

Traveling Wave Tubes (TWT) belong to high power microwave devices, which work in a density modulated mode, rather than the current modulated mode. This means that they work on the basis of clumps of flying electrons, rather than using a continuous stream of electrons. As the key driving source are electrons, thus part of TWT devices is based on the so-called electron optics and interaction of electrons with an electromagnetic field [3].

TWT devices containing helix delay structures seem to be the most popular. The main components of a helix TWT device are: electron gun, helix slow wave structure (SWS), input and output coupler and collector. Additionally, a ceramic-metal construction provides exceptional mechanical strength. Electron beam is focused by periodic permanent magnet structure. An example structure of such a device and a corresponding microwave amplifier are presented in the figure 1.

Figure 1. A simplified structure of a TWT device (a) and the detailed structure of a TWT microwave amplifier (b).
The operation principle of TWT is based on an interaction of an electromagnetic wave, which is guided by the so-called delay line (e.g. helix), with the electron beam injected along its axis of a symmetry. The axial electromagnetic field component accelerates same electrons and at the same time decelerates others. As a result an electron beam density is modulated and the energy extracted from decelerating bunches of electrons is then transferred into the outer circuit. Microwave power generated in the delay line grows exponentially with a distance along its axis of symmetry. In fact the efficiency of the energy transfer of an electron beam into the energy of a microwave signal can be estimated up to 20% [5].

As stated above, one of the basic problems is a thermal behavior of TWT based devices, which directly influences its reliability parameters and performance. As the total energy should be conserved, in case of the analysed device the main sources of energy inputs and outputs can be detected as follows:

- input power of a microwave signal, e.g. 1 W - in fact could be neglected,
- output power of a microwave signal, e.g. 450 W,
- inlet power of an electron beam, e.g. 2350 W,
- outlet power of a collector, e.g. 800 W,
- dissipation power in the delay line, e.g. 70 W,
- other energy losses in the delay line, e.g. 80 W,
- recuperation of the input output power into the input power, e.g. 950 W.

An example of a power rough equilibrium estimation and a corresponding final TWT device used for experimental analysis are given in the figure 2.

![Figure 2](image)

Figure 2. An example of a power equilibrium - rough estimation of a TWT microwave amplifier device (a) and a corresponding final TWT device used for experimental analysis (b).

As can be concluded from the above rough estimation, one of the key problems is an energy lost in the delay line, which causes temperature rise at the terminal part of the TWT device. In fact, the density of an electron beam power can be higher than 1500W/mm2. Actually, the energy lost in the delay line in a form of heat energy (e.g. 100W) is mainly due to the following phenomena:

- power associated to its resistivity \( p_{\text{res}} \),
- power associated to the electron beam current intercepted by the helix structure through a bombarding phenomenon \( p_{\text{be}} \).

The above phenomena are a direct cause of a temperature rise of the delay line and can lead to early failure or performance deterioration of TWT device. In order to avoid the unexpected temperature rise, the generated heat energy over the delay line is to be dissipated to the ambient using a proper structural design of a TWT device. The heat is mainly dissipated through conduction and convection phenomena as the radiation could be neglected due to the typical working temperature of a TWT device below 100°C.
3. Analytical approach

Microwave power of an electron beam generated in the delay line grows exponentially with a distance along its axis of symmetry and the highest temperature is expected at the final section of the delay line. In case of an analytical approach the key problem was to determine the so-called linear density function \( p_c \) of a power loss that is dissipated along the symmetry axis \( z \), as a result of an electron beam interaction with the delay line. Such relationship could be used in numerical analysis in order to evaluate and predict the temperature distribution in a TWT device. In case of the current research, such relationship was evaluated by taking into account the following assumptions [6]:

- all beam electrons in a point \( z \) inside an incremental length layer \( dz \) have the same energy,
- initial power of an electron beam coming entering the interaction zone equals to \( U_0 I_0 \),
- electrons intercepted by the delay line in point \( z \) and due to an interaction with an electromagnetic wave and cause energy decrease by value of energy transfer to the wave from \( 0 \) to \( z \) - all its energy is converted into heat,
- density of a beam current intercepted by the delay line - \( j(z) \) can be described by linear relationship of microwave power in point \( z \).

As stated above the linear power loss \( p_c \) along the delay line can be given as:

\[
p_c = p_{sf} + p_{sw}
\]

In case of the line resistivity according to the TWT’s Pierce’s theorem it is possible to assume the local power density \( P_f \) of a microwave signal along \( z \) axis as a function of a power at the end of the delay line \( P_{out} \) as:

\[
P_f = P_{out} e^{\frac{(g-a)z}{10}}
\]

where \( g \) is a gain constant, \( a \) is an attenuation constant (\([g]=\text{dB/m}, [a]=\text{dB/m}\)), \( L \) is a delay line length and

\[
B = \frac{(g-a)\ln(10)}{10}
\]

The above assumption allows for evaluation of the linear power loss of a microwave signal \( p_{sf} \) due to the attenuation constant \( a \) as:

\[
p_{sf}(z) = -\frac{dP_f(z)}{dz} = \frac{a \ln(10)}{10} P_f
\]

On the other hand, the formula on the linear power dissipation of an electron beam intercepting with the delay line \( p_{sw} \) can be given as:

\[
p_{sw}(z) dz = \frac{j(z) dz}{I_w(z)} P_w(z)
\]

where \( j(z)dz \) is a beam current intercepted at \( dz \) interval, \( P_w(z) \) and \( I_w(z) \) are correspondingly local power and current of an electron beam while the value of the intercepted current density \( j(z) \) is given by:

\[
j(z) = I_o \frac{Be^{Bu}}{e^{Bu} - 1}
\]

where \( I_o \) is an overall delay line current due to an interaction with an electromagnetic wave:

\[
I_o = \int_0^L j(z) dz
\]

Thus the local current \( I_w(z) \) function along the \( z \) axis would be given by:
\[ I_w(z) = I_0 - I_a e^{B z} - I_{lw} \]  

where \( I_0 \) is an initial current of an electron beam for \( z=0 \). The local power \( P_w(z) \) along the \( z \) axis can be extracted by using the principle of energy conservation:

\[ \frac{dP_w(z)}{dz} = -\frac{dP_f(z)}{dz} - \frac{dP_c(z)}{dz} - P_{sw}(z) \tag{9} \]

Analytical solution of the above formula for the initial condition in point \( z=0 : P_f(0) = P_{in} \) and \( P_u(0) = U_J = \chi \), while using the notation \( J/J_0 = \chi \), and taking into account that \( U_0 J_0 < P_{in} e^{B L} >> I \) and \( P_{in} = P_{out} e^{B L} \) would be given by:

\[ p_{sw}(z) = U_0 I_0 B e^{B z} \ln \left( \chi + \frac{P_{out}}{P_{in}} \ln \left( 1 - \chi e^{-B L} \right) \right) \tag{10} \]

So, the final formula for linear power density \( p_c(z) \) dissipated in the delay line can be described by formula 1, where components \( p_f \) and \( p_{sw} \) are given by equations 4 and 10. Figure 3 show an example result of the linear power loss evaluated accordingly.

![Figure 3](image.png)

**Figure 3.** Scheme of an interaction of an electron beam with the delay line (a) and an example of a linear power density \( p_c(z) \) dissipated in the delay line according to the analytical analysis (b).

Finally, the above analytically evaluated dependence was assumed as the reference one in the followed up computer simulation of a temperature distribution in the TWT device structure.

4. **Numerical approach**

In case of numerical modelling of a temperature distribution, according to the presented analytical analysis, it was assumed that only the output section of the TWT device can be taken into account. The computer / numerical model, prepared in ANSYS package v.12, with the detailed scheme is given in figure 4a and the detailed structure of the delay line in the figure 4b. In order to simply the whole structure a couple of assumptions were taken into account [7]:

- only the final part of the delay line could be simulated due to the evaluated nonuniform linear power density dissipation,
• the microwave linear power density in the delay line can be represented by a nonuniform resistivity of the helix structure and the corresponding Joule heat,
• the collector structure can be represented by a simple metal block,
• only linear material properties could be used for simulations.

![Figure 4](image)

**Figure 4.** Computer / numerical model of a final region of the analysed TWT device (a), and a detailed structure of an internal part the delay line including the helix structure (b), where: 1-clamp, 2-pole, 3-magnet, 4-vacuum shield, 5-helix, 6-ceramic rods, 7-base, 8-collector.

In order to implement the nonuniform linear power density distribution in the delay line it was assumed to use the segmented helix structure, which dissipates the total power $P_n$, according to the Joule heat:

$$P_n = I^2 R_n = I^2 \rho_n \frac{2\pi a}{d w} \quad (11)$$

where $R_n$ is the resistance of each helix segment while $\rho_n$ is its resistivity and $a$, $d$, $w$ are its geometrical dimensions.

The main goal of the numerical analysis was to compare the temperature distribution of a TWT device $T(z)$ shield with the given distribution of a linear power dissipation in the delay line $p_c(z)$ given by equation 1. It was assumed that there should be a correlation between the both along $z$ axis, which can be expressed in a form:

$$T(z) = k \cdot p_c(z) \quad (12)$$

where $k$ is a constant proportional coefficient, that does not depend on $z$. In case when the heat transfer in radial direction is dominant then both $T(z)$ and $p_c(z)$, should have a similar distribution as given in the figure 5 and additionally in the figure 6 for two different linear power dissipation dependencies - smooth and steep. In fact, both curves when normalized seem to fulfill the equation 12, except the final region of the delay line (around 2cm), which is mainly due to the collector influence. The same, it was concluded that using the presented analytical analysis and results of numerical simulations along with the so-called inverse engineering and formula 12, it should be possible to assess the linear power dissipation character along the delay line [8].
5. Experimental validation

In order to validate the conclusions based on presented analytical analysis and numerical simulations, an experimental setup was designed and manufactured, which is shown in the figure 7. The objective was to compare the temperature distribution in different parts of the helix TWT assembly during the working conditions with the analytical and numerical results for corresponding power dissipation. The experimental setup consisted of eight thermocouples bounded to the delay line shield, which were
placed between the magnets and the whole system was cooled with water. The measurements were done for the selected power supply values \((U_0=7400V, I_0=310mA)\) and for two microwave input powers 200mW \((P_{\text{in}}=412W)\) and 300mW \((P_{\text{in}}=425W)\). Figure 8 contains the comparison of a measured normalized linear power dissipation curves with three different analytical functions, which seem to fulfill the corresponding partial differential equations.

**Figure 7.** Experimental setup for temperature distribution measurements: (a) diagram, where: 1-electron gun, 2-input, 3,5,6-corresponding coolers, 4-output section, 7-eight channels of DC amplifier, ADC-converter, PC-computer, (b) view of the manufactured system.

**Figure 8.** A comparison of a measured normalized linear power dissipation in the delay line versus three different analytical dependencies.
According to the presented results, it can be concluded that the best fit of the experimental results with the analytical functions are in case of the linear power dissipation that was given by the formula 1. In fact the formula was derived under the assumption that the density of a beam current intercepted by the delay line \( j(z) \) is proportional to the local microwave power \( P_f(z) \).

6. Conclusions
The above paper describes the thermal analysis of the TWT device by combined analytical and numerical, which were validated by experimental measurements. Analytical model was focused on an evaluation of the beam current power dissipation and microwave losses along the delay line, which is not uniform and most of the power is accumulated at its terminal part. High power results in a non-uniform temperature distribution, with very high temperatures at terminal part of the delay line. The analytically evaluated power dissipation function was then used in numerical simulation of a temperature distribution in the working TWT device. The experimental results validated the proposed methodology and through the inverse engineering it was possible to validate the undertaken assumptions on the dependence of a dissipated liner power density along the delay line.

The presented results focused mainly on a problem of the temperature distribution. In fact working TWT devices are exposed to high temperatures, which can influence their reliability. Therefore, the presented methodology would be implemented at the design stage and would hopefully lead to better products, which mainly means improved thermal properties and corresponding performance and, last but not the least, more reliable final products.

7. References
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