An Analytical Lumped Thermal Circuit for the Determination of Fast Warm up and Steady State Characteristics Of Heater/Cathode Packages for TWT's

D R Dyson
TMD Technologies Limited, Swallowfield Way, Hayes, Middlesex, UB3 1DQ UK
Email: david.dyson@tmd.co.uk
Tel: 44 20 8581 5115
Fax: 44 20 8569 1839

Introduction

The challenge of determining fast warm up rates in small heater/cathode packages is critical to many tube development programs, but suffused with difficulties. An overvoltage is applied to the heater during the warm up time and current and hence power in the heater is determined by the resistance of the wire at any point in time. The heater wire usually consists of 97% tungsten/3% rhenium alloy and this has the property of resistivity variation with temperature of over an order of magnitude. This wire will also not be at a uniform temperature at any time. In addition, power is lost by a complex combination of conductions and radiation exchanges, with thermal conductivities, expansivities, emissivities, and specific heats for all materials varying markedly with temperature.

Increased demand for fast warm up solutions from TMD customers led to the decision to seek more reliable modelling of warm up characteristic. This was initially undertaken within a finite element package which offered material property variations with temperature, but, unfortunately did not allow any simple way of changing the heater power with time as the temperature increased. It was necessary to interrogate the solution at each time step in order to determine the resistance of each heater coil, and then to sum the resistances of the coils, compute the current, and hence the new power in each coil for the next timestep and apply the new powers as new boundary conditions. This was done with the aid of a spreadsheet but the process was not amenable to automation, and 5 minutes of human interaction was required between each time step (computer analysis for each time step was also around 5 minutes on a 2GHz Pentium). Upto 1 man-month of dedicated human effort could be required for a single run of a given geometry.

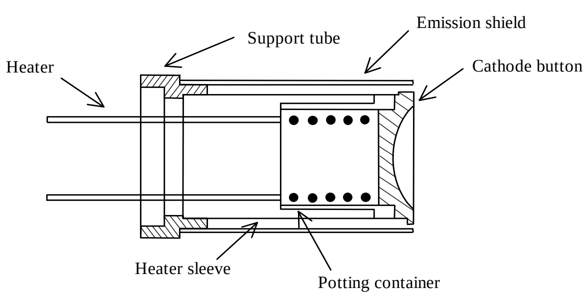
It was readily apparent that in order to determine an adequate design, a much faster way of experimenting and solving for dimensional variants was required.

The Model

TMD decided that the best approach would be to create a lumped thermal circuit approximation for the problem. The FE model results were used to provide guidance as to how best to divide the problem into blocks which were not so large as to contain excessive non linear temperature variations at any time.

Figure 1 shows the basic heater/cathode and support configuration.

FIGURE 1   Schematic of Heater Cathode Package

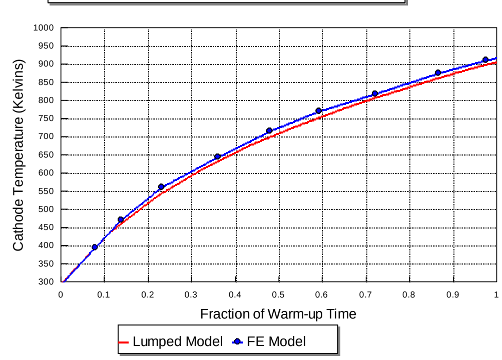


It was found sufficient to define cathode button as single ‘lump’ with a single temperature, potted heater wire as single lump at a single temperature, and a single ‘lump’ of potting at a single ‘bulk’ temperaure. Other features included potting container, a two section cathode support sleeve, grids, support configuration to external HV seal, and an emission shield.

Heat was assumed to flow both radially inwards and outwards from the heater coil into the alumina potting. An effective weighted geometric mean distance was calculated from wire to potting, from which could be calculated rate of efflux of power from the wire due to temperature difference. Power conduction from the potting bulk to potting container and cathode button interface could then be calculated according to their respective geometric mean distances, and so on through to the HV seal. The model was fully paramaterised, and also included mathematical formulations for all physical property variations with temperature. Most of these formulations were arrived at by fitting to data in public domain, whereas some properties proved somewhat elsusive and had to be determined experimentally. In particular the emissivity and resisitivity of the heater wire required a good deal of effort to formulate. The small (3%) rhenium content of the heater wire effectively adds in a fixed level of disorder and hence resistance, and a plot of resistivity versus temperature is essentially parallel to the curve for pure tungsten.

Fig 2 shows a comparison of fast-warm up characteristics between the FE model and the lumped circuit model. Agreement was found to be extremely good.

FIGURE 2   Fast Warm Up Comparison
FE Model versus Lumped Thermal Model



Combining of Models

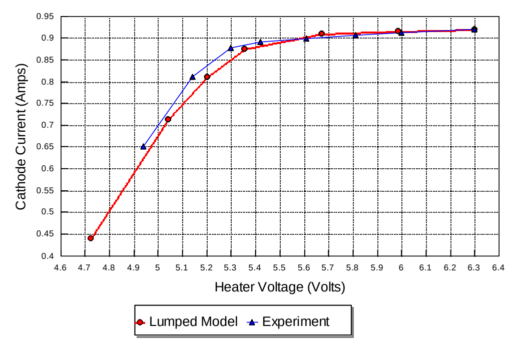
The model has been refined to include a cathode current prediction based on the expansion of cathode towards grid, and also on a separate FE model of electron beam within the remainder of the gun electrode configuration. This gun model predicted cathode current according to Langmuir Fry at a given work function, and was also used to predict variation of cathode current with grid to cathode distance. Coupled with data on how the work function actually varies with temperature, this information was programmed into the lumped circuit analysis which then normalises the cathode current under standard operating conditions, and predicts its variation with time, heater voltage, and external temperatures.

Knee Curve Prediction

The ‘knee’ curve is a plot of cathode current against heater voltage (or strictly against heater power). As the cathode becomes hotter, the beam current drawn changes from being temperature limited to space charge limited. A ‘good’ cathode has a sharp knee, whereas a rounded knee would suggest a problematic cathode with variable emission across the cathode surface.

A ‘knee curve is generated’ by the program (based on the formulations above), and, as can be seen from fig3, agreement with an experimental measurement is extremely good.

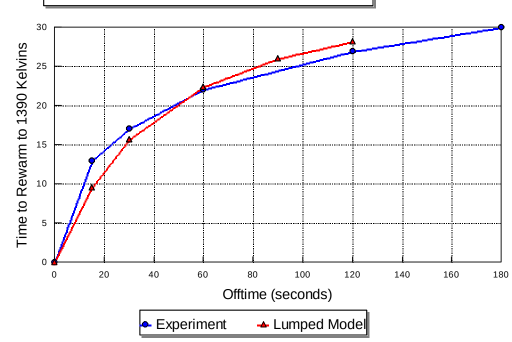
FIGURE 3 Knee Curve Comparison
Lumped Thermal Model Versus Experiment



Rewarm Computation

Another feature of the program is the facility to turn off the heater for a specified time, and calculate the time taken to warm back up to a predefined temperature after switching back on. Fig 4 shows a comparison with experiment, and although agreement is not quite so encouraging as the other results, this is thought to be due to selection of filtering on the power meter during the experimental measurements.

FIGURE 4 Rewarm Comparison
Lumped Thermal Model Versus Experiment



Other Features

Other features include the calculation of specific heats and simple minimum heat input requirements, the ability to add overwinds to the heater legs, and also heat loss due to electron evaporation if the gun is used at high duty cycles.

The following variables are output from the program over a range of time, with fine resolution during the warm up period and coarser resolution for a further 20 times the warm up period:

Total resistance of heater circuit
Burn wire resistance
Total heater current
Overwind current
Heater power
Burn Wire temperature
Heater leg temperature
(Max. heater leg temperature captured)
Overwind temperature
Potting temperature
Cathode temperature
Potting container temperature
Support temperatures
Power conducted along support sleeve
Power conducted along emission shield
Cathode movement
Beam Current
Maximum current density available

Conclusion

Agreement between the analytical model, a finite element model, and experimental results has been extremely good, and the program has been used to assist in several heater/cathode designs during the last year.

Although, the program has only been used to determine the characteristics of small cathodes, work is underway to apply it to much larger cathodes where the balance of power loss between conduction and radiation is significantly different. Lack of precise information regarding material properties, particularly emissivity, is thought to be the main problem in predicting accurate answers.

Never the less, the program is able to predict warm up characteristics of a cathode design after only seconds of computation (100,000 times faster than was possible with the original FE modelling technique), thus enabling geometry variation analysis and a good 'feel' for the sensitivity of the design to tolerances and environmental conditions to be developed.

The program will be incorporated into a wider software suite currently being developed at TMD to facilitate the optimisation of an increasing number of TWT design aspects.