

A Simple Quasi-2D Numerical Model of a Thermogage Furnace

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Abstract A simple quasi-2D model for the temperature distribution in a graphite tube furnace is presented. The model is used to estimate the temperature gradients in the furnace at temperatures above which contact sensors can be used, and to assist in the redesign of the furnace heater element to improve the temperature gradients. The Thermogage graphite tube furnace is commonly used in many NMIs as a blackbody source for radiation thermometer calibration and as a spectral irradiance standard. Although the design is robust, easy to operate and can change temperature rapidly, it is limited by its effective emissivity of typically 99.5–99.8%. At NMIA, the temperature gradient along the tube is assessed using thermocouples up to about 1,500°C, and the blackbody emissivity is calculated from this. However, at higher operating temperatures (up to 2,900°C), it is impractical to measure the gradient, and we propose to numerically model the temperature distributions used to calculate emissivity. In another paper at this conference, the model is used to design an optimized heater tube with improved temperature gradients. In the model presented here, the 2-D temperature distribution is simplified to separate the axial and radial temperature distributions within the heater tube and the surrounding insulation. Literature data for the temperature dependence of the electrical and thermal conductivities of the graphite tube were coupled to models for the thermal conductivity of the felt insulation, particularly including the effects of allowing for a gas mixture in the insulation. Experimental measurements of the

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temperature profile up to 1,500°C and radial heat fluxes up to 2,200°C were compared to the theoretical predictions of the model and good agreement was obtained.

Keywords ATJ graphite · Blackbody · Graphite felt · Numerical model · Thermogage

1 Introduction

A 48 kW Thermogage blackbody furnace is used as a spectrally calculable source of radiation for standard spectral irradiance and for the temperature calibrations of pyrometers up to 3,000°C. At NMIA, the increasingly stringent uncertainty requirements from industry necessitate improvement of the temperature uncertainty associated with using this blackbody. Presently, this uncertainty is approximately 2°C at 2,000°C, and mainly due to the emissivity of the blackbody as calculated from its temperature distribution [1]. Other blackbody designs use a profiled graphite tube to improve the temperature distribution, however, the heat transfer mechanisms change significantly over the range 1,000–3,000°C, and it is difficult to “tune” this profile to achieve the desired effect at all temperatures. Further, modifications to the furnace must ensure that the tube current and voltage, and silica tube temperature remain within design constraints. To facilitate the tube redesign, a simple quasi-2D model has been developed to numerically simulate the graphite tube inner temperature profile. This software will be used to optimize the design of the graphite tube in order to obtain good temperature uniformity over a wide temperature range.

2 Thermogage Furnace

The Thermogage blackbody furnace (Fig. 1) consists of an ATJ graphite tube surrounded by insulating material, which consists of graphite felt purged with an inert gas wrapped with two layers of graphite foils and inserted into a silica tube. For some years at NMIA we have been using graphite tubes, 289 mm long with 31.8 mm OD and 3.2 mm wall thickness, machined from rods of ATJ grade graphite. In this article we consider one of the NMIA tubes which has been machined with a region of lesser wall thickness in an attempt to improve the temperature uniformity. The graphite felt, from Morgan, has a density of $90 \text{ kg} \cdot \text{m}^{-3}$ with 22 μm -diameter fibers. The tube and its insulation are surrounded by a water-cooled jacket. The water jacket function is to prevent accidental contact with the hot surface of the silica tube and to capture the radial heat flux where it is measured calorimetrically. The ends of the tube are clamped by graphite-composite rings, which are in turn clamped to water-cooled copper rings. During operation, the graphite tube and graphite-composite rings are ohmically heated by a voltage applied across the copper rings. This electrical power is dissipated by (i) conduction along the graphite tube, (ii) radiation from the middle of the tube, and (iii) radially through the insulation.

As the temperature gradient in the insulation surrounding the tube is mostly radial, while that in the graphite tube itself is mostly axial, the 2-D heat flows in the system were separated into 1-D heat transfer problems which can be solved separately by the finite element method and then coupled (Fig. 2). The graphite-composite rings pose

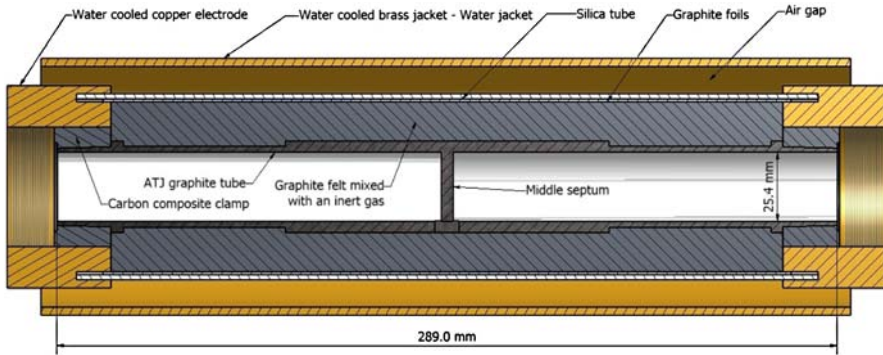


Fig. 1 Schematic diagram of the NMI 48 kW Thermogage graphite furnace

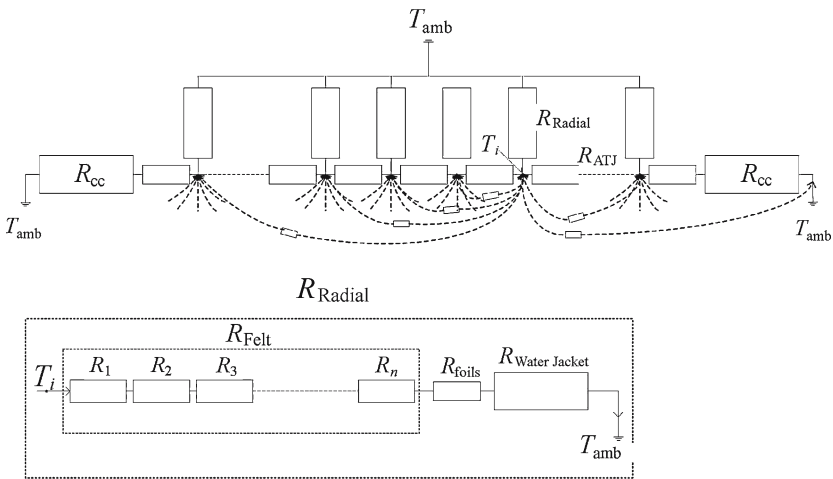


Fig. 2 Equivalent thermal circuit diagram of the ATJ graphite furnace tube

a special challenge as they have a complex 3-D structure and are affected by contact resistances that are difficult to determine. They are modelled as lumped electrical and thermal resistances that are determined experimentally.

2.1 Graphite Tube

The graphite tube is modelled as a 1-D heat transfer problem. NMIA manufactures its own tubes from ATJ graphite. We adopt the literature values for the temperature-dependent electrical [2] and thermal [2,3] conductivities. As the grain orientations in our ATJ samples appeared random, we adopted the anisotropic value $2/3k_{\perp} + 1/3k_{\parallel}$ (Fig. 3). The tube was modelled as $m \approx 50$ very short “tube elements” of varying diameter and thickness through which a fixed current flows, generating heat (I^2R) within each element. The element in the center of the tube is considered as the “tube septum,” and is a special element considered as a disk. We model three heat fluxes from each element:

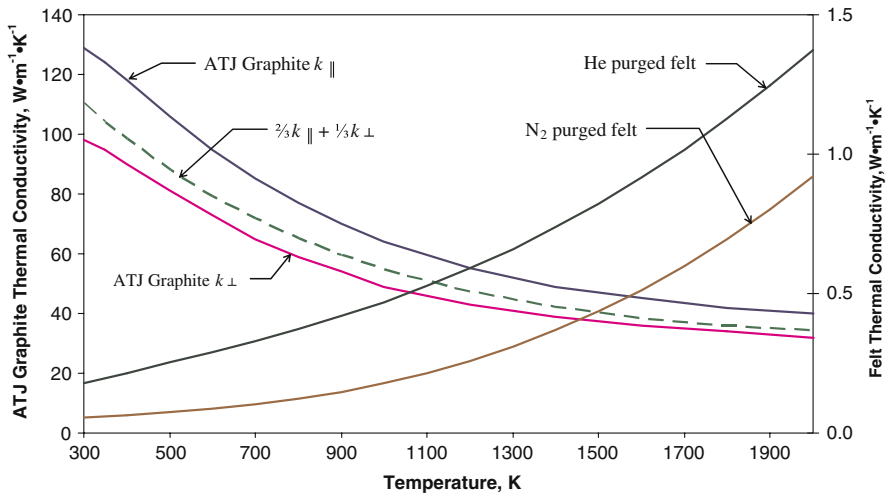


Fig. 3 Graph of the thermal conductivities of ATJ graphite in the parallel and perpendicular directions and their average, and that of the Morgan graphite felt mixed with nitrogen and helium versus the absolute temperatures

1. Thermal conduction to adjacent elements.
2. Thermal radiation between the element and other elements in the tube (the “cold” end and the “septum” are special here). This entails calculation of the order of m^2 radiant transfer view factors, given in [4]. As the emissivity of graphite is assumed to be approximately 0.8, for simplicity only direct radiative transfer is considered: second reflections are ignored.
3. Radial heat flux from the outer surface of each element to ambient. This is considered as a thermal resistor whose resistance (considered later) is dependent on the temperature of the “hot” end.

2.2 Radial Thermal Resistance, $R_{\text{Radial}}(T)$

As the radial heat flux dominates the central, uniform temperature region of the tube in which we are most interested, this is the key to the model. We consider this as a purely 1-D radial heat transfer problem (i.e. assume axial uniformity). As the insulation layer is thin (15 mm), compared to the scale length of the axial temperature gradients, this is a reasonable approximation. This problem is solved by finite elements (Fig. 2) in the radial direction. Three regions thermally in series are considered:

1. R_{Felt} : The graphite felt is modelled as $n \approx 10$ annular rings. The temperature-dependent thermal conductivity was extensively investigated in [7], resulting in a simple model giving the conductivity as a function of felt density (given by solid fraction f), fiber radius (r) and filling gas conductivity k_{gc} .

$$k_f(T) = \frac{k_{\text{gc}}(T) + C_{\text{fr}} \sigma \frac{r}{f} T^3}{1 - f} + 3.5 \times 10^{-4} k_s(T)$$

where σ is the Stefan–Boltzmann constant, k_s is the thermal conductivity of the graphite fibers, and C_{fr} is a radiation constant with values determined from the literature to be around 15.0. Figure 3 shows the computed thermal conductivity with He and N₂ used as shield gases. For other gas mixtures, the molar fraction weighted-average gas conductivity is used. Note that, at low temperatures, using He significantly increases the conductivity from the N₂ value. This was found to be important for later work using the gas mix to “tune” the furnace gradient.

2. R_{foils} : The graphite felt is surrounded by several layers of graphite foil, which act as radiation shields. The conduction from the felt to the foil, between the layers of foil, from the foils to the silica tube holding the assembly and through the silica tube are calculated from the thermal conductivity of the inert gas mixture and the radiation, assuming an emissivity of 0.8 for graphite and 1.0 for the silica. As the gaps between the layers (assumed to be 0.5 mm) are small, convection is neglected. Overall, the contribution from this resistance is very small.
3. $R_{\text{Water Jacket}}$: The thermal resistance across the 10 mm air gap between the silica tube and the water jacket is modelled as two concentric cylinders with the heat transfer between them occurring by free convection [5, p. 564] and by radiation [6, p. 299].

This heat transfer problem was solved using the iterative over-relaxation method on $n + 2$ finite elements in an EXCEL spreadsheet. It was solved for a number of temperatures of the “hot” end, to give a simple polynomial for the temperature-dependence of the total radial thermal resistance $R_{\text{Radial}}(T)$. The dominant thermal resistance is that of the graphite felt.

2.3 Tube End Thermal Resistance, R_{cc}

The two ends of the graphite tube are held in short graphite-composite (CC) sleeves, which contribute significant electrical heating and have complex 3-D geometry contact resistances making them difficult to model numerically. We note that whatever design for the graphite tube or insulation system was used, this “sleeve” section would remain the same. We therefore adopt an empirical approach and consider these end components as lumped elements whose electrical and thermal resistances are experimentally determined as a function of the temperature of the “hot” end of the CC-sleeve. The electrical resistance is determined by measuring the voltage drop between the copper electrode and the end of the ATJ graphite tube, and the current through the tube with a current transformer around the copper electrode. The thermal resistance R_{cc} is determined by measuring the temperature of the end of the ATJ graphite tube and the total heat flux passing through the CC-sleeve.

$$T_1 - T_{\text{amb}} = R_{cc}(T_1) \left[kA \frac{dT}{dx} + \frac{IV_{\text{elec}}}{2} \right]$$

This has two parts, the heat flux $kA \frac{dT}{dx}$ coming from the end of the ATJ tube and the electric power IV_{elec} heating it. The factor of 2 in the ohmic heating arises because the

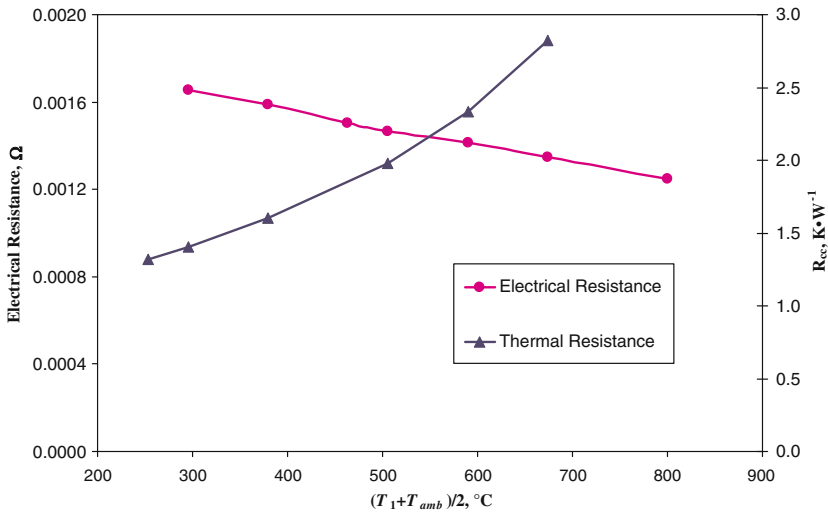


Fig. 4 Plot of the graphite-composite electrical and thermal heat fluxes versus the average of the ambient and the first node (T_1) temperatures

power is assumed to be deposited evenly throughout the CC-sleeve, not at the “hot” end only. These factors are plotted in Fig. 4.

3 Experimental Apparatus

The water cooling jacket enclosing the silica tube containing the insulation and graphite tube was used as a calorimeter to measure the total heat flux leaving the tube radially. The flow rate of cooling water was measured with a calibrated domestic water meter, and the temperature drop (typically a few $^\circ\text{C}$) between inlet and outlet temperatures was measured with an uncertainty estimated at 0.02°C with a differential type-T thermocouple. The calorimeter was estimated to capture 80–90% of the radial flux, the remainder escaping by convection from the ends of the water jacket. The temperature of the silica tube was measured with a type-K thermocouple, to allow checking the estimated value for the silica-tube to water jacket air-gap thermal resistance. The voltage across the electrodes and the current through the tube were also measured. As the tube current supply was a simple AC thyristor system providing truncated 50 Hz AC, measurements were made by a RMS integrating voltmeter with tested high frequency response.

Accurately measuring the axial temperature profile within the graphite tube is difficult because the strong axial temperature gradients can cause significant conduction errors. In [4] the effectiveness of several different designs of thermocouples and of a specially-developed optical fiber technique was assessed to determine suitable techniques for measuring the temperature profile. For the work here, it was measured using an alumina-sheathed type-R thermocouple with a few cm of the thermocouple wire formed into a “ring” against the wall of the graphite tube to avoid systematic errors, caused by conduction down the thermocouple. Thermocouple measurements are made

at 10 mm intervals along the tube by a translation stage, positioned with a precision better than 1 mm.

4 Results and Discussion

Figure 5 shows the measured temperature profiles in the tube for He and N₂ shielding gases at both 1,000 and 1,500°C. The region up to about 70 mm is relatively uniform in temperature, falling rapidly to about 400°C at the junction of the CC-sleeve and graphite tube, and the model predicts this satisfactorily for the 1,000°C case. In the 1,500°C case, the measured temperatures are systematically higher than those modelled. However, in both cases, the predicted change in profile with change from the lower conductance N₂ shield gas to the higher conductance He gas is in reasonable agreement. It is proposed to use this shield gas effect as a technique to tune the temperature profile of a given rod to achieve uniformity over a wider range of operating temperatures.

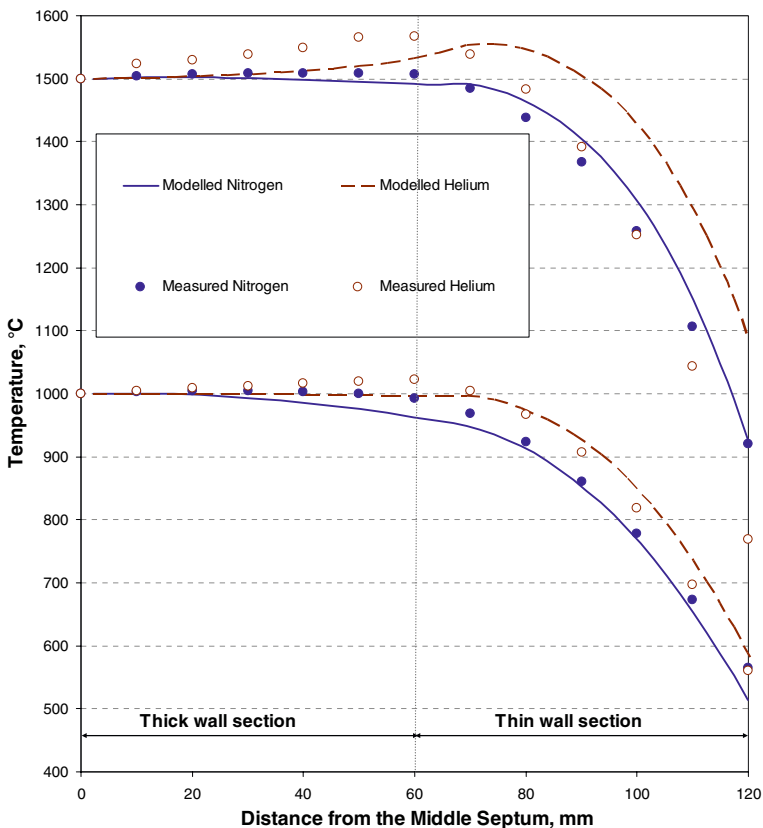


Fig. 5 Comparison of the measured temperature profile with the predictions of the model at operating temperatures of 1,000 and 1,500°C with the graphite felt purged in nitrogen and helium

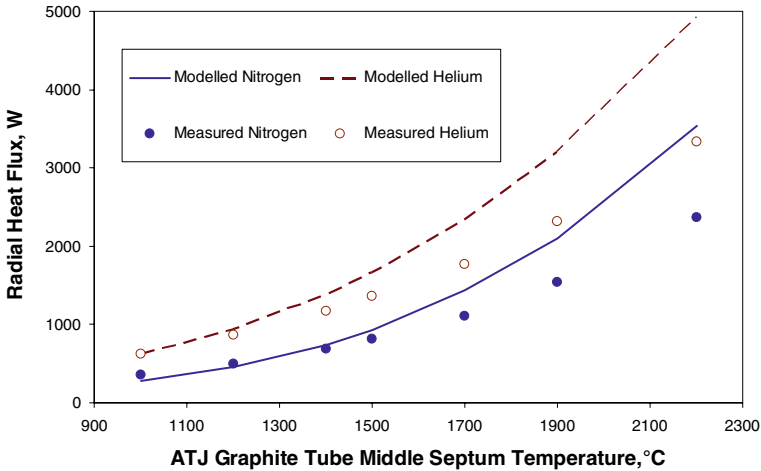


Fig. 6 Comparison of the measured radial heat fluxes with the modelled ones at operating temperatures ranging from 1,000 to 2,200°C

The increase in temperature in the region around 60 mm, arising from the N_2 to He change, can be understood to result from the higher radial heat flux decreasing the relative effect of axial conduction along the rod. At higher temperatures, the thermal conductivity of the graphite decreases, while that of the felt increases, leading to a similar effect (consider the limiting cases of zero axial heat flux, when axial uniformity may be expected, or zero radial heat flux, when a parabolic distribution may be expected). In this tube design, we can see that the “thin wall” section suitable to “peak up” the gradient at 1,000°C produces too large an effect at 1,500°C.

Figure 6 shows the measured and calculated radial heat fluxes from the graphite felt insulation. The data are in good agreement with the model at 1,000°C and increase in a similar way with increasing tube operating temperature; however, the difference between the measured data and the modelled data increases to 30% at 2,200°C. On the other hand, the predicted change in radial heat flux with change from N_2 to He shield gas is quite consistent with the measured data. Figure 7 shows the temperature of the silica tube holding the shield gas around the graphite felt. As with the heat flux data, the agreement is good at lower temperatures and diverges at higher temperatures. Again, the measured difference between N_2 and He is close to that predicted.

Part of the discrepancy in radial heat flux and consequent silica tube temperature may be due to the 10–20% convective heat loss which presently escapes from the sides of the cooling jacket; for free convection, the fraction of loss may be expected to increase with temperature as observed here. Also, upon disassembly of this tube, which had also been used up to 2,900°C, the graphite felt was observed to be loaded with graphite powder, evaporated from the rod and condensed into the lower temperature regions of the felt. This would lead to a decrease in its conductivity (dominated by the thermal photon mean free path), and a consequent decrease in observed heat flux and silica tube temperature.

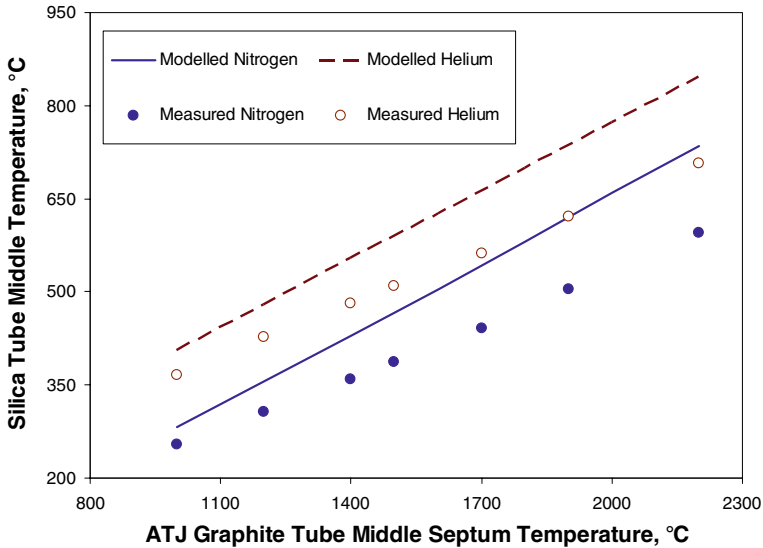


Fig. 7 Comparison of the measured silica tube middle temperatures with the model predictions at operating temperatures ranging from 1,000 to 2,200°C

5 Conclusions

A simple quasi-2D numerical model was developed with the aim of creating a simple tool for optimization of the temperature profile of NMIA's Thermogage graphite tube furnace. The model takes as input (a) physical dimensions, (b) literature values for the thermal conductivity of graphite, N₂ and He, (c) the density and fiber diameter of the graphite felt insulation, (d) the applied heating current, and (e) empirically-determined values for the electrical and thermal conductivities of the CC-sleeve. It computes the tube temperature profile, heat fluxes and tube voltage. Experimentally-measured heat fluxes and temperature profiles at 1,000 and 1,500°C using both He and N₂ shielding gases are in reasonable agreement with the model calculations. The main limitation of this model is the need to use an empirical model for the thermal conductance of the CC-sleeves. The uncertainty in knowledge of the thermal conductivity of the graphite and felt insulation, especially after heating to high temperatures, also reduces the accuracy of the model. The model has been found to be useful in developing strategies for the optimization of this type of furnace, such as changing the inert shield gas; however, it requires some additional refinement before it can be used for accurate quantitative predictions of the temperature profiles.

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