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Optimization of a Graphite Tube Blackbody Heater for a Thermogage Furnace

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Abstract Design modifications are presented for a 289-mm long, 25.4-mm inner diameter blackbody heater element of a 48 kW Thermogage blackbody furnace, based on (i) cutting a small "heater zone" into the ends of the tube and (ii) using a mixture of He and Ar or N_2 to "tune" the heat losses and, hence, gradients in the furnace. A simple numerical model for the heater tube is used to model and optimize these design changes, and experimental measurements of the modified temperature profile are presented. The convenience of the Thermogage graphite-tube furnace, commonly used in many NMIs as a blackbody source for radiation–thermometer calibration and as a spectral irradiance standard, is limited by its effective emissivity, typically between 99.5% and 99.9%. The design simplicity of the furnace is that the blackbody cavity, heater, and electrical and mechanical connections are achieved through a single piece of machined graphite. As the heater also performs a mechanical function, the required material thickness leads to significant axial heat flux and resulting temperature gradients. For operation at a single temperature, changes to the tube profile could be used to optimize the gradient. However, it is desired to use the furnace over a wide temperature range (1,000–2,900°C), and the temperature-dependence of the electrical conductivity and thermal conductivity, and that of the insulation, makes this approach much more complex; for example, insulation losses are proportional to T^4, whereas conduction losses are proportional to T. In the results presented here, a slightly thinner graphite region near each end of the tube was used to "inject heat" to compensate for the axial conduction losses, and the depth, width, and position of this region was

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adjusted to achieve a compromise in performance over a wide temperature range. To assist with this optimization, the insulation purging gas was changed from N_2 to He at the lower temperatures to change the thermal conductivity of the felt insulation, and the effectiveness of this approach has been experimentally confirmed.

Keywords Emissivity · High temperatures · Model · Simulation · Thermogage

1 Introduction

Blackbody furnaces are widely used as spectrally calculable sources of radiation, both for spectral irradiance (for example, the calibration of QTH lamps for use as spectral irradiance standards) and for spectral radiance (for example, the calibration of radiation thermometers). In both applications, the blackbody temperature is generally measured using a standard radiation thermometer at a wavelength chosen to minimize the uncertainty in determining the blackbody temperature (650 nm is commonly used for temperatures above 1,000°C). Planck's Law is then used to calculate the irradiance or radiance at other wavelengths. If the blackbody cavity emissivity is <1, the temperature measured by the radiation thermometer will be lower than the true surface temperature of the cavity, and spectral radiance calculated from Planck's law will be incorrect, with the error in radiance inversely proportional to wavelength. For example, an error of 0.5% at 650 nm leads to an error of 1.6% at 200 nm. The deviation of the emissivity of the cavity from that of a blackbody is caused by both the geometry (relatively small length/diameter) of the cavity, and the temperature gradients along the cavity. If the emissivity of graphite was wavelength independent, the former would allow the use of a single emissivity correction factor. However, the wavelength-dependent emissivity of graphite together with the variation in cavity gradients with temperature would lead to the need for an emissivity correction with both wavelength and temperature dependence. The assumptions used to calculate the emissivity, such as whether the graphite reflectance is diffuse or has a specular component and the difficulty in measuring the temperature gradient reduce the useability of this approach.

For some years at NMIA, we have been using a 48-kW Thermogage blackbody furnace using cavity elements of 289 mm length, 31.8 mm outside diameter (OD), and a maximum 3.2 mm wall thickness, machined from rods of ATJ-grade graphite. The tube OD is slightly tapered from the center to the ends, following the design of the original furnace tube provided by the manufacturer. Measurements of the temperature gradient [1,2], from Pt-based Type-R thermocouples, together with a simple diffuse-reflectance model [3] are used to calculate an effective cavity emissivity, and an equivalent "radiance temperature error" as a function of wavelength. For the tube conventionally used at NMIA, the emissivity is approximately 99.5%, and this less than ideal value results in a radiance temperature error of the order of 0.4°C at 1,000°C, increasing to 0.9°C at 1,700°C. At higher temperatures, the tube gradient, and hence the emissivity, can only be estimated by extrapolation. Increasingly stringent uncertainty requirements from both radiation thermometry users and the calibration of spectral irradiance lamps in the UV-region (e.g., extrapolating from the above to a 1.6°C error at 2,400°C corresponds to 1.6% at 200 nm) necessitate the improvement of the temperature uncertainty associated with using this blackbody. Other blackbody designs use a profiled graphite tube to improve the temperature distribution. However, because the heat transfer mechanisms change significantly over the operating temperatures of 1,000–3,000°C, it is difficult to "tune" this profile to achieve the desired emissivity for this temperature range.

Previous efforts at NMIA to modify the tube profile to minimize the axial temperature gradients have been of limited success, although good temperature uniformity could be obtained at one temperature, it was generally much worse at other temperatures. The model developed in [1] has been used in the work described in this article to optimize the graphite tube used in our Thermogage furnace to obtain cavity emissivities closer to unity over a wide temperature range.

2 Numerical Model

A relatively simple quasi-two-dimensional (2D) numerical model for the heat generation and transfer within the heater tube and insulation has been developed [1]. A 1D finite-element model of the graphite heater element is coupled to a lumped-element model for the tube-terminal region and a 1D finite-element model for the radial heat transfer through the insulation surrounding the heater.

Only axial temperature gradients in the graphite heater element are considered, and are modeled using finite elements. Literature values for the temperature-dependent thermal conductivity of the ATJ graphite tube are used to calculate the heat conducted axially along the graphite rod. The model allows the wall thickness of the graphite tube to be a function of axial position, permitting the modeling of different tube profiles. The electrical dissipation in the tube was computed as a function of the applied current, literature values for the electrical resistivity, and the local temperature and tube wall thickness.

The Thermogage furnace carbon-composite sleeves are used to obtain electrical and thermal junctions between the graphite rod and the water-cooled copper terminals. This is a geometrically complex region, and material data are inadequate to properly model it ab initio, so an empirical approach was used in this region. It was considered as a "lumped element" with a temperature-dependent electrical and thermal resistance. The electrical resistance was determined directly from measurements of the voltage drop, while the thermal resistance was determined from the temperature drop and the axial heat flux at the tube end, obtained from the measured temperature gradient. Below 1,000°C, the axial heat transfer is dominated by simple thermal conduction along the tube but, at higher temperatures, radiation within the tube becomes increasingly important. This was modeled by considering radiative heat transfer between tube segments, and between tube segments and the furnace tube center wall (septum). As the graphite emissivity is 80–90%, for simplicity only direct radiation was considered (multiple reflections were ignored).

Heat transfer radially from the tube to a water-cooled jacket occurs through 15 mm of graphite felt, two layers of graphite foil, a 2-mm thick silica retaining tube, and a 0.5-mm air gap. A model for the temperature dependence of the thermal conductivity of any graphite felt, based on literature values for the thermal conductivity of graphite,

N_2, and He, and the measured felt density and fiber diameter has been developed [4] and compared with measured thermal-conductivity data. For the work covered in this article, $90\,\mathrm{kg \cdot m^{-3}}$ felt with 21 μm diameter fibers was used. In particular, the model permits evaluation of the effect of changing the gas mixture. As the axial temperature gradients within the felt layer are much smaller than the radial gradients, they are neglected, allowing the development of a 1D finite-element heat-transfer model for the tube insulation. The solution of this model resulted in an equivalent temperature-dependent "radial loss" thermal impedance, which was then used as an additional heat loss from each node in the 1D axial model of the graphite tube.

To validate the model, techniques based on both thermocouples and optical fibers were developed [2] to reliably measure the temperature gradient in the tube. Both the axial temperature gradient in the tube and the radial heat flux (measured calorimetrically using the water-cooled jacket) were compared with that predicted by the model, at different temperatures and for both He and N_2 [1]. Although reasonable qualitative agreement was obtained for the temperature gradients, in particular, the effect of changing the felt insulation purge gas from N_2 to He, the radial heat flux was somewhat lower than calculated. This was tentatively attributed to condensed graphite dust inside the felt, which resulted in an increase in the felt density and a consequent decrease in its thermal conductivity.

3 Discussion

The measured temperature profile along the furnace tube has a maximum in the middle of the tube, falling to a few hundred °C at the ends (there is significant power dissipation and temperature drop across the carbon-composite sleeves). At higher temperatures, the temperature is generally more uniform in the central region. This behavior may be understood by considering two limiting cases. At low temperatures, the electrical heat deposited in the tube is mainly lost by conduction along the graphite tube. If the tube thickness and the thermal and electrical conductivities were constant, we would expect a purely parabolic temperature distribution. At very high temperatures, the thermal conductivity of the tube decreases, while that of the graphite felt increases significantly as it becomes dominated by radiation. In this limit, the temperature would be expected to be axially uniform.

One approach to achieving a wider uniform-temperature zone is to simply make the tube longer (refer to Fig. 1). However, there are two practical considerations limiting this; first, some radiation thermometers have F/10 optics, limiting the usable depth/diameter ratio. Second, the furnace power supply has voltage and current limitations. A reliable model is required to determine optimal tube dimensions.

The tendency for a tube furnace to be hotter in the middle due to heat losses to its ends is usually dealt with by adding separate "end heaters" that can be separately controlled to compensate for these axial heat losses. However, for a "graphite-tube" furnace of the design here, there is no convenient method to make the additional intermediate electrical connections to the tube. The approach taken here is to slightly reduce the thickness of the tube in the region near its ends. This has two effects: (i) the thinner region locally increases the thermal resistance, and so reduces the axial heat

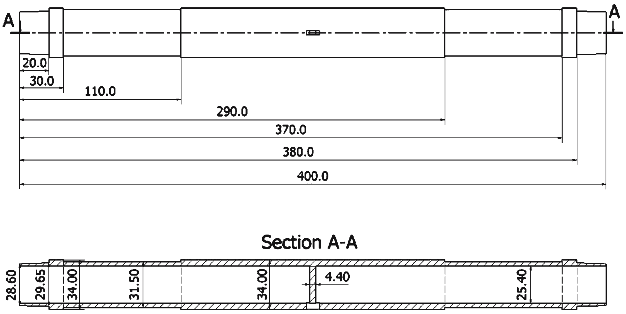

Fig. 1 Schematic diagram of the ATJ graphite tube at NMIA with two 80 mm long and 1.25 mm deep cuts at 30 mm from both ends (dimensions in mm)

flow, and (ii) the thinner region has a higher electrical resistance, and so dissipates a higher power per unit length than surrounding regions of the tube. In this second respect, the narrowed end regions act as "end heaters," as in a three-zone tube furnace.

The difficulty with this approach is that at higher temperatures the required "end heater" power contribution is lower than that required at lower temperatures. An "end heater" optimized to generate an axial temperature distribution at low temperatures will lead to overheating at higher temperatures. A small overshoot in temperature, ΔT, has a similar effect on the effective emissivity as a small decrease, being simply a region of slightly different radiance, E, $\Delta E \cdot E^{-1} = \Delta T \lambda^{-1} T^{-2} c_2^{-1}$. However, at short wavelengths and large ΔT, the radiance can be many times larger (e.g., at 200 nm, it is three times higher at 2,400°C than at 2,300°C), and the blackbody will have significantly enhanced UV emission. Also, for blackbody temperatures above approximately 2,400°C, the evaporation of graphite becomes important and the cavity life will be significantly shortened. However, because the thermal and electrical conductivities are temperature dependent, it may be possible to choose a position for the "end heater" such that its effect is reduced at higher temperatures. The numerical model developed is used to investigate this possibility.

4 Numerical Model Results

Figure 2 shows the calculated axial temperature profile at three temperatures for three different "end-heater" widths and reductions in wall thicknesses (depths). At any given temperature, the required additional end-heater power can be obtained from either a "short deep" cut in the tube or a "long shallow" cut. However, as expected from the argument presented earlier, a cut that generates a uniform temperature distribution at low temperatures generally results in a temperature "hump" at the ends of the uniform zone at higher temperatures. A careful examination of the graphs in Fig. 2 shows that the difference between 1,000 and 2,200°C profiles differs between "short deep" and "long shallow" cuts. In general, a long shallow cut is found to result in a smaller "hump" at high temperatures, and is in any case preferable on the grounds of mechanical robustness. Although there is an "optimal" width and depth to achieve a long uniform zone, the choice of "cut" alone is inadequate to achieve uniformity over a wide temperature range.

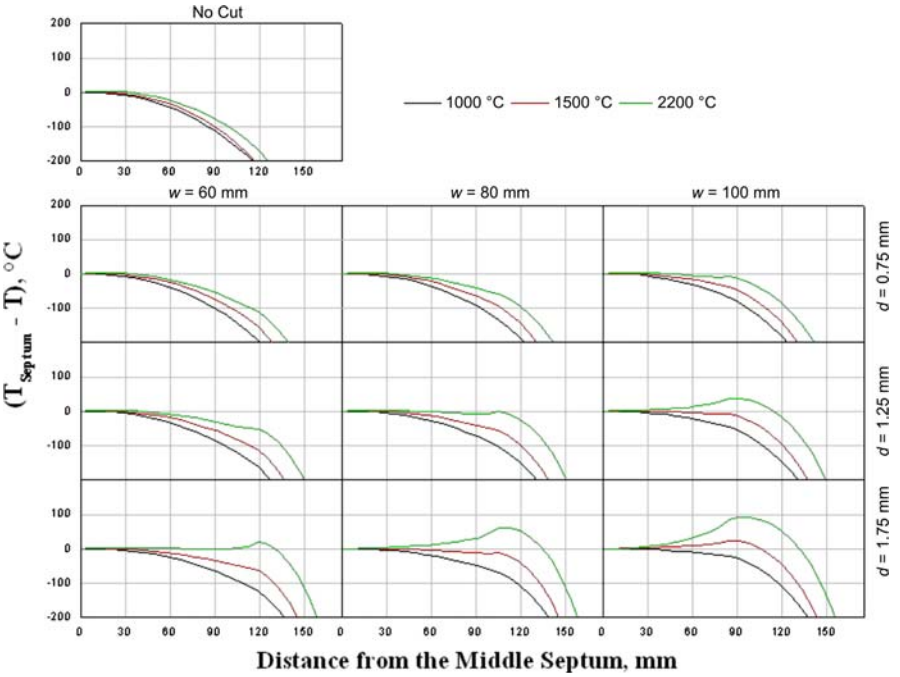

Fig. 2 Modeled axial temperatures of the 400 mm long ATJ tube at operating temperatures of 1,000, 1,500, and 2,200°C, using N_2 as the insulation purge gas

The thermal model for the graphite felt [4] predicts that its thermal conductivity becomes dominated by radiative heat transfer at temperatures above approximately 1,500°C. However, at lower temperatures, the contribution from gas conduction is significant, and changing the purge gas from N_2 (Ar is similar to N_2) to He results in a significant increase in radial conductivity (from $0.3\,W \cdot m^{-1} \cdot K^{-1}$ to $0.7\,W \cdot m^{-1} \cdot K^{-1}$ at 1,000°C). This provides a convenient mechanism to "adjust" the temperature profile in the tube. Figure 3 shows the same set of tube designs as in Fig. 2, but with the N_2 purge gas replaced by He. As expected, with a higher radial heat flux, the relative effect of axial heat losses is lower. This tends to increase the effect of a given depth of cut in the tube. A tube cut can thus be chosen to produce good tube uniformity at the highest operating temperature in Ar (or N_2) while also producing good tube uniformity at lower temperatures by adding He to the insulation purge gas.

5 Experimental Results

Figure 4 shows the temperature profiles measured using a conventional Type-R (Pt alloy) thermocouple (0.5 mm diameter wire in a 3.2-mm OD sheath), with the wire withdrawn from the end of the insulator to form a loop running circumferentially around the inside of the tube to minimize conduction errors. Profiles have been measured at 1,000 and 1,500°C for three furnace tubes: (i) the original 289 mm tube design, (ii) a tube of the same length but optimally chosen end-heater cuts

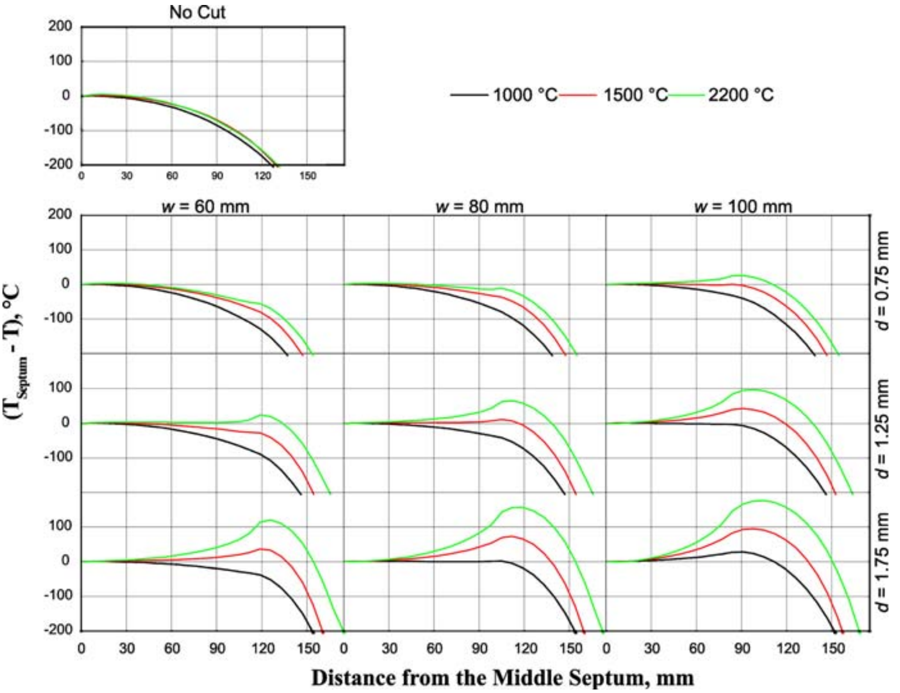

Fig. 3 Modeled axial temperatures of the 400 mm long ATJ tube at operating temperatures of 1,000, 1,500, and 2,200°C, using He as the insulation purge gas

(2-mm-diameter reduction from 30 to 90 mm from the ends in a 34-mm OD tube), and (iii) a 400-mm-long tube with optimally chosen end-heater cuts. For the latter two tubes, measurements were made using both He and N_2 insulation purge gases. The numerical results predicted by the model are also shown in this figure.

The modified "short tube" is found to have significantly better temperature uniformity than the original design, both at 1,000 and 1,500°C. At 1,000°C, the use of He as a purge gas increases the uniformity by the amount expected by the model. The "long-tube" results are, as expected, still better, and again the improvement at lower temperatures resulting from the use of He is in agreement with the model predictions.

The diffuse reflectance model in [4] and a value of $85 \pm 5\%$ for the emissivity of graphite have been used to compute an effective cavity emissivity (at 650 nm) from the temperature profiles in Fig. 4. For the original graphite tube, a value of $99.5 \pm 0.3\%$ at 1,000 and 1,500°C is obtained. The short tube with the cut has an emissivity increased to $100.1 \pm 0.02\%$ (at both 1,000 and 1,500°C). Note that the effective emissivity higher than 100% results from the temperature "hump" near the cut in the tube. When He is used with this tube, the tube emissivity increases by 1% at 1,000°C and 2.5% at 1,500°C.

For the "long tube" at 1,000°C, the emissivity is $99.84 \pm 0.1\%$; with the use of He, it increases to $99.98 \pm 0.04\%$, an emissivity increase of 0.14%. At 1,500°C in N_2, the emissivity is $99.97 \pm 0.02\%$

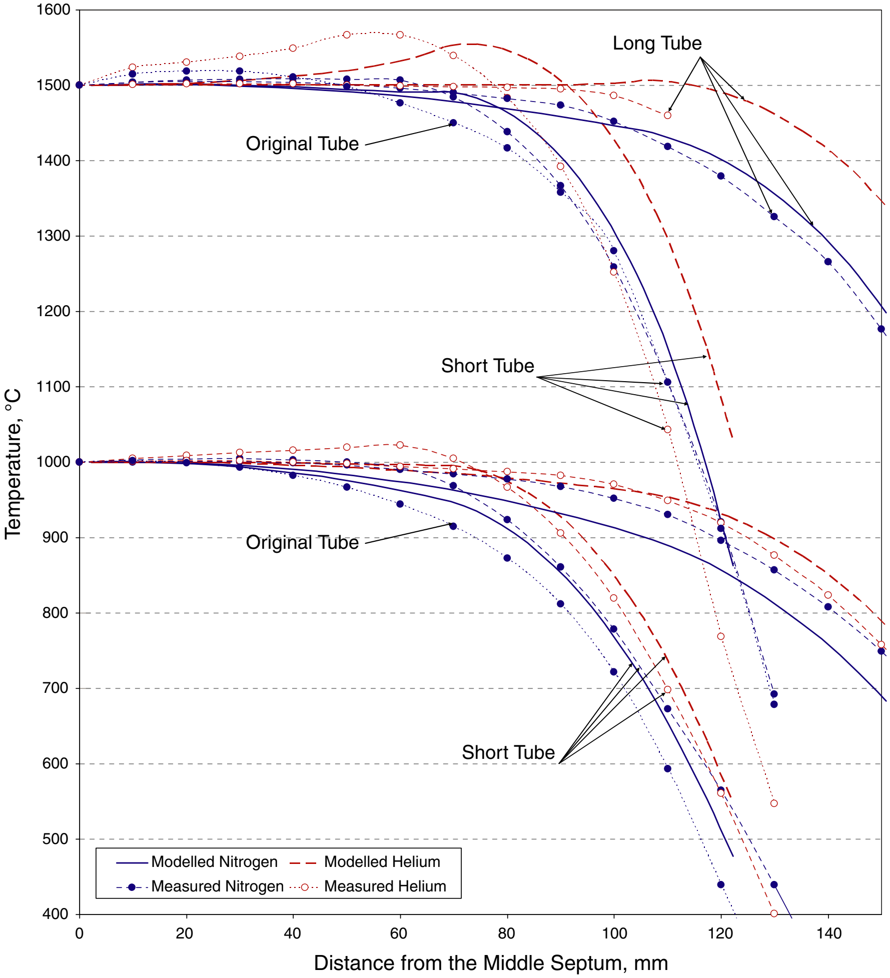

Fig. 4 Comparison of the ATJ tube measured temperature profile at 1,000 and 1,500°C for the 289 mm original tube, the modified 289 mm (*short*) tube, and the modified 400 mm (*long*) tubes with both N_2 and He purged insulation

Although the modeled and measured temperature profiles are in qualitative agreement, and in particular the effect of the change of purge gas is well modeled, further work is required to obtain exact numerical agreement of the measured and modeled axial profiles. It is suggested that this may be explained by the experimental observation of "graphite dust" loading of the felt after extended use.

6 Conclusions

Based on our numerical models of the ATJ graphite tube, three methods were devised to optimize its temperature profile: (a) constructing a longer tube and choosing the graphite thickness to remain within the supply voltage and current range thereby minimizing “end effects” on the tube central region, (b) machining “end-heater” regions into the tube ends with optimum dimensions, and (c) the use of a mixture of N_2/Ar and He to control the radial heat flux and thus tune the tube temperature profile. The latter two strategies have been applied to both “short” and “long” heater tubes, and significant improvements in the temperature uniformity over a wide temperature range have been experimentally verified. This has resulted in an improvement of the emissivity from 99.5% to over 99.95%.

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