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Virtual Experiments by Pulse Heating Techniques: Cylindrical Tungsten Specimens

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Abstract A bi-dimensional geometrical model was developed and numerically solved considering different cylindrical tungsten specimens, heated to temperatures above 3600 K with current pulses of about (500, 750, and 950) ms duration. A detailed analysis of these virtual experiments indicated large radial temperature differences in all the investigated cases. The range of validity of the long thin rod approximation was verified for various geometries and under different experimental conditions. The developed model may be used to estimate uncertainties due to the use of this approximation and to optimize experimental conditions in real experiments.

Keywords High temperatures · Numerical modeling · Pulse heating · Subsecond experiments · Tungsten

1 Introduction

The first paper that described a modern apparatus for the measurement of thermophysical properties by subsecond current pulse heating [1] included some analysis of the radial and axial temperature distributions of the specimen. These evaluations were based on approximate calculations making use of the limited computing power available in the early 1970s and indicated no significant temperature distribution problems for tubular molybdenum specimens at 2800 K [2]. All the

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following experimental work that took place in different laboratories up to recent years assumed the "long thin rod approximation" (no significant radial temperature differences) to be valid for subsecond pulse-heated specimens and based the computation of thermophysical properties from experimental data on such an approximation. This assumption was reconsidered in recent years by two different research groups, which modeled long thick rod specimens [3] and the specific geometry of tubular specimens with a blackbody hole [4]. In both cases significant temperature differences were found and therefore some reconsideration of the temperature distribution in pulse-heated specimens seems necessary. This work is a partial follow-up of previous activities [3] to apply modern modeling techniques to subsecond pulse heating experiments.

Taking advantage of the large computing power now available on desktops and of modern software packages, a new research project to evaluate virtual experiments by pulse heating techniques was recently started. The first stage of the project involved the development of a bi-dimensional model for cylindrical specimens heated by current pulses of subsecond duration. After a careful literature search and an evaluation of the relevant thermophysical properties (heat capacity, electrical resistivity, thermal conductivity, and hemispherical total emissivity), the developed model was applied to tungsten. Since experiments on tungsten cover the range from room temperature to over 3600 K, the findings may qualitatively be extended to lower melting-point materials.

2 Modeling

2.1 Software and Model

The numerical analysis of the virtual experiment was based on a commercial software package (COMSOL) that solves partial differential equations with a finite-element method. In particular, two modules of the package, specialized in the analysis of heat transfer and of conductive media, were used interactively, with two unknown variables: the temperature and the voltage. The resulting model describes the evolution in time of the unknown variables in the consequence of a time-varying input current density flowing in the virtual specimen. Different functions were checked for the current, but in the virtual experiments described later in this work, a constant current was used to avoid effects related to the current shape. The heat transfer module receives as input from the conductive media module, the Joule heating produced by the current flowing in the specimen. The present version of the model does not consider thermal expansion, and the temperature-dependent thermophysical properties were not corrected for expansion effects. The Thomson heat was neglected on account of its minimal contribution to this type of experiment.

The geometry of the specimen is fully described by its radius and its length, owing to the assumed rotational symmetry. The boundary conditions in the electrical model include the symmetry axis and the electrically insulated external surface; the current enters from the upper side, whereas the lower side is grounded. The boundary conditions in the thermal model include the symmetry axis and the external surface that irradiates to ambient temperature, with the lower and upper sides of the specimen forced to 300 K. This last condition practically simulates the connection of the specimen to massive clamps that absorb all the heat conducted away axially during the short time of the current pulse. Appropriate meshes were chosen, related to the specimen diameter and to the precision of the calculations.

Before being implemented in the present work, the model was carefully verified in three different ways:

(a) by comparison with another model. Some specific data previously used by a different simulation using a finite differences model [3] were available. We reproduced that earlier simulation with a small difference in results, of the order of 0.4 K to 0.5 K in the high-temperature range. This comparison is important because the two different methods and two different software gave similar results, providing an important crosscheck.
(b) for auto-consistency. The model was excited with a current, and the electrical potential obtained across the virtual specimen was used as input for the model. The temperatures resulting from the second simulation were practically identical to the original ones, with differences of the order of 0.01 K
(c) for computational accuracy. The optimal parameters in the numerical analysis, as the absolute and the relative tolerances for the time-dependent solver, were carefully investigated. Successive executions were performed with different parameters, whose optimal values were obtained as stationary points in the results of the simulations.

A time step of 0.1 ms was found adequate to describe well the time evolution of the specimen heating and consequently the computed temperature profiles.

2.2 Thermophysical Property Data of Tungsten

Using the developed model, some virtual experiments were performed on cylindrical tungsten specimens. The simulation depends strongly on the data used for the various thermophysical properties and on their temperature dependence. A careful review of literature data was performed, selecting as much as possible recommended curves in published reviews integrating them with more recent experimental data, in particular to extend the functions to uncovered temperature ranges. Data measured on earlier temperature scales were corrected to ITS-90 values when necessary. The chosen property data were fitted with smooth functions covering the entire range from room temperature to the melting point of the material.

The electrical-resistivity curve was obtained by combining some analyzed data [5] from the CODATA project with more recent experimental results [6,7] extending to the melting point. Similarly the heat-capacity function was obtained with a combination of some review data [8] with the more recent results [6,7]. Since the total hemispherical emissivity strongly depends on surface conditions, values from a single source were used [6]. For thermal conductivity, the review data of Hust [9] were used, refitting them to a function that covered smoothly the temperature range of interest.

3 Virtual Experiments and Discussion

Having checked the accuracy of the modeling procedure, the developed model can be used in two main ways. It can be applied as a predictive tool in searching for the optimal geometry necessary for some experimental measurements. Using available literature data, the experiment may be planned ahead by selecting both geometrical and experimental conditions that optimize the possibility of measuring the sought property or properties as best as possible.

A second way of usage, considered in detail in this work, is to perform a detailed analysis of possible experiments and evaluate if certain approximations, like the long thin rod approximation, maintain their validity. Using such a model, one can also establish uncertainty limits due to the use of approximations in elaborating experimental results and/or evaluating correction terms.

Using the developed model, we have performed virtual experiments simulating the heating phase of three different tungsten cylinders, labeled as thin, normal, and thick specimens. The normal specimen (diameter of 3.2 mm) exhibits a cross section of approximately 8 mm^2, very similar to the one of specimens typically used in real pulse heating experiments. Thin (diameter of 1 mm) and thick (diameter of 5 mm) specimens were also virtually pulse heated to evaluate differences due to the specimen geometry. All the specimens were considered to have a length between the clamps of 80 mm, closely resembling real experimental conditions. Three different virtual experiments (slow, medium, and fast) were performed on each specimen. The full details of the nine specimen–experiment combinations are reported in Table 1. Medium-speed experiments represent typical conditions, while fast and slow experiments are within the possible experimental range. All virtual experiments were performed assuming a current constant in time. This approach deviates from real experimental conditions, but does not change the significance of the obtained results. The typical radial temperature profiles of a thin specimen pulse heated above 3600 K in 750 ms are shown in Fig. 1.

We have fixed hypothetical voltage probes in the central portion of the specimen, selecting a region, defined as the effective length in Table 1, where the axial surface temperature profile remains within 0.1 K. Sometimes this region starts to show some rounding effects due to the axial heat conduction toward the clamps, as can be seen in Fig. 2. In all the virtual experiments this region extends for 16 mm to 33 mm. This central portion defines the "effective specimen" and is used for evaluating the heat capacity (C_p) and electrical resistivity (ρ) in real experiments. Radiation losses in this central region range from 4 % to 36.9 % of input power. Virtual experiments on the thin specimen have a particularly high percentage of radiation losses, making them less accurate for the evaluation of C_p and ρ, but potentially good for measuring the hemispherical total emissivity during the initial part of the cooling period. The opposite conditions occur for virtual experiments performed on the normal and thick specimens.

A significant result of the virtual experiments on tungsten is the indication that all specimens pulse heated in different conditions show a rather high radial temperature difference at their maximum temperature. Typical radial temperature profiles at the highest temperatures reached in the virtual experiments are presented in Fig. 3.

Table 1 Results of virtual experiments performed on thin, normal, and thick tungsten specimens

	Virtual experiment	Slow	Medium	Fast
Thin specimen				
Diameter 1 mm	Duration (ms)[a]	950	750	520
	Current density ($A \cdot mm^{-2}$)[b]	187.35	209.41	248.68
	Current (A)[b]	147.14	164.47	195.31
Cross-section 0.7854 mm^2	Maximum temperature (K)[c]	3655	3658	3620
	Radial temperature difference (K)[d]	10.5	10.5	9.9
	Effective length (mm)[e]	18	24	33
	Radiation loss at maximum temperature (%)[f]	36.9	29.6	20.3
Normal specimen				
Diameter 3.2 mm	Duration (ms)[a]	950	750	511
	Current density ($A \cdot mm^{-2}$)[b]	183.18	205.77	248.68
	Current (A)[b]	1473	1655	2000
Cross-section 8.0425 mm^2	Maximum temperature (K)[c]	3660	3658	3652
	Radial temperature difference (K)[d]	29.7	28.7	26.5
	Effective length (mm)[e]	16	23	33
	Radiation loss at maximum temperature (%)[f]	11.8	9.3	6.3
Thick specimen				
Diameter 5.0 mm	Duration (ms)[a]	950	750	510
	Current density ($A \cdot mm^{-2}$)[b]	182.50	205.16	248.68
	Current (A)[b]	3583	4028	4884
Cross-section 19.635 mm^2	Maximum temperature (K)[c]	3658	3655	3662
	Radial temperature difference (K)[d]	39.3	37.0	33.3
	Effective length (mm)[e]	19	23	32
	Radiation loss at maximum temperature (%)[f]	7.5	5.9	4.0

[a] Total duration of the simulated pulse heating experiment
[b] Current density and corresponding specimen current, maintained constant for each experiment
[c] Maximum temperature reached in the core at the center of the specimen
[d] Typical radial temperature difference between core and surface at the center of the specimen
[e] Central portion of the specimen where the surface temperature remains within 0.1 K
[f] Power lost by radiation as percentage of the input power in the central portion of the specimen (over the effective length)

These radial temperature differences range from around 10 K for the thin specimen to the ranges, 26 K to 30 K and 33 K to 40 K for the normal and thick specimens, respectively (details in Table 1). Such an unexpected high radial temperature difference indicates that errors can be introduced in evaluating thermophysical properties (C_p and ρ) from experimental results using the long thin rod approximation. A real experiment does have independently measured temperatures, generally via pyrometry. In the developed model, we have used the central portion of the specimen itself as a four-terminal thermometer, using the voltage drop from the hypothetical voltage probes and the current to compute the electrical resistance and hence the average

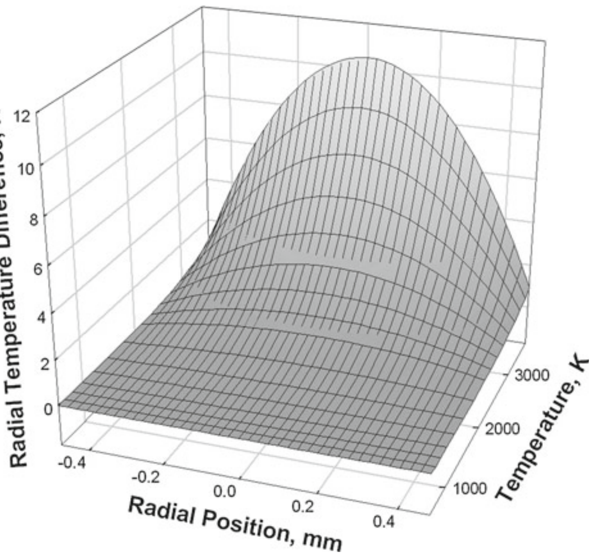

Fig. 1 Evolution with temperature of the simulated radial temperature profiles inside a tungsten specimen of 1 mm diameter taken to temperatures above 3600 K in a pulse heating experiment of 750 ms duration

resistivity of the effective specimen. From the inverse electrical resistivity function we have then computed the average temperature of the effective specimen. These three values (voltage drop, current, and average temperature of the effective specimen) were fed to a modified property elaboration program that recomputed the heat capacity and the electrical resistivity of the material, using these input values as possible experimental data. The most delicate problem in evaluating thermophysical property data in subsecond experiments is the estimation of the heating rate. For real experiments the temperature versus time is usually reasonably approximated by a low-order polynomial that is then derived analytically to obtain heating rates. The virtual experiments on tungsten extend over a very wide temperature range (typically 300 K to 3650 K) and make use of a constant current. In these conditions the temperature versus time cannot be represented by polynomials. The convolute method [10,11], originally used for similar heat-capacity measurements, has proved to be very adequate in approximating temperatures and computing heating rates at the conditions of the virtual experiments. Alternatively temperature versus time may be approximated by splines, but in this case often the results depend on the number of chosen knots over the time interval, with the possibility of oscillating residuals indicating a poor approximation.

The percentage relative deviations of recomputed properties for all specimen-experiment combinations are presented in Table 2. The electrical-resistivity values are reconstructed with negligible errors (always less than 0.01 %) and the heat-capacity values are reconstructed with minimal errors (ranging from 0.1 % to 0.4 %). A selected subset of these results is presented visually in Fig. 4.

Real experiments may also be performed by measuring the radiance temperature of the surface of the specimen, converting it to the true temperature via measured or

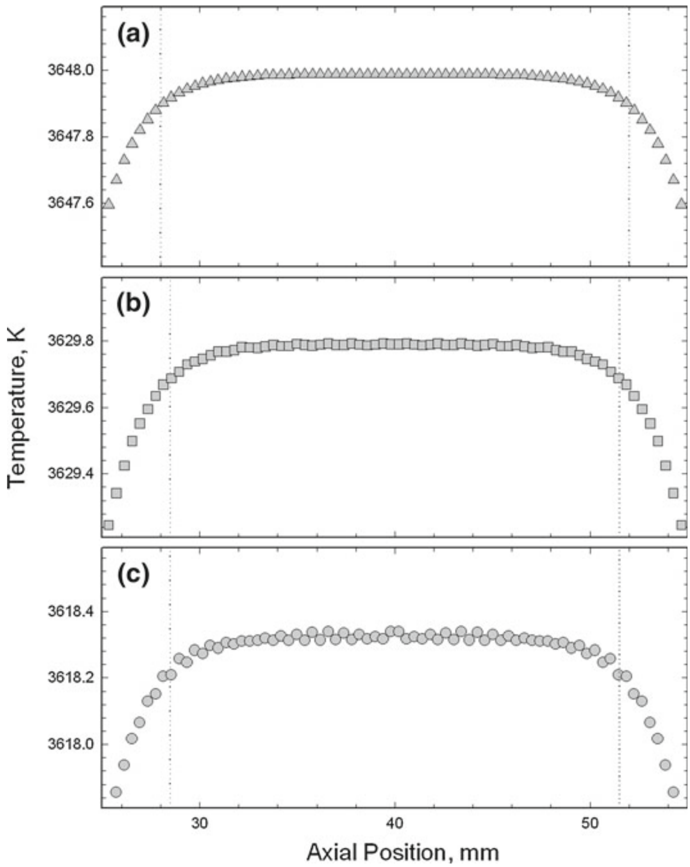

Fig. 2 Axial temperature profiles in thin (a), normal (b), and thick (c) specimens pulse-heated to high temperatures in a virtual experiment of 750 ms duration. *Dotted lines* indicate the position of the hypothetical voltage probes

estimated normal spectral emissivity values. Another used possibility is the intrinsic welding of thermocouples to the specimen surface [12]. If surface-temperature values are used for reconstructing the thermophysical properties, the long thin rod approximation errors increase significantly, as can be seen in Table 3 and Fig. 5. In these cases reconstructed electrical-resistivity values present errors of the order of 0.12 % to 0.52 %, while reconstructed heat capacity values exhibit larger errors in the range of 0.9 % to 3.9 %. This is a natural consequence of the large radial temperature gradients: using the lower surface temperatures, the long thin rod approximation is no longer adequate.

In conclusion, the long thin rod approximation can be used for computing thermophysical properties also in the presence of significant temperature gradients, provided that a good measurement or estimate of the average temperature of the effective specimen is available. In such a case the uncertainties are negligible for the electrical resistivity and small for the heat capacity. If the temperature is obtained only from

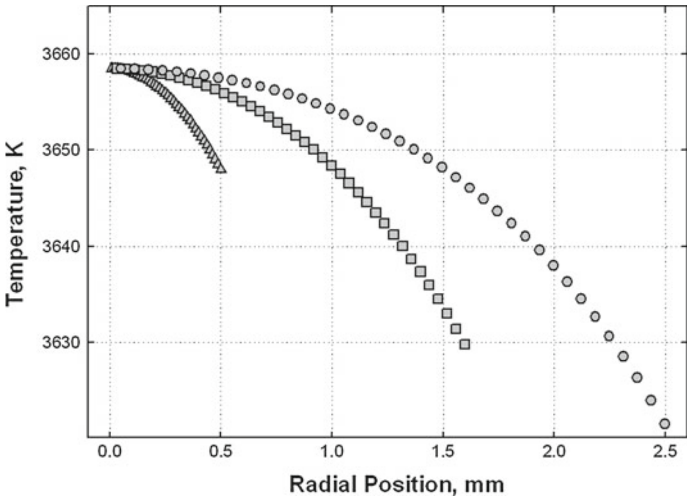

Fig. 3 Radial temperature profiles in the thick (*circle*), normal (*square*), and thin (*triangle*) specimens in a virtual experiment of 750 ms duration. Profiles are those at the maximum temperature of the simulation

Table 2 Maximum long thin rod approximation errors made in recomputing the heat capacity and the electrical resistivity of tungsten using the simulation data as input. Average temperatures of the central portion of the specimen have been used. The maximum error occurs in the very high-temperature range over 3000 K

	Virtual experiment	Slow	Medium	Fast
Thin specimen				
Diameter 1 mm	Electrical resistivity (%)	<0.01	<0.01	<0.01
	Heat capacity (%)	0.35	0.25	0.15
Normal specimen				
Diameter 3.2 mm	Electrical resistivity (%)	<0.01	<0.01	<0.01
	Heat capacity (%)	0.2	0.2	0.1
Thick specimen				
Diameter 5.0 mm	Electrical resistivity (%)	<0.01	<0.01	<0.01
	Heat capacity (%)	0.2	0.2	0.2

surface measurements, the long thin rod approximation errors are still manageable for the electrical resistivity but are very large for the heat capacity, becoming the major source of uncertainty. Thin specimens, having a diameter of 1 mm in the investigated cases, exhibit small radial temperature gradients and are the only ones where the long thin rod approximation errors provide reasonable contributions to the uncertainty budget.

Taking advantage of the directionality of these errors, a modeling program like the one developed in this work might be used to compute correction terms for the case when only surface-temperature measurements are available.

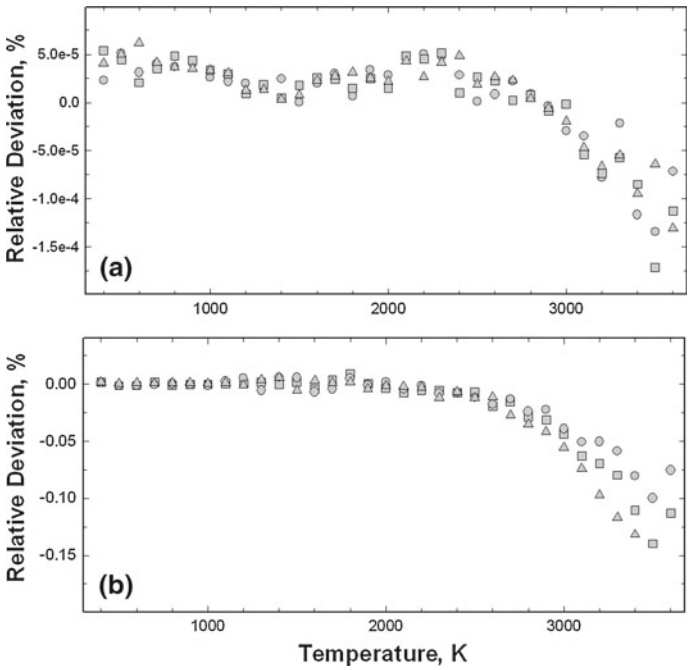

Fig. 4 Relative deviation of reconstructed (a) electrical-resistivity and (b) heat-capacity values using the average temperatures in the central portion of the specimen as input data. Graphs are indicative of errors due to the use of the long thin rod approximation for thick (*circle*), normal (*square*), and thin (*triangle*) tungsten specimens pulse-heated to high temperatures in 750 ms

Table 3 Maximum long thin rod approximation errors made in recomputing the heat capacity and the electrical resistivity of tungsten using the surface temperatures of the specimen. The error increases regularly, reaching its maximum at the highest temperature, over 3600 K

	Virtual experiment	Slow	Medium	Fast
Thin specimen				
Diameter 1 mm	Electrical resistivity (%)	0.12	0.12	0.12
	Heat capacity (%)	1.0	0.95	0.9
Normal specimen				
Diameter 3.2 mm	Electrical resistivity (%)	0.36	0.36	0.34
	Heat capacity (%)	2.8	2.8	2.7
Thick specimen				
Diameter 5.0 mm	Electrical resistivity (%)	0.52	0.49	0.46
	Heat capacity (%)	3.9	3.7	3.5

4 Conclusions

Modeling of pulse heating experiments is an important tool both to predict and to analyze the behavior of subsecond current pulse-heated specimens. The results of the

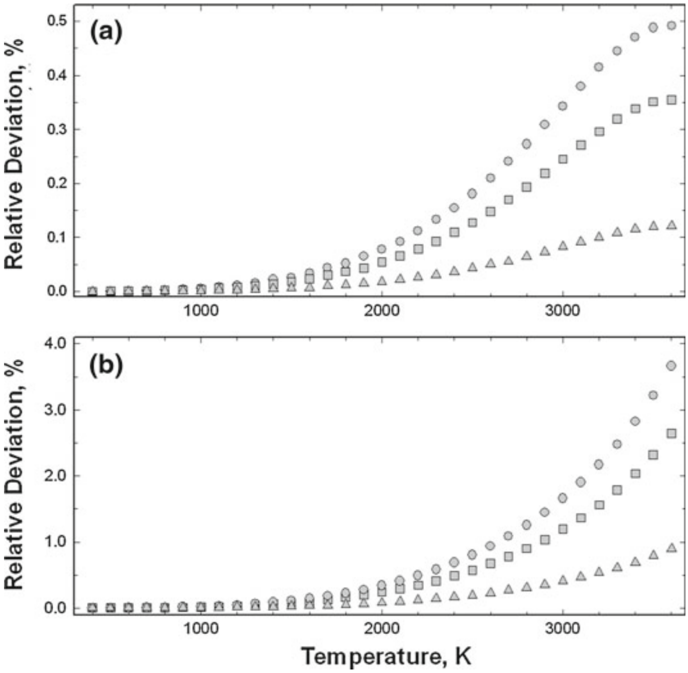

Fig. 5 Relative deviation of reconstructed (a) electrical-resistivity and (b) heat-capacity values using surface temperatures at the center of the specimen as input data. Graphs are indicative of errors due to the use of the long thin rod approximation for thick (*circle*), normal (*square*), and thin (*triangle*) tungsten specimens pulse heated to high temperatures in 750 ms

present work have demonstrated the capability of the model to analyze in depth via virtual experiments the behavior of cylindrical tungsten specimens pulse heated to very high temperatures. Future work in this research area might be related to the introduction of thermal expansion effects, to the modeling of the initial cooling phase after pulse heating, to the consideration of other specimen geometries, and to the extension to different high-temperature materials. In general terms, the available computational resources combined with the accuracy reached by the most advanced numerical programs allow exploration of a new universe of possible experimental configurations.

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