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A novel approach to temperature-dependent total emissivity estimation based on isothermal cooling

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ABSTRACT

This paper proposes a novel approach to estimate the temperature-dependent total emissivity based on the isothermal cooling process. The realizability of the ideal isothermal cooling phase has been verified through the finite-element model, even for specimens with low thermal conductivity. During the cooling process, the temperature difference of the specimen can be less than 0.8%. Moreover, based on the temperature curve of isothermal cooling, nonlinear total emissivity can be calculated using the inverse method over a broad temperature range, e.g., 500–1200 K, and the relative errors will be less than 8.83% with virtual test data. For a real-world application, we introduce the Savitzky-Golay (SG) filter to weaken the effect of noise on computation precision and successfully gain the smooth temperature-dependent total emissivity.

1. Introduction

Thermal radiation problems are prevalent in practical engineering applications [1–4], especially in the field of advanced high-temperature technology such as combustion chambers [5] and thermal protection systems in hypersonic vehicles. Surface emissivity with temperature dependence is the most crucial thermosphysical property for the thermal analysis of these structures. In specific hot structures, emissivity should be measured or estimated precisely to improve the accuracy of the thermal analysis model used in the numerical simulation or optimization design [6,7]. However, emissivity greatly depends on surface properties [8–10], surface temperature [11,12], oxidation state [13–15] and other factors, leading to difficulties measuring or estimating emissivity.

The direct measurement of emissivity is widely used by comparing the same spectral emissivity to blackbody spectral intensity at the same temperature [16]. However, experimental measurement methods are incredibly complicated [6,17,18], and if the test temperature range is broad, several tests must be conducted [19]. Indirect estimation methods for emissivity that uses an inverse algorithm have attracted the attention of many researchers because it can infer emissivity based on a simple thermal experiment. When emissivity is assumed to have no temperature dependence [20], the inverse problem is easily solved. On the other hand, when emissivity is a function of temperature, and the environment contains heat convection, it will be challenging to solve the inverse problem of emissivity estimate [21,22].

In this paper, we propose a novel method to estimate temperature-dependent total emissivity using the isothermal cooling phase in a vacuum, ignoring any convective heat transfer mechanisms. Firstly, we briefly analyze the temperature field in the specimen to verify the isothermal cooling hypothesis and calculate thermal response under different total emissivity conditions. Then, based on isothermal cooling and the lumped capacitance method, we discuss the proposed method in detail, which includes the numerical and experimental methods. Finally, this approach will be used to infer different total emissivity based on the temperature response from the numeric model and the measured temperatures from the real heating test.

2. Finite element model of laser heating and cooling

The temperature rise in specimens is due to laser heat flux with a Gaussian distribution. Meanwhile, heating loss to the surroundings occurs only due to radiation loss, due to the vacuum environment. The general governing equations and the boundary conditions of the laser heating and cooling model can be defined as the following expressions:

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Heat transfer equation:

$$\rho C_p(T)\frac{dT}{dt} = \frac{\partial}{\partial x}\left(k(T)\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k(T)\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k(T)\frac{\partial T}{\partial z}\right) \tag{1}$$

Radiation boundaries:

$$-k\frac{\partial T}{\partial n} = \varepsilon(T)\sigma(T_\infty^4 - T^4) \tag{2}$$

Adiabatic boundary:

$$-k\frac{\partial T}{\partial n} = 0 \tag{3}$$

Gauss heat flux:

$$q(x,y,t) = \frac{\bar{q}}{\sqrt{2\pi}(R/3)} \cdot \exp\left[\frac{-(x^2+y^2)}{2\times(R/3)^2}\right] \cdot f(t) \tag{4}$$

where ρ represents material density, $C_p(T)$ is the temperature-dependent heat capacity, $k(T)$ is temperature-dependent thermal conductivity, $\varepsilon(T)$ is temperature-dependent total emissivity, σ is the Stefan Boltzmann constant, T is temperature, T_∞ is ambient temperature, $f(t) = 1$ during laser heating and $f(t) = 0$ during the cooling phase, $\bar{q}$ is the average heat flux by laser, and R is the radius of the laser spot, which means 99.7% energy is located within the laser spot.

Due to the Gaussian distribution of the laser power, it is difficult to realize temperature uniformity during laser heating. However, the temperature of the wafer can be rendered more uniform by radiation cooling. We then used the finite-element method to verify temperature uniformity during cooling following laser heating. The essential assumptions of the FEM model about laser heating that we considered are as follow:

(a) The wafer samples are always kept in an ideal geometry without deformation during laser heating and cooling;
(b) The energy stored due to plastic deformation is neglected;
(c) The sophisticated laser heating model is simplified to a transient problem with a surface heat flux following a specific Gaussian distribution, considering there is no interaction between the laser and materials.

The developed numeric model was solved by finite-element method. The numerical model was discretized with two dimensional 0.2 mm linear quadratic elements, whose convergence property is excellent.

In this paper, tungsten, which is known to have high-temperature thermo-physical properties (as shown in Table 1) is used to estimate temperature-dependent total emissivity in a vacuum environment. The sample has a specified geometry size with a 12 mm radius and 2 mm thickness. The temperature uniformity condition must be ensured to obtain high accuracy for the total emissivity estimate. In this paper, the FEM method is used to analyze the temperature uniformity of the wafer samples during cooling. The formula for characterizing temperature uniformity is defined as follow:

$$UT = \left|\frac{T_{\max} - T_{\min}}{T_{\min}}\right| \tag{5}$$

where T_{max} and T_{min} are the maximum and minimum temperature at some time. The smaller the UT, the more uniform the specimen.

3. The physical and mathematical model for total emissivity inversion

3.1. The direct problem

The total emissivity of a solid object strongly depends on temperature. Different material has distinct emissivity properties, and these properties will obviously be different, even for the same material, but with different surface morphologies. The Stefan-Boltzmann equation can determine the radiation heat flux of a non-transparent solid.

$$q_{rad} = \sigma\varepsilon(T)(T - T_\infty) \tag{6}$$

where σ is the Stefan-Boltzmann constant and T_∞ is the ambient temperature.

Bi is used to characterize the spatial temperature uniformity during heating and cooling. Assume that Bi is far less than one, which means thermal resistance in the solid is much less than the convective thermal resistance across the fluid boundary layer, and the spatial temperature gradient can be neglected during the cooling phase. Then the decrease in the internal energy of the solid is equal to the radiated heat of the surroundings, as defined in the energy equilibrium equation:

$$E_{st} = E_{out} \tag{7}$$

Considering the geometry of the cooling solid in a vacuum, e.g., volume and surface area, we can obtain the following transient heat transfer equation using Eqs. (1), (5) and (7).

$$\rho V C_p(T)\frac{dT}{dt} = A\varepsilon(T)\sigma(T^4 - T_\infty^4) \tag{8}$$

where V is the volume, A is the surface area that radiates energy to the surroundings, $\varepsilon(T)$ is the temperature-dependent total emissivity, σ is Stefan-Boltzmann constant, T is the temperature and T_∞ is ambient temperature.

Based on the isothermal cooling hypothesis in a vacuum, we can establish the relationship between total emissivity, temperature, geometry, density and temperature-dependent heat capacity, which ignores the convective heat transfer coefficient, temperature-dependent thermal conductivity, temperature gradient and other factors.

3.2. The inverse problem

In a direct heat transfer problem, we solve the temperature field by using specific material properties, loads and boundaries. In order to establish temperature-dependent total emissivity, we must solve the inverse problem. If the object is uniformly cooling, based on the above formula and the cooling temperature curve, the total emissivity can be estimated by the following equation:

$$\varepsilon(T) = \frac{\rho V C_p(T)\frac{dT}{dt}}{A\sigma(T^4 - T_\infty^4)} \tag{9}$$

Table 1
Thermo-physical properties [23].

Material	ρ/kg·m^{-3}	Properties dependent on temperature k/[W/(m·K)]/C$_p$[J/(kg·K)]								
		100	200	400	600	800	1000	1200	1500	2000
W	19,300	208 87	186 122	159 137	137 142	125 145	118 148	113 152	107 157	100 167