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Contactless, non-intrusive core temperature measurement of a solid body in steady-state

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ABSTRACT

Accurate measurement of temperature is critical for understanding thermal behavior and monitoring safety and performance of engineering systems involving heating and cooling. While a number of methods are available for measurement of temperature on the outside surface of solid bodies, there is a lack of contactless, non-invasive methods for determining temperature inside solid bodies. Development of such methods is likely to impact a wide range of engineering systems. This paper describes and validates a method for measurement of internal core temperature of a solid body in steady-state based on measurement of the temperature distribution on its outside surface based on a theoretical thermal conduction model. This method is validated by determining the steady-state core temperature of a thermal test cell using infrared temperature measurement on the surface, and comparing with measurements from an embedded thermocouple. The two measurements are found to agree well with each other in a variety of heat generation and cooling conditions. While this validation is presented for a cylindrical body, the method lends itself easily to bodies of other shapes. This work contributes towards fundamental thermal metrology, with possible applications in a wide variety of engineering systems.

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1. Introduction

Temperature directly affects the performance, safety and reliability of a variety of engineering systems relevant for energy conversion. Most physical processes that occur in such systems are closely coupled to the temperature field. For example, in a Li-ion cell, electrochemical reactions during energy storage and conversion determine the temperature field in the cell [1–4], which, in turn, affects the rates of these electrochemical reactions [5]. Measurement of temperature is a critical step for ensuring safety, reliability and high performance of engineering systems involving heating and cooling, as well as for fully understanding coupled, multiphysics phenomena that occur in such systems. In general, temperature is measured based on a linear change in a measurable characteristic as a function of temperature [6,7]. This includes electrical resistance [8], thermal expansion [8], reflectance [9], circuit resonant frequency [10], color [11], surface radiation [12], etc. A number of temperature measurement methods, varying in their accuracy and complexity have been used to measure transient and steady state temperature either at discrete locations, or over an entire surface.

While a number of methods are available for temperature measurement on the outside surface of a solid, there is a relative lack of methods for non-invasively measuring temperature inside solids. Internal temperature measurement is relatively more challenging, particularly when a remote, contactless method is desired, but is also very important, since the safety and performance of systems depends critically on the internal temperature, which for heat-generating bodies is typically higher than the outside surface temperature. One example to illustrate this is a nuclear fuel rod, which is usually cylindrical in nature and has relatively low thermal conductivity [13]. Heat generation within the fuel rod due to fission reactions results in a temperature field within the rod, with the core of the rod usually being much hotter than the outside [14,15]. While the outside temperature of the fuel rod can be measured using a variety of surface temperature measurement techniques, measuring the temperature in the core of the fuel rod is not straightforward. In this case, a remote, contactless method for internal temperature measurement that does not disrupt the function of the fuel rod is very desirable. Another example is a Li-ion cell commonly used for electrochemical energy conversion and storage [1,16]. In a Li-ion cell, electrochemical reactions and electrical impedance result in significant heat generation and

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temperature rise throughout the cell volume [2,17]. Due to the poor radial thermal conductivity of the Li-ion cell [18], a significant temperature gradient within the cell is known to exist [17,19,20]. Performance optimization and safety of the cell requires information about the peak temperature of the cell, which occurs in the core of the cell, and is difficult to measure [17] as the cell is hermetically sealed, and drilling a hole through the cell to insert a temperature sensor will short circuit and disrupt the electrochemical function of the cell. On the other hand, use of the surface temperature of the cell instead of core temperature is not appropriate, and may lead to severe under-design of the thermal management of the cell. These examples illustrate the need for and importance of contactless, non-intrusive measurement of the internal temperature of engineering systems. Such a measurement method will clearly be of universal appeal.

Internal measurement of a variety of physical quantities other than temperature such as stress, chemical composition, morphology, crystal structure, etc. is possible using various measurement methods [21–24]. For example, internal morphology and chemical composition can be measured using X-ray CT scans [24] that make use of the absorptivity of electromagnetic radiation by different materials. A variety of contactless, non-intrusive methods based on synchrotron X-ray, neutron scattering and ultrasonic waves also exist for internal stress measurement [25]. In comparison, however, there is a distinct lack of contactless, non-intrusive methods for measurement of temperature inside solid bodies. Most present methods provide information about either the surface temperature or the volumetrically averaged temperature, neither of which may be representative of the internal temperature of the solid. Only very limited work exists on measuring internal temperature of solids [26–29]. For example, the temperature dependence of speed of ultrasonic waves through a solid has been utilized to measure the average temperature along a path through the solid by measuring the time of flight of an ultrasonic wave along that path [28,29]. Measurements along multiple paths through the body have been used in conjunction with information about the nature of the temperature field, obtained from solving governing energy conservation equations, to reconstruct the temperature field [29]. Ultrasonic-based temperature measurement methods, however, do not work well for materials with high rates of ultrasonic attenuation, and may be cumbersome to implement. Internal temperature of a Li-ion cell has been measured through impedance spectroscopy, based on a relationship between the cell temperature and certain electrochemical parameters of the cell [30–32]. However, these methods are very specific to the electrochemical characteristics of this system and do not apply to a general heat-generating body.

This paper presents a contactless, non-intrusive method for measurement of the steady-state core temperature in a heat-generating solid body. A theoretical heat transfer model for a heat-generating cylinder is developed to show that the steady-state core temperature of the cylinder can be measured using appropriate integrals of the measured spatial temperature distribution on the cylinder surface. Internal temperature measurement based on this approach is carried out for a thermal test cell in a variety of heat generation and convective conditions. These steady-state measurements are validated against a thermocouple embedded in the thermal test cell. The two are found to be in very good agreement. While this internal temperature measurement method is demonstrated here for a cylinder, a similar approach could be used for solids of other shapes. The next section presents theoretical models for non-intrusive determination of the core temperature based on surface temperature measurements. This is followed by a section describing the experimental test setup and methods. Results are presented and discussed next, followed by conclusions and future directions for this work.

2. Mathematical modeling

Consider a heat generating cylinder for which steady-state measurement of internal temperature at $r = 0$ is of interest, and for which temperature distribution on the outside surface is measured. This section presents the derivation of the steady-state temperature distribution within the cylinder, from where it is shown that the core temperature of the cylinder can be determined using the surface temperature distribution. Thermal conduction in the cylinder is assumed to be orthotropic, as is the case in several systems of engineering interest [18]. An infinite cylinder is considered in Section 2.1, and extension to a cylinder of finite length is discussed in Section 2.2.

2.1. Infinite cylinder

Fig. 1(a) shows a schematic of the general heat transfer problem analyzed in this section. Consider an infinitely long cylinder of radius R, with volumetric internal heat generation at a rate of Q. The radial and circumferential thermal conductivities are k_r and k_θ respectively. Assume that the temperature distribution along the outer surface at $r = R$ is measured to be a function of θ, given by $T_0(\theta)$. In steady state, the energy conservation equation that governs the temperature field in the cylinder is given by

$$\left(\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}\right)+\frac{k_\theta}{k_r}\left(\frac{1}{r^2}\frac{\partial^2 T}{\partial \theta^2}\right)+\frac{Q}{k_r}=0 \tag{1}$$

where $T(r, \theta)$ is the temperature rise above ambient. The temperature distribution within the cylinder is subject to the following boundary conditions:

$$\left.\frac{\partial T}{\partial r}\right|_{r=0}=0 \tag{2}$$

$$T(R,\theta)=T_0(\theta) \tag{3}$$

$$T(r,\theta)=T(r,\theta+2\pi) \tag{4}$$

$$\left.\frac{\partial T}{\partial \theta}\right|_{\theta}=\left.\frac{\partial T}{\partial \theta}\right|_{\theta+2\pi} \tag{5}$$

Eq. (2) represents the requirement for the temperature field to be finite at $r = 0$. Eq. (3) accounts for the measured temperature distribution T_0 on the outside surface of the cylinder. Note that if the extent of convective cooling varies significantly around the cylinder, as it does for forced convective cooling, T_0 will be a function of θ. Eqs. (4) and (5) represent periodicity in temperature and heat flux in the circumferential direction.

In order to determine the core temperature T_{core} at $r = 0$ in terms of the measured temperature distribution $T_0(\theta)$, a solution for the general temperature field $T(r,\theta)$ must be derived. To do so, the temperature field is first transformed as follows,

$$T(r,\theta)=w(r,\theta)+\frac{Q(R^2-r^2)}{4k_r} \tag{6}$$

This results in a homogeneous governing equation for $w(r, \theta)$ as follows:

$$k_r\left(\frac{\partial^2 w}{\partial r^2}+\frac{1}{r}\frac{\partial w}{\partial r}\right)+\frac{k_\theta}{k_r}\left(\frac{1}{r^2}\frac{\partial^2 w}{\partial \theta^2}\right)=0 \tag{7}$$

subject to

$$\left.\frac{\partial w}{\partial r}\right|_{r=0}=0 \tag{8}$$

$$w(R,\theta)=T_0(\theta) \tag{9}$$

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