International Journal of Thermophysics, Vol. 21, No. 1, 2000

A Method of Determining the Thermophysical Properties and Calorific Intensity of the Organ or Tissue of a Living Body

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Received March 9, 1999

A new method was developed to determine simultaneously the thermal conductivity, thermal diffusivity, specific heat, and calorific intensity of the organ or tissue of a living body either *in vivo* or *in vitro* with a thin hot probe. By using the method, the thermophysical properties and calorific intensities of a human palm and *in vivo* liver and a kidney, heart, brain, and foreleg and hindleg muscles of an anesthetized canine were measured. It is concluded that there are no significant differences in the thermophysical properties of organ or tissue of a living body either *in vivo* or *in vitro*. The measured thermophysical properties are in good agreement with those reported in the literature.

KEY WORDS: calorific intensity; hot probe; organ or tissue of a living body; specific heat; thermal conductivity; thermal diffusivity.

1. INTRODUCTION

For the development of medical science, biomedical engineering and the technology of food processing, preservation, and transportation, the thermophysical properties and calorific intensity of organs or the tissue of living bodies become essential [1–4]. One typical case is the application of human organ grafts. The thermophysical properties and calorific intensity

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0195-928X/00/0100-0207$18.00/0

of living organs are the key parameters in freezing, preserving, and reviving. Another application is in freezing or heating therapy. Localized elevated temperatures in the range 42 to 43° have a selective casualty effect on cancer cells, while higher temperatures can also harm normal cells. Consequently, having a grasp of the thermophysical properties and calorific intensity of living organs or tissue will help doctors to work out the therapeutic program safely and effectively [1]. Since this tissue tends to be irregularly shaped and small and generates heat, the difficulties in determining its thermophysical properties and calorific intensity are greatly increased. In spite of this, considerable fascinating research has been done in this field [5–17]. However, as far as we know, almost no research has demonstrated the simultaneous determination of thermal conductivity, thermal diffusivity, specific heat, and calorific intensity of the organ or tissue of living body up to now [3, 4].

In this research, a multivariate least-squares method has been developed which can simultaneously determine the thermal conductivity, thermal diffusivity, specific heat, and calorific intensity of either an *in vivo* or an *in vitro* organ or tissue of a living body with a thin hot probe.

2. THEORETICAL MODEL

The hot-probe method has evolved from the transient hot-wire method. It is a more practical and convenient line heat source method. An ideal hot probe is normally a circular cylinder with a high thermal conductivity so radial temperature differences are negligible. The probe contains a heater with uniform and steady calorific power and some means of measuring temperature at the center of its length. The idealization of "one-dimensional radial heat flow" can be employed if the length-to-diameter ratio of the hot probe is greater than 40 and the length of the measured medium is over $7.96(\alpha_m t)^{1/2}$ (where α_m is the thermal diffusivity of the medium and t is the elapsed time) [18]. The lateral surface effect of the measured medium is less than 1.0% for a sample with outer radius $R > 2.61(\alpha_m t)^{1/2}$ [18].

The organ or tissue of a living body can be considered as an infinite medium whose apparent calorific intensity Q and initial temperature T_0 are uniform. With a line heat source at the center of the medium and the condition that for time $t \geqslant 0$, a constant power q is applied to the center line source, the governing equation is

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial \theta_m}{\partial r}\right)+\frac{Q}{k_m}=\frac{1}{\alpha_m}\frac{\partial \theta_m}{\partial t} \qquad (r > r_o,\ t > 0) \tag{1}$$

subject to

$$\pi r_o^2 \rho_p c_p \left.\frac{\partial \theta_m}{\partial t}\right|_{r=r_o} = q + 2\pi r_o k_m \left.\frac{\partial \theta_m}{\partial r}\right|_{r=r_o} \tag{2}$$

$$\theta_m(r, 0) = 0 \tag{3}$$

where the subscripts p and m denote the hot probe and the medium, respectively; θ is the temperature difference $T - T_0$ at time t and radial position r, in K; k is the thermal conductivity, in $W \cdot m^{-1} \cdot K^{-1}$; α is the thermal diffusivity, in $m^2 \cdot s^{-1}$; c_p is the specific heat, in $J \cdot kg^{-1} \cdot K^{-1}$; ρ is the density, in $kg \cdot m^{-3}$; and r_o is the diameter of the hot probe. Here it is assumed that the temperature of the medium at $r = r_o$ equals that of the hot probe.

The long-time solution of the above equations can be obtained through the Laplace transformation,

$$\theta_p(t) = \frac{q - \pi r_o^2 \omega Q}{4\pi k_m} (\ln(4\mathrm{Fo}) - \gamma) + \frac{\omega Q}{\rho_p c_p} t \tag{4}$$

where $\omega = \rho_p c_p / \rho_m c_m$; $\mathrm{Fo} = \alpha_m t / r_o^2$ is Fourier's number; and $\gamma = 0.5772$ is Euler's constant.

The recorded temperature rise data of the experiment are fit by Eq. (4) using least-squares algorithm, and the values of k_m, α_m, c_m, and Q can be simultaneously determined by the following equations:

$$k_m = \frac{q - \pi r_o^2 B \rho_p c_p}{4\pi A} \tag{5}$$

$$\alpha_m = \frac{r_o^2}{4} \exp\left(\frac{C}{A} + \gamma\right) \tag{6}$$

$$c_p = \frac{4k_m}{\rho_m r_o^2 \exp(C/A + \gamma)} \tag{7}$$

$$Q = \frac{4k_m B}{r_o^2 \exp(C/A + \gamma)} \tag{8}$$

where

$$A = \frac{a - b}{e - f} \tag{9}$$

$$B = \frac{c - d}{e - f} \tag{10}$$

$$C = \frac{1}{n}\left(\sum \theta_i - A\sum \ln t_i - B\sum t_i\right) \tag{11}$$

$$a = \left(\sum \theta_i \ln t_i - \frac{1}{n}\sum \theta_i \sum \ln t_i\right)\left[\sum t_i^2 - \frac{1}{n}\left(\sum t_i\right)^2\right]$$

$$b = \left(\sum \theta_i t_i - \frac{1}{n}\sum \theta_i \sum t_i\right)\left[\sum t_i \ln t_i - \frac{1}{n}\left(\sum t_i \sum \ln t_i\right)\right]$$

$$c = \left(\sum \theta_i t_i - \frac{1}{n}\sum \theta_i \sum t_i\right)\left[\sum \ln^2 t_i - \frac{1}{n}\left(\sum \ln t_i\right)^2\right]$$

$$d = \left(\sum \theta_i \ln t_i - \frac{1}{n}\sum \theta_i \sum \ln t_i\right)\left(\sum t_i \ln t_i - \frac{1}{n}\sum t_i \sum \ln t_i\right)$$

$$e = \left[\sum t_i^2 - \frac{1}{n}\left(\sum t_i\right)^2\right]\left[\sum \ln^2 t_i - \frac{1}{n}\left(\sum \ln t_i\right)^2\right]$$

$$f = \left(\sum t_i \ln t_i - \frac{1}{n}\sum t_i \left(\sum \ln t_i\right)\right)^2$$

and i and n denote point i and the number of points employed to fit the parameters above in a measured θ–t diagram, respectively.

The essentials of this method are that the usually neglected calorific power of the measured medium is considered, and the thermal conductivity, thermal diffusivity, specific heat (knowing ρ_m), and calorific intensity of the organ or a tissue of living body can be simultaneously determined by fitting the temperature rise data from the experiment with a multivariate least-squares criterion based on the temperature equation [Eq. (4)]. This method is useful for the measurement of thermophysical properties of organs or tissue of living bodies.

3. ERROR ANALYSIS

For the case that $Q = 0$, the systematic measurement errors including the long-time expansion, truncation of the long-time series, contact resistances between the probe and the medium were analyzed and the effect of finiteness of the probe and specimens on the precision of the measurement was thoroughly discussed by Liang [18] and Healy et al. [19]. According to the conclusions presented in the aforementioned literature, the systematic error of our experiment produced by the aforementioned factors is smaller than 1%. For the case that Q is not equal to 0, and due

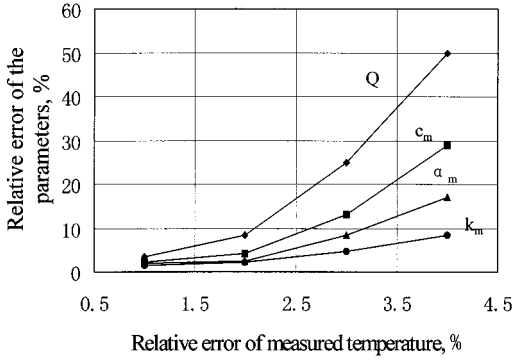

Fig. 1. Precision of the measured thermophysical properties and calorific intensity for different ranges of relative measurement error σ.

to the fact that the analysis is very complicated, the effect of the aforementioned factors on the precision of the measured results is not obtained. However, since our experimental results agree well with those in the literature, it is assumed that the systematic errors can be neglected. Certainly, the problem needs to be studied further. The errors of the measured themophysical properties and calorific intensity using this method were analyzed using computer simulation.

For given physical properties and apparent calorific intensity Q of the measured medium (k_m^g, α_m^g, $c_{p,m}^g$, ρ_m^g, Q^g), the temperature difference $\theta(t)$ can be calculated from Eq. (4). Considering the random data errors, their measured values can be simulated as

$$\theta_p^s(t) = \theta_p^g(t)(1 + \xi\lambda) \tag{12}$$

where the superscripts g and s denote the actual and simulated measured values, respectively; ξ is the error control factor; and λ denotes random numbers. The values of k_m, α_m, $c_{p,m}$, and Q can be fit with the multivariate least-squares method mentioned above.

By changing the value of ξ, the precision of the simulated values under different range of measurement errors can thus be obtained by comparing the simulated values with the given values. See Fig. 1.

4. EXPERIMENTAL

4.1. Hot-Probe and Data Logging System

Figure 2 shows the structure of the hot probe. The hot probe used in this experiment was 39 mm long and 0.7 mm in diameter. Its resistance per

unit length was determined by measuring a standard medium. Its thermal conductivity and specific heat were taken from Ref. 22. Figure 3 shows a schematic of the data logging system for the test apparatus. The timer and galvanostat are synchronous.

4.2. Animal Experiment

A canine was vivisected after being anaesthetized. The hot probe was stuck into the tissue to be measured. The timer and galvanostat started synchronously after having recorded the initial temperature of the measured position.

During the measurements of the internal organs and brain, it was found that the temperature of the hot probe rose rapidly, then reached a constant value depending on the heating power. This is due to the self-temperature regulating effect of the living organism (see Fig. 4). This phenomenon was not found during the measurements of the muscles.

Measurements of the internal organs were carried out after clamping down the blood vessels which ran in and out of the measured organs. The hot-probe temperature rose steadily with time. During these measurements, the animal breathed deeply and evenly. Measurements of the brain and heart were carried out immediately after the animal's expiration. The hot-probe temperature also rose steadily with time. Density was measured using a simple water-displacement technique.

5. RESULTS AND ANALYSIS

The experimental results are presented in Table I. From our experiment and comparison of these values with those in Refs. 23 and 24, it is found that the differences in the thermophysical properties between an *in vivo* organ or tissue of a living body and that of a dead body are not large, and the influence of calorification on the thermophysical properties is also not strong. Because the mechanism of calorification is extremely complex, the values of the calorific intensities given in Table I are for reference only.

6. CONCLUSIONS

The experiment verifies that the method presented in this paper to determine simultaneously the thermophysical properties and calorific intensity of either *in vivo* or *in vitro* organs or tissues of a living body is feasible. The differences in the thermophysical properties of *in vivo* organs or tissues of living bodies and those of dead bodies are not large. The influence of

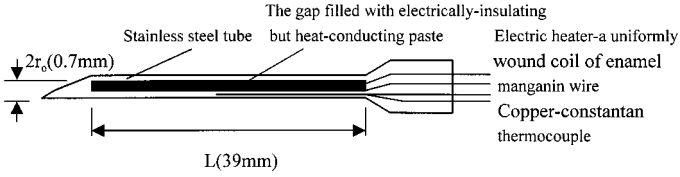

Fig. 2. Schematic of the hot probe.

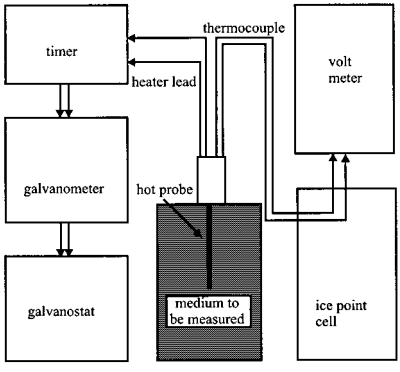

Fig. 3. Schematic circuit for the test apparatus.

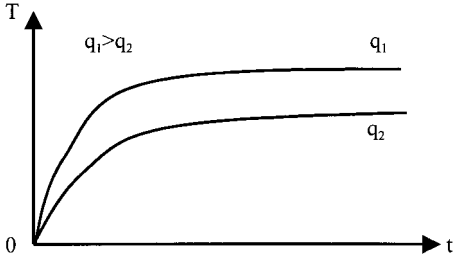

Fig. 4. The influence of the self-temperature regulation effect on the internal organs and brain.

Table I. Thermophysical Properties and Calorific Intensities of *In Vivo* Organs and Tissues of Living Bodies and Comparisons with Results in Refs. 23 and 24

	ρ_m (10^3 kg · m^{-3})		k_m (W · m^{-1} · K^{-1})		α_m (10^{-7} m^2 · s^{-1})		c_m (kJ · kg^{-1} · K^{-1})		Q^a (kJ · m^{-3})	
Organ or tissue	Measured[b]	Refs. 23 and 24	Measured[b]	Refs. 23 and 24	Measured[b]	Refs. 23 and 24	Measured[b]	Refs. 23 and 24	Measured[b]	Refs. 23 and 24
Palm	—	—	0.45 (3, 2.1%)	0.44	1.07 (3, 3.7%)	0.4–1.6	4.01 (3, 4.2%)	—	4.73 (3, 14.2%)	—
Liver	1.03 (3, 0.12%)	—	0.48 (1)	0.6–0.9	1.23 (1)	1.5–2.4	3.78 (1)	—	6.15 (1)	—
Kidney	1.05 (3, 0.17%)	—	0.57 (1)	—	1.56 (1)	—	3.49 (1)	—	1.29 (1)	—
Heart	1.06 (3, 0.11%)	—	0.49 (1)	0.48–0.59 (dead)	1.10 (1)	1.4–1.5 (dead)	4.21 (1)	—	6.32 (1)	—
Brain	1.04 (3, 0.15%)	—	0.57 (3, 2.1%) (cow, cat, and human)	0.16–0.57 (dead)	1.68 (3, 5.2%) (cow, cat, and human)	0.44–1.4 (dead)	3.25 (3, 5.8%)	—	1.08 (3, 24.2%)	—
Foreleg	1.07 (3, 0.12%)	—	0.51 (3, 1.4%)	0.70–1.0	1.20 (3, 2.1%)	0.7–1.3	3.95 (3, 3.4%)	—	—	—
Hindleg	1.07 (3, 0.13%)	—	0.51 (3, 1.6%)	0.70–1.0	1.18 (3, 2.3%)	0.7–1.3	3.99 (3, 3.9%)	—	—	—

[a] The values of the calorific intensities are apparently due to the complex mechanism of calorification.
[b] The first measurement in parentheses denote the measurement time; the latter, the relative error of the measurement.

calorification on the thermophysical properties is not strong. The blood-flow capacity of an organism strongly regulates the thermal stimulus from outside. The liver and heart are the main calorific internal organs of a living canine.

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