Sensor Based on the Hot-ball Method for Measuring Thermophysical Parameters

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Abstract. *The hot-ball method is used for measuring thermal conductivity and thermal diffusivity. The aims of this research are reliability of measurement and utilization of the hot-ball method for measuring the thermophysical properties of liquids. Known values for thermophysical properties of distilled water and glycerol are utilized to assess the criteria for method reliability. The structure of the sensor influences the sensor reliability. The viscosity of the liquid is a limiting factor in obtaining reliable data.*

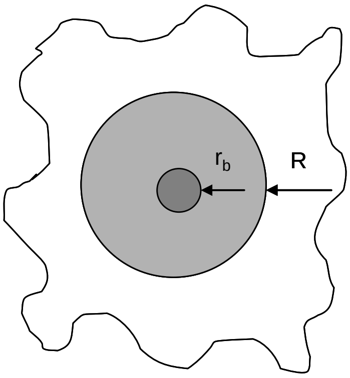
Keywords: Thermophysical Sensor, Hot-Ball Method, Thermal Conductivity, Thermal Diffusivity

1. Introduction

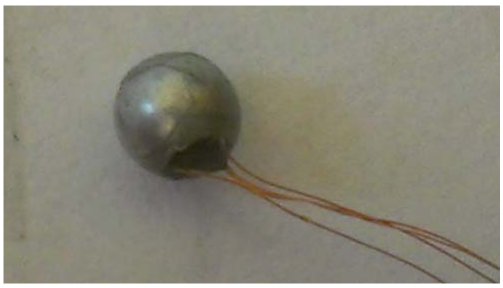
Over the last 20 years, a new class of transient methods for measuring thermophysical properties has become widespread in research laboratories as well as in technological applications. The principal differences between classical and transient methods lie in specimen size. Recently, a method based on a spherically symmetrical thermal field has been published [1]. The method uses two balls, a heater and a thermometer, at a distance of several millimeters from each other. This article deals with the hot-ball sensor in a single-function configuration, i.e. with heat source and thermometer incorporated into a single unit. Our sensor uses the hot-ball method for measuring thermophysical parameters described in [2].

2. Theory and Construction of the Hot-ball Sensor

A diagram of the hot-ball method is shown in Fig. 1a. The method uses a small ball which generates a transient temperature field in its surroundings, while simultaneously measuring the ball temperature. The temperature of the ball can be used to determine the thermophysical parameters of the surrounding material.



(a)



(b)

Fig. 1. (a) Diagram of the hot-ball and (b) photo of a hot-ball sensor. Black region: hot ball, grey region: area penetrated by heat.

The principle of measurement by the hot-ball method is as follows. A heat source, in the form of a small ball, starts to produce heat at a constant rate, whilst simultaneously measuring its own temperature, the evolution of which reflects the temperature response of the surrounding medium. The heat penetrates into a sphere with radius R during the temperature stabilization phase.

The working equation for the hot-ball sensor is based on a model which assumes a heat power q generated from a ball of radius r_b. If the ball has a heat capacity C and a high thermal conductivity ($\lambda_b \rightarrow \infty$), the surface temperature of the ball is characterized by the temperature function

$$T(t, r_b) = T_0 \left\{ 1 + \frac{1}{z_2 - z_1} \left[z_2 w(-iz_1 \sqrt{t}) - z_1 w(-iz_2 \sqrt{t}) \right] \right\} \tag{1}$$

where $w(z) = e^{-z^2} \Theta^*(-iz)$, $\theta^*(u)$ is the complementary error function, $z_{1,2} = A(-1 \pm \sqrt{1-B})$, $T_0 = \dfrac{q}{4\pi\lambda r_b}$, $A = \dfrac{2\pi r_b^2 \lambda}{\sqrt{k} C_s}$, $B = \dfrac{Ck}{\pi\lambda r_b^3}$ and λ and k are the thermal conductivity and thermal diffusivity of the surrounding medium, respectively. Equation (1) is a solution of the partial differential equation for heat conduction under the following boundary and initial conditions:

$$T(r, 0) = 0,$$

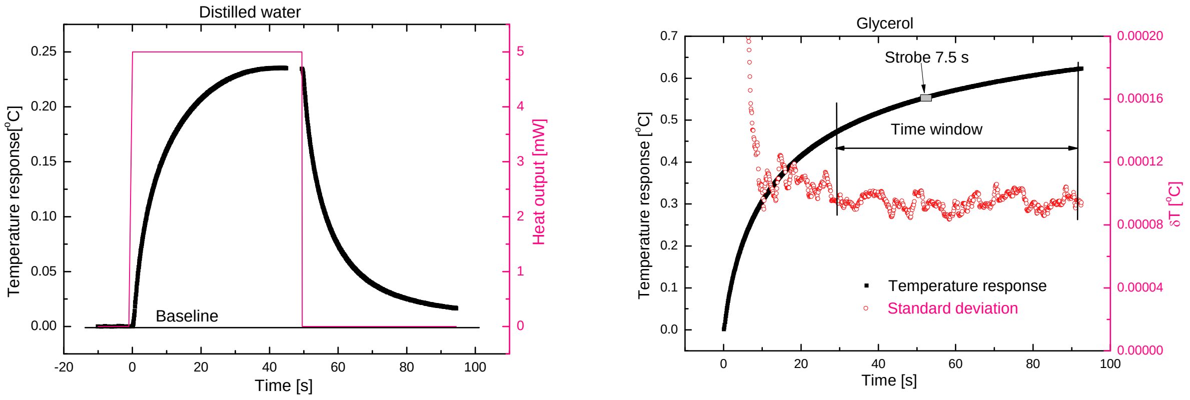
$$-\lambda \frac{\partial T}{\partial r}\bigg|_{r=r_b} \cdot 4\pi r_b^2 + C \frac{\partial T}{\partial t}\bigg|_{r=r_b} = q1(t)$$

where $1(t)$ is the step wise unit function.

The hot-ball sensor consists of two electrical components: a resistor and a thermistor. The resistor is used as a heat source for generation of the temperature field. The thermistor is used for measuring the temperature response to this heating. The sensor is made from a copper ball, cut into two halves. The electrical components are positioned on the inside surfaces of the halves. Both of these parts are glued into a ball by epoxy. The diameter of the ball is up to 3 mm. A photo of such a metallic ball sensor is shown in Fig. 1b. A typical measurement is shown in Fig. 2a. The measurement procedure consists of measuring the ball temperature before, during and after the period of heating. Temperature measurement before heating indicates the temperature of the surroundings and provides a baseline; measurement during heating is the basis of determining thermophysical parameters. When the ball temperature reaches a plateau, the heating is stopped and a period of temperature equilibration follows. After the temperature returns to the original baseline, the next measurement may start.

3. Experiment and Discussion

The position of the components in the ball plays a crucial role in the functionality of the sensor. Equation (1) assumes spherical symmetry of the temperature field around the ball. However, the construction of the hot-ball generates irregularities in the sphere due to placement of the active components in the ball. Thus deviations of the isotherms from sphericity can be found around the ball. These irregularities play a significant role in the initial stages of temperature response to heating, when penetration depth is small. The temperature field becomes more perfectly spherical after longer time-periods, i.e. with greater penetration depth. This part of the window of measurement (see Fig. 2a) meets the requirements



(a) (b)

Fig. 2. a – heat output of the-hot ball (full line) and the corresponding hot-ball temperature (square). Liquid: distilled water. b – temperature response (crosses) and the standard error of the corresponding difference analysis (point). Liquid: Glycerol, q = 5 mW.

of our model to a greater extent than the period of initial heating. These requirements are met when the spatial extent of spherical heating exceeds the spatial extent of non-spherical irregularities in the temperature field. However, when measuring properties of liquids over long timescales and with large temperature gradients, convection may occur, causing significant deviation from our model. Due to these factors, the requirements of our model (Fig. 1a), and its boundary and initial conditions, are met only for a part of our measurement period.

A critical factor in the reliability of the hot-ball is how the structure of the hot-ball affects the measured signal. For calibration, the properties of the hot-ball were calculated from measurements in distilled water and glycerol. The hot-ball sensor was affixed into a vessel made of aluminum. The vessel was filled with the liquid to be used. A wireless instrument was used for these experiments. The instrument performs data storage, communication, heating, and temperature measurement before, during and after heating [3]. Measurements were done in a Climate chamber HPP 108. Six different values of heat power were used for experiments, in the range of 2.5 to 16 mW. Three experiments were done for each heat power value. Temperature stabilization between experiments took around 2 hours. All measurements were done at 25°C and 30% environmental humidity. The function in Eq. (1) contains 4 parameters (r_b, C, λ, k). For fitting this function we used the Levenberg-Marquadt procedure. For this experiment we used the known properties of the liquids used (thermal conductivity λ and thermal diffusivity k) as input parameters, and determined the radius r_b and the heat capacity C of the sensor from fitting the data. The resulting values of r_b and C determined from the temperature responses of distilled water and glycerol serve as a measure of the sensor reliability.

To find out which portion of our window of measurement corresponds to our model, we use a special evaluation procedure. Our assumption is that each datapoint measured during heating contains information on the parameters we desire to obtain. Unfortunately, we don't know the procedure for determining the values of these parameters from a single datapoint. Therefore, we work with a strobe, i.e. a short stretch of data centred around the selected datapoint, on which the fitting procedure is performed (Fig. 2b). 75 scan points are included in each strobe. The strobe is shifted along the whole temperature response window. The time interval we are looking for, where our model applies, is that part of our measurement window in which the data show a stable standard deviation. Table 1 gives the input and output data of the parameters used in the evaluation procedure for two experiments.

Table 1. Input and output parameters of the evaluation procedure. The radius of the hot-ball sensor HB 5201 measured by caliper is r_b = 1.58 mm. The data are valid for specified measurements (last row).

Parameter	Water	Glycerol
λ [W m^{-1} K^{-1}]	0.58	0.29
k [mm^2 s^{-1}]	0.14	0.095
r_b [mm]	1.61	1.6
C [mJ K^{-1}]]	31.5	43
Measuring time [s]	37.5	95
Time window [s]	14	62
δT [^{o}C]	0.0001	0.000094
Measurement No.	i2280	i2367

4. Conclusions

Having calibration data on the radius and heat capacity of the sensor, one can begin measurements of liquids. The same evaluation procedure is used, except with the radius and heat capacity of the hot-ball as input parameters, and the thermal conductivity and thermal diffusivity of the tested liquid as the fitted output parameters. The data for radius and heat capacity given in Table 1 are influenced by the choice of surrounding liquid to a small extent. It is clear that liquids having a thermal conductivity above that of distilled water will influence the effective (as concerns our model) radius and heat capacity to a more considerable extent. Thus, for each application, calibration should be performed using appropriate liquids.

Acknowledgements

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