Applied Thermal Engineering 44 (2012) 78–84

Contents lists available at SciVerse ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

The effects of thermistor linearization techniques on the T-history characterization of phase change materials

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ARTICLE INFO

Article history:
Received 28 October 2011
Accepted 5 March 2012
Available online 28 March 2012

Keywords:
Thermistor
Linearization technique
PCM
T-history method
Temperature accuracy
Heat density

ABSTRACT

Phase Change Materials (PCMs) are increasingly being used in the area of energy sustainability. Thermal characterization is a prerequisite for any reliable utilization of these materials. Current characterization methods including the well-known T-history method depend on accurate temperature measurements. This paper investigates the impact of different thermistor linearization techniques on the temperature uncertainty in the T-history characterization of PCMs. Thermistor sensors and two linearization techniques were evaluated in terms of achievable temperature accuracy through consideration of both, nonlinearity and self-heating errors. T-history measurements of RT21 (RUBITHERM® GmbH) PCM were performed. Temperature measurement results on the RT21 sample suggest that the Serial–Parallel Resistor (SPR)[1] linearization technique gives better uncertainty (less than ±0.1 °C) in comparison with the Wheatstone Bridge (WB)[1] technique (up to ±1.5 °C). These results may considerably influence the usability of latent heat storage density of PCMs in the certain temperature range. They could also provide a solid base for the development of a T-history measuring device.

1. Introduction

In the past few years the utilization of Phase Change Materials (PCMs) in applications for reduction of energy consumption and CO_2 emission has grown significantly [1]. Thermal characterization of these materials is essential prior to any application. Namely, according to Mehling and Cabeza [1] the commercial TES systems using PCMs as well as the heat transfer models involving phase change lack the experimentally determined material data, especially in terms of the heat release/storage density variation with temperature. Additionally, the accuracy of the reported results is questionable due to variant reports by different researchers as also indicated by Mehling and Cabeza [1]. This is one of the main limiting factors for the effective applications of PCMs.

Differential Scanning Calorimeter (DSC) and T-history are the two most commonly used methods for the investigation of thermophysical properties of PCMs, as indicated in the comprehensive reviews written by Zalba et al. [2] and Zhou et al. [3] as well as in the research conducted by Castellon et al. [4], Zuo et al. [5], Cheng et al. [6] and Yinping et al. [7]. The DSC method has significant drawbacks mainly in terms of the limited sample size [7], possible temperature gradient that can be created inside the sample [4], and relatively low signal to noise ratios [1]. The small sample size in DSC tests which results in higher degree of subcooling and lower degree of phase segregation [7] is the reason T-history was used in this study.

PCMs are able to store/release large amounts of heat in a narrow temperature range of few degrees. Günther et al. [8] reported that the typical temperature ranges of PCM applications are in the order of ±10 °C around the phase change temperature of the material. Nevertheless, this range in practice is sometimes reduced to ±5 °C or less (e.g. in free cooling applications) implying that the maximum decrease in the temperature uncertainty associated with the measurements on the PCMs is very important since it could provide a more optimal usage of these materials. The decrease in uncertainty can be achieved through the application of accurate temperature sensors during T-history measurements. In addition to temperature accuracy, the size of the sensor should be kept small enough in order to reduce any interference during the phase change process. The cause of such interference is due to the physical presence of the temperature sensor inside the PCM sample which can act as a nucleating agent and thereby change the natural course of the phase change process resulting in incorrect determination of PCM properties (e.g. the degree of subcooling) [1].

The majority of the T-history studies reported in the literature has not emphasized either the accuracy of the applied sensors or any other relevant sensor selection criteria as reported in the

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[1] Serial–Parallel Resistor (SPR), Wheatstone Bridge (WB).

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doi:10.1016/j.applthermaleng.2012.03.032

studies conducted by Yinping et al. [7], Günther et al. [8], Kravvaritis et al. [9,10] and Moreno-Alvarez et al. [11]. Few studies reported by Marin et al. [12,13] and Lazaro et al. [14] identified the usage of thermocouples and Pt-100 resistance temperature sensors. However, thermocouples, despite their small size, have limitations in terms of their implicit tolerances that without any measurement system errors can go above 0.5 °C [15]. The Pt-100 resistance temperature detectors are better than thermocouples, but their disadvantages are relatively low sensitivity and long response time [15]. Hence, thermistors have been used for temperature measurements in this T-history implementation.

Thermistors have very high sensitivity, making them particularly responsive to changes in temperature. Additional advantages are accessibility of small probes and short response time [22]. The main disadvantage of these sensors is the nonlinear change of their resistance with respect to temperature [16]. This requires the application of linearization technique. Various hardware linearization techniques have been developed over the years based on voltage divider or bridge circuits as reported by Tsai et al. [17], 555 timers as reported by Nenova and Nenov [18], as well as different software solutions as indicated by Khan et al. [19]. However, there is no reported documentation on the utilization and evaluation of these linearization techniques for the T-history PCM characterization. Therefore in this study, two hardware linearization techniques, one based on the Wheatstone Bridge (WB) configuration and the other, based on simple Serial–Parallel Resistor (SPR) circuit, are evaluated in terms of achievable temperature accuracy. MATLAB® models were implemented for both linearizing configurations in order to determine the optimal circuit parameters. Subsequently, those parameters were used for the circuit development. The calibration and the T-history measurements on RT21 PCM (RUBITHERM® GmbH [23]) were performed with both, the WB and the SPR circuits. Finally, experimental results were analyzed and compared to determine the effects of thermistor linearization techniques on the T-history characterization of PCMs and consequently on the usability of these materials.

2. Materials and methods

2.1. Temperature sensors

Thermistors were selected for this study due to their two main properties: high sensitivity and size. A negative temperature coefficient (NTC) MA100BF103A thermistor model with a sensitivity of 5%/°C and a 0.762 mm diameter probe was used [24]. The temperature dependence of the thermistor resistance R_t is given by the table of resistances with the nominal resistance of 10 kΩ at 25 °C. Its operating range is from 0 °C to 50 °C.

2.2. Linearization circuits

The principle of the linearization circuit is to transform the nonlinear thermistor's resistance–temperature change into a linear voltage–temperature dependency. The accuracy of such transformation depends on many factors including, the circuit itself, the circuit component values, and the linearizing temperature range. In this case the range was fixed between 10 °C and 39 °C to meet the application requirements [25], so the accurate temperature measurements had to be secured through the development of proper circuits with optimal component values. As noted in the introductory section two different circuits, the WB and the SPR were developed. The determination of optimal component values for these circuits was established through the implementation of MATLAB® linearization models which are explained in detail in Section 3.

2.2.1. The WB thermistor linearization circuit

A circuit that is commonly used for thermistor linearization is based on the WB (Fig. 1).

The *OUTPUT* voltage of the WB circuit is given by Eq. (1):

$$OUTPUT = V_a - V_b \quad (1)$$

In order to stabilize the output of the bridge itself a differential amplifier is used. This was achieved through the utilization of three single operational amplifiers. The values for the resistor elements R_4, R_f, R_5, and R_g were selected in such way that the gain of the differential amplifier equals one and therefore the *OUTPUT* of the entire circuit equals the output voltage of the bridge. This *OUTPUT* is a single-ended voltage which is more suitable for the data acquisition systems, especially in cases of multiple channel measurements. Since the T-history implementation requires the measurement of at least three different temperatures (environmental, that of the PCM, and that of the reference material) this solution is feasible. The IC OP497FP was used for the implementation of the differential amplifier. The resistance values for resistor elements R_1, R_2, and R_3 were selected to be the same as the ones from the output of the corresponding MATLAB® model for this circuit.

2.2.2. The SPR thermistor linearization circuit

The SPR linearization circuit, shown in Fig. 2, is simpler than the WB circuit. In this circuit the input voltage V_{CC} is divided between the resistor R_1 and the parallel connection of the resistor R_2 and the NTC thermistor. The output of the SPR connection is the voltage across the parallel resistor connection. A simple voltage follower is used to provide stable, single-ended voltage *OUTPUT*. The voltage follower is implemented with a single operational amplifier from the IC OP497FP. The determination of resistance values for R_1 and R_2 is explained in Section 3.

2.3. Calibration protocol

Prior to PCM T-history measurements proper sensor calibration with both linearization circuits was performed in a temperature controlled chamber (model BINDER KMF 115 [26]). Each sensor (three different ones) was subjected to 1 °C step temperature program from 10 °C to 39 °C. Recorded *OUTPUT* voltage data were evaluated at known temperatures (10–39 °C in 1 °C step) and the calibration curves and equations were determined using the least squares method for data fitting. The calculation of absolute errors between expected and fitted measured temperature data was performed and the obtained results are presented in Subsection4.2.

2.4. T-history experimental protocol

T-history measurements of RT21 PCM were carried out in a temperature controlled chamber. The PCM sample and distilled water, used as reference, were subjected to a sharp temperature change between 30 °C and 11 °C and their temperature history recorded along with the environmental temperature. Firstly, measurements with sensors placed inside the samples were performed using both linearization circuits. Secondly, measurements with sensors placed on the surface of the samples' test tubes were also performed, but only using the SPR circuit. Data acquisition was performed utilizing a 14-bit NI DAQ USB 6212 card at a sampling frequency of 10 Hz [22]. Temperature values from the measured voltage data were calculated based on the equations obtained through linear fitting of voltage-temperature calibration curves using the least squares method. The temperature history data, obtained from the sensors placed inside the samples, were then