Characterization of Various Two-Phase Materials Based on Thermal Conductivity Using Modified Transient Plane Source Method

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Abstract. This paper presents the thermal conductivity of various two-phase materials using modified transient plane source (MTPS) technique. The values are determined by using commercially available C-Therm TCi apparatus. It is specially designed for testing of low to high thermal conductivity materials in the range of 0.02 to 100 $Wm^{-1}K^{-1}$ within a temperature range of 223-473 K. The results obtained for the two-phase materials (solids, powders and liquids) are having an accuracy better than 5%. The transient method is one of the easiest and less time consuming method to determine the thermal conductivity of the materials compared to steady state methods.

Key-words: Thermal conductivity estimation, Two-Phase Materials, Thermal Characterization, Modified transient plane source method

INTRODUCTION

The application of two-phase materials are increasing in recent times. A two-phase material consists of components with distinct chemical or physical structures. It comprises of dispersed and continuous phase and may be grouped into several different constituents based on their characteristics [1]. Thermal conductivity is an important property of the material which plays a vital role in heat transfer. In many engineering applications, such as aircraft structure, nuclear reactors, oil refineries, energy storage systems the two-phase materials are widely used. There are mainly two methods to determine the thermal conductivity of the materials. Such as steady state method and transient method [2]. Under steady state method, guarded hot plate technique is most commonly used to determine the thermal conductivity of the low conductivity materials. This method is limited to testing of some material because the sample preparation for this is difficult and also the test time for the material is very long [3-5]. The transient methods consume very less time and measurements can even be done with small samples compared to the steady state method. Some of the transient methods are hot wire technique and plane source technique. Hot wire technique is mostly used to determine the thermal conductivity of fluids [6]. The plane source technique was suggested by Gustafsson et al [7]. This technique contains a sensor in the shape of double nickel spiral with electrical insulation and placed between two samples to measure the properties [8-9]. From basics of transient plane source technique, modified transient plane source technique (MTPS) was developed [10-12]. In this study, we have measured the thermal conductivity of various two-phase materials such as rock wool, aerogel fiber insulator, light weight concrete, cement mortar, coir fiber, acrylamide phantom, phosphor bronze, Straight vegetable oil, Bio-diesel, nano fluid, soil, ammonium perchlorate, alumina ceramic powder for their characterization using MTPS technique at various temperatures.

EXPERIMENTAL WORKING PRINCIPLE

The C-Therm TCi analyzer has been used to measure the thermal conductivity of the materials. It works on MTPS technique with a spiral heater surrounded by a guard ring. The heater also act as the sensor and detect the change in voltage due to rise in temperature at the sensor-sample interface as constant current heat source is applied to the sample. The heater supplies one dimensional heat flow to the sample with the help of an insulative backing material when the sample is placed on it.

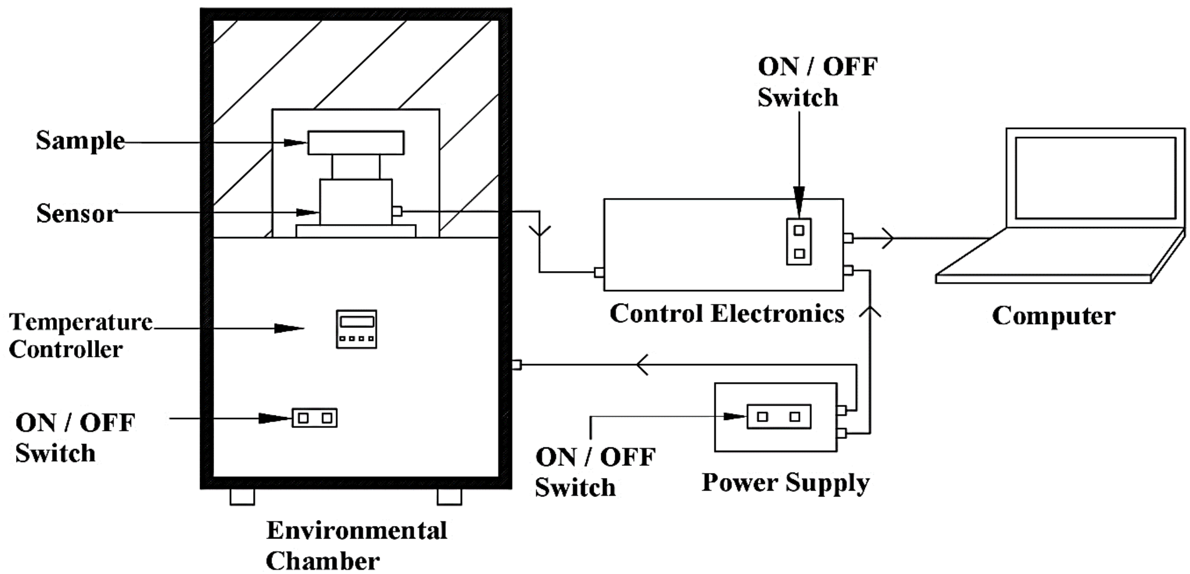


FIGURE 1. Schematic view of the experimental setup

The heat equation is one-dimensional with a constant supply of heat per time per volume G', as given in eq (1):

$$\rho c_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2} + G' \tag{1}$$

We assume that two-semi-infinite medium is in contact with the heat generated at the constant rate per unit area per unit time. Further assumption is that one medium represents effusivity sensor and the other medium is the test material. Both of them are at the same temperature and equilibrium. The solution of eq (1) is given below [10]

$$\Delta T_1(x,t) = \frac{2G\sqrt{t}}{e_1 + e_2} ierfc \frac{|x|}{2\sqrt{a_1 t}} \qquad \text{for } x < 0,\ t > 0 \tag{2}$$

$$\Delta T_2(x,t) = \frac{2G\sqrt{t}}{e_1 + e_2} ierfc \frac{|x|}{2\sqrt{a_2 t}} \qquad \text{for } x \geq 0,\ t > 0 \tag{3}$$

where ΔT is the change in sensor surface temperature, G is the heat flux supplied to the sensor (W/m^2), t is the time measured from start of process, e_1 and e_2 are the equivalent effusivity of the sensor and material, a_1 and a_2 are the equivalent diffusivity of the sensor and material. From the solutions of eq (1) the temperature rise of the sample for a constant heat flux G at the interface between the sample and sensor is measured by the instrument as explained in the TCi principles of operation [10].

TESTING PROCEDURE

A schematic representation of the setup to measure the thermal conductivity is shown in Figure 1. The sensor is placed inside the environmental chamber which is used to measure the thermal conductivity of samples at various temperature ranges from 303 K- 473 K. The sensor and a computer is connected to the control electronics. The solid samples are directly placed over the sensor, fluid and powder samples are placed with a help of small volume test kit and it is ensured that the samples have perfect contact with the sensor. Then current is supplied to the heating element in the sensor. There will be a temperature rise at the interface between sensor and sample due to the heat produced form the heating element for few seconds. The temperature rise is less than 2 ˚C and a change in voltage drop occurs at the sensor element.

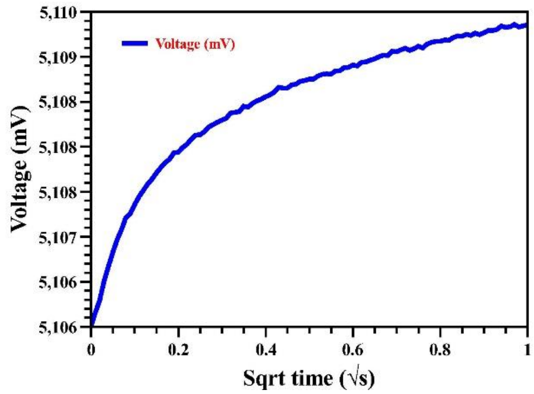


FIGURE 2. Voltage vs sqrt time

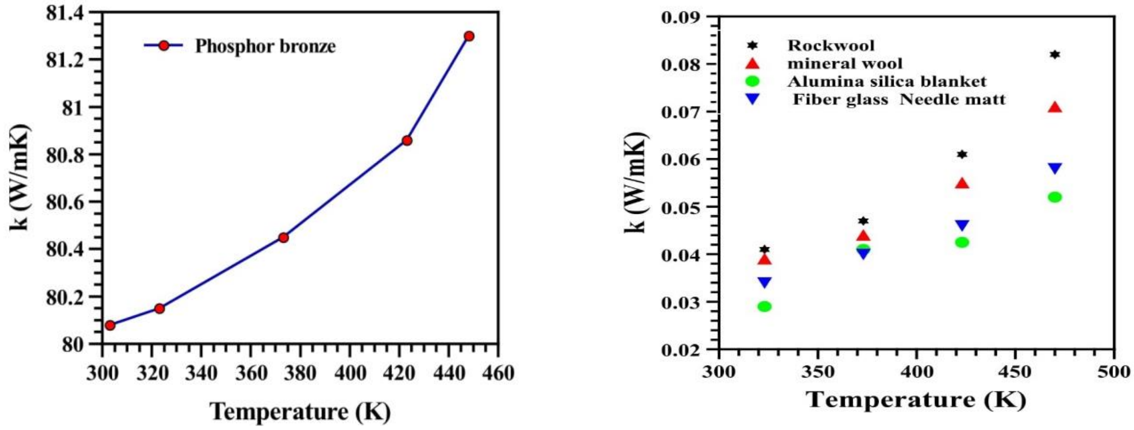
The thermal conductivity of the material is inversely proportional to the rate of temperature rise at heating element. The change in temperature of the sample is related to change in voltage when constant current is applied. So, thermal conductivity can be determined from the rate of rise in voltage, when we supply a constant current. The voltage vs sqrt time curve for phosphor bronze material obtained from TCi analyzer is shown in the Figure 2.

$$\frac{1}{m-m^*} = s \cdot k + \text{Intercept} \quad (4)$$

The slope m is obtained after a linear relation was observed from Figure 2. The instrument was calibrated by C-Therm technologies ltd [10] using Standard Reference Materials (SRM) as given in eq (4). From that calibration, we measure the thermal conductivity of the samples. The measurements of thermal conductivity and corresponding temperature readings are recorded with the help of the computer system. An average of 5 readings are calculated for each sample after the sample attains equilibrium temperature and is given in Table 1.

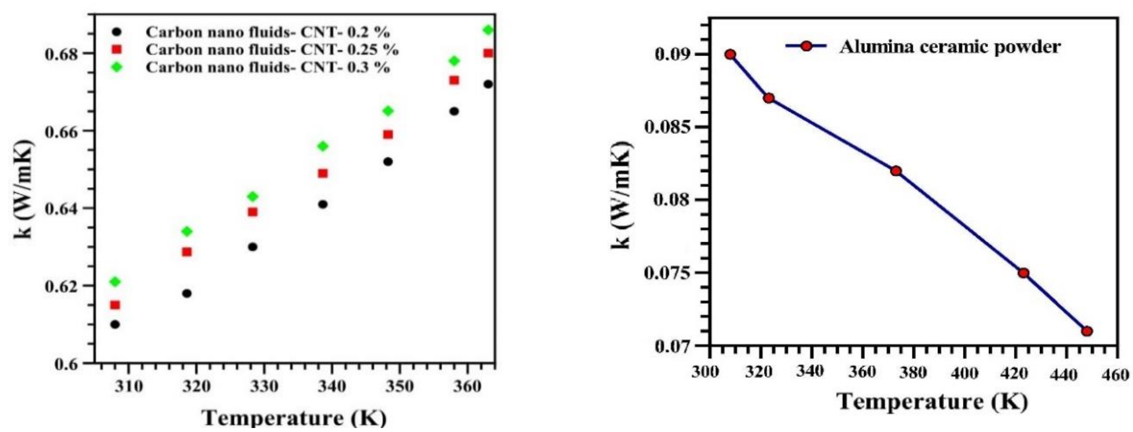
RESULTS AND DISCUSSION

Initially thermal conductivity of a Standard Reference Material phosphor bronze provided by the TCi supplier is measured at a temperature range (323 - 473K) whose thermal conductivity values are known. With the measured values a graph is plotted between temperature vs thermal conductivity as shown in Figure 3(a). In Figure 3(a), we observe that the thermal conductivity of the material increases with the increase in temperature. The insulation materials (υ-0.1 to 0.12) like Rockwool, mineral wool, alumina silica blanket, fiber glass needle mats are measured at a wide range of temperatures from 323- 473 K and the results are shown in Figure 3(b). For these insulation materials, the thermal conductivity increases with the rise in temperature. The alumina silica blanket has low thermal conductivity compared to other insulation materials in the group due to high porosity. Thermal conductivity of nano-fluid is measured for different temperature by varying their CNT volume fraction (0.2-0.3%) with base fluid. It is shown in Figure 4(a) that thermal conductivity increases with rise in temperature. As the volume concentration increases the thermal conductivity also increases. Alumina ceramic powder is also measured to determine thermal conductivity for wide range of temperature. The thermal conductivity values are plotted versus temperature in Figure 4 (b).



(a) (b)

FIGURE 3. (a) Thermal conductivity of phosphor bronze at different temperature and (b) Thermal conductivity of insulation materials at different temperature



(a) (b)

FIGURE 4. (a) Carbon nano-fluids with different temperatures and (b) Thermal conductivity of alumina ceramic powder at different temperatures

TABLE 1. Thermal conductivity values of various two-phase materials at ambient temperature (303 K)

Type of Sample	Sample Name	Thermal conductivity k (W/mK)
Two-phase Materials (Solid/Powder/ Fluid)	Rockwool (υ-0.15)	0.038 ±0.007
	Aero gel fiber insulator (υ-0.1)	0.021 ±0.006
	Light weight concrete (850 kg/m^3)	0.229 ±0.001
	Cement mortar (υ-0.7)	0.623 ±0.001
	Coir fiber (υ-0.2)	0.269 ±0.001
	Acrylamide phantom	0.453 ±0.002
	Soil (bt 30% moisture 10%)	0.298 ±0.001
	Alumina ceramic powder	0.091 ±0.001
	Ammonium perchlorate (NH_4ClO_4)	0.105 ±0.001
	Straight vegetable oil	0.165±0.003
	Bio-diesel	0.152±0.002
	Nano fluid (carbon particles)	0.623±0.002

The thermal conductivity of two-phase materials such as rock wool with a concentration of 0.15, aerogel fiber insulator with a concentration of 0.1, light weight concrete with a density of 850 kg/m3, cement mortar with a concentration of 0.8 , coir fiber with a concentration 0.2, acrylamide phantom, straight vegetable oil, bio-diesel, nano fluid, soil with bentonite (bt) 30% and moisture 10%, ammonium perchlorate (NH_4ClO_4), alumina ceramic powder, are tested at ambient temperature (303 k) and their values are tabulated in Table 1.

CONCLUSIONS

In this study, the thermal conductivity of various two-phase materials at ambient temperature (303K) and some at extended temperature range (303-473K) were determined. It shows that the aero gel fiber insulation materials have low thermal conductivity than that of fluids and powders. This kind of insulation material can highly restrict the heat transfer. Nano-fluids have a higher thermal conductivity value and can be used as a heat transfer fluid in many applications. The MTPS technique conforms to ASTM D7984, obtain reliable and high performance results with an accuracy better than 5%. An analysis of measurement data obtained from tests performed on Standard Reference Materials (SRM) yielded a measurement uncertainty of 2%. Some of the measured apparent thermal conductivities of the material in Table 1 are scarcely reported in literature. Also, this method is a simple and reliable way of measuring the thermal conductivity.

NOMENCLATURE

List of symbols

a	Equivalent diffusivity of the sensor and material (m^2/s)
e	Equivalent effusivity of sensor ($W.\sqrt{s}$)/(m^2.K)
c	Specific heat (J/kg K)
G	Heat flux supplied to sensor (W/m^2)
k	Thermal conductivity (W/mK)
m	Slope obtained from voltage vs sqrt time curve
m*	Calibration factor
s	Slope obtained calibration curve
t	Time measured from start of process (s)
T	Temperature (K)
ΔT	Change in sensor surface temperature (K)

Greek Symbols

ρ	density (kg/m^3)
υ	concentration

Subscripts

p	pressure

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