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SIMULTANEOUS MEASUREMENTS OF THERMOPHYSICAL PROPERTIES OF LOOSE DRY SAND BY A MODIFIED TRANSIENT HOT STRIP (THS) METHOD

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ABSTRACT

The recently described transient hot-strip (THS) method by Gustafsson [12], for simultaneous measurements of thermophysical properties of low-conducting isotropic solids and fluids has been developed. Thermophysical properties for a series of dry sand samples with different grain size are measured at room temperature and normal pressure. The measurements are carried out by (THS) method and thermal probe instrument for thermophysical properties of these loose porous materials. The obtained results are in good agreement compared with the recently available reported data.

INTRODUCTION

The importance of the study of thermophysical properties of porous materials comes from the fact that industrial materials are mostly of porous nature. Measuring thermophysical properties of such materials by unsteady state method using an extended plane heat source, realized by a thin metal strip has proved to give reliable results [1-8]. In the recent papers [9-12] the transient hot strip (THS) method has been described. In this method a metal foil works both as a continous plane heat source and a sensor of the temperature changes itself. The experimental procedure is very much similar to the one used in the hot wire method in the sense that the voltage variation over the strip is recorded over a period of time during which a constant current is applied on the strip. This method has been prefered for the measurement of thermophysical properties of solids and liquids such as clay, granite, fuzed quartz and glycerine at room temperature and normal pressure [10-12]. By using (THS) method it is possible to determine the thermal conductivity, thermal diffusivity and heat capacity for an isotropic material from a single transient event. The (THS) method is verysimple, quick and convenient as compared with other methods [14-16]. Athermal probe method was also employed [13] for simultaneous measurement of thermophysical properties of sand, asbestos, sawdust and fireclay.

The aim of the present work is to modify the electric circuit which was applied in the recent paper [12]. The voltage drop over the strip was compensated to measure its variation

for more accurate values. The voltage drop over the strip is recorded on (X-Y) recorder to a time base for higher accuracy, instead of measuring it every two seconds as done by Ramvir Singh [12]. Simultaneous measurements of thermophysical properties of a series of loose dry sand has been carried out as a function of grain size at room temperature and normal pressure. These materials are very different in structural form, (pore-shape-configuration-orientation and particle size), from those used by the previous works.

EXPERIMENTAL PROCEDURE

The experimental arrangement is similar to a fourprobe technique for studying electrical properties of thin metallic films; the only difference is that a well defined constant current is passed through a platinum foil, enclosed in a cell. The subsequent increase of voltage between the ends of the strip is monitored for a short period of time after switching on the current. The voltage change across the metal strip due to the increase in temperature is recorded as a function of time on (X-Y) recorder. The electrical circuit applied in the present work is a developed one of that described by Ramvir singh et al [12]. The electrical circuit used for measuring thermophysical properties is shown in Fig. (1). The power supply (E_1), the resistance (R_1) in series with the variable resistance (R_2) and the digital ammeter are used to pass and control the current in either the balancing resistance (R_b) or the strip resistance (R_s). While the source E_2, the

resistances R_3, R_4, and the decade resistance box is a secondary circuit used to induce a voltage drop on the resistance box equal in value and opposite in direction to that on the balancing resistance. Starting with the switch (K) in the upper position, the current passing in the balancing resistance (R_b) is adjusted to the desired value using the rheostat (R_2), then the value of (R_d) is changed until the voltage drop on the (X-Y) recorder equals to zero. The voltage drop on the balancing resistance (R_b) is measured using a digital millivoltmeter, When switch (K) is turned to the lower position, the current will pass in the platinum strip causing a voltage drop equal to that on the decade resistance box (R_d); at the beginning,so the (X-Y) recorder will record the voltage increase on the strip to a time base.

The dimensions of the thin platinum strip which is embeded inside the sample material are (6.9x0.57x0.0036 cm^3). The strip is laid along the length of a metallic container with outer and inner dimensions (12.70x7.00x2.71 cm^3) and (12.40 x 6.70 x 2.41 cm^3) respectively. The strip is supported by two supports insulated from the container. The sample in the (THS) cell is thoroughly tapped to get good contact between the strip and the sample. The cell is embeded in a fine powder in order to avoid mechanical disturbance of the metal strip and the sample.

The platinum strip is embeded in dry sand powder of known grain size (Particle diameter) at room temperature and normal pressure. A constant low-direct current is passed

through the strip and the increase of the voltage drop across the strip is recorded as a function of time by (X-Y) recorder of senstivity (8 μV/mm) and speed (20 cm/min).

To describe the temperature distribution around a metal strip, the differential equation of the heat conduction in three dimensions is solved [17] with the proper boundary conditions, assuming the metal strip to be in the middle of x-y plane and neglecting the end effects due to heavy electrical contacts. The change in temperature gives rise to a change in electrical resistance of the metal strip and therefore the voltage increase across the metal strip is dependent on the heat flow between the strip and the surrounding. Voltage variation between the ends of the metal strip is obtianed [8] over a period of time (t) by the relation

$$\frac{U_i - U_o}{U_o} = \frac{\alpha P_o}{2\sqrt{\pi\lambda}} f(\tau) \qquad (1)$$

where (U_i) is the voltage at a given time (t_i) from the start of the experiment, (α) is the temperature coefficient of resistivity (TCR) and is well known for most metals, (λ) is the thermal conductivity of the sample material surrounding the strip.

$$U_o = R_o I \qquad P_o = U_o I/2h$$

Here $f(\tau)$ is a complex function and is given by

$$f(\tau) = \tau - \tau \operatorname{erfc}\left(\frac{1}{\tau}\right) - \frac{\tau^2}{\sqrt{4\pi}}\left[1-\exp(-1/\tau^2)\right] + \frac{1}{\sqrt{4\pi}}\left[-Ei(-1/\tau^2)\right] \quad (2)$$

where

$$-Ei(-u) = \int_u^x \nu^{-1} \exp(-\nu)\, d\nu$$

$$\tau = (t/\theta)^{\frac{1}{2}} \qquad \theta = d^2/k$$

The characteristic time (θ) is determined [1] by the width (2d) of the strip and by the thermal diffusivity (K) of the surrounding medium. Equation (1) could be written as

$$U_i = U_o + Cf\,(B\sqrt{t_i}) \quad (3)$$

where

$$C = I\,U_o^2\,\alpha\,/4h\lambda\sqrt{\pi} \quad (4)$$

and

$$B = \sqrt{K/d} \quad (5)$$

The second measurements of thermophysical properties for the samples have been done directly by (TPA 1000) thermal probe instrument. Switching on the instrument the probe heats up and the relation of the probe temperature to the logarithm of time is computed using a running least squares fit to a straight line. The goodness of fit of each calculation is determined by calculating the coefficient of determination and the best fit is stored in memory. The slope of the best fit line is used to calculate the thermal conductivity and

the intercept of that line is used to calculate the thermal diffusivity.

RESULTS AND DISCUSSION

A test was carried out to measure the average particle size of each sample, by sifting the sample through standard sieves. A series of five sand samples of known various grain size were used after being oven drived at 120°C for 24 hours to eliminate the existing moisture in the pores. The increase of voltage over the strip as a function of time for each sample is recorded on the (X-Y) recorder. A representative curve for the increase of voltage against time; as recorded on the (X-Y) recorder; in the case of dry sand powder (14) which has a particle diameter nearly (1.4 mm) is shown in Fig. (2). This curve shows that in all of the samples, the rate of dissipation of heat from the strip is faster in the initial stage of the experiment and then slows down, causing relatively less change in the resistance, leading to a low potential rise. Since the current is constant, the output power per unit length (P_o) of the heat source varies as the voltage does. However, it is seen that the variation of (P_o) is less than ($5x10^{-3}$) [12]. The relation of the voltage against the time for the samples of different particle diameter is given in table (1).

Fig. (3) shows the plot of equation (3) in the case of dry sand (14), (U_i versus $f(B\sqrt{t_i})$, choosing an appropriate

Table 1. Recording of the increase of voltage U_i(v) over the hot strip versus time at room temperature and normal pressure, for dry sand powder of various particle diameter.

Time (s)	Dry sand (100)* (I=0.792A)	Dry sand (52) (I=0.867A)	Dry sand (25) (I=0.795A)	Dry sand (14) (I=0.812A)	Dry sand (7) (I=0.880A)
3	0.112328	0.123600	0.113724	0.115840	0.126504
6	0.112392	0.123688	0.113784	0.115888	0.126552
9	0.112440	0.123732	0.113812	0.115912	0.126582
12	0.112480	0.123768	0.113828	0.115928	0.126596
15	0.112504	0.123792	0.113834	0.115944	0.126606
18	0.112528	0.123808	0.113844	0.115960	0.126614

* The number in parentheses indicates the sieve size.

value of (B) for the given values of time, this value of (B) was determined using an iteration, by computer, so that it was changed until the plot of (U_i) versus f(B $\sqrt{t_i}$) became the best fit straight line. Then the thermal diffusivity of the sample material was estimated using equation (5). From the intercept (U_o) and the slope (c) of this straight line, the thermal conductivity was estimated using equation (4). Table (2) gives the values of thermal conductivity and thermal diffusivity of the sample material

at various values of particle diameter. For comparison, values of thermal conductivity and thermal diffusivity measured by the thermal probe (TPA 1000) method are given in the table (2). A good agreement is observed for the values of thermophysical parameters with those measured by the thermal probe method, the (THS) method gives slightly higher values of thermal parameters of these samples than those obtained by the thermal probe method. However, this could be taken as a good agreement because of the fact that in the case of the (THS) method, the heat source and sensor are the same strip, and heat dissipation in the material may be more rapid than with the thermal probe method.

As a result of this work, it was found that the porosity of the sample increases as the particle size increase, table (2). The variation of porosity is so slight to give a reasonable change with the thermal conductivity and thermal diffusivity, so it is impossible-from the heat transfer point of view-to construct a model to calculate these thermophysical parameters as a two phase system (solid-air). This (THS) method is equally good and quick for simultaneous determination of thermophysical parameters of loose building sample of different grain size at room temperature and normal pressure. The method has been found to be very reliable. The overall error in the measurement of conductivity is around 2-3% percent and for diffusivity is around 9-10 percent.

It is proposed to extend the use of the (THS) method for the measurement of these thermophysical parameters for one

Table 2. Values of thermal conductivity (λ) and thermal diffusivity (K) of five dry sand powder samples with different particle diameter measured by the (THS) method and thermal probe at room temperature and normal pressure.

Material Dry sand powder	Particle diameter (mm)	Porosity (φ)%	U (V)	λ ($W\ m^{-1}K^{-1}$) THS Method	λ ($W\ m^{-1}K^{-1}$) Thermal Probe	K($10^{7}m^{2}s^{-1}$) THS Method	K($10^{7}m^{2}s^{-1}$) Thermal Probe
100	0.15	41.3	0.112118	0.310	0.296	5.92	5.73
52	0.30	41.5	0.123370	0.445	0.425	9.95	9.45
25	0.60	41.84	0.113594	0.640	0.602	12.35	11.58
4	1.40	42.33	0.115696	0.733	0.684	17.19	15.97
7	2.36	43.13	0.126342	0.900	0.837	20.31	18.34

mple at various interstitial air pressures and also for teresting liquidsat different temperatures.

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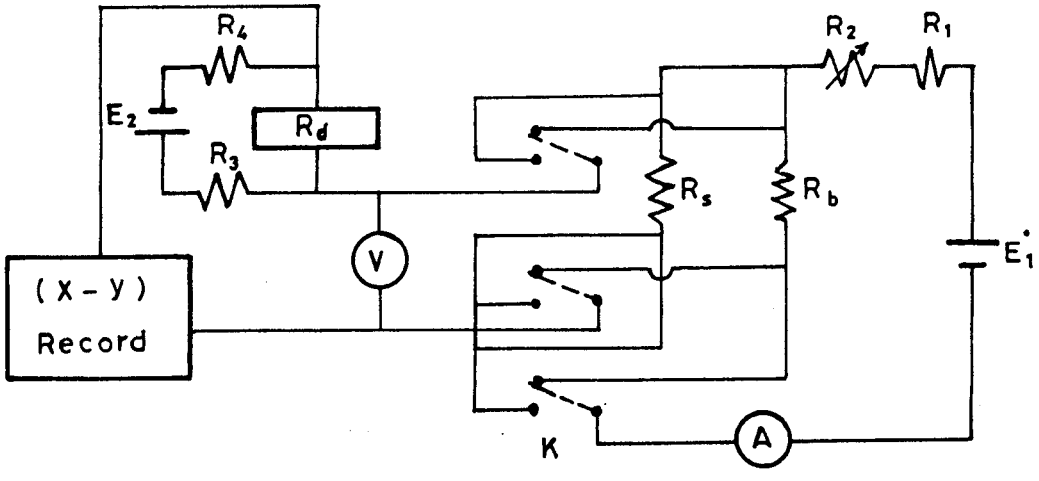

Fig.(1) Block diagram of the electric circuit E_1 and E_2 power supply; R_1, resistane ; R_2, variable resistance; R_b, balancing resistance; R_s, strip resistance; R_3 and R_4, resistances; R_d, decade resistance box; K, three face switch; A, digital ammter ; V, digital millivoltmeter, (X-Y), Recorder

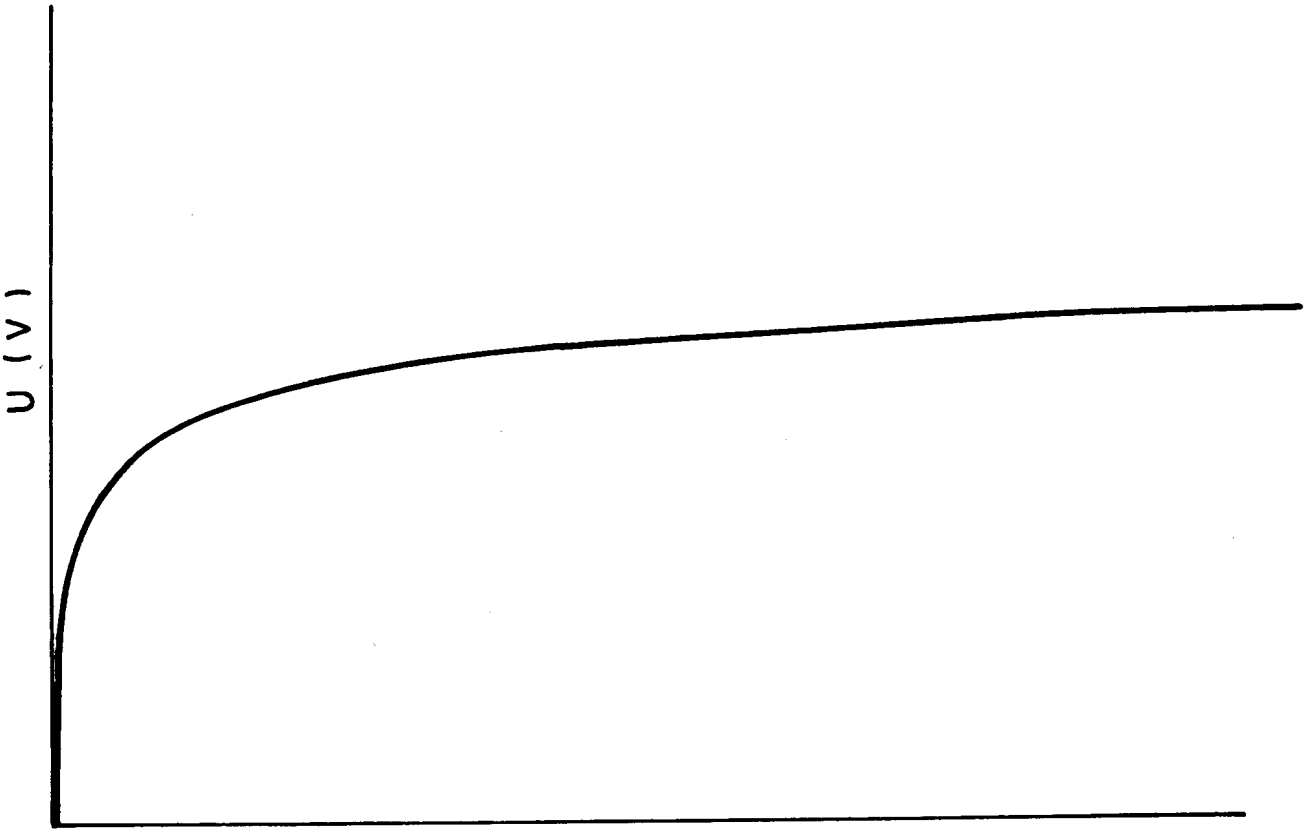

Fig.(2) Increase of voltage over the hot strip versus time in dry sand powder (14). current = 0.812 A. Identical curve given by (X-Y) recorder

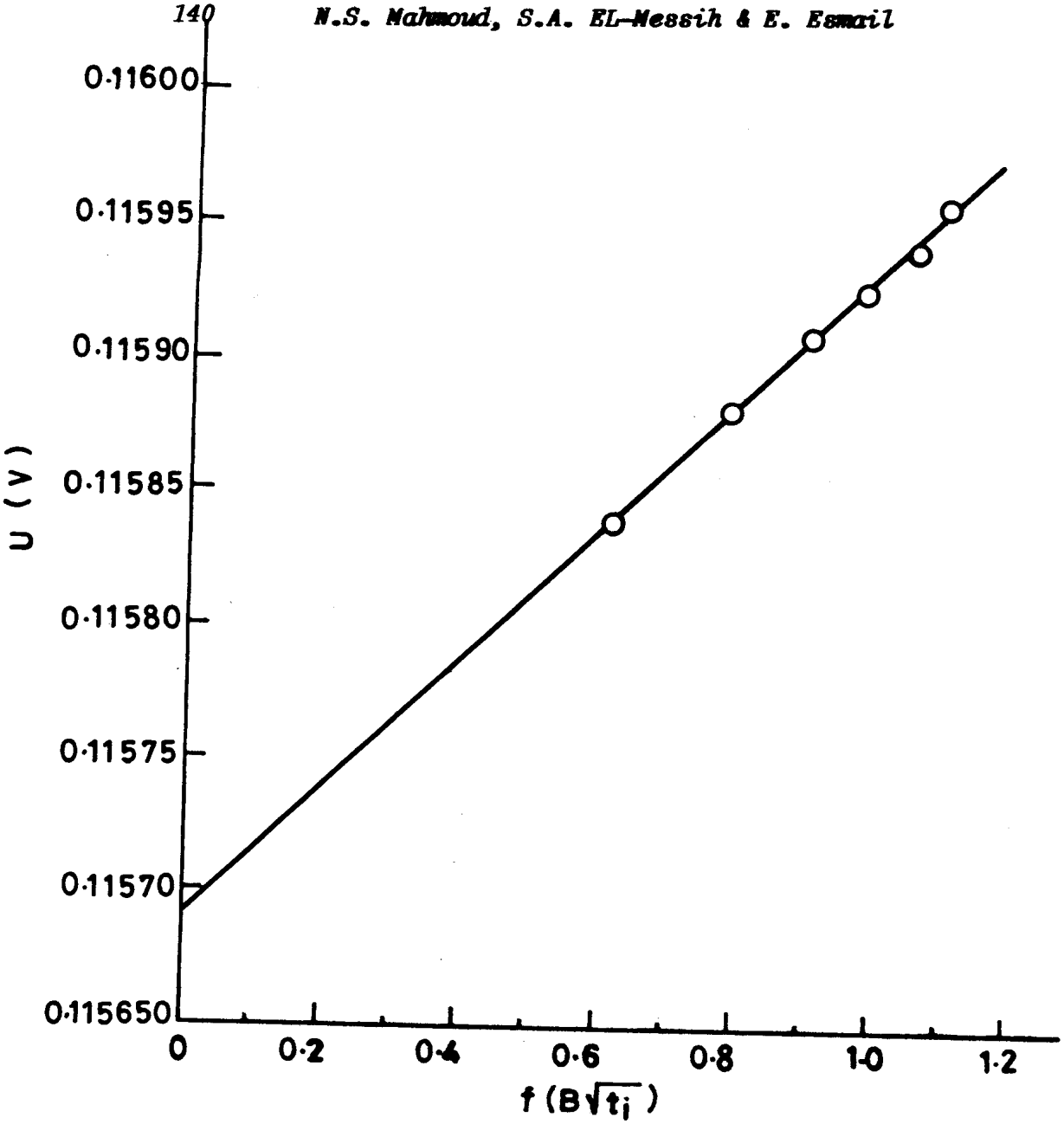

Fig.(3) Increase of voltage over the hot strip versus $f(B\sqrt{t_i})$ in dry sand powder (14). Intercept $U_o = 0.115696$ V; $B = 0.46$.

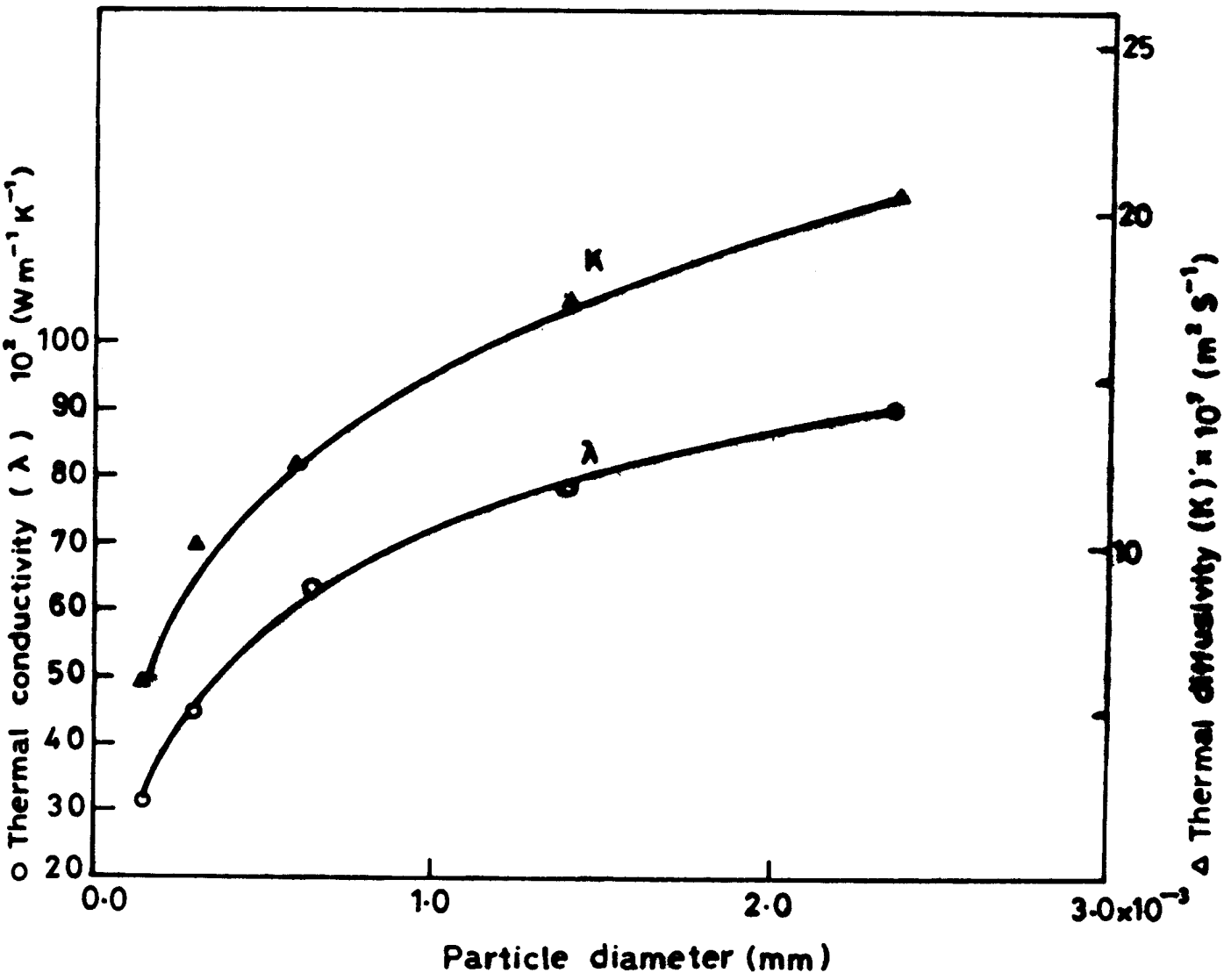

Fig.(4) Thermophysical parameters Vs. particle size.