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Measurement of effective specific heat of packed bed materials by the continuous flow electrical method

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Abstract. The theory of the continuous flow electrical method for the determination of specific heat of liquids has been extended to the measurements of effective specific heat of packed bed materials consisting of solid-liquid phase systems. Experimental data are reported showing the variation of effective specific heat with mass porosity and saturating liquid specific heat. The weighted arithmetic mean equation of constituent specific heats is in fair agreement with the measured values.

Keywords. Effective specific heat; packed bed material.

1. Introduction

The effective specific heat of two-phase media consisting of a solid phase and a saturating liquid phase is frequently required for the calculation of effective thermal conductivity from measured thermal diffusivity. The assessment of this effective specific heat has been considered from the analytical rather than the experimental point of view. In the present paper, continuous flow electrical method used by Callendar and Barnes (Glazebrook 1922, McCullough and Scott 1969) for the determination of specific heats of liquids has been extended for an experimental investigation of effective specific heats of packed bed materials over a wide range of mass porosity.

The advantage of the present method is that it is free from calorimetric error inherent in other methods: (i) The heat loss while in transfer from the source to the object can be eliminated; (ii) No correction need be applied for thermal capacity of the calorimeter; and (iii) the value of specific heat can be measured over a narrow range of temperature.

2. Experimental procedure and theory

The experimental arrangement is shown in figure 1. It is a three walled glass tube assembly having a nichrome heater wire of 12·5 ohm, in the form of a spiral, stretched in the innermost tube of internal diameter 2 cm and length 45 cm which is filled with the grain specimen. This glass tube is surrounded by a vacuum tube silvered on both sides and is further jacketed for water circulation at room temperature. Liquid entering from reservoir flows through the grains and finally comes out in a steady stream through a nozzle. An electric current, from a set of acid accumulators, is passed through the heating coil and the corresponding resistance of the coil is simultaneously measured. A copper-constantan thermocouple is

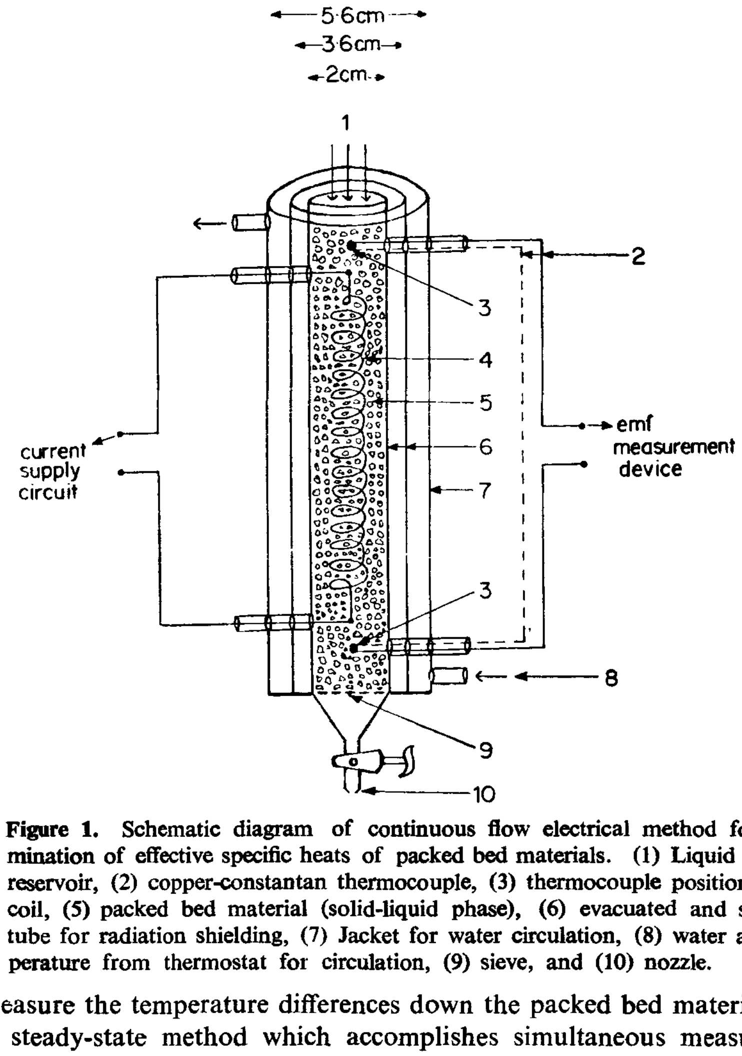

Figure 1. Schematic diagram of continuous flow electrical method for the determination of effective specific heats of packed bed materials. (1) Liquid coming from reservoir, (2) copper-constantan thermocouple, (3) thermocouple position, (4) heater coil, (5) packed bed material (solid-liquid phase), (6) evacuated and silvered glass tube for radiation shielding, (7) Jacket for water circulation, (8) water at room temperature from thermostat for circulation, (9) sieve, and (10) nozzle.

used to measure the temperature differences down the packed bed material column. This is a steady-state method which accomplishes simultaneous measurement of temperature rise of packed bed material column, quantity of electrical energy supplied to the heating coil and mass flow rate of liquid per second.

In addition to Joule heating, the heat may also be contributed by friction between grain specimen and the liquid flowing through it. This heat energy is absorbed by surrounding packed bed material, container wall and some heat is lost by radiation, etc. As such we can write

$$\begin{aligned} I^2Rt + \text{Friction energy} &= M_lC_l\triangle T_l + M_sC_s\triangle T_s \\ &\quad + M_cC_c\triangle T_c + \text{heat loss} \end{aligned} \tag{1}$$

where I is the current (amp), R the resistance (ohm), t the time (sec), M the mass (g), C the specific heat (joule/g/° C), and $\triangle T$ the temperature rise (°C). Subscript l stands for liquid, s for solid and c for container.

For the estimation of friction energy contribution the liquid was allowed to flow through the grain sample filled in the tube with no electric current passing through the heater wire, when the temperature rise of the packed bed material column was found to be less than 0·05° C (2 μV). During the measurements of effective specific heat the order of temperature rise was 10° C (400 μV). Hence, we can neglect the friction energy term as compared to Joule heating. Thus we have,

$$I^2Rt = M_lC_l\triangle T_l + M_sC_s\triangle T_s + X \tag{1a}$$

where

$$X = M_cC_c\triangle T_c + \text{heat loss}$$

Since in the steady-state

$$\triangle T_l = \triangle T_s = \triangle T$$

$$I^2Rt = M_l\triangle T\left[C_l - C_s + C_s\left(\frac{M_l + M_s}{M_l}\right)\right] + X \tag{2}$$

Now we define mass porosity by:

$$\phi = \frac{\text{Mass of liquid}}{\text{Total mass}} = \left(\frac{M_l}{M_s + M_l}\right)$$

Equation (2) can be rewritten as:

$$I^2Rt = \frac{M_l\triangle T}{\phi}\,[\phi C_l + (1 - \phi)\,C_s] + X$$

The factor $[\phi C_l + (1 - \phi)\,C_s]$ is the effective specific heat of the packed bed material and is denoted by C_E. We obtain,

$$I^2R = \frac{M_l'C_E\triangle T}{\phi} + X' \tag{3}$$

where M' is the rate of mass flow of liquid per second, and X' the rate of heat loss per second.

For the elimination of loss factor, the measurements were repeated by repeating the experiment at different rates of mass flow and adjusting the current for the same rise of temperature, $\triangle T$. Thus,

$$C_E = \frac{(I_1^2 - I_2^2)\,R}{(M_{11}' - M_{21}')\,\triangle T} \times \phi \tag{4}$$

where M_{11}' and M_{21}' are the two rates of mass flow corresponding to current values I_1 and I_2 respectively for the same rise of temperature, $\triangle T$.

It is somewhat difficult experimentally to obtain exactly the same rise of temperature $\triangle T$. In the measurement $\triangle T$ was of the order of 10° C (400 μV) and one can regard X' to be almost the same whenever in practice $\triangle T$ differed by 0·1° C (5 μV). Thus, the effective specific heat can be conveniently calculated from

$$C_E = \frac{(I_1^2 - I_2^2)\,R}{(M_{11}'\triangle T_{11} - M_{21}'\triangle T_2)} \times \phi \tag{5}$$

A potentiometer was used to measure the emf generated in the thermocouple, current flowing in the heater wire and its resistance with an accuracy of ± 1 μV (1 μV = 0·025° C), ± 0·001 amp and ± 0·1 ohm respectively. The mass was measured to an accuracy of ± 0·001 g and time to an accuracy of ± 0·2 sec. The accuracy in the specific heat measurement is taken to be the square root of the sum of the

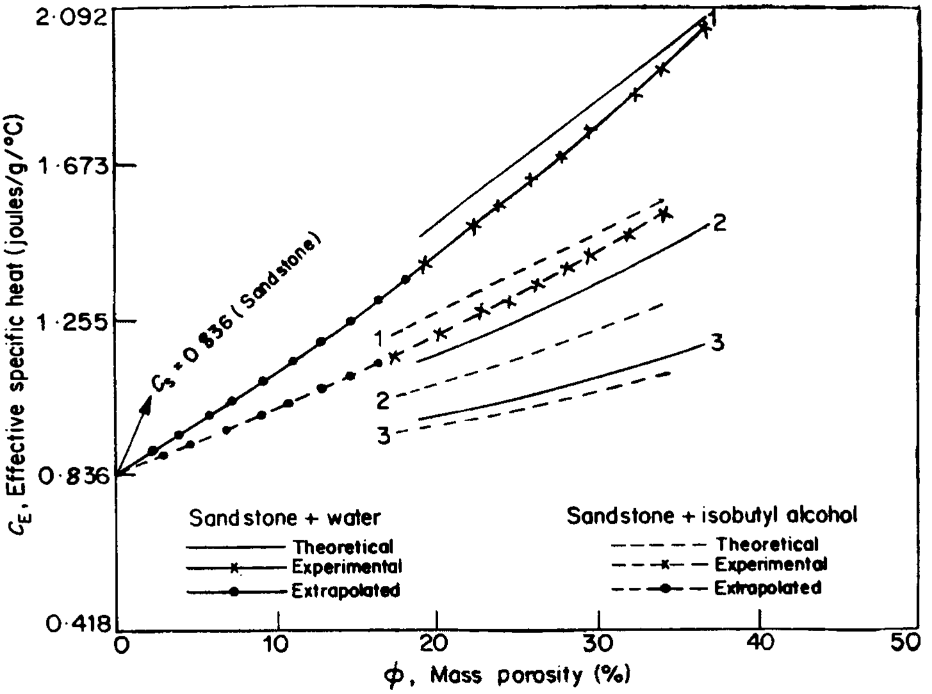

Figure 2. Variation of effective specific heat as a function of mass porosity for the systems sandstone + water and sandstone + isobutyl alcohol. (1) Weighted arithmetic mean, (2) Weighted geometric mean, and (3) Weighted harmonic mean.

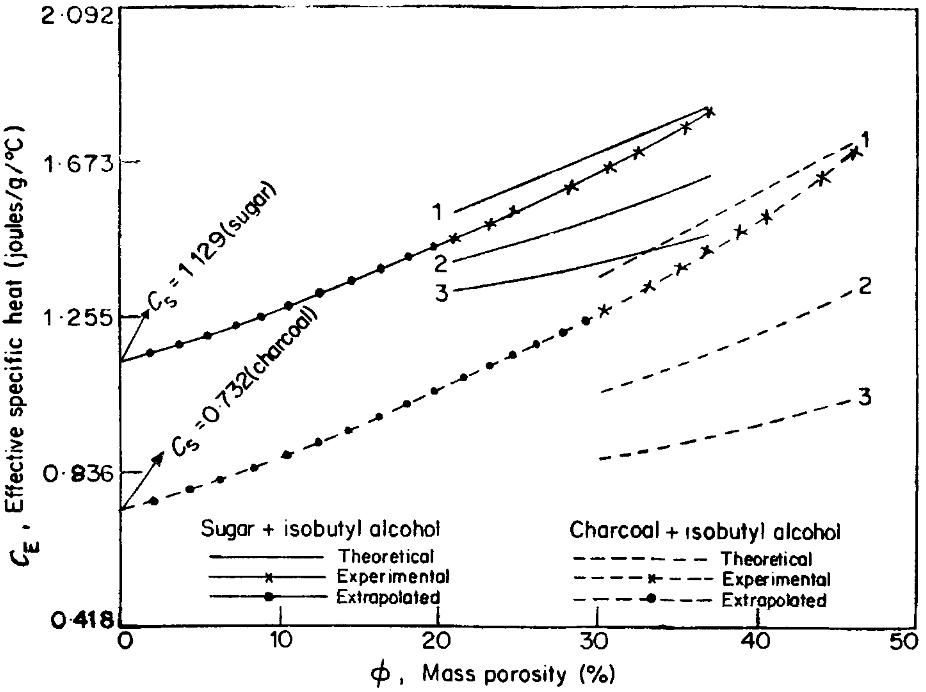

Figure 3. Variation of effective specific heat as a function of mass porosity for the systems sugar + isobutyl alcohol and charcoal + isobutyl alcohol. (1) Weighted arithmetic mean, (2) Weighted geometric mean, and (3) Weighted harmonic mean.

squares of these uncertainties in observed quantities. This estimates the error in the specific heat to be approximately ± 3 per cent.

Sandstones, charcoal and sugar of the following description were used as the packed bed materials:

Sample	Colour	Particle size (mm)	Absorption (g/g) %	Specific gravity (g/cc)	Specific heat (Joules/ g/°C)	Source of information
Sandstones	**Reddish**	0·3–3·5	0·23	2·63	0·836	Chaudhary (1968)
Charcoal	**Black**	0·4–3·4	0·20	0·88	0·669	Chaudhary (1968)
Sugar	White	0·4–3·2	0·12	1·54	1·146	Hodgman (1959)

We used samples of different size to obtain a range of mass porosity. The range of sandstones used varied from 17·6% to 36·5%, charcoal from 30·2% to 45·8% and sugar from 21·2% to 36·8%.

3. Results and discussion

The effective specific heats of the three samples with different saturating liquids are reported in table 1. The quoted experimental results are averages of several determinations. The effective specific heats of sandstones with isobutyl alcohol and water saturants are plotted against mass porosity in figure 2 and those of charcoal and sugar with isobutyl alcohol saturant in figure 3. Figure 4 shows the effective specific heats of the sandstones plotted against the specific heats of the saturating liquids; the iso-specific heat line, *i.e.*, the line for which $C_E = C_l$, is also shown. All measurements were made at room temperature.

For the development of a theoretical expression correlating the experimental results, we tried three well known approximations for fitting with the experimental data. These approximations are used for the assessment of effective thermal conductivity of two-phase materials and have been discussed by Woodside *et al* (1961):

(i) Weighted harmonic mean, $C_E = \left(\frac{\phi}{C_l} + \frac{1-\phi}{C_s}\right)^{-1}$;

(ii) Weighted geometric mean, $C_E = (C_l^{\phi} \cdot C_s^{1-\phi})$; and

(iii) Weighted arithmetic mean, $C_E = [\phi C_l + (1-\phi) C_s]$.

It can be seen from figures 2, 3 and 4 and table 1 that experimental data are in fair agreement with the weighted Arithmetic mean equation, as has been suggested by Ulrich (1894) and Kersten (1949).

These experimental data may further be used to determine specific heats of the solid phase. This has been done by extrapolating the experimental curves up to the zero mass porosity line shown in figures 2 and 3. The intersection points give the following specific heats: sandstones = 0·836 joules/g/°C (figure 2), sugar = 1·129 joules/g/°C and charcoal=0·732 joules/g/°C (figure 3). Similarly, in figure 4 the experimental curve extrapolated up to the iso-specific heat line gives a value of 0·836 joules/g/°C. for the specific heat of sandstones.

Table 1. Effective specific heats of packed bed materials

Samples		Mass porosity (g/g) %	Saturant sp. heat from literature Hodgman (1959) joules/g/°C	Effective sp. heat by weighted harmonic mean joules/g/°C	Effective sp. heat by weighted geometric mean joules/g/°C	Effective sp. heat by weighted arithmetic mean joules/g/°C	Effective sp. heat by present method joules/g/°C
Solid phase	Saturant phase						
Sugar	Turpentine oil	28·0	1·719	1·263	1·284	1·305	1·301±0·016
	Kerosene oil	31·2	2·175	1·343	1·397	1·468	1·443±0·020
	n-Octane	25·1	2·418	1·317	1·380	1·464	1·430±0·018
	Isobutyl alcohol	30·4	2·995	1·410	1·531	1·707	1·665±0·021
Sandstones	Turpentine oil	20·1	1·719	0·933	0·966	1·025	1·008±0·015
	Kerosene oil	21·5	2·175	0·962	1·033	1·209	1·133±0·018
	n-Octane	19·0	2·418	0·953	1·029	1·138	1·121±0·024
	Isobutyl alcohol	34·0	2·995	1·104	1·288	1·569	1·531±0·022
	Water	34·0	4·184	1·146	1·443	1·974	1·924±0·036
Charcoal	Turpentine oil	40·5	1·719	0·874	0·979	1·092	1·092±0·035
	Kerosene oil	43·4	2·175	0·953	1·112	1·324	1·238±0·038
	n-Octane	38·1	2·418	0·920	1·092	1·334	1·259±0·031
	Isobutyl alcohol	39·4	2·995	0·995	1·209	1·585	1·451±0·026
	Water	44·1	4·184	1·062	1·497	2·217	2·100±0·050

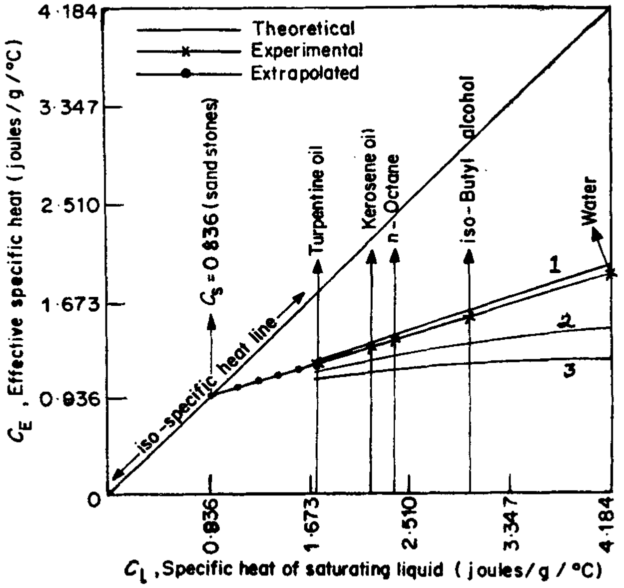

Figure 4. Variation of effective specific heat of sandstones (ϕ = 34·0%) with specific heat of saturating liquids. (1) Weighted arithmetic mean; (2) Weighted geometric mean, and (3) Weighted harmonic mean.

4. Conclusions

(i) The continuous flow electrical method gives reproducible values of effective specific heats of packed bed materials over a wide range of mass porosity.

(ii) Effective specific heats of sandstones, charcoal and sugar ranging in mass porosity from 17·6% to 45·8% measured by this method with different saturating liquids can be fitted to the weighted arithmetic mean expression. This expression can be used to predict the values of effective specific heats of packed bed materials.

(iii) The specific heats of solid phases can be determined from the intersection of the experimental curves with the zero mass porosity line and the iso-speicfic heat line, but the accuracy of values obtained by such extrapolation is doubtful.

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