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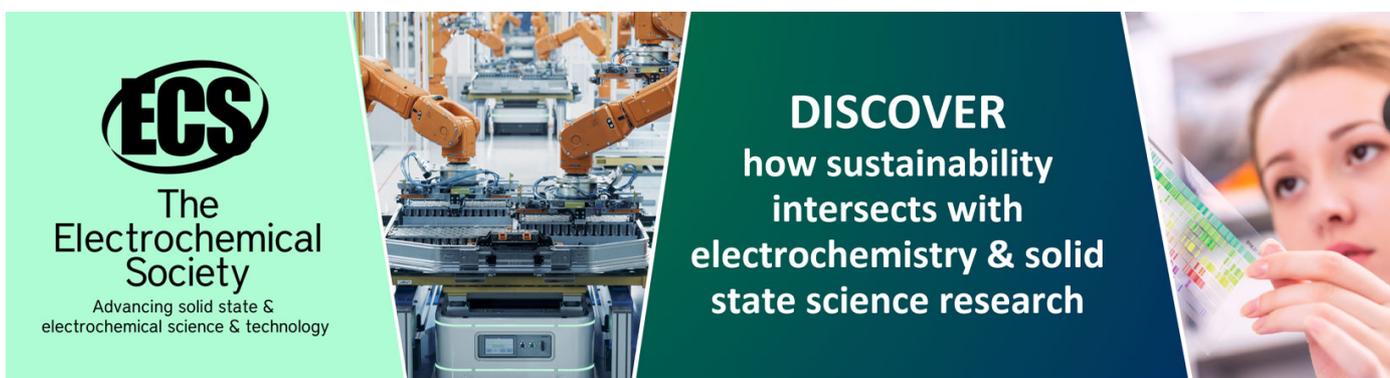
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Thermophysical properties of consolidated porous rocks

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Abstract. Thermal conductivity, thermal diffusivity and heat capacity per unit volume of consolidated porous rocks have been studied as a function of temperature with air as a saturant, at atmospheric pressure. The transient plane source (TPS) technique is used for the simultaneous measurement of these parameters. An empirical formulation is shown to account for the computation of thermal conductivity of porous rocks in terms of porosity and thermal conductivities of mineral constituents. The measurements showed a linear increase in thermal conductivity with temperature.

1. Introduction

To understand the thermal structure of rocks, the investigation of thermophysical properties, which characterize their capacity to accumulate and conduct heat, and the changes that take place in them under the action of heat, is very important. In connection with geological exploration and thermal oil recovery methods, many physical models have been proposed (Beck 1976, Kingery 1959, Somerton 1958, Sugawara and Yoshizawa 1962, Zimmerman 1989) to explain the measured thermal conductivity of porous materials with porosity, chemical composition, grain size, temperature or pressure etc as parameters. The number of pores in a porous materials, plays an important role among the many factors that affect thermal conductivity. In the present study, the effective conductivity of the porous rocks was estimated in two steps: (a) conductivity of the solid phase is obtained from a non-porous parallel model using conductivities of constituent minerals and (b) porosity correction is then applied using the porous model proposed by Sugawara (1960).

2. Estimation of thermal conductivity

The thermal conductivity of rocks depends on the ability of their constituent minerals to conduct heat and is an additive function of the conductivity of these minerals. If we assume that the minerals with conductivities λ_i and volume concentrations V_i are arranged in parallel in a non-porous rock, then the thermal conductivity λ_s of the solid rock will be

$$\lambda_s = \sum \lambda_i V_i. \quad (1)$$

When a low-conductivity phase such as a pore with porosity (φ) is present along with a solid phase of conductivity

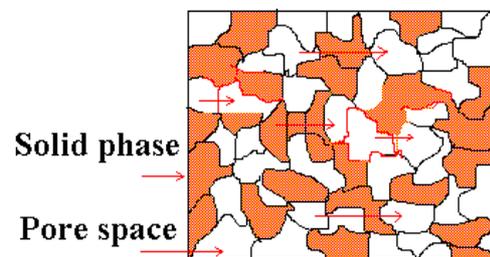


Figure 1. Schematic diagram of the physical picture of a porous rock; where the arrows inside show the heat flow, the dark regions are the solid phases and the empty regions are the pore spaces.

λ_s (figure 1), there is equal probability of their occurring in parallel or in series. The resulting effective conductivity takes the following forms;

$$1/\lambda_e = \varphi/\lambda_f + (1 - \varphi)/\lambda_s \quad (2)$$

(series, giving minimum value)

$$\lambda_e = \varphi\lambda_f + (1 - \varphi)\lambda_s \quad (3)$$

(parallel, giving maximum value).

Sugawara and Youshizawa (1962) obtained good agreement between their experimental and calculated thermal conductivities of two-phase, fluid-saturated rocks. They used the empirical formula presented by Sugawara (1960), which is actually a modification of the parallel model (equation (3)) and is given below;

$$\lambda_e = (1 - A)\lambda_s + A\lambda_f \quad (4)$$

where

$$A = [(2n)(2n - 1)^{-1}][1 - (1 - \varphi^n)^{-1}]$$

and $n > 0$ is the empirical exponent depending on the porosity, shape, orientation and emissivity inside the pores.

Table 1. Physical characteristics by visual inspection, mineral contents obtained by x-ray diffraction, porosity ϕ , thermal conductivity λ , thermal diffusivity κ and the heat capacity per unit volume ρC_p measured at room temperature.

Property	Sample				
	SST-1	SST-2	SST-3	SST-4	SST-5
Colour	Purple brown to dark brown	Light brown to greenish grey	Whitish grey	Purple brown to dark brown	Yellowish to reddish brown
Hardness	Medium to soft	Medium to hard	Medium to hard	Medium to hard	Medium to hard
Graininess	Fine grained	Fine grained to crystalline	Fine crystalline	Fine grained	Fine to medium grained
Density (kg m^{-3})	3051	2701	2641	2581	2298
Porosity (%)	8.00	10.00	16.00	19.00	26.00
Quartz (%)	61	50	62	74	53
Dolomite (%)	15	31	20	16	34
Potassium feldspars (%)	16	15	15	10	13
Calcite (%)	8	4	3	—	—
λ ($\text{W m}^{-1} \text{K}^{-1}$)	4.200	3.431	3.237	2.914	2.817
κ ($\text{m}^{-2} \text{s}^{-1}$) $\times 10^{-6}$	1.487	1.652	1.638	1.534	1.025
ρC_p ($\text{MJ m}^{-3} \text{K}^{-1}$)	2.025	1.677	1.752	1.926	2.154

Kingery (1959) showed that the effect of the pores in the porous rock structure on the thermal conductivity is more of a series effect for a continuous low-conductivity phase (high porosity), and parallel when the low-conductivity phase is distributed randomly in the solid phase. Because, for the specimens under investigation, the porosity was not too high, we considered the effect of porosity and various mineral phases on the thermal conductivity to be parallel. Following this approach, the thermal conductivity of the solid phase λ_s was calculated from equation (1) as a function of the volume fractions and conductivities of the constituent minerals. This value of λ_s was then used in equation (4), taking $\lambda_f = \lambda_{air}$, and the effective conductivity (λ_e) of the rock was thus estimated.

The mineral and air thermal conductivity values at room temperature, were taken from Horai (1971) and Zimmerman (1989) as: quartz = $7.69 \text{ W m}^{-1} \text{K}^{-1}$, calcite = $3.59 \text{ W m}^{-1} \text{K}^{-1}$, potassium feldspar = $2.31 \text{ W m}^{-1} \text{K}^{-1}$, dolomite = $3.34 \text{ W m}^{-1} \text{K}^{-1}$ and air = $0.026 \text{ W m}^{-1} \text{K}^{-1}$.

3. Experimental technique

The transient plane source (TPS) technique was used to perform the simultaneous measurements of thermal conductivity, thermal diffusivity and heat capacity per unit volume of the sandstones. This technique is based on three-dimensional heat flow inside the sample, which can be regarded as an infinite medium, if the time of the transient recording is ended before the thermal wave reaches the sample boundaries. The TPS method uses a resistive element (the TPS element) both as a heat source and a temperature sensor. For data collection the TPS element (20 mm diameter) is sandwiched between two specimen halves in a bridge circuit (Shabbir *et al* 1993). When a sufficiently large amount of direct current is passed through the TPS element its temperature changes, which causes its resistance to change, and consequently there is a voltage drop across the TPS element. By recording this voltage drop for a particular time interval, detailed information about the thermal conductivity

and thermal diffusivity of the test specimen is obtained. The heat capacity per unit volume is then calculated from $\rho C_p = \lambda/\kappa$. For further details see Gustafsson (1991).

4. Sample description and measurements

The test specimens were obtained from Khewara Gorge district Jhelum, Pakistan. Five samples were selected as to be representative of the porosity range and average mineralogical contents of the sampling site. The samples were cut into rectangular slabs of approximate size $0.065 \times 0.054 \times 0.052 \text{ m}^3$ and were polished to give a good thermal contact with the TPS sensor.

The measurements for thermophysical properties were carried out with air as the saturant in the pore spaces. For this purpose the samples were dried in air at 373 K for 2 h and then placed in a closed oven (to avoid any moisture interference) in which the temperature-dependent experiments were made. On every sample, four measurements were made at all of the temperature intervals. A constant current of the order of 150–300 mA (so as to not cause a temperature increase of more than 1 K) was applied to the TPS sensor through a HP 6633A microprocessor-controlled power supply and subsequently one hundred data points were recorded with an integration time of 1 s, via a digital multimeter (HP 3478A) on line to a microcomputer. The data were processed further on computer to obtain the thermal conductivity, thermal diffusivity and heat capacity per unit volume of the samples. The values for the temperature coefficient of resistivity of the TPS sensor were taken from Shabbir *et al* (1993).

5. Results and discussion

The physical characteristics by visual inspection, mineral content, porosity, density and room-temperature (303 K) measured data on the thermal conductivity, thermal diffusivity and heat capacity per unit volume of the five sandstones are summarized in table 1.

All of the samples were multimineral, with porosity ranging from 0.08 to 0.26 and the as-measured thermal

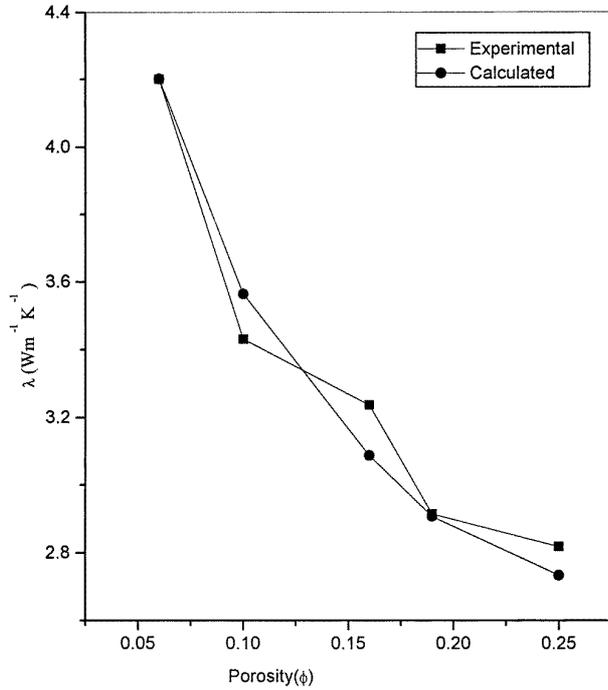


Figure 2. Change in experimental and calculated thermal conductivities as a function of a sandstone’s porosity at $T = 303 \pm 1$ K, and at atmospheric pressure: where the data points connected with straight lines segments are for measured data (■) and using λ_s calculated from (1) and then λ_e from (4) for $n = 4$ (●).

conductivities ranged from 2.817 to 4.200 $\text{W m}^{-1} \text{K}^{-1}$. The effect of sample porosity on the measured and calculated thermal conductivities is shown in figure 2. The decrease in the thermal conductivity with increasing porosity is in complete agreement with the reported results of Woodside and Messmer (1961) and Sugawara and Youshizawa (1962). These curves show that the low-conductivity phase (saturant) has an appreciable effect on the total conductivity of the sandstone. Increasing porosity gives a greater contribution from the pore-filling fluid and a fall in the apparent density, and hence the thermal conductivity is lowered. However, minimum conductivity will not be less than that of the fluid in the pores.

In figure 3 the variation of the thermal conductivity with temperature is plotted. All of the samples show a small rise in the thermal conductivity with temperature, which is in agreement with the published data (Sugawara and Youshizawa 1962). This plot also shows that the rise in conductivity for the pairs SST-1, SST-3 and SST-2, SST-5 follows the same trend. This can be traced back into their respective similar mineral contents (table 1).

Theoretically, the thermal energy in solids consists of waves which travel with the velocity of sound. They are therefore capable of transporting energy. From the kinetic theory of gases we have (Peierls 1964)

$$\lambda = \frac{1}{3}(CV_{ph}L) \quad (5)$$

where C is the heat capacity, V_{ph} is the phonon velocity and L is the mean free path. Under harmonic approximation the waves travel freely without attenuation, giving infinite

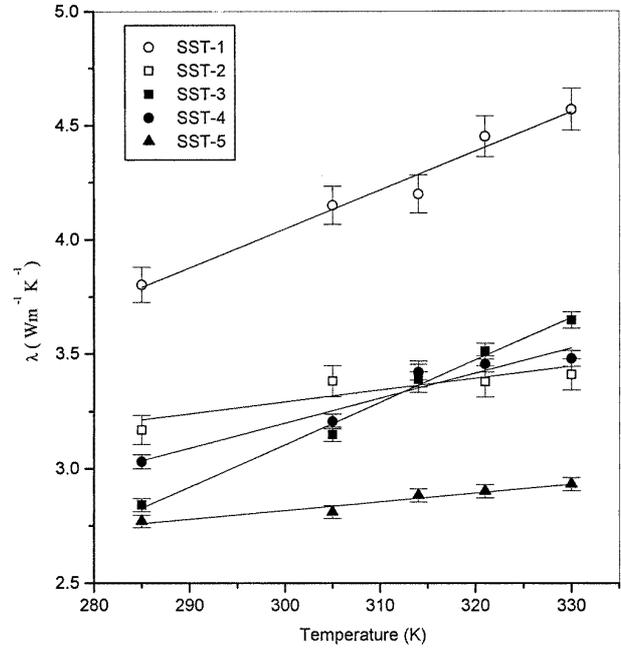


Figure 3. Variation of experimental thermal conductivity (within $\pm 2\%$) against temperature (within ± 1 K) of the five sandstones; where the symbols show the measured values at atmospheric pressure and the lines represent the linear fit of the data points.

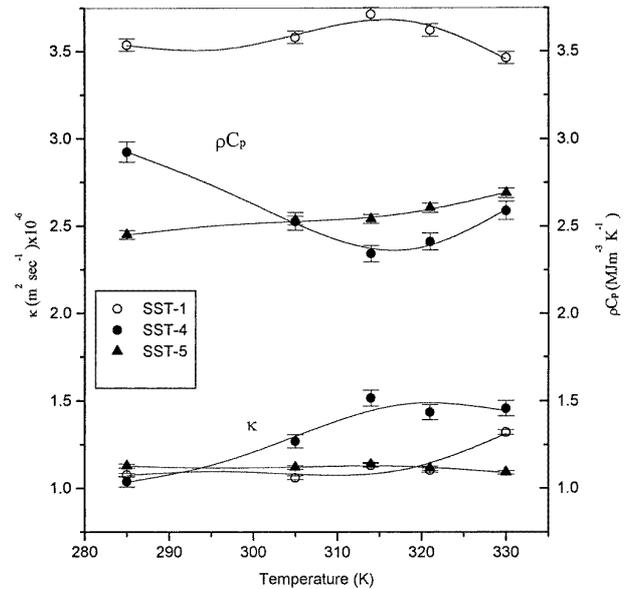


Figure 4. The temperature dependence of the measured thermal diffusivity κ (within $\pm 2\%$, lower curves) and heat capacity (within $\pm 2\%$) per unit volume ρC_p (upper curves) at atmospheric pressure.

conductivity. In reality anharmonic terms, impurities, imperfections and the grain size limit their path. If we consider the lattice waves as a phonon gas and see, in the light of equation (5), it seems that with an increase in the temperature in the porous rocks that the mean free path of the phonons increases, at least in the temperature range of interest. Also, depending on the number of interconnected pores, there is latent heat flow due to air molecules inside the pores. Moreover, the conductivity of air, calcite and

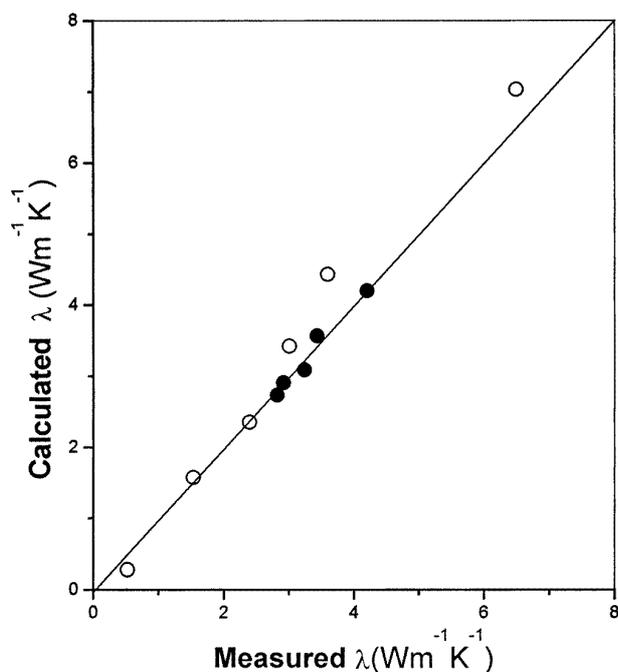


Figure 5. Comparison of the measured and calculated thermal conductivities for the present work at $T = 300 \pm 1$ K, atmospheric pressure and $n = 4$ in (4) (●) and Woodside and Messmer (1961) measured data with the line source method at $T = 303$ K, atmospheric pressure and λ_s calculated from (1) and then λ_e from (4) for $n = 7$ (○).

feldspars aggregates increases with temperature (Birch and Clark 1940) and hence the effective conductivity increases accordingly. Another implication of equation (5) is the decrease in the thermal conductivity with increasing porosity, due to the lowering trend of the lattice wave velocity in a low-density medium.

The thermal diffusivities and heat capacities per unit volume at 300 K ranged from 1.025×10^{-6} to 1.652×10^{-6} $\text{m}^2 \text{s}^{-1}$ and from 1.677 to 2.154 $\text{MJ m}^{-3} \text{K}^{-1}$, respectively; the measured values at different temperatures are plotted in figure 4. The change in thermal diffusivity is similar to that of conductivity as it depends directly upon the thermal conductivity, whereas the heat capacity remains constant to within the experimental error.

In figure 5 the estimated and experimental thermal conductivity results (full circles for the present work) are plotted and a good agreement between the two is shown, to within $\pm 5\%$. Appropriate data against which the proposed scheme for calculation of thermal conductivity can be tested is that of Woodside and Messmer (1961) who reported conductivity measurements on six sandstones; along with detailed information on mineral contents and porosities. Calculating λ_s from equation (1) and λ_e from equation (4) for $n = 7$, gave good results ($\pm 8\%$), which are shown by

open circles in figure 5. For the estimated conductivity, an interesting phenomena is observed—that for the same value of exponent n in equation (4) the conductivity is slightly overestimated when $\phi < 0.30$ (approx) and underestimated (somewhat) when $\phi > 0.30$. As an example, for $\phi = 0.59$ (in the case of the Woodside and Messmer (1961) data) the calculated conductivity is less by about 40.0% than the corresponding measured value. This deviation may be attributed to the fact that, for $\phi > 0.30$, the effect of component phases on the total conductivity is in series rather than in parallel as the rock resembles an open-pore structure and *vice versa* for $\phi < 0.30$. This observation is under investigation on other porous sandstones.

6. Conclusions

All of the experiments were performed at atmospheric pressure and with air as the fluid in the pore spaces. From these measurements we may conclude that the TPS technique is satisfactory for the simultaneous measurement of thermal conductivity, thermal diffusivity and heat capacity per unit volume of porous sandstones. The results show that thermal conductivity of a porous rock is an additive function of the conductivity of its constituent phases. The good agreement between the measured and calculated data support the idea that in the low-porosity range ($\phi < 0.30$ approximately) the different phases may be assumed to be in parallel, and in series for $\phi > 0.30$. However, this boundary value of porosity may not be assumed to be exact, but is approximate.

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