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Thermophysical Properties of Porous Media: Consolidated Sandstones

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Abstract. Thermal conductivity and thermal diffusivity of porous rocks have been measured simultaneously by Gustafsson probe in the temperature range of 280-330 K at normal pressure using air as the saturant. Data are presented for five types of samples ranging in porosity from 8 to 17%, and to show the variation of thermal conductivity with porosity. An empirical formula is suggested to account for the estimation of thermal conductivity of porous sandstones in terms of porosity and thermal conductivities of the mineral constituents. Thermal conductivities of the samples do not change much within the temperature of measurement.

Keywords: porosity, thermal conductivity, thermal diffusivity, sandstones, porous media

Introduction

The thermal parameters of rocks include thermal conductivity, heat capacity and thermal diffusivity. The first two parameters give the capability of a material to conduct and accumulate heat, respectively, and the third parameter gives an estimate of what area of the material has been affected by heat per second. The knowledge of thermal transport properties of rocks, as a function of temperature, has become important with the wide spread interest in thermal processes of underground fluid-bearing reservoirs. Some of these processes include thermal methods of enhanced oil recovery, management of geothermal reservoirs and underground disposal of nuclear waste.

The thermal properties of porous media are useful in many scientific and engineering disciplines. The design of thermal insulating materials depends upon the heat transfer characteristics of porous media. Thermal conductivity of a given rock depends, at constant temperature and pressure, on its mineralogical composition as well as on its porosity and pore filling. It is customary to subdivide the bulk thermal conductivity into the contribution due to the rock matrix (which accounts for the mineralogical constituents) and into the contribution of the pore space. The latter accounts for the type of pore fillings (which can be air, water, oil, etc.) and also depends on the geometrical configuration of the pores.

In connection with the geological exploration and thermal oil recovery methods, several models have been proposed to explain the measured thermal conductivity of porous materials with porosity, chemical composition, grain size, temperature or pressure, etc. (Zimmerman, 1989; Beck, 1976; Sugawara and Yoshizawa, 1962; Somerton, 1958). Thermal properties and the temperature-related behaviour of rock/fluid systems are described by Somerton (1992) at length.

Models of predicting thermal conductivity are of three general types (Somerton, 1992). The first type involves application of the mixing laws for porous mineral aggregates containing various fluids. Since these models do not take into account the structural characteristics of rocks, they are of limited applicability. The second is the empirical model in which other more easily-measured physical properties are related to thermal conductivity through application of regression analysis to laboratory data. This method has also its shortcomings in that the resulting model may be applicable only to the particular suite of rocks being investigated. The third type is the theoretical model based on the mechanisms of heat transfer applicable to simplified geometries of the rock/fluid system. The difficulty here is the degree of simplification necessary to obtain a solution.

In the present work, thermal parameters of five porous rock samples have been measured. All the samples were obtained from Khewra (Jehlum, Pakistan), with the collaboration of Pakistan Natural History Museum, Shakar Parian, Islamabad. The Khewra sandstones of Cambrian age are exposed to Khewra Gorge in the north of Khewra town, Pakistan. The sandstone is 155.84 m thick and displays fine grained to medium grained sandstones, siltstones, shale and occasional carbonates. The Khewra sandstones have been proved as oil reservoir in some of the oil fields located in Potohar areas of Pakistan. The variation of thermal conductivity as a function of temperature has been reported in the present study. The porosity, density and chemical composition of the samples have been determined and the effect of these parameters on the estimation of thermal conductivity was also undertaken. A modified formula proposed by Sugawara and Yoshizawa

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(1962) for porous materials was found to fit very well to the porosity and thermal conductivity data obtained during these investigations.

Materials and Methods

The samples were cut in rectangular shapes of approximate size 0.043 m x 0.045 m x 0.025 m with the cooperation of Earth Sciences Department, Quaid-i-Azam University, Islamabad, Pakistan.

ASTM standard methods (ASTM, 1973) were applied to measure density and porosity of these materials. These methods have been described earlier (Maqsood *et al.*, 2004; 2003). The chemical composition was determined by using X-ray fluorescence technique and the corresponding mineral content per unit volume was calculated. The physicochemical characteristics of all the five samples are summarized in Table 1. The nomenclature of the samples used in the present study is after Baqri (1988).

Thermal parameters of the samples were studied as a function of temperature by a transient plane source (TPS) technique, also known as the Gustafsson probe (Gustafsson, 1991). In this technique, a TPS-element is used both as a constant heat source and sensor of temperature. For data collection, the TPS-element (20 mm dia) sandwiched between two specimen halves in a bridge circuit was used (Rehman and Maqsood, 2003). When sufficiently large amount of direct current was passed through the TPS-element, its temperature changed and consequently there was a voltage drop across the TPS-element. By recording this voltage drop for a particular time interval, detailed information about the thermal conductivity (λ) and thermal diffusivity (κ) of the test specimens was obtained. The heat capacity per unit volume (ρC_p) was calculated from the following relation:

$$\rho C_p = \lambda/\kappa$$

The other advantages of the TPS-method are the simplicity of the technique and applicability to insulators, fluids and metals (Maqsood *et al.*, 1996), and to superconductors (Suleiman *et al.*, 1993). This technique has been successfully used at high pressure (Rehman *et al.*, 1999) and high temperature (Maqsood *et al.*, 2000).

Each sample consisted of two identical rectangular slabs. The surfaces of the samples were polished to have a good thermal contact with the TPS-sensor and to minimize thermal contact resistance. Thickness of the samples was chosen appropriately so as to satisfy the probing depth criteria (Gustafsson *et al.*, 1979).

The thermal conductivity and thermal diffusivity of all the dried samples, at different temperatures, were measured and are given in Fig. 1. Every measurement was repeated four times under identical conditions and the mean values were used to express the data in Fig. 1. Taking into consideration the standard deviations of the measurements and errors of the technique (Rehman and Maqsood, 2002; Maqsood *et al.*, 1996), the thermal conductivity and thermal diffusivity data contained error of 6% and 7%, respectively.

Results and Discussion

The visual characteristics of the samples, and their density, porosity and mineral contents are summarized in Table 1. The porosity of the samples varied from 8 to 17%. The porosity and the density of the samples were measured at 307 K. Therefore, for the comparison of the experimental and effective thermal conductivities, the conductivity data corresponding to this temperature were considered.

The experimental results of thermal conductivity and thermal diffusivity of the five sandstones, as a function of tempera-

Table 1. Characteristics of the samples at room temperature

Sample type*	Colour	Density (kg m^{-3}±1)	Porosity φ (%)	Main lithology	Mineral content (vol, %)				Position above base (m)
					Quartz	Calcite	Potassium feldspar	Dolomite	
kh-khs 9/88	purple brown to dark brown	2350	8	silty shale to clay	54.94	5.70	5.17	34.20	26.40
kh-khs 11/88	light brown to greenish gray	1950	11	fine sandstone to dolomitic	59.46	2.48	5.58	32.48	45.92
kh-khs 15/88	grey	2190	14	silty sandy calcareous	64.52	4.26	4.01	27.21	54.92
kh-khs 22/88	brown to dark brown	1750	16	sandstone	76.97	4.04	2.83	16.15	74.73
kh-khs 29/88	reddish brown	2480	17	sandstone	71.14	6.16	2.48	19.76	119.89

*the nomenclature of the samples is after Baqri (1988); kh-khs stands for Khewra- Khewra sandstones ture, are shown in Fig. 1. The values of thermal conductivity in all the five samples ranged between 2.75 and 4.20 $Wm^{-1} K^{-1}$ at room temperature. The thermal conductivity of the sandstones varied slightly in the temperature range of the experiments.

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 it is assumed 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:

$$\lambda_s = \frac{\Sigma \lambda_i V_i}{\Sigma V_i} \tag{1}$$

When a low-conductivity phase, (λ_i) such as a pore with porosity (Φ), is present along with a solid phase of conductivity λ_s, there is equal probability of their occurring in parallel or in series. The resulting effective conductivity (λ_e) takes the following forms:

$$\lambda_e = \phi\lambda_f + (1 - \phi)\lambda_s \tag{2}$$

$$\lambda_e = \left(\frac{\phi}{\lambda_f} + \frac{1 - \Phi}{\lambda_s}\right)^{-1} \tag{3}$$

Equation (2) gives the highest values of thermal conductivity of the rock/fluid system of all the mixing models (Somerton, 1992). The series arrangement, equation (3), gives the lowest value of thermal conductivity. Sugawara and Youshizawa (1962) obtained good agreement between their experimental and calculated thermal conductivities of the two-phase, and fluid-saturated rocks. They used the empirical relation for $\Phi > 1\%$ as:

$$\lambda_e = (1 - A)\lambda_s + A\lambda_f \tag{4}$$

where:

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

λ_e = effective thermal conductivity of porous material

λ_f = thermal conductivity of saturating fluid

Φ = porosity of the material

n = an empirical exponent

n > 0 = depending on the porosity, shape, orientation and emmisivity inside the pores

Equation (4) indicates that thermal conductivity depended on the ability of constituent minerals to conduct heat. 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 feldspar aggregates increases with temperature (Birch and Clark, 1940), and hence the effective thermal conductivity increases accordingly.

The dependence of thermal conductivity with temperature (Fig. 1) was shown by a slight increase in thermal conductivity with temperature for all samples, except kh-khs 15/88, which showed a decreasing trend but within the experimental errors. The thermal diffusivity of the samples, as a function of temperature, showed similar trends to that of conductivity as it depended directly upon the thermal conductivity.

Fig. 2 shows the variation of experimental thermal conductivity and thermal diffusivity of the five sandstone samples with porosity at 307±1 K. It is interesting to note that both thermal conductivity and thermal diffusivity decreased with the increase of porosity, which is in agreement with the reported results of Sugawara and Youshizawa (1962), and Wooside and Messmer (1961). Increasing porosity makes a greater contribution from the pore filling and a fall in the apparent density, and hence the thermal conductivity is lowered. However, minimum thermal conductivity will not be less than that of the fluid in the pores.

For the estimation of λ_e, the mineral and air thermal conductivity values, at room temperature, were taken from Horai (1971) and Zimmerman (1989) as: air = 0.026 $Wm^{-1}K^{-1}$, quartz = 7.69

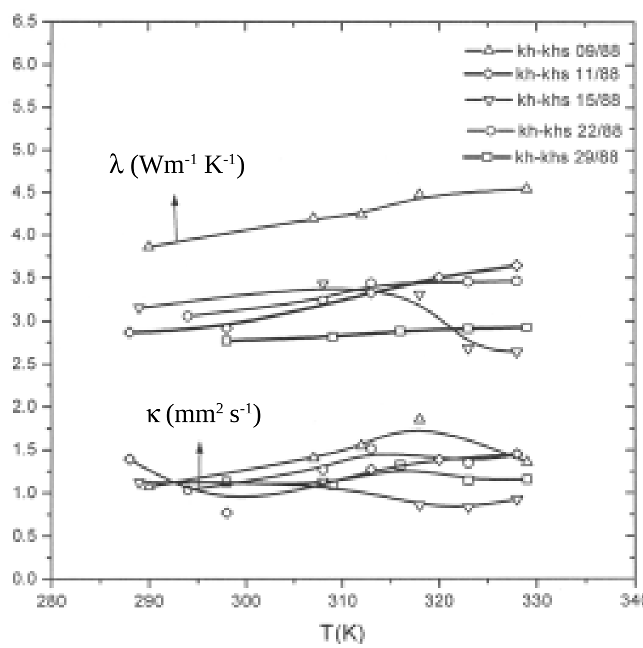

Fig. 1. Variations in thermal conductivity and thermal diffusivity with rising temperature (K); the estimated errors in λ ($Wm^{-1} K^{-1}$) and κ ($mm^2 s^{-1}$) were about 6% and 7%, respectively; mean values of four repeated observations.

$Wm^{-1}K^{-1}$, calcite = 3.59 $Wm^{-1}K^{-1}$, dolomite = 3.34 $Wm^{-1}K^{-1}$, and potassium feldspar = 2.31 $Wm^{-1}K^{-1}$.

All the samples were multimineral, with porosity ranging from 8 to 17%. Fig. 3 shows the variation in the experimental and effective thermal conductivities of the samples as a function of porosity at 307±1 K. Here, λ_e was calculated using equation (4), and the thermal conductivity of the solid phase (λ_s) was determined from equation (1) as a function of the volume fractions of the conductivities of the constituent minerals (Table 1). In estimating the value of λ_e it was noticed that our data gave a better agreement if the expression of equation (4) was modified as:

$$A = 2^{n+1}\left[\frac{1}{(2^n - 1)}\right]\left\{1 - \left[\frac{1}{(1+\phi)^n}\right]\right\}$$

with n = 1

This decrease in the thermal conductivity with increasing porosity is in agreement with the previous observations (Sugawara and Yoshizawa, 1962; Wooside and Messmer, 1961). From the plot (Fig. 3) it is clear that the experimental and effective thermal conductivities are in good agreement within experimental errors.

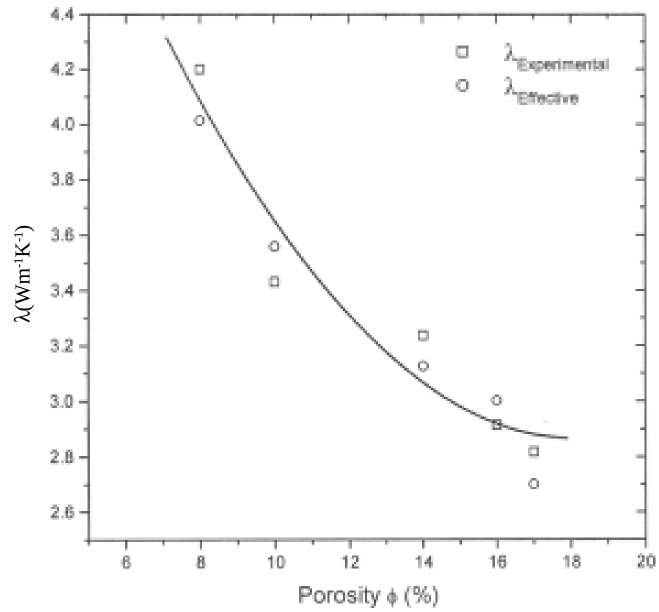

Fig. 3. Variation and comparison of experimental and effective thermal conductivities [$\lambda(Wm^{-1}K^{-1})$] with porosity [ϕ, %] of sandstones at 307±1 K, and at normal pressure: (——) fitted to least squares polynomial of second order.

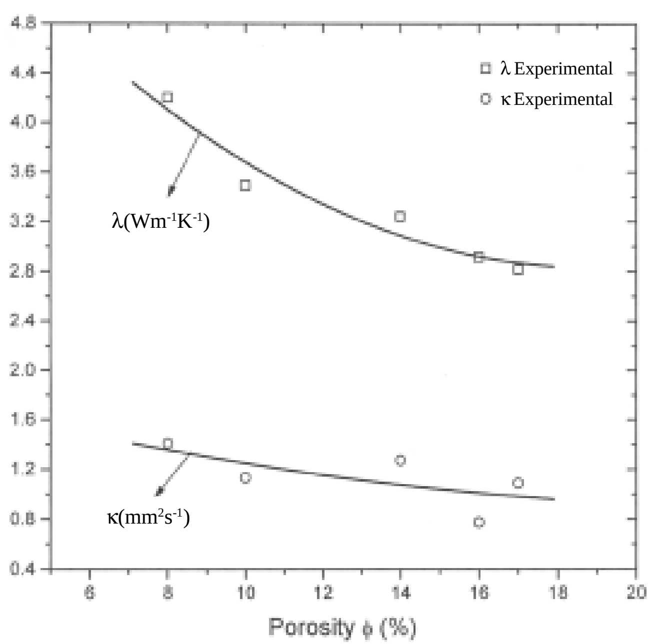

Fig. 2. Variation of measured thermal conductivity and thermal diffusivity of the five sandstones with the change in porosity at 307±1 K and at normal pressure: (——) fitted to least squares polynomial of second order; the estimated errors in λ and κ were 6% and 7%, respectively.

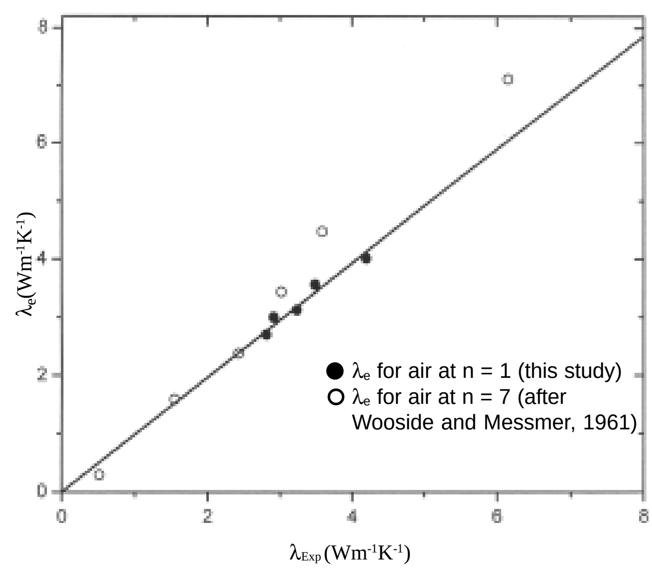

Fig. 4. Comparison of the experimental [$\lambda_{Exp}(Wm^{-1}K^{-1})$] and effective thermal [$\lambda_e(Wm^{-1}K^{-1})$] conductivities for the present work at 307±1 K and normal pressure according to equation (4) and the Wooside and Messmer (1961) measured data with the line source method at T = 303 K normal pressure, and λ_s calculated from equation (1) and then λ_e from equation (4) for n = 7.

Fig. 4 shows the comparison of the experimental and estimated (effective) thermal conductivities obtained during the present work at 307±1 K and normal pressure. There existed a good agreement between the two within experimental errors. Appropriate data against which the proposed model for calculation of thermal conductivity can be tested is that of Wooside and Messmer (1961) who reported thermal 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 results within 8%, which are again shown in Fig. 4. For lower thermal conductivities, the experimental and estimated values are in good agreement, but for higher values of thermal conductivities that are corresponding to lower values of porosity, the results differ to some extent. Further investigations, such as the effect of saturant pore size and pressure on the thermal transport properties are in progress.

Conclusion

All the experiments were performed at atmospheric pressure and with air as the fluid in the pore spaces. From these measurements, it was clear that TPS-element can be used repeatedly over large temperature ranges (Maqsood *et al.,* 2000). Further, when comparing this technique with other methods, such as the hot-wire and transient hot-strip technique (Gustafsson *et al.,* 1979), it must be remembered that the experiments were performed with very small temperature perturbations of the sample material. Under these circumstances, the agreement must be considered exceptionally good, particularly in view of the fact that the thermal conductivity, thermal diffusivity and volumetric heat capacity can be obtained from a single determination.

The density and the porosity of all the sandstones have been determined using the ASTM standard methods at 307±1 K. The experimental and estimated thermal conductivities of all the five sandstones, as a function of porosity at 307±1 K, are in good agreement. For the estimation of the thermal conductivity, the formula proposed by Sugawara and Yoshizawa (1962) was slightly modified.

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