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Thermophysical properties of dunite rocks as a function of temperature along with the prediction of effective thermal conductivity

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ABSTRACT

The thermal conductivity, thermal diffusivity and heat capacity per unit volume of dunite rocks taken from Chillas near Gilgit, Pakistan have been measured simultaneously using transient plane source technique. The temperature dependence of thermal transport properties is studied in the temperature range 83-303 K. Different relations for the estimation of thermal conductivity are also tested. Thermal conductivity data obey the modified Eucken's law in the temperature range of measurements.

Keywords: Dunite; Density; Porosity; Thermal Conductivity; Transient Plane Source (TPS) Technique

1. INTRODUCTION

The most relevant thermal parameters of rocks are thermal conductivity, heat capacity per unit volume and thermal diffusivity. The first two parameters give the capability of a material to conduct and accumulate heat, respectively; and the last one represents how fast heat diffuses through a material [1].

1.1. Introduction to Samples

Igneous rocks are classified on the basis of texture and chemical composition.

On the basis of texture igneous rocks are classified in to two groups.

1.1.1. Extrusive or Volcanic

When magma comes out of the surface of earth (called lava) then rapid cooling and crystallization of that magma above the earth surface form volcanic igneous rocks. Most types of lavas cool rapidly, resulting in the formation of rocks composed mainly of microscopic crystals. Some lavas cool so quickly that they form a smooth volcanic glass called obsidian. These are too fine-grained or glassy that their mineral composition cannot be observed without the use of petrographic microscope.

1.1.2. Intrusive or Plutonic

The cooling and crystallization of molten magma below the surface of earth form these rocks. Magma that forms the intrusive rocks solidifies relatively slow; and so, most of the intrusive rocks have larger crystals than of extrusive rocks. The mineral grain size of these rocks is visible to naked eye even.

On the basis of chemistry igneous rocks are classified in to four groups [2].

1.1.3. Felsic

Igneous rocks derived from felsic magma contain relatively high quantities of sodium, aluminium and potassium and are composed of more than 65% silica (SiO_2). Some common felsic igneous rocks include fine-grained Rhyolite and coarse-grained Granite. All of felsic rocks are light in colour because of the dominance of quartz, potassium and sodium feldspars, and plagioclase feldspars minerals.

1.1.4. Intermediate

Some igneous rocks having chemistry between felsic and mafic rocks are known as intermediate. Silica amounts from 52% to 65%. Andesite (intrusive) and Diorite (extrusive) are intermediate igneous rocks. These rocks are composed predominantly Plagioclase feldspar, Amphibole and Pyroxene minerals.

1.1.5. Mafic

Igneous rocks derived from mafic magma rich in cal-

cium, iron and magnesium and relatively poor in silica, amounts from 45% to 52%. Some common mafic igneous rocks include-fine grained Basalt and coarse-grained Gabbro. Mafic igneous rocks tend to be dark in colour because they contain a large proportion of minerals rich in iron and magnesium (Pyroxene, Amphiboles and Olivine).

1.1.6. Ultramafic

These rocks contain relatively low amount of silica < 45% and are dominated by the minerals olivine, calcium rich plagioclase feldspars and pyroxene. Peridotite and Dunite are the most common ultramafic rocks having coarse-grained texture. There is no known modern fine-grained ultramafic rock. The samples studied here belong to the dunite group of igneous rocks.

The density related properties of the selected samples at room temperature along with their thermal properties in temperature range (303-483 K) are already published [3]. In this paper only the thermal transport properties are measured in temperature range 83 to 303 K at normal pressure, with air as saturant in pore spaces, using Transient Plane Source Technique [4].

In continuation of our previous work [5,6], the aim in this work is to study thermal transport properties of dunite rocks as a function of temperature and to test various relations for the prediction of effective thermal conductivity of porous media.

2. EXPERIMENTAL TECHNIQUES AND SAMPLE CHARACTERIZATION

The thermal transport properties of the samples were measured as a function of temperature, using transient plane source (TPS) technique. The beauty of TPS technique is that it allows measurements without any disturbance from the interfaces between the sensor and the bulk samples. Also, simultaneous measurement of thermal conductivity and thermal diffusivity is possible [4]. In this technique, a TPS-element (**Figure 1**) sandwiched between two halves of the sample is used both as a constant heat source and a sensor of temperature.

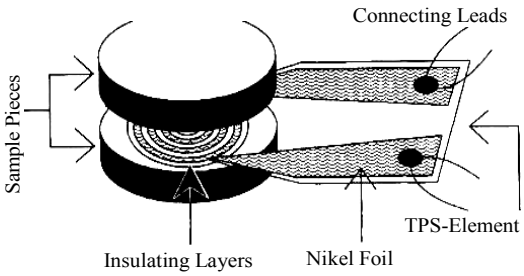

Figure 1. A TPS-sensor sandwiched between sample pieces [7].

For data collection the TPS-element (20 mm diameter) was used in a bridge circuit, shown in **Figure 2**.

When sufficiently large (constant) amount of direct current is passed through the TPS-element, its temperature changes consequently and 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 (λ) and thermal diffusivity (κ) of the test specimen is obtained. The heat capacity per unit volume (ρC_P) can then be calculated from the relation:

$$\rho C_P = \frac{\lambda}{\kappa}, \tag{1}$$

The results of the thermophysical measurements on the samples at different temperatures and normal pressure are shown in **Figure 3**.

It is to be noted that the results of thermal properties in high temperature range 303 to 483 K [3] are also included in **Figure 3**, so that one can observe the overall behavior of thermal properties of these samples over a wide range of temperature (83-483 K).

Taking into consideration the errors of the technique [7,8], standard deviations of the measurements and the sampling errors, the thermal conductivity and thermal diffusivity data contain errors of 5% and 7% respectively. The errors in volumetric heat capacity are around 10%.

3. THERMAL CONDUCTIVITY PREDICTION

A typical equation used for temperature dependence of lattice (phonon) thermal conductivity is:

$$\frac{1}{\lambda(T)} = A + BT, \tag{2}$$

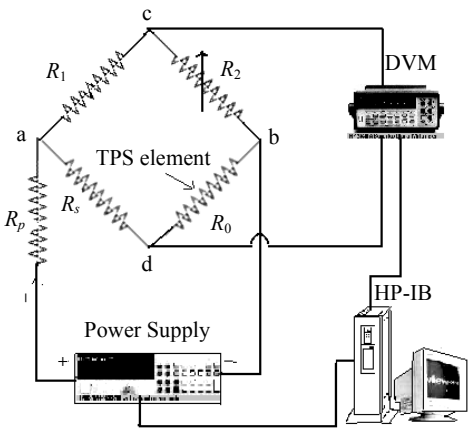

Figure 2. Bridge circuit diagram for TPS technique: R_s = Standard resistance, R_0 = Resistance of TPS sensor [9].

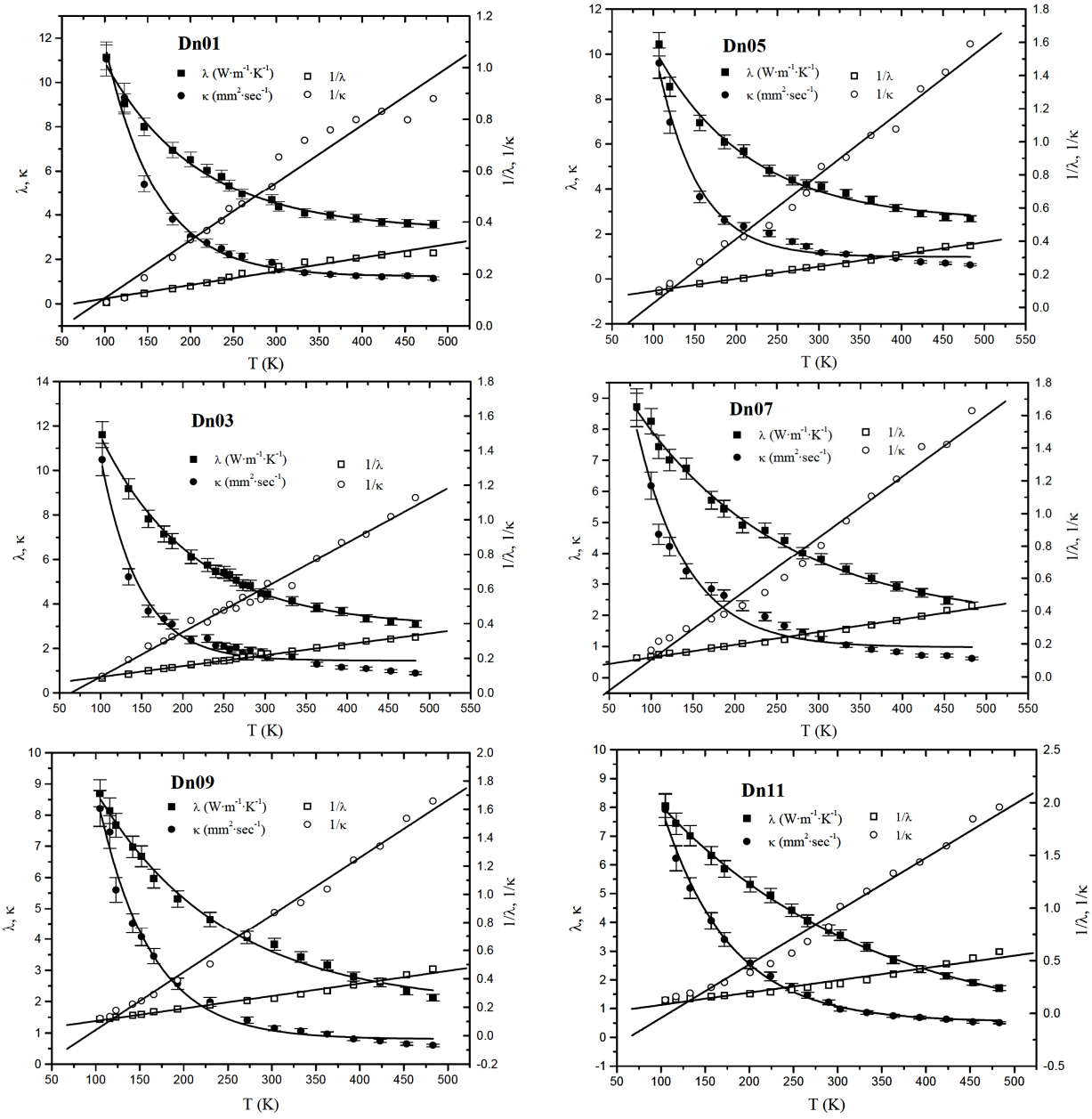

Figure 3. Temperature dependence of thermal conductivity, thermal diffusivity and heat capacity per unit volume, $\frac{1}{\lambda(T)} = A + BT$ and $\frac{1}{\kappa(T)} = R + ST$. Estimated uncertainties in λ and κ are about 5% and 7% respectively.

where $A(\mathrm{W}^{-1}\cdot\mathrm{m}\cdot\mathrm{K})$ and $B(\mathrm{W}^{-1}\cdot\mathrm{m})$ are constants related to the scattering properties of phonons. A is related to scattering of phonons by impurities and imperfections [10]; and B is related to phonon-phonon scattering and is approximately proportional to an inverse power of sound velocity [11].

The physical justification of the term A is the existence of numerous additional scattering centers for phonons in materials, caused by structural and chemical imperfections and the influence of the grain boundaries. **Eq.2** is analogous to Matthiessen's rule of electrical resistivity in metals, which is:

$$\rho_e = \rho_{eo} + \rho_e(T), \tag{3}$$

where ρ_{eo} is the extrapolated electrical resistivity at 0 K and is called the residual resistivity. This is the temperature independent part of the resistivity. That is, the value of ρ_{eo} depends upon the concentration of impurities and other imperfections in the sample. It can be taken as the measure of impurity of the specimen. The tempera-

ture dependent part of resistivity $\rho_e(T)$ is decided by the phonons. It is called the lattice resistivity [12].

For diffusivity (having the same trend as thermal conductivity), the analogous equation was assumed to be:

$$\frac{1}{\kappa(T)} = R + ST \tag{4}$$

The results obtained using **Eqs.2** and **4** along with the experimental results / values of λ and κ are shown in **Figure 3**. The correlation coefficients for thermal conductivity (r_λ) and thermal diffusivity (r_κ) are also listed in **Table 1**.

The data appear to fit very well (above 97%). The values of ρC_p can be calculated using **Eq.1**.

Eq.2 may also be written as [13,14]:

$$\lambda(T) = \lambda_r(1 + bT_r)/(1 + bT), \tag{5}$$

where λ_r ($W \cdot m^{-1} \cdot K^{-1}$) is the thermal conductivity at a reference temperature and $b(K^{-1})$ is a single temperature coefficient of thermal conductivity parameter, controlling the temperature dependence of thermal conductivity. b is related to parameters A and B of **Eq.2**, as:

$$b = B/A \tag{6}$$

The reference value of thermal conductivity (λ_r) is simply derived from **Eq.2**, using $T = T_r$ (reference/ room temperature). It is to be noted that each of the **Eq.2** or 5 is the modified Eucken's rule.

A recently proposed empirical model [6] for the prediction of thermal conductivity as a function of temperature is:

$$\frac{1}{\lambda_e} = \frac{1}{\lambda_s} + \frac{m\Phi}{\lambda_f}\left(\frac{T}{T_r}\right), \tag{7}$$

where m is the empirical coefficient whose value can be determined at suitable temperatures, using the corresponding experimental values of thermal conductivity and the room temperature values of Φ, λ_f and λ_s; by

$$m = \lambda_f T_r \left(\frac{\sum\left(1/\lambda_{\exp} - 1/\lambda_s\right)}{\sum(T\Phi)} \right) \tag{8}$$

The empirical coefficients, exponents or adjustable parameters may vary according to the suite of rocks. Therefore, the extrapolations of empirical models to suites of rocks other than those used in developing these models may not be satisfactory [15].

4. RESULTS AND DISCUSSION

It is well known that thermal transport properties of porous rocks depend upon their structure, mineral composition, porosity, density, the ability of their constituent minerals to conduct heat, temperature, pressure; etc.

The temperature dependence of thermal conductivity and thermal diffusivity in the temperature range 83 to 483 K at suitable intervals is shown in **Figure 3**. It is observed that thermal conductivity decreases in the measured temperature range. This is in agreement with the theory of thermal conductivity. The thermal diffusivity shows decreasing trend; again in agreement with the theory.

For dunite samples, in **Eq.5**, the empirical coefficient b is taken to be 0.0172 which is equal to the mean of all the values of b listed in **Table 1**. Similarly the mean value of λ_r is found to be 3.858 $W \cdot m^{-1} \cdot K^{-1}$ at 303 K. Using these values of adjustable parameters λ_r and b, thermal conductivity values are predicted along with the experimental measurements and are plotted in **Figure 4**.

It is to be noted that in **Eq.5**, all the parameters effecting thermal conductivity (such as porosity, density, thermal conductivity values of constituent minerals and the fluid inside the pores, etc.) are dumped into adjustable parameters and the errors in predicting thermal conductivity are only up to 10% in the temperature range 243 K to 333 K, which is the most interesting range for construction purposes.

Table 1. Parameters *A, B, R* and *S* for the thermal resistivity $1/\lambda(T)$ and the inverse of thermal diffusivity $1/\kappa(T)$ of dunites as represented by **Eqs.2** and **4**. r_λ and r_κ are the respective correlation coefficients.

Specimen	A $W^{-1} \cdot m \cdot K$	B $10^{-4} W^{-1} \cdot m$	r_λ	R $m^{-2} \cdot sec$	S $10^{-3} m^{-2} \cdot sec \cdot K^{-1}$	r_κ	$b = B/A$ K^{-1}	λ_r $W \cdot m^{-1} \cdot K^{-1}$
Dn01	0.053	5.24	0.98	–0.116	2.23	0.98	0.010	4.728
Dn03	0.029	6.29	1.00	–0.165	2.58	0.99	0.021	4.545
Dn05	0.025	7.36	1.00	–0.362	3.88	0.99	0.029	4.027
Dn07	0.040	7.75	1.00	–0.271	3.74	0.99	0.019	3.639
Dn09	0.016	8.80	0.99	–0.365	4.06	1.00	0.056	3.545
Dn11	–0.036	1.17	0.98	–0.550	5.06	0.99	–0.032	3.140

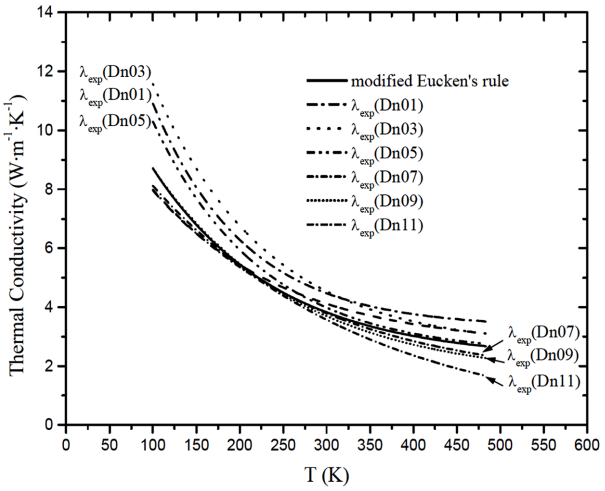

Figure 4. The comparison of experimental and predicted thermal conductivity of dunite samples as a function of temperature.

As far as the results of **Eq.7** are concerned, these are fairly good at room temperature and above (with in 10%) [3]. But, this proposal is not recommended for the prediction of thermal conductivity in temperature range lower than the room temperature. This is the limitation of this model. It is because of the fact that we have used the room temperature values of λ_s, λ_f and Φ in **Eqs.7** and **8**. This makes the value of m (calculated by **Eq.8**) negative in the temperature range lower than room temperature. This reverses the effect of second term on R.H.S. of **Eq.7**. As a consequence, we get the increasing effect in thermal conductivity with temperature due to this term which is against experimental results.

5. CONCLUSIONS

To predict the thermal conductivity of dunite samples as a function of temperature, modified Eucken's rule has been used. It is noted that the experimental thermal conductivity and the predicted conductivity are in good agreement (up to 10%) in the temperature range 243 K to 333 K, which is important for construction purposes.

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