PREDICTING THERMAL CONDUCTIVITY OF ROCKS FROM THE LOS AZUFRES GEOTHERMAL FIELD, MEXICO, FROM EASILY MEASURABLE PROPERTIES

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ABSTRACT

A correlation is developed to predict thermal conductivity of drill cores from the Los Azufres geothermal field. Only andesites are included as they are predominant. Thermal conductivity of geothermal rocks is in general scarce and its determination is not simple. Almost all published correlations were developed for sedimentary rocks. Typically, for igneous rocks, chemical or mineral analyses are used for estimating conductivity by using some type of additive rule. This requires specialized analytical techniques and the procedure may not be sufficiently accurate if, for instance, a chemical analysis is to be changed into a mineral analysis. Thus a simple and accurate estimation method would be useful for engineering purposes. The present correlation predicts thermal conductivity from a knowledge of bulk density and total porosity, properties which provide basic rock characterization and are easy to measure. They may be determined from drill cores or cuttings, and the procedures represent a real advantage given the cost and low availability of cores. The multivariate correlation proposed is a quadratic polynomial and represents a useful tool to estimate thermal conductivity of igneous rocks since data on this property is very limited. For porosities between 0% and 25%, thermal conductivity is estimated with a maximum deviation of 22% and a residual mean square deviation of 4.62E-3 in terms of the $\log_{10}(k\rho_b)$ variable. The data were determined as part of a project which includes physical, thermal and mechanical properties of drill cores from Los Azufres. For the correlation, sixteen determinations of thermal conductivity, bulk density and total porosity are included. The conductivity data represent the first determinations ever made on these rocks.

NOMENCLATURE

- A_i coefficients of proposed model
- F formation factor
- k thermal conductivity
- s standard deviation
- y $\log_{10}(k\rho_b)$
- ρ_b bulk density
- ρ_s solids density
- ϕ_t total porosity

INTRODUCTION

Maximum recovery of the energy content of a geothermal resource is a basic objective of geothermal energy development. The determination of the resource's size, heat and mass reserves and deliverability are tasks undertaken by geothermal reservoir engineering. These studies require data on the thermal and physical properties of the reservoir's fluids and rocks among which, thermal conductivity, density and porosity are very important. Reservoir rock properties are normally obtained through core analysis, but core extraction requires special sampling which makes cores expensive and not so readily available. Furthermore, determination of thermal conductivity is not straightforward but it may be indirectly estimated from other rock properties which are easier to measure or are more readily available. It thus becomes convenient to have correlations to predict rock properties such as thermal conductivity from a knowledge of other rock properties which may be measured both on cores and drill cuttings, the latter being much more abundant. Notwithstanding, published correlations to predict thermal conductivity include sedimentary rocks but not igneous rocks.

The objective of the present study is to present a correlation to predict thermal conductivity of igneous rocks from density and porosity data measured on andesitic rocks from the Los Azufres geothermal field [1]. A more extensive treatment of this work will be published in the series Developments in Geothermal Energy in Mexico [2].

A summary of experimental methods used to determine thermal conductivity of rocks is presented in [3]. Correlations to predict thermal conductivity variation with temperature were developed in [4] while pressure effects were considered in [5]. Estimation of conductivity from the rock mineral composition and the conductivity of the rock-forming minerals has been the subject of a number of studies [6-10]. Birch and Clark [6] found that a series combination of the rock-forming minerals is appropriate for this purpose. Woodside and Messmer [8] claimed that the geometric mean arrangement was more satisfactory while Beck [9] proposed a Maxwell-type model which accounts for thermal contact resistance effects. Horai and Baldridge [10] proposed three methods for estimating the conductivity of non-porous, macroscopically isotropic and homogeneous rocks. To obtain the conductivity of the rock as a consolidated medium, a correction for porosity is needed. On the other hand, a common disadvantage of all these methods is the need for specialized equipment to perform the chemical or mineral analysis. Even if the analysis is available, the procedure might not be sufficiently accurate if, for instance, a chemical analysis is to be converted into a mineral analysis or if the thermal conductivity of a rock-forming mineral is not available Although these methods are typically used for igneous rocks, some are also applicable to other rocks.

Other published correlations include Krupiczka's theoretical models [11] for granular material arranged in cylindrical and spherical packings for which the porosity was 21.5 % and 47.6 % respectively. Martinez [7] extended this model to account for intergranular effects through the use of grain size. Anand et al [12] developed multivariate correlations for dry and saturated rocks. Zierfuss and Van der Vliet [13] developed a correlation which included the formation factor F. This factor must be determined from electrical resistivity measurements. Reddy [14] modified the model of [13] and proposed a simple correlation of conductivity with density and porosity as independent variables, properties which are easy to measure. These correlations were developed for sedimentary rocks, except for Krupiczka's model [11], but none for igneous rocks. This fact lends further support to the correlation presented here and in [2] for igneous rocks.

THE EXPERIMENTS

Thermal conductivity, porosity and density were determined. Conductivity was measured using oven-dried cylindrical specimens, 2" diameter by 4" lentgh employing the thermal needle transient method which simulates a line source in an infinite homogeneous medium [15]. Fig. 1 shows the experimental set-up: an electric heater and its attached type-K thermocouple are introduced along a longitudinal borehole in the sample, with the thermocouple tip sensing temperature at mid-length in the cylindrical sample. Any gaps left in the hole are stuffed with copper powder to minimize contact resistance.

Controlled power is then applied which results in a constant heat generation per unit length. The temperature history is then recorded using an automatic data logger along with the heat input and finally, conductivity is computed from the slope of a best-fit straight line of the curve of temperature versus the logarithm of time. Test runs on a standard sample of fused quartz showed an error of ± 0.03W/(m-K) for the present determinations. Density was measured employing standard techniques [16]. Mass was measured using an electronic balance and bulk volume was measured in a Ruska Universal porometer by mercury injection, and from these, bulk density was computed. Solids (grain) volume was determined by the pulverization method whereby grain volume was measured by displacing an equivalent volume of liquid in a volumetric flask. Total porosity was then computed from its definition:

$$\phi_t = 1 - (\rho_b/\rho_s) \qquad (1)$$

RESULTS AND CORRELATION ANALYSIS

The experiments were performed on fifteen cores from eleven wells from Los Azufres. Fig. 2 shows the location of the wells under study. Samples tested include basaltic andesites and andesites of igneous origin which are the predominant type of rock in the field. The results of the present study include sixteen determinations of thermal conductivity,

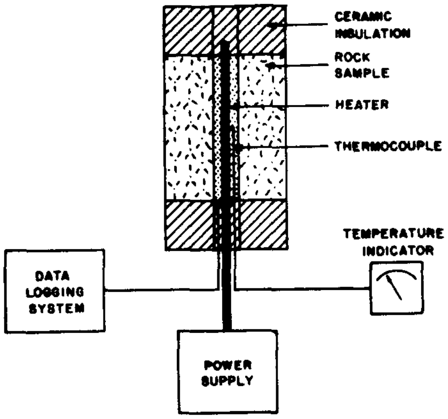

FIG. 1 SCHEMATICS OF EXPERIMENTAL SET-UP FOR THERMAL CONDUCTIVITY MEASUREMENT.

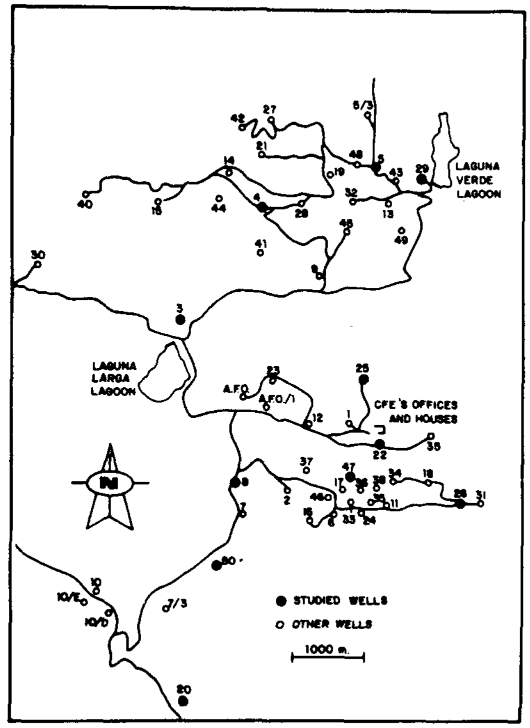

FIG. 2 MAP OF LOS AZUFRES GEOTHERMAL FIELD SHOWING THE LOCATION OF THE WELLS STUDIED.

bulk and solids density and total porosity and are shown in Table 1. It may be noted that thermal conductivity varied between 1.05W/(m-K) and 2.34W/(m-K) with a mean conductivity value of 1.72W/(m-K) and a standard deviation of 0.34W/(m-K) for the 16 determinations. Similarly, the range of variation of solids density is from 2610 to 2940kg/m^3 whereas that for bulk density is from 2050 to 2740kg/m^3 The corresponding mean density values are 2760kg/m^3 and 2450kg/m^3, respectively. Total porosity varied from 1.9 to 24.7 %, with an average value of 11.2 %.

With the data just described, a correlation to predict thermal conductivity from density and porosity was developed. In developing the correlation, bulk density and total porosity were selected as independent variables since they are easy-to-measure or may be readily available. Also, they have a direct effect on heat flow path through a rock and affect the thermal conductivity of the rock. This contrasts with correlations which have been developed for sedimentary rocks and include variables such as formation factors which might be widely available for sedimentary rocks but not for igneous rocks. Furthermore, formation factors may be as difficult to measure as the thermal conductivity itself.

Table 1 Measured thermophysical properties of cores from The Los Azufres geothermal field

Well, core and sample	Density (kg/m^3) bulk	Density (kg/m^3) solids	Total porosity (%)	Thermal conductivity [W/(m-K)]
AZ3-N1-1	2340	2760	15.5	1.68
AZ3-N4.1-1	2560	2940	13.2	1.84
AZ3-N5-1	2740	2800	2.2	1.99
AZ4-N3-1	2440	2790	12.7	1.58
AZ4-N3-2	2430	2790	12.9	1.53
AZ5-N1-1	2050	2730	24.7	1.17
AZ8-N2-1	2600	2790	6.9	2.34
AZ20-N1-1	2270	2610	13.0	1.58
AZ20-N3-1	2690	2810	4.2	1.71
AZ22-N2-1	2450	2800	12.6	2.17
AZ25-N1-1	2320	2730	14.8	1.75
AZ26-N2-1	2610	2740	4.9	2.20
AZ26-N3-1	2430	2700	10.1	1.55
AZ29-N1-1	2050	2660	23.1	1.05
AZ47-N4-1	2740	2790	1.9	1.89
AZ50-N3-1	2490	2680	7.2	1.52

For the correlation, a new variable $y = \log_{10}(k\rho_b)$ is defined and a polynomial regression of y as function of total porosity was performed. Polynomials tested include first and second degree models. Figures 3 and 4 show plots of experimental values of the $y-\Phi_t$

pairs as well as the corresponding fitted curves. It is seen from Fig. 3 that the linear model follows reasonably well the central points but fails to follow the points at both left and right ends while Fig. 4 shows that the quadratic model follows such points better and its behavior in the central part of the figure is quite similar to that of the linear case. Statistical computations revealed a correlation coefficient of 0.83 and a r.m.s. deviation of 5.23E-3 for the linear fit. Correspondig values for the quadratic model are a correlation coefficient of 0.87 with a r.m.s. deviation of 4.62E-3. These observations show that the quadratic model is the best of the two. The resulting equation is

$$\log_{10} (k\rho_b) = A_0 + A_1\phi_{tot} + A_2\phi^2_{tot} \quad (2)$$

where:

A_0=3.7228809, A_1=-0.94476092E-3

and A_2=-0.581068E-3

Comparison between predicted and measured conductivity values showed a maximum difference of ±22% for fifteen of the sixteen points. The discrepancy for the other point was 28% and may be due to a possible error in the determination of the total porosity which resulted to be less than its corresponding effective porosity value, a fact that is physically incongruent. The density and porosity values for this case are being reviewed. However, the point is included to show the complete set of data. This correlation will be updated as more data are gathered.

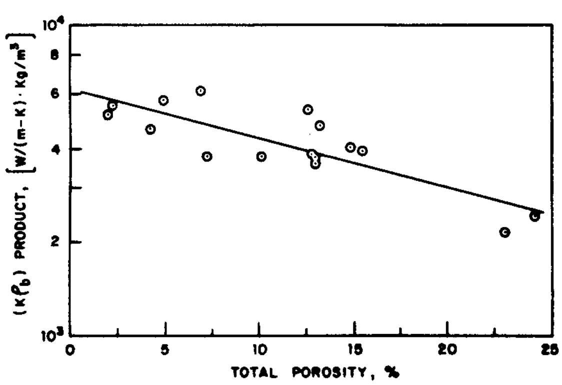

FIG. 3 EXPERIMENTAL POINTS AND LINEAR MODEL FITTED

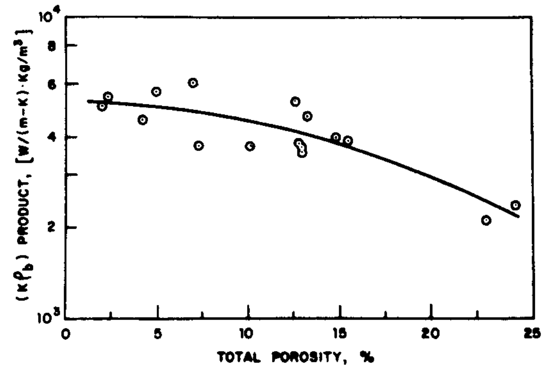

FIG. 4 EXPERIMENTAL POINTS AND QUADRATIC MODEL FITTED

CONCLUSIONS

Sixteen determinations of thermal conductivity, density and porosity were performed on drill cores from Los Azufres. The mean conductivity value was found to be 1.72W/(m-K) while mean values of bulk density and total porosity were 2451kg/m^3 and 11.2% respectively. A regression analysis was made using two models which included thermal conductivity, density and porosity. A quadratic polynomial correlation in the form of the log of the product between thermal conductivity and bulk density as function of total porosity proved to be better on the basis of statistical and error analysis. For such model, the correlation coefficient was 0.87 and the r.m.s. deviation was 4.62E-3 with a maximum error of ±22% for 94% of the cases. This correlation should have a significant practical value since it predicts thermal conductivity from a knowledge of density and porosity, properties which are simple to determine and may be measured not only on drill cores but also on drill cuttings which are more abundant and less expensive than cores. The model could be used to perform numerical studies of the Los Azufres field.

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REFERENCES

1. Apoyo para diagnósticos de perforación de pozos mediante la determinación de propiedades

físicas de rocas en medios geotérmicos-Fase I: Correlaciones entre Petrología y Petrofísica en campos del eje neovolcánico, Informe IIE/11/2014/I 03/F, Instituto de Investigaciones Eléctricas, Cuernavaca, Mor., México, in preparation, (1987).

2. A. García, E. Contreras, E. Iglesias and B. Domínguez, Developments in geothermal energy in Mexico--Part seventeen: Thermal conductivity of drill cores from the Los Azufres geothermal field: experimental results and accurate prediction method, J. Heat Recovery Systems, in press, (1988).

3. A. García, and E. Contreras, Métodos para la determinación de la conductividad y la difusividad térmica de rocas: estudio bibliográfico, Informe IIE/10/11/1663/FE-G29/I 07/P, Instituto de Investigaciones Eléctricas, Cuernavaca, Mor., México, (1985).

4. W. H. Somerton and G. D. Boozer, Thermal characteristics of porous rocks at elevated temperatures, Petroleum Trans. of AIME, Vol. 219, pp. 418-422, (1960).

5. G. Backstrom, Measurement of thermophysical properties of solids under high pressure, Invited paper, Proc. Seventh Symposium on Thermophysical Properties, Standing Committee on Thermophysical Properties, Heat Transfer Division of ASME, Gaithersburg, Md., pp. 169-180, 10-12 May, (1977).

6. F. Birch and H. Clark, The thermal conductivity of rocks and its dependence upon temperature and composition, Am. Jour. Sci., **238**, 527-558, 613-635, (1940).

7. L. F. Martínez, Thermal conductivity of core samples from the Cerro Prieto geothermal field: experimental results and an improved prediction method, Proc. First Symp. on the Cerro Prieto Geothermal Field, Baja California, México, Lawrence Berkeley Laboratory, Report LBL-7098, pp. 342-351, (1978).

8. W. Woodside and J. H. Messmer, Thermal conductivity of porous media: I-unconsolidated sands; II-consolidated rocks, J. Appl. Phys., **32**, 1688-1699, 1699-1706, (1961).

9. A. E. Beck, An improved method of computing the thermal conductivity of fluid-filled sedimentary rocks, The Log Analyst, p. 30, (1976).

10. K. Horai and S. Baldridge, Thermal conductivity of nineteen igneous rocks, II: Estimation of the thermal conductivity of rock from the mineral and chemical compositions, Phys. Earth Planet Interiors, **5**, 157-166, (1972).

11. R. Krupiczka, Analysis of thermal conductivity in granular materials, Intl. Chem. Engng. 7, 122-144, (1967).

12. J. Anand, W. H. Somerton and E. Gomaa, Predicting thermal conductivities of formations from other known properties, J. Soc. Pet. Engrs., **13**, 267-273, (1973).

13. H. Zierfuss and G. van der Vliet, Laboratory measurements of heat conductivity of sedimentary rocks, Bull. Amer. Assoc. of Pet. Geol., **40**, 2475-2488, (1956).

14. M. S. Reddy, Estimating the thermal conductivity of rocks-an analytical approach, Proc. Seventh Symposium on Thermophysical Properties, Standing Committee on Thermophysical Properties, Heat Transfer Division of ASME, Gaithersburg, Md., pp. 404-411, 10-12 May, (1977).

15. H. S. Carslaw and J. C. Jaeger, Conduction of heat in solids, 2nd. ed., Oxford, Oxford University Press, (1959).

16. ISRM, Suggested methods for determining water content, porosity, density, absorption and related properties, Society for Rock Mechanics, Commission on Standarization of Laboratory and Field Tests, Document No. 2, Lisbon, Portugal, (1972).