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Thermal Properties of Mexican Cementing Systems for Geothermal Wells

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ABSTRACT

An experimental program to determine the effective thermal conductivity and diffusivity of six cementing systems used in the completion of Mexican geothermal wells was carried out in the temperature range from ambient to 220°C. The classical line-source method (CLSM) and the Jaeger (JM) methods were used for this purpose. The experimental system was calibrated by measuring the thermal properties of fused-quartz samples used as standard. An experimental procedure for preparation of the cement samples was also developed. It was found that thermal conductivity and specific heat capacity depend on each particular cement system and increase with temperature for most cement systems while thermal diffusivity decreases with temperature for most systems. Uncertainties of 4% and 9.5% were found for thermal conductivity determined by the line source and Jaeger’s methods, respectively, while the Jaeger method yielded uncertainties of 11.8% and 8.5% for thermal diffusivity and specific heat capacity respectively.

Introduction

The exploitation of geothermal energy in Mexico for electricity purposes has experienced a notable increase in accordance with the strategies of the national energy program planned for the Mexican government (Martinez and Best, 1991; Holland et al., 1992). Thus, many adverse problems on the exploration and exploitation of these resources need to be solved. The optimized geothermal well completion has been recognized as one of these problems (Mulas et al., 1985; Morales-Rosas et al., 1990; Santoyo-Gutiérrez et al., 1991; Kelsey and Carson, 1987), and hence a number of heat transfer phenomena found in well-reservoir systems need to be studied. These include studies on terrestrial heat flow, estimation of temperature-depth profiles during drilling, and cementing and completion of geothermal wells. To properly model such phenomena, it is fundamental to have a detailed knowledge of the thermal and transport properties of all the materials involved in such processes. Of these, the thermophysical properties of cement systems used in geothermal wells are less well characterised. Published works only include scarce data, obtained in a narrow range of pressures and temperatures. The uncertainties of such data are as high as ±30%.

Likewise, very few properties for set cements were found in the literature. Due to this data unavailability, geothermal wellbore drilling simulators usually provide inaccurate results because they normally use empirical correlations that do not fully represent actual drilling fluids and cementing slurries (Beirute, 1991). Furthermore, property dependence on temperature and pressure is not known and constant properties are often used during simulations. Thus, the properties of geothermal cementing systems need to be studied in detail. The present work concentrates on the determination of the thermal conductivity and diffusivity and specific heat capacity of six cementing systems used in Mexican geothermal wells as a function of temperature. This comprehensive study is perhaps the first on the effect of temperature on the thermal properties of cements used in geothermal wells.

Theoretical Aspects

Thermal properties were determined using the classical line-source method (CLSM) (Garcia et al., 1989) and Jaeger’s (Jaeger, 1959; Contreras and Garcia, 1996) methods. In the CLSM, the relation between thermal conductivity and the temperature rise of an infinite homogeneous medium caused by a line-source of heat of constant strength is described by radial transient conduction. For sufficiently long times, the solution (Garcia et al., 1989) for a medium with uniform initial temperature and constant heat input Q per unit length of heater is:

\[ T(r, t) = \left( \frac{Q}{4nk} \right) \ln \left( \frac{4at}{r^2} \right) - \gamma \]  

(1)
where \( r \) denotes the radial coordinate, \( \alpha \) is thermal diffusivity and \( \gamma \) is Euler's constant. Applying Eq. (2) at times \( t_1 \) and \( t_2 \) and solving for the thermal conductivity, one obtains:

\[
k = \frac{Q}{4\pi} \left( \frac{\Delta T}{\Delta t} \right)
\]

Eq. (1) describes a straight line of \( T \) vs \( \ln(t) \) and the term in parenthesis in Eq. (2) is the inverse of the slope \((1/m)\) of this curve, from which thermal conductivity is obtained by the CLSM.

**Thermal Diffusivity and Conductivity by Jaeger Method (JM)**

The JM method is also based on the concept of a linear heat source of constant intensity immersed in an infinite medium, however, temperature is measured at a distance \( a \) from the heat source. Using Eq. (1) at times \( 2t \) and \( t \) yields, with \( r = a \),

\[
\frac{T(a, 2t)}{T(a, t)} = \frac{E_1 \left( \frac{a^2}{8\alpha t} \right)}{E_1 \left( \frac{a^2}{4\alpha t} \right)}
\]

Eqs. (1) and (3) constitute the mathematical model proposed by Jaeger for the experimental determination of thermal diffusivity. The practical application of Jaeger's method (JM) is simple from a conceptual point of view. Different values of the \( T(2t)/T(t) \) ratio for different values of time \( t \) are determined from the experimental temperature-time record. Since these values are governed by Eq. (4), therefore, the argument \((x = a^2/8\alpha t)\) can be determined for each value of the ratio \( T(2t)/T(t) \) from the corresponding single-valued theoretical function \( G(x) \) (Carslaw and Jaeger, 1959) that defines Eq. (3). Once the argument \( x \) is determined, the thermal diffusivity \( \alpha \) of the specimen can be obtained from Eq. (4):

\[
x = \frac{a^2}{8\alpha t}
\]

Thermal conductivity is then determined from Eq. (5):

\[
k = \frac{Q}{4\pi T(a, t)} \frac{E_1 \left( \frac{a^2}{4\alpha t} \right)}{E_1 \left( \frac{a^2}{8\alpha t} \right)}
\]

Finally, specific heat capacity (\( C_p \)) is obtained from the definition of thermal diffusivity:

\[
\alpha = \frac{k}{\rho C_p}
\]

**Experimental Aspects**

Both methods (CLSM and JM) are based on the concept of an infinite line heat conductive medium with an ideal heat source immersed in it. The line source dissipates heat uniformly at a constant rate along its length. The basic difference is that the former method is used for thermal conductivity determination based on the temperature history measured close to the heat source. The JM method is used primarily for determination of thermal diffusivity based on the temperature history measured at a known distance \( r = a \) from the heat source. Figure 1 shows these concepts and the variables that describe the temperature distribution around an ideal heat source immersed in an infinite medium. The experimental system, the sample preparation and instrumentation procedures, the experimental procedure and the technique validation used for thermal property measurement are described in detail in (Morales, 1997).

**Experimental Procedure**

The experimental procedure employed to obtain the primary temperature and time data consisted of applying an electric current of constant intensity to the sample heater during a given period of time while recording the primary temperature-time data. At the same time, the heater voltage drop and the circulating current were monitored and recorded in order to compute the source strength (dissipated power per unit length) and to complete all the experimental data required by both methods. For each cement system, two instrumented specimens were obtained. One sample was used for thermal conductivity measurement by the CLSM method. The other specimen was used for thermal diffusivity, thermal conductivity and specific heat capacity determination by JM method.

**System Validation**

Final system validation was accomplished by performing two series of tests in which the uncertainty and repeatability of the technique were determined. In one series, the thermal conductivity of a fused quartz standard sample was determined by the CLSM a number of times keeping constant the experimental conditions. The mean and standard deviation of the thermal conductivity values were 1.3897 and 0.0241 W/m K, respectively. This compares well with manufacturer data who reports a thermal conductivity value of 1.38 W/m K. In the other series, the sample thermal diffusivity and conductivity were determined by the JM method. The results showed mean thermal conductivity and diffusivity values of 1.383 W/m K and 0.824 mm²/s which compare well with data for fused quartz.

**Results and Discussion**

Six typical geothermal cement systems (GCS) used in Mexican geothermal wells were selected for evaluation in the present work. Cement systems compositions are shown in Table 1. The compositions vary from one GCS to another. This is because the conditions encountered also vary from field to field, and often from well to well in the same field.
Table 1. Cement system compositions (in parts by weight).

<table>
<thead>
<tr>
<th>Component</th>
<th>Cementing system</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
</tr>
<tr>
<td>Alumina cement</td>
<td>100.0</td>
</tr>
<tr>
<td>API Cement G</td>
<td>100.0</td>
</tr>
<tr>
<td>API Cement H</td>
<td>100.0</td>
</tr>
<tr>
<td>Silica Flour</td>
<td>35.0</td>
</tr>
<tr>
<td>Expanded Perlite</td>
<td></td>
</tr>
<tr>
<td>Bentonite</td>
<td>4.0</td>
</tr>
<tr>
<td>A-2</td>
<td>1.2</td>
</tr>
<tr>
<td>D-19</td>
<td>0.5</td>
</tr>
<tr>
<td>Retarder</td>
<td>0.5</td>
</tr>
<tr>
<td>Water</td>
<td>59.4</td>
</tr>
<tr>
<td>Density (Kg/m³)</td>
<td>1.80</td>
</tr>
</tbody>
</table>

Thermal Conductivity of Geothermal Cementing Systems

The thermal conductivity ($k$) results of the GCS were divided into two groups. The selection criterion was based on the magnitude of their thermal conductivity values. Figures 2 and 4 group the experimental measurements related to GCS’s A, B and E obtained by the CLSM and JM methods, respectively. Figures 3 and 5 present the experimental results obtained for the C, D and F GCS’s samples by the CLSM and JM methods, respectively. In all these figures, the experimental uncertainties associated with the thermal conductivity measurements were represented as vertical bars of error. Uncertainties due to temperature readings were not graphically represented since they were so small. Straight lines are shown for each set of data. These lines are discussed in relation with the regression analysis below.
From the figures, it is observed that except for system A, the thermal conductivity results obtained by the line source method exhibit an increasing variation with temperature. However, the conductivity values obtained by the JM method show an increasing variation with increasing temperature for all CGS’s. The observed differences on the behaviour of cement A with respect to the other CGS’s may be due to cement composition, cement system characteristics, experimental errors and to differences between both methods. From a theoretical point of view, in the line source method, thermal conductivity is independent of the position where temperature is measured and thus, experimental errors arise from measurements of other variables. In the JM method, the radial position from the heat source where the temperature is measured appears to the second power in the argument of the exponential integral. Hence, from an experimental point of view, application of JM method is more sensitive to measurement errors. This became evident in the statistical error analysis described in (Morales, 1997; Garcia-Gutierrez and Espinosa-Paredes, 2003). Also, the error bars associated with each data point indicate a larger experimental error in the JM method.

Additionally, the observed behaviour for cement A in Figure 2 may be due to its silica, expanded perlite (a thermal insulator), or bentonite content since normally the individual conductivity of silica or bentonite tends to decrease with increasing temperature. CGS B is similar in composition to CGS A except for the silica content. In this case the results show a slightly increasing conductivity, Figure 2. However, the different trend of the thermal conductivity of cement A obtained by both methods must be further studied in order to define its actual behaviour with temperature. Finally, it is worth noting that the \( k \) values obtained for the CGS A, B and E agree with average conductivity values reported or assumed by other authors (Corre et al., 1984; Marshall and Bentsen, 1982) while those of CGS’s C,D and F appear to be somewhat smaller than most reported values.

**Thermal Diffusivity of Geothermal Cementing Systems**

Thermal diffusivity was determined using JM method. Figure 6 shows the experimental results obtained for the A, B and E CGS’s while Figure 7 shows the corresponding results for the C, D and F CGS’s. Straight lines are shown for each set of data. These lines are discussed in relation with the regression analysis below. It may be observed that in all cases, thermal diffusivity decreases with increasing temperature. This result is somehow expected since it has been observed in similar materials (Beirute, 1991; Jaeger, 1959; Garcia et al., 1998a). From a conceptual point of view, thermal diffusivity is independent of the line source strength \( Q \) but depends on the square of the radial distance from the source where the temperature is measured. However, in spite of the errors associated with the data points of Figures 6 and 7, well defined trends of thermal diffusivity with temperature are observed. The diffusivity curves for CGS D and F are very close and this may be due to their chemical compositions where the API cement G, silica flour and water content are similar for both systems. Finally, the order of magnitude of the thermal diffusivity values obtained in the present study are in line with reported values for other cementing systems at ambient or near ambient conditions (Morales, 1997; Garcia et al., 1998a,b; Raymond, 1969; Arnold, 1990).

Specific Heat Capacity of Geothermal Cementing Systems

The specific heat capacity results of the cement systems considered in this study are shown in Figures 8 and 9. These results were obtained using the thermal conductivity and diffusivity results of the JM method and the set cement experimental densities. Again, straight lines are shown for each set of data. It is observed from these figures that specific heat capacities increase with increasing temperature for all cases. These results are of the same order of magnitude as those of similar materials like rocks, bricks, concrete and cements at ambient conditions (Morales, 1997; Garcia et al, 1996).
The effect of temperature on the thermal conductivity and diffusivity and specific heat of six geothermal cement systems (CGS) used in geothermal wells was studied experimentally in the range from ambient to 220°C. Thermal conductivity was determined by means of the CLSM technique and JM method while thermal diffusivity and specific heat were determined by the latter method only. It was found that thermal conductivity increases with temperature for all cement systems except for the thermal conductivity of CGS A obtained by the CLSM method while the thermal conductivity of this system obtained by JM method showed an a decreasing trend. This fact requires more experimentation in order to resolve this contradicting behaviour. The thermal conductivities of CGS's A, B and E are somewhat higher than the conductivities of CGS's C, D and F. Cement composition was found to play an important role in the thermal conductivity values obtained for these cements. Thermal diffusivity of all systems was found to decrease with increasing temperature and its values are of similar magnitude as those of similar materials. On the other hand, the specific heat capacity of all cement systems was found to increase with increasing temperature. This behaviour has also been observed in similar and thermal insulating materials like expanded perlite. Comparison of the two methods shows that the JM method is more sensitive to experimental errors, mainly due to measurement errors of the exact radial position where temperature is measured, although the thermocouples positions are nominally kept the same. The results of a linear regression and error propagation analysis (Morales, 1997; Garcia-Gutierrez and Espinosa-Paredes, 2003) show that the CLSM has errors ranging from 3.9 to 4% and the JM method shows propagated errors from 7.3 to 9.8% for thermal diffusivity determination and from 5.8 to 8.5% for specific heat capacity determination. The regression analysis shows significant correlation coefficients and the correlation probability indicates that the thermophysical properties are correlated variables with an approximate confidence level of 95%. In principle, the results of the present study can already be used to compute temperatures in geothermal wells during drilling, circulation and shut-in where the effect of temperature-dependent thermal properties of the cement systems is accounted for in calculating the well heat transfer coefficients. Finally, although the variations in thermal properties with temperature are small for a given cement system, it is cement composition that becomes more important regarding the magnitude of these properties. Thus, from a numerical simulation point of view, what is important is to know the variation of cement thermal properties with temperature for a more realistic estimation of temperatures. However, mechanical properties are also important in the completion of a geothermal well, and thus well integrity is affected by the thermo-mechanical behavior of cements. Both the mechanical and the thermal properties of cements are influenced by cement composition.

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