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Thermal Conductivity Measurements of Bitumen Bearing Reservoir Rocks

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Summary

The increasing imperative to reliably forecast thermal recovery in bituminous reservoirs has heightened interest to study thermal properties of rock-fluid systems, notably that of thermal conductivity. Several measurement techniques have been developed. However, these are typically fraught with limitations aiming at an amenable analytical asssessment. As a result, complex calibrations are implemented, which are susceptible to numerous errors. In this paper, an alternative, more accurate and unique method of thermal conductivity measurement is presented. The method combines two different measurement systems that are capable of measuring heat flux axially and radially. Nonetheless, in both experimental systems, heat is transferred across the test sample after a temperature gradient is established between two defined regions of the sample. The apparati are complemented by computational fluid dynamic models that mimic the physical models at the measurement conditions. A combination of the physical measurements and numerical simulations under steady state conditions is used to provide the final thermal conductivity values. A number of fluid and reservoir samples are tested in order to demonstrate the capabilities of the method. These tests provide evidence of the utility of the method in allowing for variability of sample form, as well as temperature and pressure conditions. Furthermore, both physical experiments and computational models permit and sufficiently account for fluid flow while thermal conductivity is being measured. It is shown that this method is distinctively able to yield accurate results irrespective of the sample size and shape limitations, and attendant heat losses.

Introduction

The economic demand for optimized exploration has led to a pressing need to build reliable thermal reservoir models for forecasting production in bituminous reservoirs. This has in turn furthered an interest in determining accurately reservoir thermal properties. One of the primary thermal property inputs of interest is that of thermal conductivity.

By definition, thermal conductivity is a transport property that quantifies the capacity of a material to conduct heat. Several methods have been developed over the years to measure this property, details of which are subjects of comprehensive discussion elsewhere in the literature, such as Tritt (2004). Despite the variety of methods proposed so far, the methods may be generally classified into two main types, namely steady-state methods, and transient methods. The steady-state methods generate thermal conductivity results for a condition of measurement in which temperature is not a function of time. In contrast, the transient methods are based on measurements taken during conditions in which sample temperature changes with time (such as in the process of cooling or heating). While the transient methods are generally much faster than the steady-state methods, the steady-state methods are known to provide much more accurate measurements, and are more suited for simulated reservoir conditions (Somerton, 1992).

In previous works, thermal conductivity values from steady-state measurements have been typically obtained by analyzing data from the experiments. One such method of analysis is by using simple theoretical solutions. While this approach of determining thermal conductivity seems straight forward and easy to apply, it is unrealistic, particularly with reservoir samples. It is hardly adequate to simplify the experimental arrangments as a one-dimensional study without limiting the sample in shape, form and type. Furthermore, there is a high possibility of significant losses to metal fittings in the system cap designs, as well as by convection within the sample itself, which may be difficult to assess. This makes analytical derivations either inapplicable, or inaccurate.

An alternative method of deriving thermal conductivities from experiments is the use of dimensionless arguments that are used in determining the thermal conductivities. However, to do this accurately usually requires several careful calibrations at finite ranges of sample properties, as shown in MacDonald et al. (2013). Such calibration can be cumbersome and complex, with intricacies compounding with the form and shape of the test sample, as well as physics of fluid and heat transfer at play (as for bituminous slabbed porous media). Moreso, the final results obtained through dimensional analyses are susceptible to large errors not just due to sample properties, but also due to assessment of heat losses.

In view of the foregoing limitations associated with theoretical assessments of thermal conductivity data, the proposed approach to measure thermal conductivity of reservoir samples integrates steady-state physical experiments with computational modeling. By using steady state measurements using apparati suited to model reservoir conditions, better accuracy of measurements is assured compared to transient measurements. By complementing computational modeling complexities to the experimental measurements the final results are far more reliable compared with previous other techniques of assessment.

Method

In the technique described in this work, steady-state measurement techniques are employed in two apparati capable of conducting flux axially and radially in the test sample. Temperature measurements were made using temperature sensors at various locations in the apparati. The heat flux into the apparati was also measured. Having such an array of measurements, the thermal conductivity of the sample could be ascertained through further computations. In the present work, numerical modelling was accomplished by means of COMSOL, a multi-physics software package. This state-of-the-art simulation software uses a finite element analyses to solve multi-dimensional single and coupled physical phenomena. Utilizing this package enabled for the radial and axial test cases to be modeled in detail. The temperature measurements of each test case were matched through multiple iterations of thermal conductivity input trials, until a correct thermal conductivity value was found.

Unlike other techniques of thermal conductivity measurement, the proposed method does not require extensive calibrations except that which is just sufficient enough to validate the numerical models. This validation is usually achievable by testing with materials of known thermal conductivity. By doing this the associated uncertain thermal contact resistances are obtained after iteratively adjusting it as an input, until temperature matches were identical, or closest to the experimentally measured temperature points.

Examples

To demonstrate the utility of the present apparatus and methodology, measurements of various forms of samples were conducted. These include calibration tests, tests with reservoir fluid samples such as synthetic brine (1.2% NaCl) and de-watered oil and tests with rock materials such as sand, oil sands, caprock and carbonate rock. Various sizes and shapes of samples were measured. In this work, it should be noted that only fluid and uniform packs of unconsolidated core samples (such as sand) were measured using the radial apparatus. Core materials were tested in their consolidated states using the axial thermal conductivity system. As shown in the Table 1, the results compare reasonably with published data. Figure 1 also shows the utility of the present measurement method in determining effective thermal conductivities of oil sand samples.

Table 1: Test Results for Thermal Conductivity Tests.

Test Sample	Experimental Average Sample Temperature (ºC)	Simulated Sample Temperature (ºC)	Thermal Conductivity, *k* (W/m/K)	Published Results (W/m/K)
Water	23.55	23.55	0.61	0.61(1)
Water	63.54	63.56	0.66	0.66(1)
Water	106.87	106.54	0.68	0.66(1)
Water	184.64	184.68	0.67	0.67(1)
PEEK	31.10	31.18	0.28	0.28(2)
PEEK	31.20	31.26	0.28	0.28(2)
PEEK	31.17	31.24	0.28	0.28(2)
PEEK	31.17	31.24	0.28	0.28(2)
Brine	23.94	23.94	0.61	0.61(1)
Brine	60.71	60.73	0.65	0.65(1)
Brine	99.91	99.89	0.68	0.68(1)
Brine	191.30	190.83	0.67	0.67(1)
Oil	20.25	20.27	0.14	0.11(3)
Oil	60.19	60.22	0.13	0.11(3)
Oil	105.89	105.84	0.13	0.11(3)
Oil	190.32	190.26	0.12	0.10(3)
(Clean) Oil Sand	31.48	31.41	2.20	3.27(4)
Oil Sand (60)	30.99	30.73	1.70	2.69(4)
Oil Sand(30)	30.54	30.57	1.45	2.01(4)
Oil Sand(0)	31.25	31.53	0.52	0.51(4)
Oil Sand	29.72	29.77	0.54	0.58(4)
Oil Sand	29.45	29.52	0.56	0.58(4)
Oil Sand	29.41	29.47	0.56	0.58(4)
Clearwater Caprock	27.98	28.01	2.56	-
Clearwater Caprock	34.66	34.70	2.50	-
Clearwater Caprock	44.31	44.34	2.50	-
Calcitic Carbonate	32.98	33.01	2.75	2.93(5)
Calcitic Carbonate	46.75	46.72	2.45	2.83(5)
Calcitic Carbonate	25.69	25.72	2.85	3.20(5)

(1) Yusufova *et al*. (1975); (2) Rule and Sparks (1990); (3) Bland and Davidson (1967); (4) Somerton (1992); (5) Zoth and Hänel (1988).

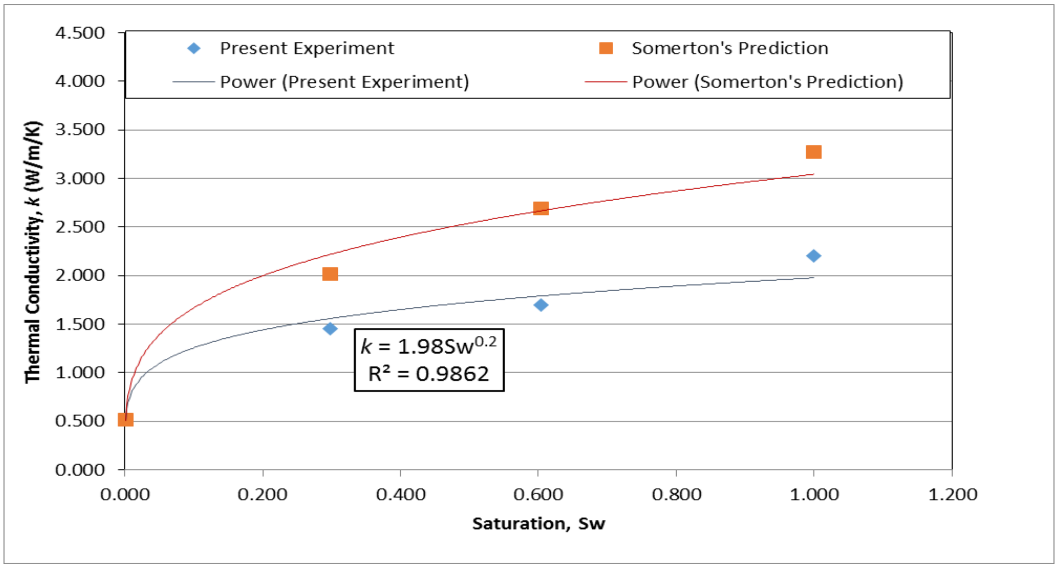

Figure 1: Thermal Conductivity of Oil Sands at Various Saturations of Water Compared with Prediction of Somerton (1992)

Conclusions

In this work, a technique for determing thermal conductivity has been presented. Its working principles have been demonstrated. It has been further shown through the use of tests of homogenous materials of known thermal conductivity such as water and PEEK, that the technique is able to produce results of high degree of repeatability and accuracy.Various tests of reservoir fluids (such as brine and bitumen), as well as unconsolidated and slabbed consolidated rock materials have also been tested to show the utility of the technique to produce reliable results for reservoir samples of various forms.

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