EFFECTIVE THERMAL CONDUCTIVITY ASSESSMENTS OF AN OIL SAND RESERVOIR

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This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Snow Mass, Colorado, USA, 21-26 August 2016

ABSTRACT

In order to properly assess the effective thermal conductivity of an oil sand reservoir undergoing thermal production, adequate mixing rules that incorporate grain statistics, porosity, and relative contributions of the saturations and thermal conductivities of the constituent fluids and solids, are required. However, such a requirement is often not adequately met because it can result in a considerable volume of costly physical tests with limited application. In this work, a method consisting of a combination of physical experimental tests and numerical computations is used to provide a resolution to the problem. The proposed method shows how adequate mixing models may be generated in a timely and cost-effective manner and used for specific oil sand reservoir applications. To achieve this goal, using a recently developed thermal conductivity measurement approach, a limited number of thermal conductivity tests are also conducted on oil sand samples to provide effective thermal conductivities of multi-fluid phase combinations. Additionally, porous pattern generation algorithms together with geometry-based meshing and heat transfer computational physics, are used to develop a model that includes particle size distribution as a parameter. The evaluations of both physical and numerical tests are then used to develop and demonstrate robust effective thermal conductivity models. The results show that using a combination of selected tests and computations, adequate mixing rules can be developed that predict effective thermal conductivity for an oil sand thermal reservoir. In the particular example demonstrated, a combination of a numerical sigmoid model and empirical models are generated to sufficiently account for grain distribution, porosity, and relative contributions of the saturations and thermal conductivities of the constituent fluids and solids.

INTRODUCTION

A proper assessment of effective thermal conductivity is a requirement for an adequate assessment of the heat transfer effects of oil sand reservoirs undergoing thermal production. However, such a determination is often complicated by the multiple factors associated with porous media. While some mixing models have been proposed in the literature (Evgeny 2015), they typically have serious limitations, making it necessary for the conduct of an array of physical tests to cover a wide range of parameters such as grain distribution, porosity, and relative contributions of the saturations and thermal conductivities of the reservoir materials. Physical testing on the other hand, can also be a challenging task, giving the very intricate nature of porous media materials. In this work, a solution to the above mentioned problems is presented for which adequate mixing models may be generated in a timely and cost-effective manner and yet applicable for specific and varied oil sand reservoirs.

Analytical Justification

Assuming conduction as the main means of heat transfer in a multicomponent porous media system, its effective thermal conductivity k_{eff} at a given sample temperature can be defined in multi-dependent terms such as the following

$$k_{eff} = f\,(k_s,\ k_{fi},\ \varepsilon,\ \text{parameter for particle size distribution } (PSD),\ S_i,\ \text{wettability factors}) \quad (1)$$

where, k_s, k_{fi}, ε and S_{fi}, are respectively the thermal conductivity (in W/m/K) of the solid phase, the thermal conductivity (in W/m/K) of a fluid component i, the total porosity of the porous medium and the saturation of a fluid component i. The symbol f represents the functional relationships between the parameters. The sheer number of factors in equation (1) does not only suggest the complexity of the heat transfer phenomena in view, but also the volumes of experimental tests required to adequately characterize the system.

However, if such a system is limited to a porous medium saturated with a single fluid component and a given PSD, equation (1) may be streamlined to

$$\frac{k_{eff}}{k_f} = f\left(\frac{k_s}{k_f}, \varepsilon\right) \quad (2)$$

With such a simplification, estimates of effective thermal conductivity are possible through analytical derivations. The result of such have been some effective thermal conductivity models (*e.g.* Kunii and Smith 1960, Krupiczka 1967). The limitation of such models however, is that they may not be applicable for the reservoir's PSD. However, with computational physics modelling, it is possible to obtain an equation such that

$$\frac{k_{eff}}{k_f} = f\left(\frac{k_s}{k_f}, PSD\right) \quad (3)$$

Furthermore, while it may be computationally expensive to consider wettability and saturation effects, it is possible to use experiments to discern these effects in multi-fluid considerations. Previous measurements (Somerton 1990) show that a polynomial relation exists and may be defined for a limited range of tests of appropriate spread. From this, it is reasonable to hypothesize the following form of mixing rule for the thermal conductivity of a multi-fluid porous medium

$$k_{eff} = k_{eg}S_g^{\alpha} + k_{eo}S_o^{\beta} + k_{ew}S_w^{\gamma} \quad (4)$$

In equation (4) subscripts S_g, S_o and S_w are saturations of gas, oil and water respectively; and k_{eg}, k_{eo}, k_{ew} are the effective thermal conductivities (in W/m/K) of porous medium of the same solids component when fully saturated with single fluid components gas, oil and water respectively. The parameters α, β, and γ are saturation exponential constants which may be tuned to fit a given set of empirical data to give a measure of wettability.

The above analysis infers then that it is possible to contrive adequate models of effective thermal conductivity considering PSD by: (a) Sampling portions of the reservoir and determine the PSDs of representative zones; (b) Conducting thermal conductivity tests of constituent fluids of the reservoir if it is established that there are multiple PSDs identified in the reservoir; (c) Testing sand packs of similar PSD and porosity to determine the effective thermal conductivity k_{ei} when respectively fully saturated with each constituent fluid (if the sand grain mineralogy is unknown); (d) Testing for effective thermal conductivities for at least 3 varying but known saturations; (e) Undertaking a parametric numerical study to determine porosity effects; and (f) Repeating steps (c) to (e) for any additional PSD consideration. Utilizing such a method can reduce test experiments (and its related time and money costs) by more than half when a pair of PSDs are at play in a reservoir, and by far more when more PSDs are considered. In the following sections the method is briefly described, followed by a sample demonstration.

MEASUREMENT AND NUMERICAL APPROACH

An important aspect of the assessment of effective thermal conductivity is the conduct of tests that provide reliably accurate data. To this end, the present approach was to use two different apparati that conduct heat radially or axially respectively through a standard material, and then through the test medium, under steady state conditions. The power input and temperature distribution across multiple collinear locations in the test section are measured. The thermal conductivity is then determined through numerical analyses. The distinctive feature of this approach is that it accommodates various forms and shapes of samples, and at more realistic reservoir conditions. Furthermore, this approach uniquely allows for the accurate assessment of the physics of the set-up by using a detailed real-size dimensioned numerical analyses that solves the thermal-fluid flow field. Schematic arrangements of the radial and axial systems are shown in Figure 1. A more comprehensive description of the test systems is described in Arthur *et al.* (2015). In that work, the accuracy and reliability of data are demonstrated.

Current computational resources have opened up the possibility of modelling detailed fluid flow and heat transfer assessments on a porous medium at pore scale level. To do this however involves the generation of an adequate virtual geometry. In this study, a pattern generation approach was used in generating that virtual porous media. The pattern generation method is executed by an algorithm that fills a box of a given size with rigid spheres of radii from a specific particle size distribution. The spheres are added on by a simultaneous generation procedure (called particle swelling). Starting points are randomly distributed along with designations of growth (swelling) rate at each point. The sphere radii are increased iteratively from point to final value according to the assigned growth rate until the target porosity is reached without any conflict. The result of this algorithm is a porous medium pattern, as shown in Figure 2. This is then meshed using an appropriate meshing software that is preferably geometry-based. In this work, all meshing and computational solutions were obtained using COMSOL Multiphysics considering only single fluid and single solid phases. Each phase is taken to be isotropic in heat transfer, and the heat equation is then numerically solved under requisite assumptions. The effective thermal conductivity is then calculated through Fourier's law In a thorough review and assessment, Skripkin (2015) has shown that using the right configuration, this method is capable of generating accurate and valid results.

SAMPLE TEST PROGRAM

The aims of the current study are met in a sample test program. The tests were conducted using one synthetic and one reservoir oil sand from three different sources obtained from in-house inventory. The constituent fluids were that of water, air and light oil for the synthetic oil sand, and formation water, air and dewatered bitumen of 7.29˚API for the reservoir sample. The sand grain sizes were measured using an AS 200 vibratory sieve shaker. In the present tests, preliminary review showed no evidence of PSD variability in sample source, implying no need to conduct studies to determine the effect of PSD. However, the utility of the method described in this work shows that the necessary tests identified in the analyses conducted earlier for the constituent reservoir materials, and for selected saturations of the porous media. Thermal conductivities of the constituent fluids and porous media were determined at 25ºC sample temperature using the integrated measurement approach. Where required, saturations were determined using nuclear magnetic resonance or Dean-Stark extraction analyses. The utility of the porous pattern generation numerical approach was tested using input of PSD to show how this can be used to determine the effects of PSD and porosity.

RESULTS AND DISCUSSION

Results indicate that at 25ºC, the thermal conductivities of light oil and bitumen are 0.13 and 0.17 W/m/K respectively. The results of de-ionized water and 0.33M NaCl solution. All of these data are comparable with published results (Arthur *et al*. 2015). Having determined the thermal conductivities of the constituent fluids, oil sands at selected fluid saturations of the oil sand were tested for effective thermal conductivity. The results are plotted against the saturation of water S_w and oil S_o in Figure 3. In Figure 3(a) in particular, plots indicate a non-linear relationship between the effective thermal conductivities and the wetting saturation for values obtained at a porosity value of 46%. Testing the hypothesized equation (4), the parameters α, β, and γ were set at 0.1, 0.01 and 0.85 respectively. While the physical meaning of these empirical values are not totally clear, it is possible that these are related to the contact between the fluid and solid grains. The values fit the data plots optimally with a maximum deviation of 10% between data points and the model.

In an earlier analytical justification, the need to obtain measurements at the same porosity was emphasized. However, the result of mixing model in equation (4) is demonstrably not a factor of porosity. This is proven in Figure 3(b) where despite the variation of porosity of the tests (38% to 48%), the results depicted a functional relationship described by equation (4). This means that equation (4) is an incomplete model when it comes to predicting effective thermal conductivity in response to porosity changes. Regardless, for this specific case shown in Figure 3(a), it was determined that equation (4) curve fit was best suited when parameters α, β, and γ were set at 0.1, 0.90 and 0.75 respectively. While such a result suggests that parameters α, β, and γ may be saturation / wettability indicators, this is something to be explored in a future study.

To complete the effective thermal conductivity model, numerical experiments may be carried out with the aid of a porous pattern generation method using a typical PSD as an input parameter. The results (Figure 4a) show that the effective thermal conductivity for a single fluid component oil sand k_{ei} is related to constituent fluid and solid components thermal conductivity (*i.e.* k_i, k_s respectively) through the following sigmoid function

$$k_{ei} = \frac{g}{h + e^{-\left(c\ln\left(k_s/k_i\right)\right)}} \tag{5}$$

Where c, g and h are constants that can be determined through analyses. Of note, the result of equation (5) follows the form expressed in equation (3). Additionally, the implication then is that if constants c, g and h are known as well as input measurement results of k_{ei} , k_i, and k_s, then k_{ei} (for every related fluid component i) can be determined using equation (5) without measurement, reducing cost of time and money. Furthermore, results showed that for a given PSD, there is a linear relationship between effective thermal conductivity and porosity at the porosity of interest ($0.38 \leq \varepsilon \leq 0.48$) so that

$$k_{eff} = \mathrm{A} + \mathrm{B}\varepsilon \tag{6}$$

where A and B are respectively constants in W/m/K units. It is pointed out that this result is reasonable as models in the literature of the form of equation (2) typically show that the relationship between effective thermal conductivity and porosity at that porosity of interest can be estimated to be linear with a good level of accuracy (coefficient of determination $R^2 \geq 0.90$). Thus with equations (4) to (6), a complete set of mixing models is realized to predict the effective thermal conductivity of an oil sand, as desired in equation (1). This was done with a limited array of tests and numerical assessments.

CONCLUSIONS

The study demonstrates a cost and time-effective method for determining effective thermal conductivity of an oil sand reservoir. This is achieved through a combination of a numerical sigmoid model and empirical models to sufficiently account for grain distribution, porosity, saturations and the thermal conductivities of reservoir materials.

ACKNOWLEDGEMENTS

The financial contributions of Laricina Energy Ltd., Cenovus Energy, Alberta Innovates, Athabasca Oil Corporation, Devon, Barrick, Husky Energy, Foundation CMG, Dover Operation Corp., Schulich School of Engineering, NSERC-CRSNG, Maersk Oil and Suncor Energy through the FUR Chair held by Prof. A. Kantzas, are gratefully acknowledged.

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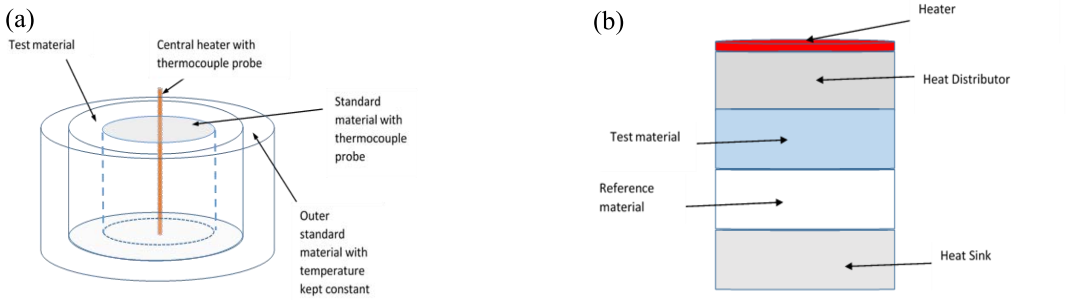

Figure 1: Typical arrangements of (a) radial and (b) axial testing apparati.

Figure 2: Porous patterns generated in (a) two and (b) three dimensions.

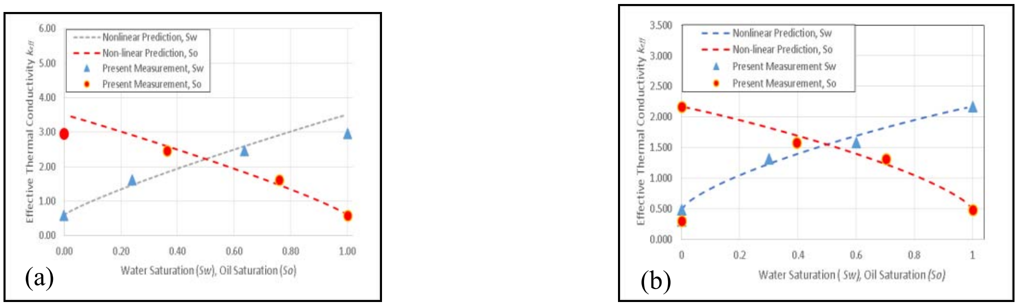

Figure 3: Results of tests for (a) synthetic oil sand and (b) real oil sand system

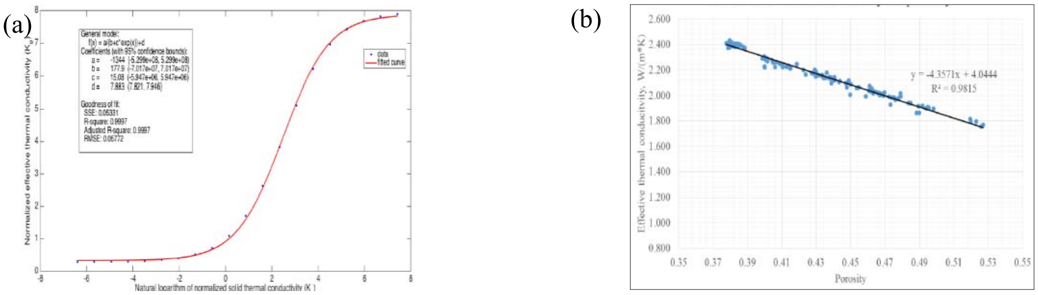

Figure 4 (a) Custom mixing rule generated for an oil sand (b) Porosity effects demonstrated.