Determination and Modelling of the Mobility of Connate Water in Oil Sands under Initial Reservoir Conditions

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ABSTRACT

The initial water saturation of the most bitumen reservoirs in western Canada ranges between 20% and 30%. At the initial reservoir conditions, the viscosity of the bitumen can be as high as several million centipoises and the crude is immobile. The interstitial water in oil sands can form a continuous water network to flow at initial reservoir conditions. In industry, however, due to the lack of experimental data on the initial water mobility in this type of reservoirs, the value of the irreducible water saturation in these sands has been commonly defined to be approximately 15% in most of the reservoir simulations. Several simulation studies have shown that to have a reasonable historically match of the field SAGD production history, the water movement both at initial conditions and ahead of the steam chamber front have to be taken into account.

In this study, a new method is developed to determine the initial water permeability in oil sands at various immobile oil saturations. In this method, packed sand in a holder is first saturated with water and displaced with heated wax at 70°C to set a desired initial water saturation. After that, the sand is kept at the same temperature for three days for the oil and water phase to reach uniform distribution and then cooled down to ambient temperature. Then single water phase flow test is performed in the sand which contains immobile oil (wax) and interstitial water. Initial water permeability has been determined at various water saturations up to 40% for three types of sands of different average meshes. A triangular tube bundle model is constructed and successfully used to model the interstitial water permeability curves obtained in the experiments. A correlation has been developed for predicting the initial water permeability in oil sands as a function of water saturation and the absolute permeability of the sands. This correlation can be used to fit experimental results for different oil sands samples and then be used in reservoir simulations for oil sands recovery.

INTRODUCTION

The research of the Alberta Energy Resources Conservation Board (ERCB) indicated that initial water saturations in most bitumen reservoirs were between 20% and 30%[1]. As the initial water saturation is higher than the irreducible water saturation in bitumen reservoirs, the initial water in such reservoirs is mobile. Aherhe and Maini[3] studied water movement in the Dover SAGD (Steam Assisted Gravity Drainage) Pilot at its mature stage. They investigated the cold water injectivity and the accelerated pressure movement ahead of the steam chamber, using numerical simulations to match the production history. Their simulation results indicated that water is mobile both at initial conditions and ahead of the steam chamber front. Chan et al.[4] conducted an experimental and numerical study of initial water mobility for SAGD operations. They revealed that the initial water saturations of reservoirs were not necessarily equal to the irreducible water saturations. In addition, their reservoir simulations showed that due to the initial water flow, the high pressure in the steam chamber will make the steam finger into the non-thermal zones, affecting the growth of the steam chamber and resulting in steam loss, energy loss and pressure dissipation. Therefore, it is crucial for the oil industry to determine the irreducible water saturation for bitumen reservoirs, quantify initial water mobility at different initial water saturations and investigate the detrimental effects of initial water mobility on SAGD operations.

Dullien et al.[5] first examined the mobility and distribution of the interstitial water in porous media. Their study showed that the residual wetting phase could form a continuous network. Magnetic resonance imaging techniques were successfully applied by Graue et al.[6] to examine the distribution of the water phase in a porous medium. High resolution images of each section of the porous medium revealed that the wetting water phase could bridge and exist as a continuous network. The distribution of the initial water phase was also investigated by Clayton et al.[7]. The measured results of low resistivity in the majority of North Sea oil reservoirs indicated that the water phase was continuous, even if water saturation was less than 20%. All of these previous studies have focused on the existence of the continuous water network at initial water saturation, in a porous medium, or investigated the initial water mobility in a conventional oil-water system. To the authors' knowledge, an effective method to measure the mobility of initial water in bitumen reservoirs has not yet been developed. Moreover, a correlation of initial water mobility with wide application in bitumen reservoirs has not yet been obtained.

In this study, a method of using wax as the oil phase is adapted to simulate the stationary oil phase in bitumen reservoirs and oil sands. The effective permeabilities of the initial water in different sandpacks, and at different initial water saturations, are measured using this method. In order to obtain a general correlation of initial water mobility, a triangular tube bundle model is constructed and applied to simulate the experimental water effective permeability at different initial water saturations. Subsequently, a general correlation of initial water mobility is developed by performing analysis of the data from the triangular tube bundle model.

EXPERIMENTAL

The technique of using wax to represent the stationary oil in porous media[8] was adapted for bitumen reservoirs. A wax sample from Loblaws Inc. (Model EE10081800) was used to represent the stationary oil phase in the experiments. Distilled water was used as the water phase for all experiments. Silica sands #730 (Bell & Mackenzie Co. Ltd, Canada) were sieved to 40-170, 70-170 and 100-170 meshes to make three types of sandpacks.

For all experiments, the wet-packing method was adopted for preparing the sandpacks. Before packing, sand was put into a furnace (at 100 °C) for 8 hours in order to obtain strong water wettability. The experimental procedures are as follows: 1) Place the sandpack and the transfer cylinder filled with wax into the oven at the temperature of 70 °C, for 5 hours, to preheat the sandpack and melt the wax. 2) Inject the liquid wax from the transfer cylinder into the sandpack to set desired initial water saturation. 3) Let the sandpack age at 70^{o}C for 3 days to achieve capillary equilibrium. 4) Cool down the sandpack and carefully open the ends of the sandpack to remove the solid wax from the spaces in the distributors and end-caps, and saturate them with water. 5) Measure the water permeability of the sandpack using the "falling head" method at room temperature (21°C). 6) Extract the water from the sandpack using a Dean-Stark distillation to confirm the water saturation in the sandpack.

RESULTS AND DISCUSSION

As an example, Fig. 1 shows the measured curves of $\ln(h_o/h_t)$ vs. $At\rho g/(aL\mu)$ in the falling head method at 10 water saturations for Sands A, where the slope of each straight line represents the water effective permeability at that saturation. Fig. 2 shows the measured effective permeability vs. water saturation for Sands A, B, and C. All three curves show that the water effective permeability declines rapidly with the decrease of the initial water saturation. When water saturation approaches the irreducible water saturation, the water effective permeability will become zero. In the wax displacement tests for Sand A, there was no water production when the water saturation in the sandpack decreased to 0.10. Thus, 0.10 could be considered as the irreducible water saturation for Sand A under the current experimental conditions. Similarly, the irreducible water saturation for Sand B and C are 0.075 and 0.050, respectively.

It can also be seen from Fig. 2 that, under the same initial water saturation, the water effective permeability increases with increasing the absolute permeability of the sandpack. This is due to the higher absolute permeability of the sandpack representing a higher average pore radius, when the porosities of bitumen reservoirs are similar. Thus, although the initial water saturations are same, the porous medium with a higher absolute permeability has a more permeable water network.

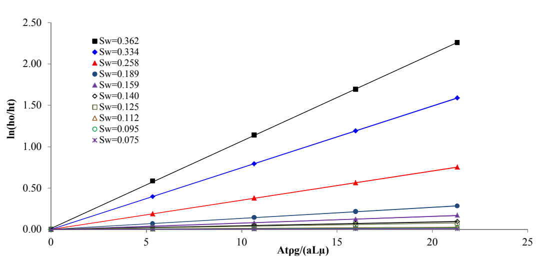

Fig. 1 Determined $\ln(h_o/h_t)$ vs. $At\rho g/(aL\mu)$ for Sand A at 10 water saturations.

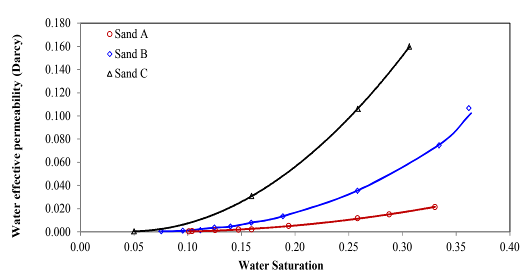

Fig. 2 Effective permeability vs. water saturation for Sands A, B, and C.

In this work, a triangular tube bundle model was built using n parallel equilateral triangular tubes, with each tube having a cross sectional area A_j and inscribed radius r_j (j is the tube size sequence number, j= 1, 2, …, n, with j = 1 representing the biggest tube). During the drainage process, wax (the non-wetting phase) tended to occupy the biggest tubes first. Wax then gradually penetrated the smaller tubes. When the wax began to break into tube (k-1) (k >= 2), the threshold drainage curvature radius was $r_{d(r-1)}$, while in tube k there was no wax. Once the central part of the entire tube (k-1) was occupied by wax, the drainage curvature radius of the tube (k-1) began to decrease by further removal of water from the corners. When it decreased to r_{dk} (the threshold drainage curvature radius of the tube k), wax began to penetrate tube k. Thus, when the wax began to enter tube k, the drainage curvature radii in Tubes 1 to k could be assumed to be equal to r_{dk}, while there was no wax in Tubes k+1 to n. Therefore, the water saturation, $S_w(k)$, can be calculated by:

$$S_w(k) = \frac{A_w(k)}{\sum_{j=1}^{n} A_j} = \frac{3k(\sqrt{3} - \frac{\pi}{3})r_{dk}^2 + \sum_{j=k+1}^{n} r_j^2 \Big/ 0.192}{\sum_{j=1}^{n} r_j^2 \Big/ 0.192} \quad (1)$$

Water saturation is the function of k (tube size sequence number) if the inscribed radius distribution of the triangular tubes ($r_1, r_2, \ldots, r_n$) is given. The water effective permeability in the triangular tube bundle model, $K_w(S_w(k))$, can be calculated as:

$$K_{rw}(S_w(k)) = \frac{K_w(S_w(k))}{K_a} = \frac{0.576 \cdot k \cdot A_{eff}^2 + \sum_{j=k+1}^{n} r_j^2 A_j}{\sum_{j=1}^{n} r_j^2 A_j} \quad (2)$$

To apply the triangular tube bundle model to simulate the phase flow in porous media, the inscribed radius distribution of the triangular tubes is required. A Weibull distribution has frequently been used to develop the models of porous media[7] and was selected to describe the distribution of the inscribed radii of the triangular tubes. A triangular tube bundle model composed of 1000 equilateral triangular tubes was applied to simulate the experimental results of the water relative permeability. The derived tube size distributions for the model to match the experimental data, which were obtained from the Weibull distribution, are shown in Fig. 3. Using the three inscribed radius distributions, the simulated absolute permeability for Sands A, B and C were 5.2, 7.1 and 11.4 Darcies, respectively. Comparison between experimental water relative permeability and simulated results for Sands A, B and C are also shown in Fig. 4. It is observed that a very close match between experimental results and the simulated water relative permeability curves is obtained using the triangular tube bundle model. Therefore, the triangular tube bundle model is effective to simulate the single water phase flow in the corners of the triangular tubes. Also, it is capable of predicting water relative permeability in different bitumen reservoirs and oil sands, especially for different water saturations and absolute permeabilities of bitumen reservoirs. Furthermore, it can be used to theoretically calculate the water effective permeability curves which are basic properties of the fluid-porous media system for numerical simulation study of initial water mobility in bitumen reservoirs.

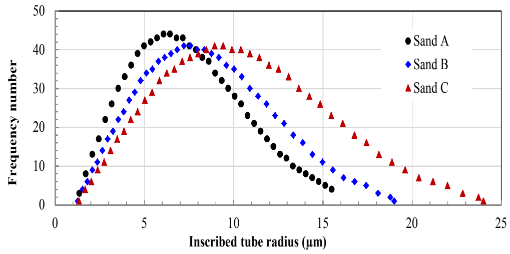

Fig. 3 Inscribed tube radius distributions for Sands A, B, and C.

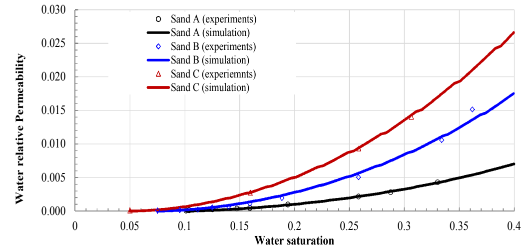

Fig. 4 Comparison of measure and simulated initial water relative permeabilities.

The simulation data from the triangular tube bundle model were used to generate an empirical correlation between the initial water mobility and the properties of the oil sands:

$$K_w(S_w) = K_a \cdot \left[K_{rw}(S_w{=}0.4)\right] \cdot \left(\frac{S_w - S_{wir}}{0.4 - S_{wir}}\right)^{1.95} \quad (3)$$

where $K_w(S_w)$ is the water effective permeability, K_a is the absolute permeability, $K_{rw}(S_w=0.4)$ is the water relative permeability at the reference water saturation of 0.4, and S_{wir} is the irreducible water saturation of the sand. Because the Alberta Energy Resources Conservation Board (ERCB) revealed that initial water saturations in most bitumen reservoirs were between 20% and 30%, and in some bitumen reservoirs were between 30% and 40% [2], the water saturation of 0.4 was applied in Eq. (3) in order to cover the range of all initial water saturations. When three parameters in Eq. (3), namely, water relative permeability at water saturation of 0.4, absolute permeability and the irreducible water saturation for a specific bitumen reservoir, are known, Eq. (3) can be used to predict the water effective permeabilities as a function of initial water saturation and the absolute permeability of the bitumen reservoir. In this work, Eq. (3) has been used for the first time to calculate the initial water mobility for bitumen reservoirs. Fig. 5 shows experimental water relative permeabilities and the predicted values using Eq. (3) for Sands A, B and C. The absolute average relative error and the R^2 value were found to be 1.99%, 0.994, respectively. The maximum deviation between the experimental data and the proposed correlation results was equal to 3.94%. This indicates that the newly developed correlation is capable of predicting the water relative permeability in different water saturations and different bitumen reservoirs.

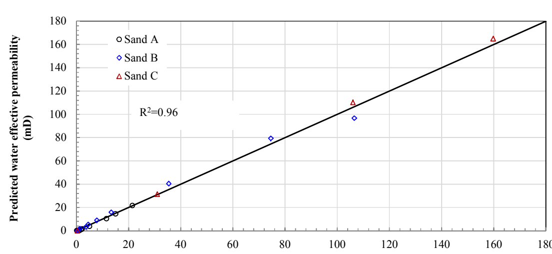

Fig. 5. Experimental data vs. proposed correlation results for Sands A, B and C.

CONCLUSIONS

1) A new method of using wax as the oil phase to simulate the stationary oil phase and determine initial water mobility in bitumen reservoirs and oil sands is proposed. This method has been proven by experimental results to be an effective and accurate method.
2) Experimental results indicate that the interstitial water can still flow when the water saturation is lower than 10% in the simulated bitumen-water system.
3) A triangular tube bundle model was constructed and successfully used to simulate the water relative permeability curves at different initial water saturations. By adjusting the model parameters, a very close match between experimental data and the simulated results was obtained.
4) A new general correlation of initial water mobility in bitumen reservoirs was developed.

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