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Characterization of Foamy Oil and Gas-Oil Flow for Heavy Oil/Propane System in Pressure Depletion Tests

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Abstract—This work presents a non-equilibrium kinetic model to characterize foamy oil and gas/oil two-phase flow in heavy oil and propane system from pressure depletion tests. Good agreement between experiments data and simulation results are obtained in terms of production data as well as pressure distribution. The following parameters are tuned in the history match process, including k values, gas-liquid relative permeability curves, and reaction frequency factors. The simulation results suggest that bubbles pass through pore throat smoothly and have low dissolve rate in oil phase at low pressure drop rate, which results in high gas recovery factor and low oil recovery factor. Gas bubbles expand to a larger size and block the pore throat when increasing pressure drop rate to intermediate pressure depletion rate. At this range of pressure drop rate, foamy oil and gas/oil flow characterization is influenced by both gas bubbles evolve and dissolve process, which results in low gas recovery and high oil recovery. Continue to increase the pressure drop rate could cause gas bubbles to evolve faster than dissolve back and shorten production period, which results in a relatively low gas recovery as well as low oil recovery. The simulation work presented in this paper successfully characterized foamy oil behavior in the porous media for heavy oil/propane system. The innovative methodology presented in this work could be used as a general method to characterize foamy oil flow in heavy oil/propane system.

Keywords—heavy oil, propane, two-phase flow, non-equilibrium kinetic model, foam oil

I. Introduction

Many heavy oil reservoirs are now applying solvent-based recovery techniques to enhance oil recovery. The most important heavy oil enhancement mechanism of solvent-based recovery techniques among all the other mechanism is foamy oil flow [1–3]. When the pressure of heavy oil-solvent system depletes to bubble point pressure, solution gas bubbles evolve from solution and dispersed in the oil phase, which is defined as foamy oil. Continuous gas phase forms until reservoir pressure further decrease to pseudo bubble point. Previous researches mainly focused on characterize oil/gas phase property [4,5], describe foamy oil behavior in waterflooding [6] as well as the cyclic solvent injection process [7] in the heavy oil-solvent system. Compare with other solvents, propane has the advantage of high solubility in heavy oil [8] to reduce the viscosity of heavy oil [9]. Meanwhile, unique properties of the heavy oil-propane system were observed in the experimental studies regarding phase behavior [10] and non-equilibrium PVT properties [11]. However, the simulation study seldom focused on heavy oil/propane system. Therefore, numerical simulations are conducted in this work to characterize foamy oil and gas-oil flow for the heavy oil-propane system in pressure depletion tests.

II. Experiment Study

The research data for the simulation study is from previous research [12]. The pressure depletion tests were conducted in a 1-meter long sand-pack. The sand-pack model was saturated with live oil. The experiments were performed under different pressure depletion rates (0.34 kPa/min, 0.76 kPa/min, 1.92 kPa/min and 4.52 kPa/min) to investigate the influence of pressure depletion rates on foamy oil flow for the heavy oil-propane system. Live oil system was generated by recombining pure propane into the dead oil samples. The properties of the sand-pack model and reservoir fluids are presented in Table I and Table II. Four pressure transducers evenly distributed along the sand-pack model to collect pressure data during the production period. For more information regarding the detailed experimental description and experiment process, please see our previous study[12].

TABLE I. PROPERTIES OF THE SAND-PACK MODEL UNDER 21.0 ° C

Porosity (%)	Permeability (D)	Inner diameter (m)	Oil saturation (%)	Water saturation (%)
35.94	5.91	0.038	96.34	3.66

TABLE II. PROPERTIES OF RESERVOIR FLUIDSODEL UNDER 21.0 ° C

Density (kg/m^3)		Viscosity (mPa.s)		Mole fraction (%)	
Dead oil	*Live oil*	*Dead oil*	*Live oil*	*Dead oil*	*Live oil*
964.3	891	2200	58	44.25	55.75
Solution GOR (Sm^3/ m^3)			Saturation pressure (kPa)		
71.70			500		

III. SIMULATION MODEL SETUP

The numerical simulation study is performed by using the STARS® simulator. The simulation model has dimensions of 3.368cm×3.368cm×100cm, and there are 100 grids in the Z direction. The grid size of the simulation model is the equivalent size based on the cross-section area of the sand-pack model. The non-equilibrium kinetic model has four components and two reactions to describe the foamy oil characterization in the heavy oil-propane system, as presented in (1) and (2).

$$Solution\ Gas(oil) \rightarrow Dispersed\ Gas(oi) \quad (1)$$

$$Dispersed\ Gas(oil) \rightarrow Free\ Gas(gas) \quad (2)$$

The equilibrium ratio, which is defined as $k_i=y_i/x_i$, is used to predict gas-liquid equilibrium at a certain temperature and pressure. yi and xi are mole fraction of component i in the gas phase and the liquid phase. K values are calculated by (3) [13,14]. P and T are pressure and temperature. kv1, kv2, kv3, kv4 and kv5 are k value coefficients.

$$k = (kv_1/p + kv_2 \times p + kv_3) \times exp (kv_4 / (T - kv_5)) \quad (3)$$

The relative permeability curves are calculated by Corey's correlation, as shown in (4) and (5) [14].

$$k_{ro} = k_{roc} [(S_l - S_{or} - S_{wc}) / (1 - S_{gc} - S_{or} - S_{wc})] \wedge N_o \quad (4)$$

$$k_{rg} = k_{rgc} [(S_g - S_{gcri}) / (1 - S_{gcri} - S_{oir} - S_{wc})] \wedge N_g \quad (5)$$

where, k_{ro} and k_{rg} represent oil phase and gas phase relative permeability. k_{roc} and k_{rgc} represent oil phase and gas phase relative permeability at connate gas saturation. S_l and S_g are liquid and gas saturation. S_{or} and S_{oir} are residual oil saturation and irreducible oil saturation. S_{wc} and S_{gc} represent connate water saturation and connate gas saturation. S_{gcri} is critical gas saturation. N_o and N_g are exponent.

IV. RESULTS AND DISCUSSIONS

k values, gas-liquid relative permeability, and reaction frequency factors are tuned during the history matching process. Good agreements between the simulated calculation results and experimentally measurement have been achieved, as presented in Fig. 1 to Fig. 3.

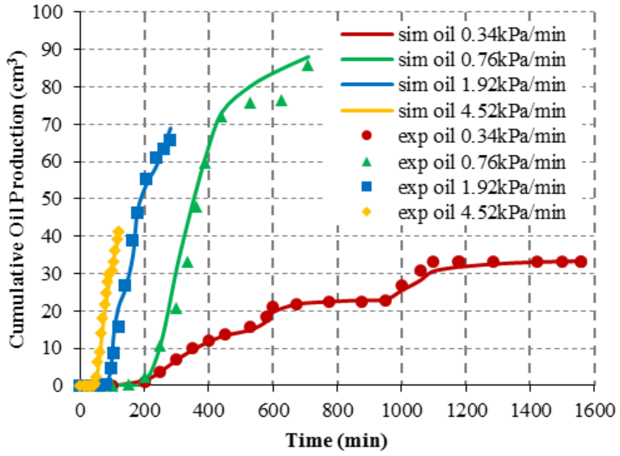

Fig. 1. History matching results of oil production

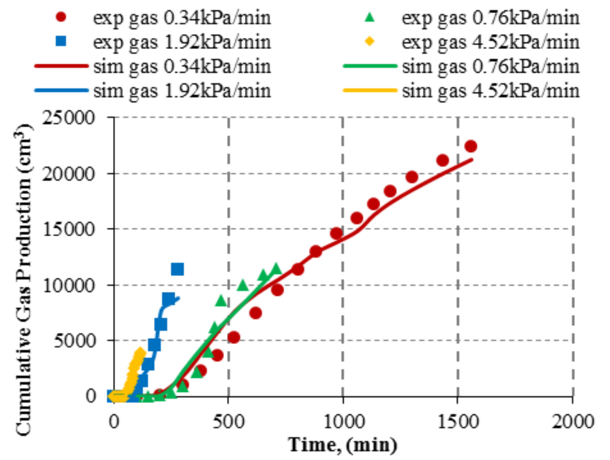

Fig. 2. History matching results of gas production

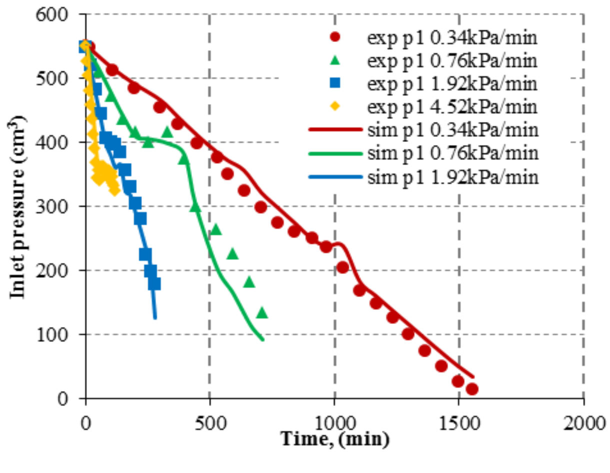

Fig. 3. History matching results of inlet pressure

A. *Effect of k values*

Simulated k values of four cases are shown in Table III. Increasing pressure depletion rate reducing the k value, which means gas bubbles remain longer in the oil phase. As a result, pseudo-bubble point pressure decreases.

TABLE III. K VALUES OF FOUR SIMULATION CASES

Case No	1	2	3	4
Pressure depletion rate (kPa/min)	0.34	0.76	1.92	4.52
Pseudo-bubble point pressure (kPa)	480	440	390	350
k value	1.77	1.41	1.37	1.08

B. *Effect of relative permeability curves*

The simulated gas-liquid relative permeability curves of four cases are shown in Fig. 4 and Fig. 5. The gas-liquid relative permeability of cast 1 to case 3 is compared in Fig. 4. Fig. 5 presents the gas-liquid relative permeability of case 4 since the pressure drop rate of this case is much higher than the other cases.

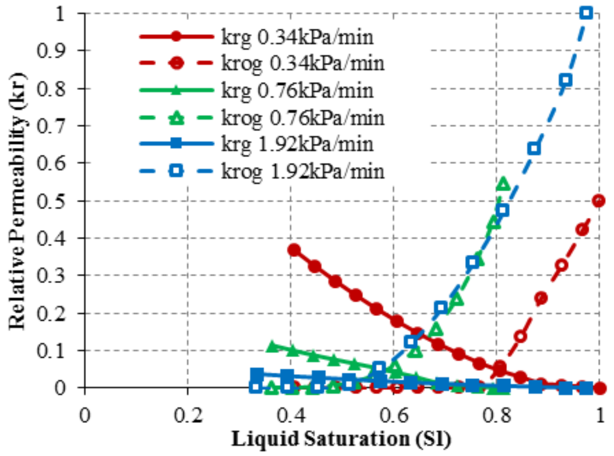

Fig. 4. Relative permeability curves of case 1 to case 3

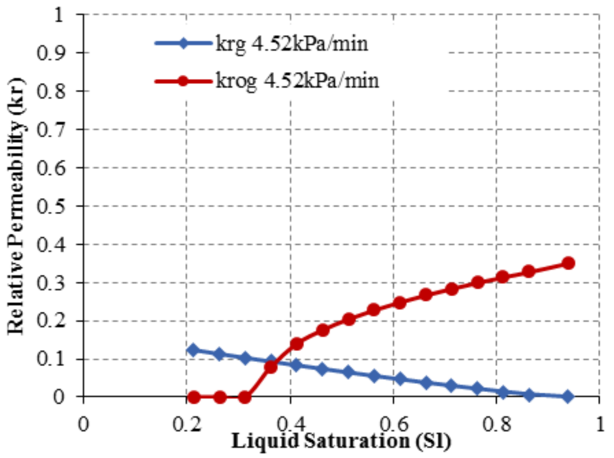

Fig. 5. Relative permeability curves of case 4

In general, the simulated gas phase relative permeability is very low to describe low gas mobility and the simulated oil phase relative permeability increases with increases of pressure drop rate. For the lowest pressure depletion rate, dispersed gas bubbles would not be trapped in the oil phase because of the high solubility of propane. As a result, gas phase relative permeability is the highest among the four cases. For intermediate pressure depletion rate, gas bubbles evolve faster from the oil phase and form larger gas bubbles, and hence, the size of some large gas bubbles is larger than the size of pore throat which preventing large gas bubbles pass through. Therefore, gas phase relative permeability is lower at intermediate pressure depletion rate. For highest pressure depletion rate, although large gas bubbles are blocked in the pore throat, some gas bubbles still pass through pore throat due to the highest pressure drop. The oil phase is trapped in the porous media because some pore throats are blocked by gas bubbles, which would cause different gas-liquid relative permeability of the highest depletion rate case.

C. *Effect of reaction frequency factors*

The reaction rates are controlled by keyword *FREQFAC to assigned reaction frequency factor values. The simulated reaction frequency factor of Reaction 1 is proportional to the pressure depletion rate, as presented in Table IV. The simulated reaction rate of Reaction 2 in heavy oil/propane system is changing with pressure, as presented in Fig. 6.

TABLE IV. REACTION FREQUENCY FACTORS OF REACTION1

Case No	1	2	3	4
Pressure depletion rate (kPa/min)	0.34	0.76	1.92	4.52
Reaction frequency factor (gmole/cm3·min)	0.0075	0.0018	0.0080	0.0412

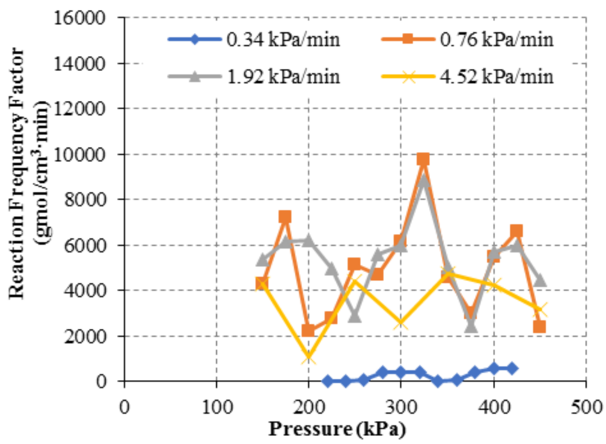

Fig. 6. Reaction frequency factor of Reaction 2

The simulation results suggest gas bubbles evolve process is a dominant process at a lower pressure depletion rate. At this pressure range, gas bubbles smoothly evolve from the oil phase and slowly form the free gas phase. At intermediate pressure depletion rate, gas bubbles evolve and dissolve processes happened at the same time. Dispersed gas bubbles expand to a larger size which could block the pore throat. At the same time, gas bubbles dissolve back into the oil phase. Hence, the reaction rate of Reaction 2 drastic change with pressure at the intermediate pressure depletion rate. Gas bubbles evolve faster than gas bubbles dissolve rate with higher pressure depletion rate. Also, the reaction time is short at higher pressure depletion rate compare with other pressure depletion rate. Only a small portion of gas bubbles dissolve back during this short reaction time. As a result, the reaction rate curve of Reaction 2 is relatively gentle than the other two cases at higher pressure depletion rate.

V. CONCLUSIONS

This work presents a non-equilibrium kinetic model for the application of characterizing foamy oil and gas/oil two-phase flow in heavy oil and propane system from pressure depletion tests.

Good agreement between experiments data and simulation results are obtained in terms of production data as well as pressure distribution.

Increasing pressure depletion rate reducing the k value, which means gas bubbles remain longer in the oil phase. As a result, pseudo-bubble point pressure decreases.

For the lowest pressure depletion rate, solution gas slowly evolve from solution. Dispersed gas bubbles smoothly pass through pore throat and slowly form free gas phase, which results in high gas recovery factor and low oil recovery factor. At this pressure range, gas bubbles evolve process is a dominant process. As a result, gas phase relative permeability is the highest among the four cases. Also, reaction rate of Reaction 1 is relatively low but not the lowest among four cases. Reaction rate of Reaction 2 is changing with pressure at lower range.

For the intermediate pressure depletion rate, gas bubbles evolve faster from the oil phase and form larger gas bubbles, and hence, the size of some large gas bubbles is larger than the size of pore throat which preventing large gas bubbles pass through. At this range of pressure drop rate, foamy oil and gas/oil flow characterization is influenced by both gas bubbles evolve and dissolve process, which results in low gas recovery and high oil recovery. Therefore, gas phase relative permeability is lower at intermediate pressure depletion rate. Also, reaction rates of Reaction 1 at this pressure range are the lowest among four cases. Reaction rate of Reaction 2 is drastic change with pressure.

For highest pressure depletion rate, gas bubbles to evolve faster than dissolve back and shorten production period, which results in a relatively low gas recovery as well as low oil recovery. Although large gas bubbles are blocked in the pore throat, some gas bubbles still pass through pore throat due to the high pressure drop. The oil phase is trapped in the porous media because some pore throats are blocked by gas bubbles, which would cause different gas-liquid relative permeability of the highest depletion rate case. The reaction rate of Reaction 1 is the highest among four cases. The reaction rate curve of Reaction 2 is relatively gentle than the other two cases at higher pressure depletion rate.

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