STUDY ON HEAVY OIL PRODUCTION BY CO_2-GAS FOAMING USING HUFF-AND-PUFF PROCESS

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https://hdl.handle.net/2324/1470566

出版情報：九州大学, 2014, 博士（工学）, 課程博士
バージョン：

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論 文 名　：　STUDY ON HEAVY OIL PRODUCTION BY CO_2-GAS FOAMING USING HUFF-AND-PUFF PROCESS
（ハフ・パフプロセスを利用した CO_2 ガスフォーミングによる重質原油の生産に関する研究）

区　　分　：　甲

論 文 内 容 の 要 旨

Non-thermal or cold production process has recently received attention for enhanced oil recovery (EOR), especially for heavy oils that reserves are expected to be almost twice of conventional light oil. Foamy oil is defined as heavy oil that gives rise to stable dispersed bubbles of gas, especially CO_2 which has much higher solubility in heavy oils than CH_4. The CO_2 gas foaming in heavy oil reservoirs is one of cold EOR processes and a part of carbon capture, utilization and storage (CCUS) that provides either environmental benefit or revenue. In Canadian heavy oil reservoirs, the high oil production rate and primary recovery factor were obtained by the foaming process. However, the discussions on viscosity and mobility of foamy oil were controversial, either a decrease or an increase once after bubbles generated. Moreover, stability and diameter distribution of bubbles under shearing condition in porous flow have not been well understood.

This research has focused on foaming process using the heavy oil with 13.06 ºAPI, sampled from a reservoir located in Hokkaido, Japan. The foamy oil was generated by depressurizing from CO_2 saturated condition at given pressure less than 10 MPa. The measurements of CO_2 gas solubility in heavy oil and characteristics of apparent swelling and viscosity of the foamy oil were carried out to design an appropriate production process by changing saturated pressure and pressure drop during 0.1 – 10 MPa at mainly 50 ºC almost equal to the reservoir temperature.

The dissertation, which has discussed on characteristics of the foamy oil to develop an appropriate production process from heavy oil reservoirs, consists of six chapters as the following:

Chapter 1 is the introductory chapter which introduces to importance of cold EOR production processes for heavy oil, definitions of gas solubility and foamy oil, previous studies on foamy oil viscosity and previous approaches on heavy oil production by foaming oil.

Chapter 2 presents the measurement results of gas solubility of CO_2 and CH_4 in heavy oil by PVT experiments from 1 – 10 MPa in pressure range and 20 – 50 ºC in temperature range. Oil swelling due to gas dissolution was also measured by visualization of oil column placed in a high pressure cell during 0.1 – 10 MPa in pressure range and at temperature of 50 ºC. In order to compare the results of the heavy oil hexadecane was also measured, since it is a typical component in heavy oils and a single pure component. The CO_2 gas solubility measured by PVT experiments, hereinafter called as complete solubility, and its swelling in the original heavy oil were 47 and 74% of those in hexadecane, respectively. The CO_2 gas molecular diffusion coefficients in oil phase were measured from unsteady time-swelling curves in considering oil evaporation rate into CO_2 gas phase in order to predict dissolution time in reservoirs.

Chapter 3 describes the characteristics of foamy hexadecane taking precedence heavy oil, since hexadecane is easier to prepare and visualize behaviors than heavy oil. The foamy hexadecane was generated by depressurizing CO_2 gas from saturated pressure of 1 – 6 MPa to atmospheric pressure and 20 – 50 ºC in temperature range. The diameter distribution of bubbles was measured with microscope visualization pictures. Discussions involve apparent viscosity measured under high shear rate of 1575 s^{-1} and effects of CO_2 gas bubble diameter distributes in the 1 – 100 μm range. Based on the measurements, it has been analyzed that bubbles in small diameter range less than 10 μm were strongly related to apparent viscosity of foamy hexadecane.

Chapter 4 presents viscosity characteristics of foamy heavy oil generated by depressurization from the CO_2 saturated condition at 10 MPa in pressure. The apparent foam viscosity ratio, foamy oil over saturated heavy oil, was measured in conditions of 1 – 7 MPa and 20 – 50 ºC. The relationship between apparent foam viscosity ratio and density of foamy heavy oil was also measured for different depressurizing pressures. The diameter distribution of bubbles in foamy heavy oil was identified by kurtosis value and it was decreased with elapsed time of bubble exposing under high shear rate. In addition, the stability of bubbles was investigated by placing foamy heavy oil under high shearing of 76.8 s^{-1} for 5 minutes of measurement, then it was confirmed CO_2 bubbles less than 10 μm (micro-bubble) in diameter have contributed to keep lowering viscosity of foamy oil to 80% of saturated oil after reducing apparent swelling due to disappearing larger size of bubbles of 1 – 1000 μm in diameter.

Chapter 5 describes the numerical simulations on oil drainage observed by laboratory experiments using core samples and oil production in typical field scale of heavy oil reservoirs by CO_2 foaming by a commercial simulator, CMG-STARS. The numerical modellings were studied based on the CO_2 solubility model in porous media given by incomplete solubility that is 60% of the complete solubility measured in PVT experiments. A model was introduced to numerical simulations to predict apparent foam viscosity ratio of heavy oil against gas saturated condition as a function of pressure, 0.1 – 10 MPa, and temperature, 20 – 50 ºC. Furthermore, a new model has been proposed to predict foamy heavy oil production behavior by defining four kinds of foamy oils with different density and viscosity setting discretely at pressure drops of 2, 4, 6 and 8 MPa to simulate the special transitions of foamy oil against depressurization based on the measurement data. Those transitions of foamy oils were successfully simulated by constructing four pressure initiative pseudo chemical-reactions between saturated oil and four foamy oils in the CMG-STARS.

The result of numerical simulations of oil drainage from a core saturated by heavy oil, placed in the high pressure cell with 10 MPa in CO_2 pressure for 3 weeks of soak, was matched with experimental results using Berea sandstone cores showing about 31% of oil recovery after depressurization to atmospheric pressure. The numerical simulation model was scaled up to the typical field scale of heavy oil-reservoirs by applying the huff-and-puff process that was considered as the appropriate commercial production method. The numerical simulations were carried out to study sensitivities of initial oil saturation (0.7 – 0.3) and effective radius of CO_2 saturated zone (20 – 50 m). In case of a heavy oil reservoir with conditions of 0.7 of initial oil saturation, 20 m of effective radius and 10 MPa CO_2 injection and shut-in, the maximum heavy oil production rate and cumulative oil production reached to 68 m^3/day and 145 m^3 after depressurization in the first cycle of huff-and-puff process. Therefore a possibility of cold production of the heavy oil by CO_2 gas foaming and huff-and-puff process has been shown numerically.

Chapter 6 is a summary and conclusion of major findings of present research including the research interest for the future study on CCUS projects.