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Experimental study and numerical simulation of nitrogen-assisted SAGD in developing heavy oil reservoirs

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ABSTRACT

The presence of significant amounts of injected steam and heat loss are unavoidable issues occurred that are observed during the steam-assisted gravity drainage (SAGD) process in developing heavy oil reservoirs. Because of these limitations and concerns, non-condensable gas co-injection has become a potential technique to enhancing oil recovery and reducing energy consumption. However, the oil production mechanism is complicated and has not been totally understood, thereby requiring further discussion. In this work, a two-dimensional physical model was designed to investigate the production mechanisms of nitrogen on SAGD. Two comparative injection schemes, specifically the conventional SAGD and nitrogen assisted SAGD (NA-SAGD), were conducted to investigate the effect of nitrogen co-injection with steam on the SAGD performance. Dynamic temperature profile changes during the two experiment processes were monitored and recorded. The observation results indicate that nitrogen accumulation at the upper part of the model resulted in the effective expansion of the NA-SAGD process steam chamber along the horizontal direction. The swept area of steam increased significantly and the residual oil saturation was reduced. The cumulative oil production of NA-SAGD was higher than that of the conventional SAGD. Moreover, the apparent heat loss reduction, which defines the heat utilization efficiency, exhibited an increase following nitrogen injection. In addition, a numerical simulation was generated to compare and verify the results obtained in the two experiments. Nitrogen co-injection with steam effectively enhanced the oil recovery. Studies indicate that NA-SAGD is a feasible method for improving oil production in developing heavy oil reservoirs.

1. Introduction

Thermal methods are the most effective way for the development of bitumen and heavy oil reservoirs given the presence of a high initial viscosity at reservoir conditions (Hu et al., 2017). To enhance the mobility of oil using the strong temperature sensitivity of viscosity, the steam assisted gravity drainage (SAGD) technique is one of the major thermal recovery methods in developing heavy oil reservoirs (Butler and Stephens, 1981; Butler, 1994). However, during the SAGD process, the low utilization rate of resources is observed as one of the most important problems, specifically high energy consumption and heat loss through overburden, which affect the production efficiency (Ji et al., 2015). Meanwhile, the enormous volume of CO_2 emissions also generates environmental problems. As a result, the cost of the production process is expensive and applications are economically limited (Kazeem, 2014).

Improving the economy and efficiency of the oil production process has recently become the focus of many research projects given the requirement of a more economic method to improve the production efficiency (Jha et al., 2013; Yuan et al., 2017). To solve these problems, many attempts have been performed to study the efficiency of chemical solvent injections to enhance the oil recovery in both physical experiments and oilfield pilot projects (Leyva-Gomez and Babadagli, 2013; Liu et al., 2013, 2015). To take the advantage of the mass transfer of the light hydrocarbon component, Nasr et al. (2003) presented an expanding solvent-SAGD (ES-SAGD), wherein hydrocarbons (alkanes, aromatic hydrocarbons) mixed with steam were injected into a heavy oil reservoir, to reduce the amount of injected steam and enhance oil recovery. As compared to the SAGD process, the results of these attempts exhibited an apparent increase in oil production (Souraki et al., 2013; Al-Murayri et al., 2016; Zheng et al., 2016). However, the selection of the most correct and appropriate solvent is crucial for the success of solvent-aided injection processes (Hascakir, 2016). However, some solvents are

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poisonous and cause irreparable damage to the formation. Furthermore, due to the high content of asphaltene in super-heavy oil, asphaltene precipitation was observed following the mixture of some solvents and heavy oil (Stachowiak et al., 2005; Gonzale et al., 2006). Asphaltene precipitation blocks the pore space and prevents the liquid from flowing, which is bad for the mobility and the production of oil (Mukhametshina et al., 2016).

Therefore, an improved technique named steam assisted and gas push (SAGP) is presented to improve oil recovery in developing heavy oil reservoirs and obtain the economic benefits (Butler et al., 2000; Jiang et al., 2000). During the SAGP process, non-condensable gases such as carbon dioxide, nitrogen, and methane are added by co-injection of steam (Ito et al., 2001; Rahnema et al., 2011; Zheng et al., 2013). These gases can exist in the steam chamber and have insignificant condensations to the liquid phase (Yang and Xi, 2012). Several researchers have examined the effect of methane gas on SAGP through physical experiments and numerical simulations. Bagci and Gumrah (2004) demonstrated how the injection of gases such as CO_2 and methane increased the cumulative oil production in physical experiments. Al-Murayri et al. (2011a, 2011b) developed a simulation model, wherein the amount of injected steam and the cumulative steam oil ratio (cSOR) were less than that of SAGD as a non-condensable gas methane injection. However, the production rate and the oil recovery were reduced under the same conditions. Liu et al. (2012) also reported similar results. Gittins et al. (2011) studied the effect of non-condensate gas on the development of an SAGD steam chamber. Others reports also generated the simulation models to investigate the effects of methane as a solution gas or injected gas for cumulative oil recovery (Ardali et al., 2012; Sharma et al., 2012; Nourozieh et al., 2015). However, methane is still relative expensive and is easily flammable at high temperatures, which limit the widespread application during the SAGP process.

During the SAGP process, non-condensate gas such as nitrogen and carbon dioxide was injected with high temperature steam into the formation when the edge of the steam chamber was closed to cap rock. The mechanisms of this process include low heat conductivity, thermal expansion effect, and interfacial tension reduction (Yuan et al., 2011; Yang and Xi, 2012). Nitrogen is easily and inexpensively prepared, and is clean and non-poisonous. It also has a large compressibility coefficient and a low heat conductivity coefficient. This improved technique has exhibited good production performance in heavy oil reservoirs in recent years (Rios et al., 2010). A nitrogen gas assisted SAGD pilot test was performed, of which the oil steam ratio exhibited an 80% increase. In contrast, the injection of nitrogen in the Liaohe oil field, China exhibited a 20% oil production increase (Guo et al., 2015). Lu et al. (2014) indicated that the addition of nitrogen during steam injection can significantly improve the oil displacement efficiency according to laboratory research. However, these experiments were one-dimensional sand pack experiments, which exhibited limited steam chamber development and could not describe the dynamic pressure and temperature changes in the steam chamber. In addition, an increase in the injection volume of nitrogen does not generate better results given that nitrogen is concentrated at the upper part of the steam chamber where it is hardly produced, thereby increase the mole fraction of nitrogen (Wang et al., 2015). The pressure of the steam chamber is too high to allow continuous injection of steam. Therefore, it is better to adopt a plug injection method.

Nitrogen has been previously applied as a non-condensable gas in oilfield pilot projects to enhance the oil production performance (Gao and Liu, 2008; Du et al., 2013). However, these production mechanisms are complicated and have not been totally understood, thereby requiring additional discussions. In this study, two-dimensional physical experiments with different injection schemes were performed to investigate the production mechanisms of nitrogen assisted SAGD, which we named NA-SAGD, to distinguish it from the conventional SAGD. The present study aims to examine and evaluate the effects of nitrogen on the development of the steam chamber and the residual oil saturation distribution. The dynamic changes of the steam chamber and its oil recovery following the application of different schemes were compared. The experimental performance and produced results were discussed, of which the results indicated that nitrogen as non-condensable gas that is co-injection with steam is an effective technique to enhance the oil recovery. In addition, a numerical simulation was built to verify the results obtained in the two experiments. The temperature distribution characteristics and oil recovery of the simulation results were in good agreement with the experimental results. This work can serve as a reference for the selection of nitrogen injection during SAGD in developing heavy oil reservoirs.

2. Experiments

2.1. Experimental apparatus

The experimental apparatus of the two-dimensional physical simulation experiments for SAGD and NA-SAGD are shown in Fig. 1. The apparatus mainly consists of four parts, specifically the injection system, model body, collection system, and data acquisition system.

An ISCO pump displaced water and oil into the steam generator and model, respectively, or controlled the flow rate of the inlet during the experiments. Model body is composed of a stainless shell with a glass cover, which is wrapped in insulation cotton to reduce the heat loss during the experiments. To prevent the glass cover from crushing, the maximum working pressure during the experiment was controlled under 10.0 MPa. The injection of nitrogen was controlled and monitored by an air compressor and gas mass flow controller. High temperature steam was generated by a steam generator, which can produce steam at a maximum temperature of 300 °C.

A piston container stored the experimental oil sample, which had a volume of 2.0 L, and the maximum working pressure was set at 20.0 MPa. Back-pressure valves maintained the pressure of the production well and ensured the security of the experiment. A data acquisition system with 24 pressure sensors and 24 temperature sensors recorded the transient pressures and temperatures inside the model. The system also recorded the transient flow rate and the cumulative water injection volume of the pump. A scale was employed to measure the weight of the production emulsions to calculate the oil recovery.

2.2. Experimental materials

The experimental materials used in this study are as follows:

Model body: The model has a length and width of 100.0 and 4.0 cm, respectively. The height is 25.0 cm and the measured volume is 10,000 cm^2. The injection well and production well are located in the

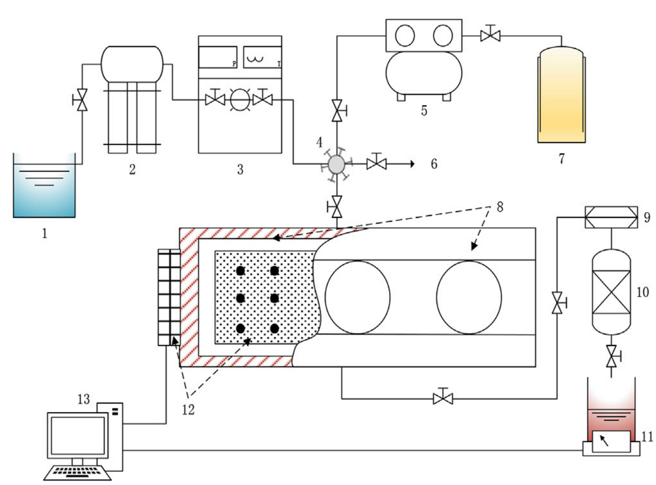

Fig. 1. Schematic of the apparatus employed for the NA-SAGD and conventional SAGD experiments.