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Multi-thermal fluid assisted gravity drainage process: A new improved-oil-recovery technique for thick heavy oil reservoir

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ABSTRACT

Multi-thermal fluid is a new heat-carrier proposed in decades. This paper introduces multi-thermal fluid into the thermal recovery process of thick heavy oil reservoir (THOR). First, using the method of physical simulation, the superiority of multi-thermal fluid is investigated from the Pressure–Volume–Temperature (PVT) performance and displacing characteristics. Thereafter, based on multi-thermal fluid injection technology and steam-assisted-gravity-drainage (SAGD) theory, a new Improved-Oil-Recovery technique for THORs, Multi-thermal Fluid Assisted Gravity Drainage (MFAGD) technique is proposed in this paper. Applying the dimensionless scaling criterion of gravity-drainage process, two 3D gravity-drainage experiments (SAGD, SAGD-to-MFAGD) are conducted. Thus, the enhanced-oil-recovery (EOR) mechanisms of multi-thermal fluid in heavy oil reservoirs are analyzed, and the thermal recovery performance of MFAGD process is discussed. Results indicate that compared with SAGD process, MFAGD process has a higher recovery rate, and it could further improve the gravity-drainage effect in THOR. Besides the conventional operation of SAGD, the EOR mechanisms of MFAGD technique also include heat insulation, energy recovery, gas dissolution and auxiliary cleanup of non-condensable gas. This method technologically supports the effective and efficient development of THORs.

1. Introduction

Thick heavy oil reservoir (THOR) is a widespread petroleum reservoir type all over the world. How to effectively and efficiently recover the THOR is of importance to guarantee the energy demand. Currently, the commonly-used exploitation methods for THOR include huff and puff, steam drive, steam-assisted-gravity-drainage (SAGD) and in-situ combustion etc (e.g., Kern River projects in USA, Qi 40 block and Du 84 block in China, Xinjiang oilfield in China, Long Lake and Marguerite Lake reservoir in Canada etc.) (Blevins and Billingsley, 1975; Grabowski et al., 1981; Liu, 1998; Thomas, 2008; Ursenbach et al., 2010; Desheng et al., 2014). But most of them are based on the conventional steam injection technology. In recent years, a new heat-carrier, multi-thermal fluid is introduced into the petroleum reservoir development (Liu et al., 2011; Tang et al., 2011; Dong et al., 2014). It is a gas mixture of steam and non-condensable gas, and the main components include steam, nitrogen gas (N_2) and carbon dioxide (CO_2). In this paper, the new fluid is introduced to recover the THORs. Different with the conventional saturated steam, multi-thermal fluid is produced from the multi-thermal fluid generator (Tang et al., 2011). This generator utilizes the combustion and jetting mechanisms of rocket engine. Considering the unique generation method of multi-thermal fluid, this heat-carrier has higher temperature and enthalpy compared with the conventional steam. For the development process of heavy oil reservoir, it is a highly potential EOR fluid. Furthermore, as a new heat-carrier, multi-thermal fluid is also different from the conventional gas mixture of steam and non-condensable gas. First, multi-thermal fluid is produced from the combustion process in multi-thermal fluid generator, and it is a high-temperature and high-pressure gas mixture. The non-condensable gas fraction in multi-thermal fluid is the gas mixture of N_2, CO_2, CH_4 and CO etc. That is different from the conventional case. Second, in field test, multi-thermal fluid is always injected into the reservoir directly after generation. It is different from the separate injection method of conventional case. Third, the steam fraction in multi-thermal fluid is always the superheated steam. It has higher enthalpy than the conventional saturated steam (Sun et al., 2011; Liu et al., 2012; Dong et al., 2014).

For the application of multi-thermal fluid in the development process of heavy oil reservoirs, most of the current studies are focused on the pilot test and technological process. In 2009, it is introduced into an EOR project in Shengli oilfield in China. A multi-thermal fluid stimulation process is performed in a typical multicycle CSS well, GDN5-604 well (Ren, 2013; Li, 2013). The field location is shown in Fig. 1. During this stimulation process, the

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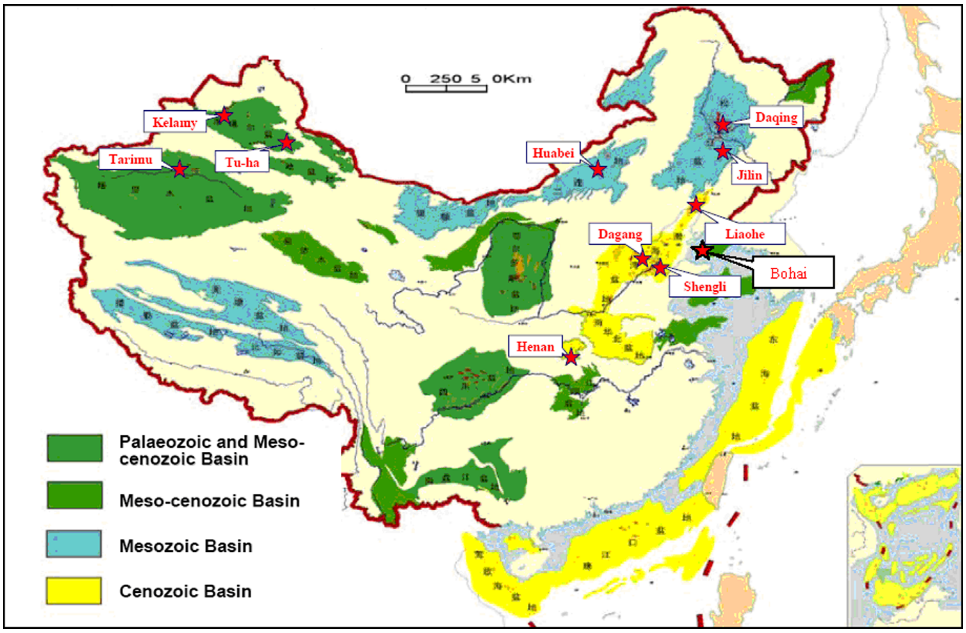

Fig. 1. Heavy oil fields location in China (Shiyi et al., 2005).

cycle N_2 injecting volume is 21×10^4 m^3; the cycle CO_2 injecting volume is 3.7×10^4 m^3; the cycle steam injecting volume is 480 t. After operation, the average water cut of this well is reduced by about 27.2%, and the oil daily rate is increased from 2.8 t to 10.1 t. The cumulative oil increment is about 1009 t. Considering the successful operation of multi-thermal fluid stimulation technique in this well, two well groups in C20 block of Shengli oilfield have been operated as the new testing sites. In 2010, multi-thermal fluid stimulation technique is also introduced into the development of NB35-2S heavy oil block of Bohai offshore oilfield in China (Liu et al., 2010, 2011; Sun et al., 2011; Yu et al. 2014), as shown in Fig. 1. About 6 stimulation cycles in four horizontal wells are performed, and this test also achieves good oil production increment results. The successful operation of multi-thermal fluid stimulation process in Shengli oilfield and Bohai offshore oilfield technologically supports the development of heavy oil reservoirs after multicycle huff and puff process and the heavy oil reservoirs with active border water.

For the development mechanisms of multi-thermal fluid in heavy oil reservoir, most of the current researches are focused on the conventional gas mixture of steam and non-condensable gas (Stone and Malcolm, 1985; Nasr et al., 1987; Frauenfeld et al., 1988; Ferguson et al., 2001; Wang et al., 2013). Metwally (1990) Hornbrook et al. (1991) and Li et al. (2011) performed some high-pressure displacement experiments to evaluate the effects of adding CO_2 to steam on the recovery of heavy oils. They found the co-injection of steam and CO_2 tremendously increased the oil recovery, reduced the injection temperature and reduced the heat input required. Stone and Nasr (1985) performed a series of experiments to study the mechanisms of steam–CO_2 injection process and steam–N_2 injection process in bitumen production. Due to the dissolution of CO_2, steam–CO_2 injection process had a better recovery performance. The injection of CO_2 enhanced the bitumen stripping process and formed a gas zone around the injector and increased the bitumen production. Simultaneously, the pressure gradient between the injection and production wells was also increased. Güimrah, Okandan (1992) conducted the steam–CO_2 experiments in 1D and 3D scaled models to study the effect of CO_2 addition to steam on the recovery process. Results indicated the oil recovery was increased with the increasing CO_2/steam ratios until an optimum level. Using a high pressure and high temperature (HPHT) scaled model, Nasr and Pierce (1995) experimentally evaluated the recovery process of bottom water oil reservoirs. They found the co-injection of CO_2 with steam accelerated and improved the recovery rate compared with steam-only injection process. Gümrah and Bagcl (1997) studied the application of steam–CO_2 drive process and the effects of well configurations in a physical model of 1/12th of an inverted regular seven-spot pattern. Besides the value of CO_2/steam ratio, the well type of injector and producer whether it is horizontal or vertical and the distance between the wells could also influence the performance of steam–CO_2 injection process. Srivastava Raj et al. (1999) conducted a laboratory investigation including PVT studies and coreflood experiments to assess the suitability and effectiveness of three gases (flue-gas [15 mol% CO_2 in N_2], produced-gas [15 mol% CO_2 in CH_4] and pure CO_2) for heavy oil recovery. They found CO_2 was the best suited gas for EOR process for recovering heavy oils. In the pure CO_2 runs, the solubilization mechanism of CO_2 dominated the process, whereas the free-gas drive (mainly provided by N_2) and solubilization mechanisms contributed to the oil recovery in produced-gas and flue-gas floods. Liu et al. (2001) experimentally investigated the displacement efficiency of gas-mixture injection method of steam and flue gas. Then, through the theory computation and simulated distillation data, the displacement mechanism was discussed. Aiming at Du32 heavy oil block of Liaohe oilfield in China, Gao et al. (2003) experimentally and numerically studied the influence of N_2 and solvent on the displacement efficiency of steam injection process. In order to quantify the effect of well spacing and the addition of noncondensable gas to steam, using a scaled physical model, Canbolat et al. (2004) conducted a suite of SAGD experiments with carbon dioxide or *n*butane added to the injected steam. A smaller injector-to-producer well separation could provide more rapid heating, larger recovery efficiency and greater steam/oil ratio. The addition of noncondensable gas to steam slows the upward movement of the steam chamber, and delays the formation of steam chamber, and decrease its size. Mohsenzadeh et al. (2012) performed the experiments of gas–oil gravity drainage process and steam–gas assisted gravity drainage process using three different gases (pure CO_2, pure N_2 and mixture of 15% CO_2 and 85% N_2) in a fractured heavy oil core model. The flue gas shows a high performance for heavy oil recovery from fractured reservoirs during gas–oil gravity drainage process and steam–gas assisted gravity process. From a sand pack model, Monte-Mor and Trevisan (2013) investigated the