Fuel 228 (2018) 379–389

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

Experimental and numerical study of solvent optimization during horizontal-well solvent-enhanced steam flooding in thin heavy-oil reservoirs

Shijun Huang, Xiao Chen*, Hao Liu, Jun Jiang, Meng Cao, Yun Xia

Department of Petroleum Engineering, China University of Petroleum, Beijing 102249, China

ARTICLE INFO

Keywords:
Horizontal-well solvent-enhanced steam flooding (HW-SESF)
Solvent optimization
Steam chamber expansion
Production performance
Temperature profile

ABSTRACT

As a major technique for enhancing heavy-oil recovery, steam flooding has been used successfully at large scales around the world. Long-term indoor experiments and field trials, however, have revealed problems, such as heat loss to the overburden and a limited steam zone for steam flooding in thin heavy-oil reservoirs, which severely limit the thermal efficiency of the steam and the economic benefits of the reservoirs. Therefore, we established a set of two-dimensional sandpack models to study the steam chamber expansion characteristics of the horizontal-well solvent-enhanced steam flooding (HW-SESF) of different solvents and its influence on production performance. We established a numerical model based on the experimental parameters to simulate the solvent migration in the steam chamber and its effect on temperature, viscosity, and oil saturation profile. The results demonstrate that, compared with steam flooding, the HW-SESF strategy can effectively reduce the oil viscosity both at the front and inside the steam chamber and improve the steam-injection capability (the stronger the steam-injection capability is, the easier the steam can be injected into the model) of the horizontal injection well, which enhances displacement efficiency and enlarges the swept area of the steam chamber. For HW-SESF of light solvents, the displacement efficiency at the low water-cut production was high, and water cut increased rapidly as the steam front reached the production well. For HW-SESF of medium solvents, the period of stabilized production was long, and the recovery ratio was the highest compared with other solvents. For HW-SESF of heavy solvents, the peak oil production rate was high, and the oil production rate dropped quickly. Therefore, the HW-SESF strategy reduced the heavy-oil viscosity more effectively than conventional steam flooding, and thus the zone of the steam chamber was enlarged and the recovery ratio enhanced. Compared with light and heavy solvents, medium solvents can achieve the best results for steam chamber optimization and the highest recovery ratio; thus, it is considered the most effective method to exploit thin heavy-oil reservoirs.

1. Introduction

Heavy-oil resources are rich worldwide [1], and approximately 80% of heavy-oil resources are found in reservoirs less than 5 m thick in Western Canada [2]. Although conventional thermal-based techniques, including steam-assisted gravity drainage (SAGD) and cyclic steam stimulation (CSS), are thought to be useful for recovering heavy oil from thick pay zones (> 15 m) [3], their application in thin heavy-oil (< 6 m) reservoirs is generally limited because of their high commercial cost [4]. The high steam-to-oil ratio caused by significant heat losses to the overburden greatly increases the cost of development [5,6], which is economically unfeasible during periods of low oil prices. Heavy-oil cold production employs small energy input, but its average recovery is usually as low as 10% because of the viscosity of heavy oil [7]. By employing the cold heavy-oil production with sand (CHOPS) technique, the recovery ratio can reach as high as 15%. The follow-up processes to recover additional oil beyond CHOPS, however, face new challenges because of wormhole formation and lower producing energy during CHOPS operations [7]. Thus, both conventional thermal-based techniques and cold production cannot meet the needs of developing thin heavy-oil reservoirs [8].

Existing thermal-based techniques of developing thin heavy-oil reservoirs that have been developed from field trials, reservoir simulation, and laboratory experiments are rare [3]. Steam flooding technique has been applied widely to increase the recovery factor and has achieved significant effects [9]. As a result, many studies have applied steam flooding to thin heavy-oil reservoirs. Both field trials and laboratory experiments have shown that steam flooding of thin heavy-oil reservoirs has the problems of great heat losses and limited swept area, which makes the steam-flooding process uneconomical [10–15]. The solvent-enhanced thermal recovery process for heavy oil was first proposed by Ali, and has been proven to enhance the recovery ratio in

* Corresponding author.
E-mail address: 2016212111@student.cup.edu.cn (X. Chen).

https://doi.org/10.1016/j.fuel.2018.05.001
Received 2 February 2018; Received in revised form 5 April 2018; Accepted 1 May 2018
0016-2361/

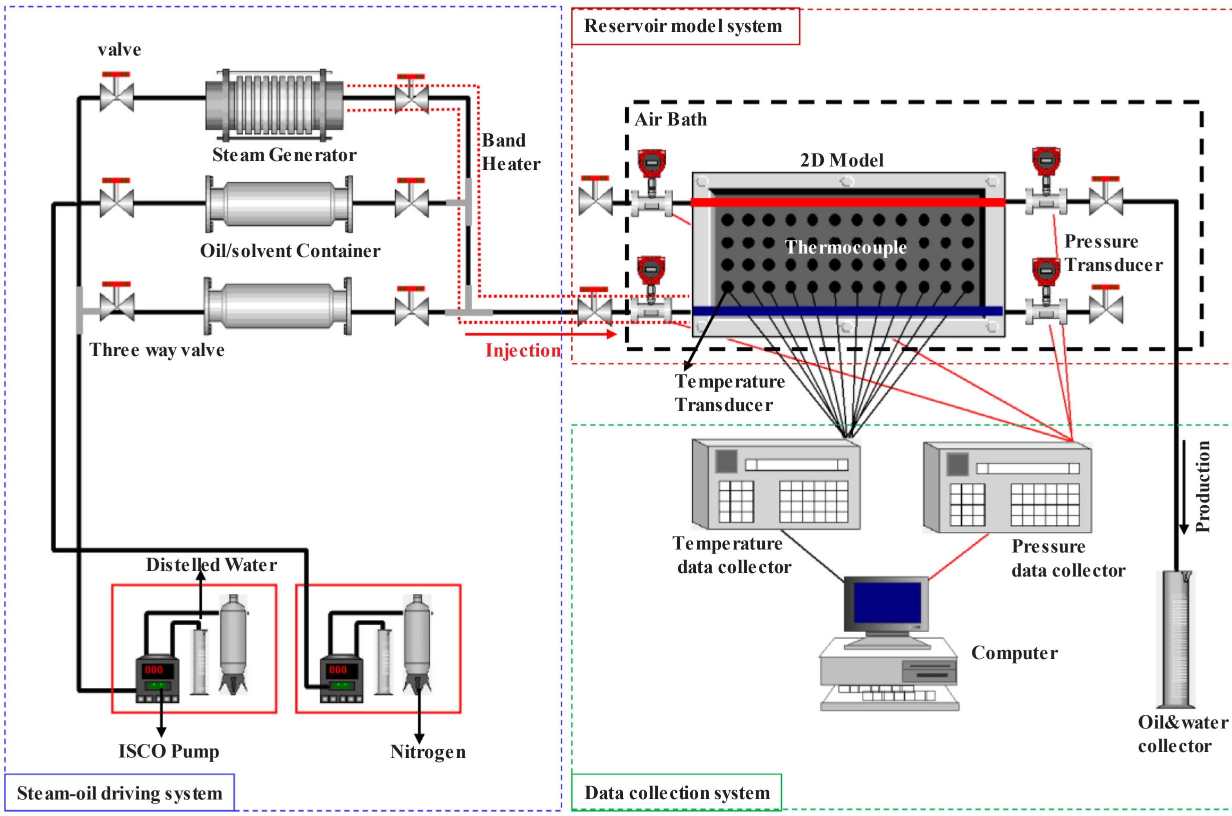

Fig. 1. Experimental apparatus for HW-SESF physical simulation.

both the laboratory and the oil-field pilot by greatly decreasing steam usage and increasing vertical sweep efficiency [16]. Solvents can be used as thinners when developing heavy-oil reservoirs. When solvent is vaporized and injected into the reservoir along with the saturated steam, it dissolves into oil to enhance the oil mobility of the region in the vicinity of the steam chamber boundary [17,18]. Moreover, part of the solvent can go deep into the reservoir by diffusion. Previous research showed that the oil of viscosity of 200 cP at 100 °C can drop to as low as 10 cP at the same temperature when the C6 mol fraction is higher than 0.48 [19]. Compared with conventional SAGD, based on data of the Athabasca oil and sand reservoirs, oil recovery improved effectively with the addition of solvent and oil production increased by 20% [20,21]. Expanding-solvent SAGD (ES-SAGD), however, is still not suitable for thin-oil-layer development [6,22,23]. Gates [24] applied the solvent-enhanced thermal recovery process to an 8-m-thick oil sand reservoir, and the solvent-enhanced process was found to substantially lower the steam usage and ratio of net-injected energy and oil compared with that of traditional SAGD. However, considering the Gates case involved steam injection of a vertical well, the injection pressure was high and the process was actually more like a hot water drive. Therefore, the development effect would be better if the horizontal well was applied. By studying the results of Shell's first SESF field trials conducted in Peace River, Canada, Verlaan reported that bitumen production increased greatly after the addition of solvent [25]. David conducted, for the first time, a numerical study on the strategy optimization of SESF in thin-layer (4-m) reservoirs [3]. The research suggested that water influx occurred in the presence of a bottom water zone, which reduced the effectiveness of steam flooding. After the addition of solvent, the bottom water zone became a beneficial factor, because a solvent-rich channel formed at the top of the reservoir and helped oil-solvent mixing, which, in turn, resulted in higher recovery and economic performance.

Arciniegas [26] studied the effects of thermodynamic conditions, solvent types, and other factors on solvent recovery by one-dimensional core displacement experiments. The results indicated that 1) recovery of the light solvent was higher than that of the heavy solvent, 2) recovery of the vapor solvent was usually higher than that of the liquid solvent, 3) recovery could be enhanced if the temperature and pressure were close to the saturated vapor pressure curve, and 4) the de-asphalting of the solvent would result in reservoir damage. Li [27] conducted an ES-SAGD experiment and used an infrared camera to record the steam chamber expansion process and temperature distribution over time, and the results demonstrated that the solvent co-injection in the vapor and liquid phases could change the condensation time of light hydrocarbons (C7) to improve the development effect. Ardali [28] conducted an experiment in a two-dimensional cylindrical model with a medium pressure of 0.55 MPa, in which n-hexane and n-heptane were injected separately with a volume fraction of 15%. The results indicated that n-hexane and n-heptane could enhance oil recovery by 20% and 8%, respectively, compared with pure steam. Jamaloei [29] applied the physical experiment to study the effect of solvent type and injection sequence on CSS of thin heavy-oil reservoirs. The experimental results suggested that the best injection strategy was to inject a volatile methane slug first, and then to inject the ethane and propane, which is highly soluble. Gupta [30] studied the effect of solvent concentration on ultimate recovery and concluded that a concentration of 10% would achieve the best result. Ye [31] studied the effect of solvent types on the development result of CSS, and proposed that the co-injection of methane and steam would achieve superior performance in enhancing oil recovery

Much research has been done theoretically and numerically on HW-SESF [3,12,32,33], but some problems remain. Currently, there are many types of solvents to choose from when applying HW-SESF strategy, which has a complicated influence on the steam chamber expansion process. Therefore, solvent optimization is critical to the success of HW-SESF. In our study, we designed an experiment that used different solvents to improve the development effectiveness of HW-SESF of thin heavy-oil reservoirs. We first studied the characteristics of