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Evaluation of the hybrid process of electrical resistive heating and solvent injection through numerical simulations

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HIGHLIGHTS

- We proposed a hybrid process of electrical heating and solvent injection to enhance heavy oil and bitumen production.
- The mechanisms of enhanced heavy oil recovery of this process are discussed through numerical simulation.
- Numerical simulation suggested that this process have much better performance than the solvent injection alone.
- This method is suitable for many oil reservoirs in western Canada.

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ABSTRACT

Electrical Resistive Heating (ERH) has been proposed as a thermal recovery method for heavy oil reservoirs with low environmental impact. ERH could potentially be an alternative to steam-related processes in the reservoirs which are not suitable for steam injection methods due to low incipient injectivity and formation incompatibility. Meanwhile, Vapor Extraction (VAPEX) has been tested as an environmentally sustainable oil recovery method in both lab scale and field scale. However, the field test results showed that this process is not efficient and economical due to low mass transfer and low horizontal well efficiency. This paper presents a hybrid process of ERH with VAPEX. The hybrid process could enhance horizontal well efficiency and overall oil production rate, with less environmental impact than other steam-related thermal processes. Numerical simulations were conducted to evaluate this process via CMG-STARS (a Steam, Thermal, and Advanced Processes Reservoir Simulator of Computer Modeling Group). Well pattern similar to that in classical Steam-Assisted Gravity Drainage (SAGD) process is used. The electrode is placed along with the producer or injector and solvent is injected from the injector. This process has three features which contribute to the enhanced oil flow: (1) the heat from electrode establishes good communication between the injector and the producer by viscosity reduction; (2) the in situ generated heat through ERH along with the horizontal wellbore is insusceptible to reservoir heterogeneity. Thereby the horizontal well conformity can be improved; (3) the solvent can reduce the viscosity of the heavy oil in unheated zone where the ERH cannot reach; it can also assist viscosity reduction of heavy oil in the heated zone. The factors affecting this hybrid process, such as electrode placement, voltage, well distance and heterogeneity effect, lateral pattern and water saturation, were also discussed in this paper. The simulation results showed that this hybrid process can improve the oil rate 2–5 times over VAPEX.

1. Introduction

The vast oil sand deposits in Canada, Venezuela, and Russia are estimated 2100 billion barrels of oil in place. Nearly half of these oil sand resources or about 980 billion barrels are located in Alberta, Canada, in which 12% of the Alberta deposit lies at a depth of 75 m and less with an average seam thickness of 32 m, and 88% lies at a depth of 75–750 m with an average seam thickness of somewhat below 20 m. The deposits are usually under and overlain by beds of water–sands and shales and all rest on a limestone basement rock. Some deposits are stacked, physically segregated from one another by heavy impermeable, shale strata [1].

Conventional thermal recovery processes, such as steam flooding, cyclic steam stimulation (CSS), and in situ combustion, inject one fluid to change oil properties to make it flow easier. Therefore, there are complications of generating, transporting (while avoiding excessive heat losses), and disposing of the injected fluid. ERH does not require a heat transporting fluid, which can be particularly beneficial to deep reservoirs or reservoirs with thin pay-zones

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where conventional thermal methods are not cost-effective due to excessive heat loss. Since the heat is generated within the formation, this method is slightly affected by the depth and heterogeneity of reservoir and is hardly influenced by permeability variations within the formation.

Vapor Extraction (VAPEX) is analogous to the Steam-Assisted Gravity Drainage (SAGD) process where the steam is replaced with gaseous hydrocarbon. The hydrocarbon vapor rises from the upper horizontal well, creating a chamber, then diffuses to the heavy oil surface and dissolves into the bulk oil in a miscible process. However, potential disadvantages are the high cost of the solvent and the loss of the solvent which remains in the vapor chamber. Also, the process of VAPEX is likely to be slow and a long period before there is sufficient penetration of the vapor into the oil over a large enough area.

Interest in hybrid process technologies is growing. Recent investigations have considered combining steam and solvent injection processes [2–5]. These processes combine the benefits of steam and solvents in the recovery of heavy oil and bitumen and lead to accelerated oil production rate, higher oil recovery and lower energy to oil ratio. Gupta et al. (2004) found the solvent-aided process actually has a lower oil production rate at the early stage but can efficiently reduce the oil production decline rate [6]. Zhao (2007) proposed a steam alternating solvent process, which involves injecting steam and solvent alternately, and the basic well configurations are the same as those in the SAGD process. Numerical simulation suggested that the oil production rate of a steam assisted solvent process could be higher than that of a SAGD process, while the energy input was 18% less than that of SAGD [7]. Cristofari et al. (2006) studied the effects of solvent injection on in situ combustion and found that solvent extraction of light and medium components from the oil phase followed by air injection may realize significant synergies by combining the benefits of both technologies [8].

This paper proposes a hybrid process of Electrical Resistive Heating (ERH) and VAPEX, which might provide a new insight into the heavy oil EOR techniques. The hybrid process is found quite successful in terms of oil recovery factor. The effects of operation conditions (such as electrode placement, voltage and well placement) and reservoir properties (such as water saturation and formation heterogeneity) on the performance of the hybrid process are thoroughly analyzed through a series of numerical simulation.

Table 1
Basic Parameters.

Parameters	Value
Reservoir dimension	30 m × 30 m × 10 m
Permeability	5000 mD (in base case)
Porosity	0.35
Initial water saturation	30%
Oil viscosity @ 27 °C and 400 kPa	6217.86 cp
KV1 (*k* value correlation) of C1[a]	5.4547×10^5 kPa
KV2 (*k* value correlation)of C1[a]	0
KV3 (*k* value correlation) of C1[a]	0
KV4 (*k* value correlation) of C1[a]	−879.84 °C
KV5 (*k* value correlation) of C1[a]	−265.99.4 °C
KV1 (*k* value correlation) of n-C4[a]	8.5881×10^5 kPa
KV2 (*k* value correlation)of n-C4[a]	0
KV3 (*k* value correlation) of n-C4[a]	0
KV4 (*k* value correlation) of n-C4[a]	−2154.9 °C
KV5 (*k* value correlation) of n-C4[a]	−238.73 °C
Dispersion coefficients in oil phase	0.000864 m^2/day
Dispersion coefficients in gas phase	0.002 m^2/day
Production pressure	490 kPa
Injection pressure	400–490 kPa (changing with position)
Top injection pressure	490 kPa
Standard voltage	110–250 V (changing in different simulations)

[a] [9].

2. Methodology

Electrical resistive heating in heavy oil reservoir is widely known in the petroleum industry. CMG's STARS (*a Steam, Thermal, and Advanced Processes Reservoir Simulator of Computer Modeling Group*) simulator can simulate this process. CMG's STARS also is capable of modeling solvent injection process by using solubility equilibrium values (K values) to calculate the concentration fraction of solvent in each fluid phase.

A series of simulations was run to evaluate the performance of this hybrid process, ERH and VAPEX. Due to the symmetry of this well pattern, only a half of this model needed to be simulated. The dimensions of the model are 30 m × 30 m × 10 m. The grid size used in the simulation was 1 m × 3 m × 0.5 m for the model. The total grid number is 30 × 10 × 20 = 6000. The basic parameters of the simulation model are shown in Table 1.

The viscosity and density of the dead oil used in this simulation at 27 °C and 400 kPa are 6217.86 mPa s and 979.92 kg/m^3, respectively. The oil viscosity decreases with the temperature increase and the relationship is shown in Fig. 1. The viscosities shown here were originally taken from lab experiments [10]. The solvent used in the simulation is C1 + n-C4. The viscosity and density at different n-C4 concentrations were modeled with CMG. Oil-phase viscosity, μ_o, is obtained by a logarithmic mixing rule:

$$\ln(\mu_o) = \sum_{i=1}^{n_c} f_i \ln(\mu_i)$$

where μ_i is the component viscosity and n_c is the number of components in the oil-phase.

In CMG's STARS, solubility is defined by the K-values of the components. As a function of pressure and temperature, the K-value can be calculated by the following correlation:

$$K = (KV1/p + KV26 * p + KV3) * EXP(KV4/(T - KV5))$$

where T is temperature, °C; p is gas phase pressure, kPa. The units of KV1, KV4 and KV5 correspond to the units of p and T, KV2 and KV3 are 0. The coefficient of the correlation is included in Table 1. The water–oil and gas–liquid relative permeability data are shown in Figs. 2 and 3, which both are obtained through matching the physical lab experiments [10].

In the simulation model of the hybrid process, the voltage of top of the reservoir is set as 0 V (ground) and the electrode which has the high voltage is placed along with injector or producer. The top of the reservoir and electrode form a circuit which makes the current flow from electrode to the top of the reservoir and causes the energy consumption to heat the reservoir. Thermal and electrical properties of the basic model are in Table 2.

3. Main results and discussion

3.1. Operational parameter sensitivity analysis

This section discusses the sensitivity analysis that was done to further evaluate the performance of the hybrid process. The water content plays an important role during the ERH. An electrical path through the formation is provided by the water in the reservoir. With the temperature increasing, the water around the electrode could be vaporized due to the overheating of the electrode area, resulting in the cut-off of electrical circuit and process termination. When the water vaporizes into steam around the electrode, the conductivity of electrical current drops to zero; however, the steam could form a chamber which assists in reducing the oil viscosity as well. Wang et al. (2008) has simulated pure electrical heating process and concluded that the incremental bitumen recovery is significant when the formation water is heated to vaporize. In this