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A parabolic solvent chamber model for simulating the solvent vapor extraction (VAPEX) heavy oil recovery process

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ABSTRACT

During the solvent vapor extraction (VAPEX) process, a heavy oil reservoir can be divided into three different zones in terms of its fluid saturations, namely, the solvent chamber, transition zone, and untouched heavy oil zone. In the past, the solvent chamber was assumed to be a linear or circular shape in the previous studies. However, it has been observed to be close to a parabolic shape in many laboratory VAPEX tests. In this paper, a new parabolic solvent chamber model in the concave or convex case is formulated to predict the solvent chamber evolution and the heavy oil production in the VAPEX heavy oil recovery process. In the experiment, each recorded digital solvent chamber image at a different time is digitized to determine the solvent chamber shape by analyzing the sudden change of the gray level of each pixel. In theory, the overall discrepancy between the predicted and digitized solvent chambers is minimized by adjusting the transition-zone thickness. It is found that in comparison with the linear and circular solvent chamber models, the parabolic solvent chamber model gives the best prediction of the solvent chamber evolution, especially in the spreading phase. In addition, the maximum transition-zone thickness variation of 13.1% during the entire VAPEX test indicates that the transition-zone thickness can be assumed to be constant. Similar to the other solvent chamber models, the parabolic solvent chamber model can adequately predict the cumulative heavy oil production. The relatively large error of the predicted cumulative heavy oil production is caused by a commonly used assumption. The initial oil saturation in the transition zone is assumed to reduce to the residual oil saturation once the transition zone becomes an incremental part of the solvent chamber. This major theoretical assumption needs to be further investigated.

1. Introduction

The solvent vapor extraction (VAPEX) process is a promising enhanced heavy oil recovery method, in which a gaseous solvent is injected into an oil reservoir from an upper horizontal injection well and the solvent-diluted heavy oil is produced from a lower horizontal production well. The injected solvent dissolves into the heavy oil through the molecular diffusion and convective dispersion predominantly in the thin transition zone. The heavy oil viscosity is drastically reduced due to sufficient solvent dissolution, which is the major enhanced oil recovery (EOR) mechanism of the VAPEX process (Butler and Mokrys, 1991; Das, 1998). The solvent-diluted heavy oil drains downward by gravity to the production well. At the same time, the solvent chamber expands upward and laterally. The solvent VAPEX heavy oil recovery process has received a considerable attention since its invention by Butler and Mokrys (1989) due to its distinct technical advantages over the thermal-based heavy oil recovery methods. First, the solvent VAPEX heavy oil recovery process can be applied especially in the thin oil reservoirs with bottom water or low rock thermal diffusivities, for which the thermal processes, such as steam assisted gravity drainage (SAGD) and cyclic steam stimulation (CSS), may not be suitable (Karmaker and Maini, 2003). Second, this heavy oil recovery technology has a much higher energy efficiency because it is operated at the actual reservoir temperature (Singhal et al., 1996). Third, the produced heavy oil may be in-situ deasphalted due to possible asphaltene precipitation (Luo et al., 2007).

The experimental studies of the VAPEX heavy oil recovery process have been reviewed in the literature (Upreti et al., 2007; Pourabdollah and Mokhtari, 2013). In the theoretical work, several theoretical models have been developed to predict the heavy oil production in

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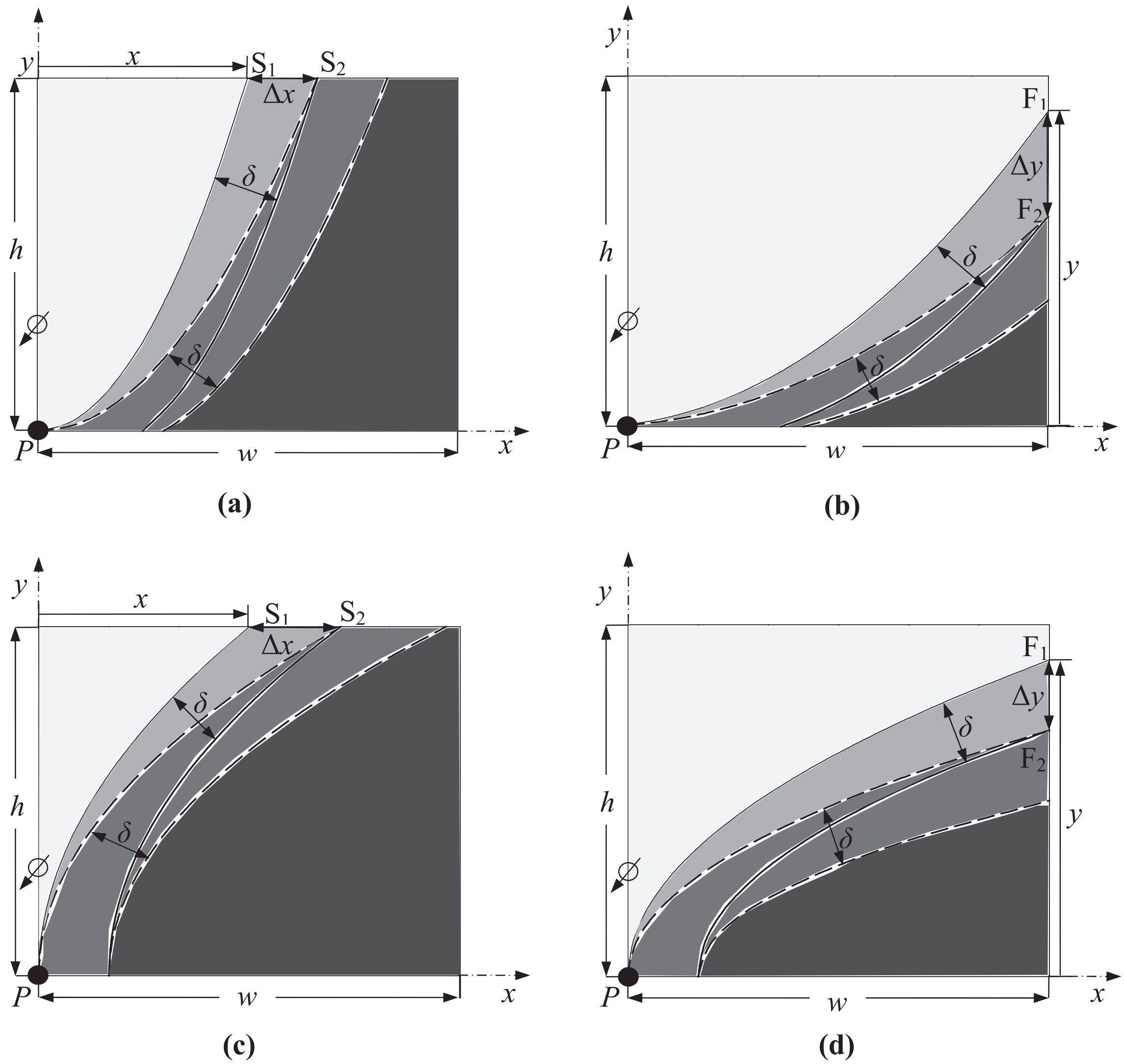

Fig. 1. The transition zones at t and $t+\Delta t$ during **(a)** the solvent chamber spreading phase and **(b)** the solvent chamber falling phase for a parabolic solvent chamber in the concave case; **(c)** the solvent chamber spreading phase and **(d)** the solvent chamber falling phase for a parabolic solvent chamber in the convex case, where the gray levels from low to high represent the solvent chamber, incremental solvent chamber in each time step Δt, transition zone, and untouched heavy oil zone, respectively.

the VAPEX heavy oil recovery process. Butler and Mokrys (1989) derived the first analytical model to predict the constant heavy oil production rate in the solvent chamber spreading phase. It was assumed that the solvent-diluted heavy oil gravity drainage takes place in the transition zone alone and that the heavy oil saturation in the transition zone is quickly reduced from the initial oil saturation to the residual oil saturation once the transition zone becomes part of the solvent chamber. Das and Butler (1998) introduced the so-called cementation factor into the Butler and Mokrys model to account for the presence of porous media. Yazdani and Maini (2008) established a useful empirical correlation to scale up the heavy oil production rates obtained from the laboratory tests to those in the field applications. It was found that the heavy oil production rate is proportional to the drainage height with a power of 1.13–1.17, instead of 0.5 in the Butler and Mokrys model. These theoretical models can be used to predict the constant heavy oil production rate in the solvent chamber spreading phase only. Nevertheless, they cannot be used to predict the solvent chamber evolution during the VAPEX process. As a first approximation, Moghadam et al. (2009) derived a linear solvent chamber model for the solvent chamber spreading and falling phases, in which the transition zone was assumedly bounded by two straight lines that are separated by a constant distance. The linear solvent chamber model is fairly accurate and useful to predict the heavy oil production rate and solvent chamber evolution, especially in the solvent chamber falling phase. More recently, Lin et al. (2014) formulated a circular solvent chamber model, which is particularly useful to predict the heavy oil production rate and solvent chamber evolution in the solvent chamber rising phase. However, the actual solvent chambers observed in many laboratory VAPEX tests are of neither an inverted triangle nor a full/partial circle.

In this paper, a parabolic solvent chamber model in the concave or convex case is developed to best represent the observed solvent chamber evolution and predict the measured heavy oil production during the VAPEX heavy oil recovery process. The transition-zone thickness is assumed to be constant and determined by minimizing an objective function, which represents the average normal distance between the predicted and digitized solvent chambers. With the determined transition-zone thickness, the parabolic solvent chamber model can be used to accurately predict the transient solvent chamber evolution and heavy oil production at any time.

2. Mathematical model

The solvent VAPEX heavy oil recovery process has three different phases: namely, the solvent chamber rising, spreading, and falling phases. The solvent chamber rising phase begins after the initial