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# Preliminary considerations on the application of toe-to-heel steam flooding (THSF): Injection well–producer well configurations

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ABSTRACT

This work examines the operational parameters that may influence the performance of toe-to-heel steamflooding in a laboratory-scale simulation model built on the basis of the fluid and rock samples from a fractured, low-permeable, carbonate heavy oil reservoir in Southwestern Iran, called KEM (Kuh-e-Mond). Using vertical (V) or horizontal (H) injectors (I) and producers (P), the effects of different well configurations including VIVP, VIHP, 2VIHP, VI2HP, HIHP, and HI2HP, injectors' traversal distance, producers' traversal distance, and horizontal producer length have been investigated. In summary, the results show that 2VIHP scheme performs best in terms of oil recovery and areal/volumetric sweep efficiency. Also, traversal distance of the vertical injectors and horizontal producer length should be optimized to have the maximum performance.


*Keywords:* Toe-to-heel injections; Steamflooding; Wells type and arrangement; Persian Gulf; Heavy oil

## 1. Introduction

Steam injection is considered as one of the primary methods of thermal enhanced oil recovery. Conventional steam flooding (CSF) (using vertical injectors and vertical producers) commonly applied to oil reservoirs which are relatively shallow and contain very viscous crude oils at the temperature of the native underground formation. Considering the fact that displacing of the mobilized oil (from injector to producer) takes place over long distances of the order of hundreds of meters, CSF is categorized as a long distance oil displacement (LDOD) processes.

High viscosity of oil makes its displacement to a producer (located a long distance away) usually inefficient (considering high required pressure drop along with adverse mobility ratio between the injectant and oil). It is known that the injected steam normally tends to travel to the top of the reservoir driven by gravity (Butler, 1991). Hence, either gravity override or very intensive channeling may take place, resulting in extremely low volumetric sweep efficiency (Xia et al., 2003).

With the advent of horizontal wells, a distinct change is taking place in enhancing recovery of heavy oil from LDOD processes towards short-distance oil displacement (SDOD) processes (typically over a few meters). SDOD processes are aimed at mobilizing oil and producing it immediately into a horizontal well. SDOD processes can utilize horizontal producers and injectors, or combinations of horizontal producers and vertical injectors (Turta and Singhal, 2004). Based on the displacement front's position relative to the horizontal section of a producer, Turta and Singhal (2004) and Xia et al. (2003) divided SDOD processes into two categories: (i) SDOD with a displacement front quasi-parallel to the horizontal producer and (ii) SDOD with a displacement front quasi-perpendicular to the horizontal producer. The first category uses two parallel horizontal wells (one for injection and the other one for production such as steam assisted gravity drainage (SAGD) and

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vapor extraction (VAPEX)). The second type of SDODs uses a vertical injector and a horizontal producer with the toe of the producer located in the closeness of the shoe of the injector (such as toe-to-heel air injection (THAI) or its catalytic version CAPRI, toe-to-heel steam flooding (THSF) and toe-to-heel water injection (THWI) processes). In the first type of the SDOD processes, production occurs throughout the entire horizontal section. In the case of the second type, however, the swept zone extends and moves from the toe towards the heel, utilizing reduced sections of the horizontal well for the drainage of the mobilized oil (Xia et al., 2003).

The well arrangement in THSF, like THAI (Xia et al., 2002; Fatemi et al., 2008a, 2009a), includes a vertical injection well and one horizontal producer well in direct line drive (VIHP), or one vertical injection well and two horizontal producer wells, in staggered line drive (VI2HP). The concept of THSF involves propagating a steam condensation front in the oil-bearing formation along the horizontal producer well, in a 'toe-to-heel' manner (Xia and Greaves, 2000). By placing the horizontal producer at the bottom of the reservoir, as the steam front overrides due to gravity, the only possible exit is via top-to-bottom flow into the horizontal producer. Therefore, the mobilized oil together with the steam condensate ahead of the steam front is drawn into the exposed section of the horizontal producer (Bağci et al., 2008).

Some experimental and numerical simulation studies regarding steam-flooding using horizontal wells have been reported in the literature. Bağci and Gümrah (1992) carried out steam-drive experiments in a three-dimensional physical model containing 17 °API crude oil in different combinations including a vertical injector–horizontal producer, horizontal injector–horizontal producer, and vertical injector–vertical producer. They inferred that the combination of two horizontal wells gave the best performance and use of horizontal wells reduced steam gravity override. Gümrah and Bağci (1997) conducted experiments to study steam and steam-$CO_2$ drive processes and examined different well configurations including vertical injector–vertical producer, vertical injector–horizontal producer, and horizontal injector–horizontal producer. In steam-alone tests, the vertical injector–horizontal producer scheme supplied a higher recovery and the lowest ultimate recovery was obtained from the horizontal injector–horizontal producer scheme. Bağci et al. (1998) reported the applicability of the steam injection process to medium and light oil reservoirs by conducting laboratory tests in a 3-D physical model. They inferred that the higher API gravity oils resulted in considerably higher values for the oil recovery and the oil recovery increased with decrease in the steam injection rate. Bağci et al. (2008) performed different runs in three numerical simulation models with different well types and arrangements (VIVP, VIHP, and VI2HP) using STARS reservoir simulator of CMG (Computer Modeling Group) package on a selected field scale prototype reservoir. They proposed that THSF has superior performance in low permeability reservoirs provided that vertical permeability is sufficient. They also concluded that the reservoir layering and low pay thickness reduced the effectiveness of the THSF process when the wells were placed in direct line drive. Finally, according to their results, THSF offered the potential to replace three vertical producers with one horizontal producer and achieved higher oil recovery in addition to reduced investment and operational costs. The first description and result of a THSF experiment (using Athabasca tar sand bitumen in a series of 3-D experiments) was reported by Xia and Greaves (2006). They conducted the THAI process as a secondary recovery method, which followed a prior THSF. The results show that the oil recovery in THSF was much lower than that in the THAI, due to the low steam temperature in the sandpack. Recently, Turta et al. (2009) reported the results from 3-D steam injection tests indicating that THSF was feasible even for heavy oil with a viscosity of 15,000 mPa s. They stated that it is very important to run the steam flooding in a toe-to-heel manner. It is crucial to clarify that any steam injection using vertical injector–horizontal producer (VIHP) does not necessarily fall in the category of toe-to-heel displacement. Turta et al. (2009) proposed that in order to provide a solid mechanism for a stable THSF process, it is very important to control intensive steam channeling through the horizontal well.

Considering the provided literature, it is inferred that there exist few works which have thoroughly examined the effect of wells type and arrangement on the performance of THSF process. The present work gives an insight into the THSF performance by considering different possible well types and arrangements, which has not been previously reported in the subject literature. In this simulation task, STARS module of CMG package was used. The effects of different well types and arrangements have been examined with comprehensive comparisons of their results using criteria such as areal/vertical/sweep efficiency and steam chamber volume. Moreover, effects of injectors' traversal distance, producers' traversal distance, and horizontal producer length have been investigated on THSF performance.

The simulation results of this study firmly confirmed some of the experimental observations cited by Turta et al. (2009). The aim of the present work was not to quantitatively history-match the previously published experimental data (Turta et al., 2009; Xia et al., 2003; Xia and Greaves, 2006). Instead, the aim was to obtain a stable toe-to-heel propagation in the simulation results so as to validate our numerical model (in the case of KEM's crude oil and rock) in accordance with their qualitative observations. In fact, the main objective was to develop a simulation model that could capture essential features of the THSF process.

Ideally, to investigate the effect of different injector–producer arrangements in THSF, one should carry out numerous experiments, which are not only tedious but also time consuming and expensive. The best alternative is to perform numerical simulations that could replicate the laboratory experiments. Although one cannot replace the experiments with a computer model, it is possible to use the carefully designed and validated simulation models in order to gain insight into the effects of various factors. Additionally, numerically simulated experiments help to identify the important design criteria in the process application so as to improve the design of the actual laboratory experiments. The outcome of this simulation work can be used as a guide for the future experimental studies and for constructing full-fledged physical models. A full-fledged physical model is the one that is capable of capturing major features and physics of THSF. It also allows one to comprehensively evaluate the effect of different factors that may influence the performance of THSF. Moreover, a full-fledged physical model should have the feature of switching between different injector–producer arrangements and different well spacings, all of which significantly influence the performance of THSF.