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Research paper

Predicting wellbore dynamics in a steam-assisted gravity drainage system: Numeric and semi-analytic model, and validation

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HIGHLIGHTS

- An unsteady state nonisothermal two-phase wellbore model is reconstructed.
- A numeric and a semi-analytic structures of the model are derived.
- Two computer-assisted simulation algorithms are formulated.
- Both the model structures are validated with real field data.
- The models are compared in predicting the dynamic behavior of the wellbore.

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ABSTRACT

Steam injection is an integral and a crucial element of the steam-assisted gravity drainage (SAGD) process that has emerged as a leading technology to recover heavy crude oil from oil sands. In this contribution, we have developed a simulation algorithm for an unsteady state nonisothermal two-phase wellbore model to predict the downward flow of a wet steam. This numeric model is reconstructed by incorporating the mass and energy conservation equations, and a pressure drop relationship, along with a couple of algebraic equations/correlations. A drift-flux model is used to consider the slipping occurred between the phases inside the wellbore. Further, the existence of four flow regimes in the wellbore is also taken into account. This dynamic wellbore flow model is attempted to simulate by developing a numerical algorithm. Furthermore, an analytical expression for wellbore pressure is determined to derive a semi-analytic model. Formulating a computer-assisted simulation algorithm for this, it is shown that the semi-analytic model offers a reduced complexity and computational time over the numeric model. A series of numerical and analytical results are presented to validate the wellbore models against the real field data. Subsequently, both the models are extended to predict the transient behavior of the steam injection system. It is investigated that both the solution methods provide similar results.

1. Introduction

A significant percent of reserve oil (more than 2 trillion barrels) is existed in the form of oil sands. The largest deposit of oil sands in the world is found in Canada (Alberta), Venezuela, United States and a few countries in the Middle East. Oil sands are typically formed by combining clay, sand, water, and bitumen. Unlike the conventional oil recovery processes that primarily involve the mining followed by pumping of crude oil before the refinement into several cuts, the recovery of heavy oil (e.g., bitumen) from rest of the oil sand components is much more challenging. Aiming to make the production of this resource efficient, some amount of heat needs to be used for decreasing the oil viscosity, enabling flow at reasonable pressure gradients. In this light, steam injection method has gained tremendous importance in heavy oil recovery and it is an integral part of the steam-assisted gravity drainage (SAGD) system, which is a promising innovation in oil sands extraction technology. This steam injection technique is currently used in the San Joaquin Valley of California (US), the Lake Maracaibo area of Venezuela, and the oil sands of northern Alberta (Canada).

Estimation of temperature, pressure and steam quality with respect to depth and time is a crucial issue in designing and

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monitoring the steam injection wells. Both temperature and pressure of the injected steam vary mainly because of [1]: (i) the heat transferred between the hot stream (i.e., wellbore steam) and cold formation surrounding the well, (ii) the change of hydrostatic pressure with depth, and (iii) the frictional loss between the steam and inner tubing surface. As a consequence, the steam quality should drop with depth, starting from wellhead to bottomhole. It is with this intention that the present work has been undertaken to find a rigorous model for developing efficient simulation algorithms to precisely estimate the temperature, pressure as well as steam quality.

The first work on the modeling of injection well goes back to early 1960s [2]. Under the assumption of steady state incompressible single-phase flow with fixed fluid and formation properties with reference to both depth and time, Ramey's analytical model provides the temperature inside the well as a function of depth and time. In that simplified model, the frictional loss and kinetic energy effects are not taken into account, and the estimation is made with supposing a constant overall heat transfer coefficient.

Subsequently, Satter [3] has improved Ramey's model by avoiding a couple of idealizations. The work considers the variation of fluid properties with phase and temperature, and the depth-dependent overall heat transfer coefficient. The affect of frictional loss and kinetic energy is taken care of by Holst and Flock [4]. A year later, Willhite [5] has introduced a method to determine the overall heat transfer coefficient. After a long gap, Fontanilla and Aziz [6] have proposed an alternative procedure in their multiphase nonisothermal wellbore model to estimate the heat transfer coefficient, and this method is adopted in this paper.

Hasan and Kabir [7] have started working on wellbore flow modeling since 1994. They [8] have included two-phase flow using the drift-flux approach, and kinetic energy and Joule–Thomson effects. Livescu et al. [9] have proposed a comprehensive numerical nonisothermal multiphase wellbore model. Initially, their approach has solved the fully coupled conservation equations. Later, they have decoupled the wellbore energy balance equation from the mass balance equation in most of their investigations. Further, it is shown that their model simplifies to Ramey's model under a couple of assumptions. At the same time period, Bahonar et al. [1] have developed a numerical nonisothermal two-phase wellbore model to simulate the flow of steam/water mixture. Their semi-unsteady state model considers the steady-state condition for the complete wellbore system (i.e., no accumulation terms) and unsteady state condition for the formation that surrounds the wellbore system. Very recently, Hasan and Kabir [11] have published a review paper discussing a unified approach for modeling the wellbore heat transfer in various situations and applications. The analytical temperature equation proposed by the same group [8] is used in their modeling study, and then tested it to many routine production-operation problems.

The modeling of an injection well is really challenging because of: (i) the existence of multiple phases in the wellbore, (ii) the dynamic nature of fluid flow and (iii) the complexity involved in heat transfer between the wellbore and the cold formation. In this work, an unsteady state nonisothermal two-phase wellbore flow model is adopted. Aiming to capture the spatial and temporal variations of temperature, pressure and hence, steam quality for the downward flow of steam/water mixture in an injection well, a numeric model is restructured by the application of the conservation principle on all three fundamental quantities, namely mass, energy and momentum. The slip between the phases in the wellbore is taken into account by the employment of a drift-flux model. This rigorous model also considers the existence of four flow regimes in the wellbore. The variation of overall heat transfer coefficient with temperature and depth is accounted for in the model. This transient wellbore flow model that yields a coupled differential algebraic equation (DAE) system is simulated by developing a numerical algorithm. All computational steps are arranged sequentially for this complex simulation problem. Furthermore, an analytical expression for wellbore pressure is determined to derive a semi-analytic model. Formulating a computer-assisted simulation algorithm for this, it is inspected that the semi-analytic model offers a reduced complexity and computational effort over the numeric model. Validating both the mathematical models at steady state condition with field data, those structures are subsequently compared in predicting the dynamic behavior of the unsteady state injection wells, for which, perhaps no experimental data are available.

2. Wellbore flow model: steam injection system

The widespread application of steam injection approaches to oil fields has necessitated investigations of changing temperature, pressure and steam quality. In this section, we build the basic structure of an unsteady state nonisothermal two-phase fundamental model of a wellbore system. Later, two different forms of this transient model will be extracted to formulate the respective computer-assisted simulation algorithm to conduct a systematic comparison for finding their relative benefits.

2.1. *Unsteady state model structure: basic equations*

Transient behavior of the wellbore fluid develops as the heating medium (here, steam) moves downward from wellhead, exchanging heat with the surrounding formation. As stated before, the temperature profile in the wellbore cannot remain constant with time mainly because of the heat exchanged between the hot fluid and the formation. The changes in fluid temperature lead to a changing pressure and therefore, steam quality profile throughout the wellbore. Apart from their changes with time, the temperature, pressure and quality also vary with depth owing to the frictional loss, changes in kinetic and potential energy, and geothermal gradient.

As stated, once steam is injected into the wellbore, the spatial and temporal variations of temperature and pressure, and therefore the quality are inevitable. The variations with depth can conveniently be captured by the static model. On the other hand, the unsteady state heat transfer model will give the time-dependent temperature profile at each incremental depth for a particular operating condition. With this objective, at first we find an unsteady state energy balance equation followed by the coupled static modeling equations.

2.1.1. *Unsteady state energy balance*

An energy balance for the wellbore fluid is needed to model the heat transport. It is true that the fluid (i.e., wet steam) receives heat through fluid convection and it loses heat to the surroundings (i.e., formation) through conduction. Fig. 1 depicts the schematic representation of the wellbore system and formation. It is a fact that in addition to the energy accumulation (storage) of the fluid, there is also some sort of energy stored in the tubing, casing, and cement material in the wellbore [11]. Note that the effect of mass transient on energy transport usually becomes negligible very rapidly. Accordingly, one can decouple the heat transfer from both the mass and momentum transports, yielding the following energy balance equation [8]: