International Journal of Heat and Mass Transfer 127 (2018) 949–958

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

# Heat and mass transfer characteristics of steam in a horizontal wellbore with multi-point injection technique considering wellbore stock liquid

Shijun Huang, Meng Cao *, Yun Xia, Xiao Chen, Menglu Yang

*College of Petroleum Engineering, China University of Petroleum, 102249 Beijing, China*

ARTICLE INFO

*Article history:*
Received 21 February 2018
Received in revised form 24 June 2018
Accepted 25 July 2018

*Keywords:*
Long horizontal well
Steam injection
Uneven employment
Wellbore stock liquid
Steam distribution

ABSTRACT

In this paper, a novel model is proposed to study the variable mass flow process in a long horizontal well and to predict the distribution of thermophysical properties along the horizontal wellbore.

First, a physical simulation device is designed to carry out a steam-injection experiment. Second, considering both the uneven distribution of steam and the effect of wellbore stock liquid, a steam-absorption model and a pressure drop model are proposed to predict the distribution of steam and pressure along the horizontal wellbore. Third, the effects of different parameters on steam distribution are analyzed in detail. The results indicate that: (1) an uneven employment phenomenon exists along the wellbore; (2) the pressure distribution along the wellbore is higher when wellbore stock liquid is taken into consideration; (3) the length of the unemployed section along the wellbore increases with an increase in the wellbore stock liquid viscosity; (4) the length of the unemployed section along the wellbore decreases with an increase in the steam injection rate; and (5) the reasonable wellbore length can prevent an unemployed section along the wellbore.

This paper presents a basic reference for engineering for parameter optimization as well as for the prediction of steam distribution along the horizontal wellbore.



## 1. Introduction

China is rich in heavy oil resources, which account for more than 20% of the total oil reserves in the world [1,2]. Steam injection recovery methods using horizontal wells, such as cyclic steam stimulation (CSS) [3,4], steam flooding [5–8], and steam-assisted gravity drainage (SAGD) [9–13], have been proven to be effective and economic in exploiting heavy oil reservoirs [14–20]. Horizontal well steam injection technology has been used to develop heavy oil in China which is commonly used to inject steam into horizontal wells that were several kilometers deep [21,22]. In the application of horizontal well steam injection, the uneven utilization of horizontal well sections and the uneven distribution of steam in reservoirs have become increasingly prominent issues [23–26]. Production monitoring data shows that the uneven utilization of steam injection horizontal wells will significantly decrease the economic benefit of developing heavy oil reservoirs [27].

The study of steam distribution along horizontal wells is based on the study of the horizontal wellbore flow. The research on horizontal wellbore flow developed from single-phase flow to multi-phase flow, from ignoring the pressure drop along the wellbore to considering the pressure drop along the wellbore. In 1984, Peter [28] summarized the related research on wellbore flow and analyzed the factors influencing the pressure drop along wellbore flow, such as flow rate, fluid viscosity, and wellbore inner diameter. In 1990, Dikken [29] used the discretization wellbore model to calculate the relationship between flow rate and pressure drop during wellbore flow and formed a plate. In addition, the calculation results showed that ignoring pressure drop along a horizontal wellbore would cause fairly large errors. In 1991, Folefac [30] proposed a drift-flow model to solve the problem of the velocity difference between the gas phase and the liquid phase in the horizontal wellbore and found that the horizontal well length was one of the important factors affecting the pressure loss along the horizontal wellbore. In 1995, Ozkand [31] proposed a complete and comprehensive mathematical model to study wellbore hydraulics in horizontal wells. In addition, he found that if the pressure drop in the wellbore was significant, a larger proportion of the fluid would enter the wellbore near the heel of the well. In 1997, Zhou [32] established an analytical model of pressure drop along the wellbore according to the flow characteristics of fluids. The results showed that when the horizontal well length was longer, pressure loss could not be ignored. In 2011, Li [33] established a mathematical model of pressure drop along the horizontal well, using the

* Corresponding author.
*E-mail address:* 2016212083@student.cup.edu.cn (M. Cao).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.07.136
0017-9310/

**Nomenclature**

| | |
|---|---|
| $Q$ | volumetric outflow rate, $m^3/d$ |
| $\Delta P$ | pressure drop, MPa |
| $J$ | fluid productivity index of horizontal well, $m^3/(d\cdot MPa)$ |
| $I_s$ | steam-absorbed index, dimensionless |
| $K$ | permeability, $\mu m^2$ |
| $\beta$ | unit conversion factor, dimensionless |
| $K_r$ | relative permeability, dimensionless |
| $B$ | volume factor, $m^3/m^3$ |
| $\mu$ | viscosity, mPa·s |
| $L$ | horizontal well length, m |
| $A_o$ | drainage area, $m^2$ |
| $r_w$ | radius of horizontal wellbore, m |
| $S$ | skin factor, dimensionless |
| $\rho$ | density, $kg/m^3$ |
| $H_l$ | liquid holdup |
| g | acceleration of gravity, $m/s^2$ |
| $\lambda$ | drag coefficient, dimensionless |
| $G$ | mass flow rate of mixture, kg/s |
| $v$ | velocity, m/s |
| $D$ | wellbore diameter, m |
| $A$ | wellbore cross section area, $m^2$ |
| $v_{sg}$ | apparent gas velocity, m/s |
| $P$ | pressure, Pa |
| $Re$ | Reynolds number |
| $T_i$ | initial reservoir temperature, K |

*Subscripts*

| | |
|---|---|
| $s$ | steam |
| $oi$ | radial outflow in $i$ element intervals |
| $oe$ | sum of radial outflow |
| $h$ | horizontal direction |
| $v$ | vertical direction |
| $w$ | water |
| $o$ | oil |
| $l$ | liquid |
| $se$ | the end of steam section |
| $ob$ | the beginning of wellbore stock liquid section |
| $interface$ | vapor-liquid interface |
| $f$ | flow pressure |
| $i$ | initial state |

corresponding mathematical model to analyze the effect of the Reynolds number, two-phase fluid flow rate, and roughness of the wellbore on the pressure drop.

With the development of horizontal well steam injection technology, many researchers have studied steam distribution and parameter prediction along the horizontal well borehole based on the study of horizontal wellbore flow. In the 1960s, Ramey [34] and Willhite [35] conducted groundbreaking study on the thermal calculation of steam injection wellbores and proposed an approximate solution to the problem of wellbore heat transfer. By using this model, the temperature distribution of the fluid, oil tube, and casing pipe could be obtained at different depths and different times, which laid the foundation for the prediction of the wellbore thermal parameters. In 1996, Wang et al. [36] established a semi-analytical model to improve the uniformity of the two-phase steam outflow from horizontal wells along the wellbore and calculated the steam distribution of mass flow rate, temperature, pressure, and dryness. In 1999, Yang et al. [26] indicated that it was important for steam injection to accurately predict the parameter (pressure, temperature, dryness) change along the wellbore. In addition, they established a two-phase flow model of steam injection based on heat transfer and the two-phase flow principle. In 2010, according to the principles of mass conservation, energy conservation, and momentum conservation, Wang [37] derived a formula to calculate the distribution of dryness and pressure of steam along the horizontal wellbore. In 2012, on the basis of the mass flow rate calculation coupled with a double-tube pipe, Wu et al. [38] established a calculation model of the parameters along the wellbore of double-tubing steam injection. Using this model, the minimum steam injection rate during the SAGD preheating stage and the longest horizontal section length of the steam-injection well could be obtained.

One of the most important tasks in the design of steam injection projects is to estimate the properties of steam, such as mass flow rate and pressure distribution, before the fluid inside the horizontal wellbore enters the formation. Ni et al. [39] established a mathematical model for calculating the mass flow rate of wet-steam injection in the horizontal wellbores. Dong et al. [40] created a predictive model aimed at the thermophysical properties of multi-thermal fluid in perforated horizontal wellbores. Gu et al. [41] established a comprehensive mathematical model to estimate thermophysical properties and to analyze the performance of superheated-steam injection in horizontal wells. Sun et al. [42,43] presented numerical models for predicting the pressure and temperature of superheated steam & non-condensing gases (SNG) or superheated steam in horizontal wellbores. They found that the thermophysical properties of SNG influenced the mass flow. Previous research has been based on the assumptions that the wellbore is nearly empty or full of air before steam injection. That is to say, the wellbore is immediately filled with the steam when the steam injection is started. However, before steam injection, horizontal wells contain wellbore stock liquid, such as crude oil, drilling fluid, or well completion fluid. This wellbore stock liquid prevents the steam from advancing in the horizontal section, which seriously affects the steam distribution. The present prediction model of steam parameters along the well does not consider the influence of the wellbore stock liquid, which causes the calculation results to deviate from the actual situation.

In this paper, we conducted a series of studies on the distribution of thermophysical properties along the horizontal wellbore with a multi-point steam injection technique. This paper has four main innovations: (1) A steam injection physical simulation experimental device was designed independently. (2) Considering the effect of wellbore stock liquid, a new steam-absorption model was proposed. (3) Considering physical properties and flow states of the wellbore stock fluid, an improved pressure drop model was proposed; and (4) the influence of parameters on steam distribution was studied in detail.

This study uncovered some important intrinsic distribution characteristics of pressure and steam along the horizontal wellbore, which will be useful for oil field.

## 2. Experiment

### 2.1. Experimental system

A SAGD two-dimensional (2D) physical simulation experimental device is designed independently to simulate the SAGD production process. A schematic diagram of the experimental device is shown in Fig. 1. The experimental system has four main