Energy Conversion and Management 99 (2015) 119–131

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Thermophysical properties estimation and performance analysis of superheated-steam injection in horizontal wells considering phase change

Hao Gu [a,*], Linsong Cheng [a], Shijun Huang [a], Bing Bo [b], Yinguo Zhou [a], Zhongyi Xu [a]

[a] Department of Petroleum Engineering, China University of Petroleum, Beijing, 18 Fuxue Road, Changping, Beijing 102249, China
[b] Research Institute of Petroleum Exploration & Development, PetroChina, 20 Xueyuan Road, Haidian, Beijing 100083, China

ARTICLE INFO

Article history:
Received 1 February 2015
Accepted 11 April 2015
Available online 25 April 2015

Keywords:
Superheated-steam injection
Thermophysical properties
Performance analysis
Phase change
Horizontal wells

ABSTRACT

The objectives of this work are to establish a comprehensive mathematical model for estimating thermophysical properties and to analyze the performance of superheated-steam injection in horizontal wells. In this paper, governing equations for mass flow rate and pressure drop are firstly established according to mass and momentum balance principles. More importantly, phase change behavior of superheated steam is taken into account. Then, implicit equations for both the degree of superheat and steam quality are further derived based on energy balance in the wellbore. Next, the mathematical model is solved using an iterative technique and a calculation flowchart is provided. Finally, after the proposed model is validated by comparison with measured field data, the effects of some important factors on the profiles of thermophysical properties are analyzed in detail. The results indicate that for a given degree of superheat, the mass flow rate drops faster after superheated steam is cooled to wet steam. Secondly, to ensure that the toe section of horizontal well can also be heated effectively, the injection rate should not be too slow. Thirdly, the mass flow rate and the degree of superheat in the same position of horizontal wellbore decrease with injection pressure. Finally, it is found that when reservoir permeability is high or oil viscosity is low, the mass flow rate and the degree of superheat decline rapidly.

1. Introduction

Thermal recovery methods [1], such as CSS (cyclic steam stimulation), steamflooding and SAGD (steam-assisted gravity drainage) [2], have already been proved effective and economic in exploiting heavy oil reservoirs. Moreover, wet steam is usually chosen as heat carrier when these methods are used, and one of the main reasons is that both the latent heat of vaporization and the specific heat capacity of water are higher than those of any other commonly-used liquid. In other words, injecting wet steam into pay zones can release a large amount of latent heat and sensible heat to raise reservoir temperature and to lower oil viscosity. However, superheated steam may also be a good choice for the heat carrier. Compared with wet steam, superheated steam is characterized by high steam quality, high temperature and low pressure [3], which guarantees that it has many advantages in thermal recovery of heavy oils. For example, not only the specific enthalpy of superheated steam is larger than that of wet steam at the same pressure, but also superheated steam can further improve flow environment in porous media [4] and promote aquathermolysis of heavy oils [5]. At present, cyclic superheated-steam stimulation using vertical wells is widely applied in Kenkiyak Oilfield, Aktyubinsk, northwest of Kazakhstan. But if an oil layer is not thick enough, a horizontal well would be more productive than a vertical well due to its larger reservoir contact area. As superheated steam flows along a horizontal wellbore, its thermophysical properties, such as mass flow rate and the degree of superheat, always change with horizontal well length, more importantly, superheated steam may undergo phase change and be cooled to wet steam in a certain position of the wellbore, in this case, steam quality is another key parameter that needs to be determined. Therefore, one of the most important tasks in the design of superheated-steam injection projects is to estimate these thermophysical properties before the fluid inside the horizontal wellbore enters the formation.

The classic work in this area was firstly developed by Ramey [6], who derived an important expression for fluid temperature as a function of well depth and injection time by combining wellbore/formation heat-transfer model with energy balance equation. Hasan and Kabir [7] set up a detailed formation heat-transfer model and proposed a new expression for transient heat-conduction time function, which was further improved by

* Corresponding author. Tel.: +86 10 89733726.
E-mail address: guhao110110@163.com (H. Gu).

http://dx.doi.org/10.1016/j.enconman.2015.04.029
0196-8904/

Nomenclature

A_c	cross-sectional area of casing, m^2
A_d	drainage area, m^2
B	volume factor, m^3/m^3
dp/dL	pressure drop gradient, Pa/m
D_{ci}	inside diameter of casing, m
f	friction factor, dimensionless
f_{ci}	forced-convection heat transfer coefficient on inside of casing, W/(m^2 K)
$f(t)$	transient heat-conduction time function, dimensionless
g	gravitational acceleration, m/s^2
h	specific enthalpy, J/kg
H	thickness of oil layer, m
H_L	liquid holdup, dimensionless
I	volumetric outflow rate of fluid injected into the formation, m^3/s
I_r	injectivity ratio, dimensionless
J_0	first kind Bessel functions of zero order
J_1	first kind Bessel functions of first order
J_{pi}	productivity index, m^3/(s Pa)
K	permeability, μm^2
K_r	relative permeability, dimensionless
L	horizontal well length, m
ΔL	length of perforation unit, m
M_r	volumetric heat capacity of pay zone, J/(m^3 K)
n_{perf}	perforation density, m^{-1}
N	total number of perforations or perforation units
p	pressure, Pa
$\overline{p}$	average pressure, Pa
Δp	pressure drop, Pa
Q_c	heat conduction rate, W
Q_{in}	energy carried by hot fluid at the inlet, W
$Q_{rad,i}$	energy transferred to the formation due to radial outflow, W
Q_{out}	energy carried by hot fluid at the outlet, W
r_{ci}	inside radius of casing, m
r_{co}	outside radius of casing, m
r_h	heated radius, m
r_{ph}	radius of perforation hole, m
r_w	radius of horizontal wellbore, m
Re_i	Reynolds number, dimensionless
s	skin factor, dimensionless
$\overline{S_w}$	average water saturation, dimensionless
S_{wi}	initial water saturation, dimensionless
t	injection time, s
T	temperature, K
T_{deg}	degree of superheat, K
T_{ei}	initial temperature of the formation, K
T_{interf}	cement/formation interface temperature, K
$\overline{T}$	average fluid temperature, K
ΔT	temperature drop, K
u	dummy variable for integration, dimensionless
U_{co}	over-all heat transfer coefficient between fluid and cement/formation interface, W/(m^2 K)
$\Delta u/u^*$	roughness function
v	velocity, m/s
v_r	radial velocity, m/s
v_{sg}	superficial gas velocity, m/s
w	mass flow rate, kg/s
x	steam quality, dimensionless
Δx	steam quality drop, dimensionless
Y_0	the second kind Bessel functions of zero order
Y_1	the second kind Bessel functions of first order

Greek letters

α	thermal diffusivity of formation, m^2/h
β	unit conversion factor, dimensionless
ε	roughness of casing wall, m
θ	well angle from horizontal
λ_{cas}	thermal conductivity of casing wall, W/(m K)
λ_{cem}	thermal conductivity of cement sheath, W/(m K)
λ_e	thermal conductivity of formation, W/(m K)
μ	viscosity, mPa s
ρ	density, kg/m^3
τ_D	dimensionless time
ω	ratio of the formation heat capacity to the wellbore heat capacity, dimensionless
ϕ	porosity of oil layer, dimensionless

Subscripts

acc	acceleration
h	horizontal
m	mixture
ns	no-slip
o	oil
perf	perforation roughness
pot	potential energy
r	reservoir
s	dry steam
superh	superheated steam
v	vertical
w	saturated water
i, j, k	index

Cheng et al. [8] who considered the effect of wellbore heat capacity on heat flow in cement/formation interface. Satter [9] presented a method of predicting steam quality distribution by taking into account the effect of condensation. Farouq Ali [10] proposed a comprehensive mathematical model for calculating steam quality according to energy balance in the injected fluid. Gu et al. [11] suggested a simplified approach for estimating steam pressure and derived a complete expression for steam quality in wellbores. Although, the above classic researches are all about fluid injection in vertical wells, they lay a solid foundation for estimation of thermophysical properties of fluid in horizontal injection wells. Ni et al. [12] established a mathematical model for calculating mass flow rate of wet-steam injection in horizontal wellbores, but they ignored the energy change due to radial outflow when modeling steam quality based on energy conservation principle, which was corrected by Wang et al. [13]. Dong et al. [14] created a predictive model aimed at thermophysical properties of multi-thermal fluid in perforated horizontal wellbores. Su and Gudmundsson [15,16], whose work was very crucial to determining the total pressure drop in horizontal wellbores, carried out pressure drop experiments in perforated pipes and suggested a governing equation for friction factor of perforation roughness. Emami-Meybodi et al. [17] developed a transient heat conduction model to estimate heat transfer from horizontal wellbore to the formation.

The authors and their team have done a series of researches on estimation of thermophysical properties in the cases of wet-steam injection [18], unsteady-state steam injection conditions [19], concentric dual-tubing steam injection [20] and superheated-steam injection in vertical wells [21]. Based on previous studies, the authors begin to focus on cyclic superheated-steam stimulation using horizontal wells that is applied in KMK Oilfield, Aktyubinsk, Kazakhstan. However, superheated-steam injection