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Heat and mass transfer characteristics of superheated fluid for hybrid solvent-steam process in perforated horizontal wellbores

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ABSTRACT

In this paper, the authors presented a novel model for estimating thermophysical properties of solvent in perforated horizontal wellbores (PHWs) considering the complex heat and mass transfer characteristics in the PHWs, so that the phase state of the fluid in hybrid solvent-steam process can be predicted. Firstly, governing equations for mass flow and pressure drop were established based on mass and momentum balance principles and the Equation of State. More importantly, implicit equations for phase changes from superheated steam and solvent to wet steam and superheated solvent, and to wet steam and solvent, were derived based on heat and mass transfer in the wellbore. Next, the mathematical model was solved using Levenberg-Marquardt Algorithm (LMA). Finally, validation and sensitivity analysis of the model were conducted sequentially. The validated results showed that, when injecting heavier solvent in the hybrid process, the temperature along the PHWs tends to stay at a high level and the solvent condenses at position far away from the toe position of the wellbore, but that of lighter solvent injection shows an opposite trend. Furthermore, to increase the temperature at toe position of the PHWs when injecting lighter solvent in the hybrid process, a higher superheat degree at the heel of PHWs is preferred, while the increased superheat degree may not help to ease condensing of heavier solvent in the PHWs. Besides, increasing the injection rate is more beneficial to reducing the solvent loss along the horizontal wellbore for both heavy and light solvent injection, than that of increasing the superheat degree at the wellbore head.

1. Introduction

Thermal recovery method, by injecting saturated steam or superheated steam into the formation, is one of the most successful commercialized recovery methods for heavy oil reservoirs [1,2]. The heavy oil is heated near the steam chamber edge and flows towards the production well [3]. Therefore, it is a highly energy-intensive process, which not only forces the economics of the method to be susceptible to oil prices but also causes large Green House Gas (GHG) emissions associated with steam generation by the burning of fossil fuels [4].

To save energy and to be more environmentally friendly, the technique of hybrid solvent-steam process has been proposed [5]. In the process, a hydrocarbon solvent is co-injected with steam to reduce further the viscosity of heavy oil due to the combined effects of dilution and heat [6–10]. Previous research shows that the technique boasts an improvement of the steam-oil ratio (SOR), which means a lower energy consumption and GHG emission in comparison with conventional thermal recovery method [10–16]. However, the high cost of solvent makes it necessary to ensure the vapor phase of the most solvent at injection point [17–19], so that the solvent can travel through the steam chamber and contact with heavy oil. In this case, superheated fluid, characterized by high quality and high temperature, can guarantee the phase state of the solvent at the injection point. Besides, a horizontal well would be superior to a vertical well due to a larger contact area between the solvent and heavy oil. As a result, a hybrid solvent-steam process by injecting superheated mixture at the injection end of a perforated horizontal wellbore (PHW) has many advantages over injecting saturated fluid in the vertical well.

As superheated solvent and steam travels along a PHW, thermophysical properties, such as temperature and pressure, always change with horizontal well length, more importantly, superheated steam and solvent may undergo phase change successively [20] and be cooled to wet fluid at certain positions on the wellbore. In this case, in order to make full use of the costly solvent, solvent

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Nomenclature

a	geothermal gradient, K/m
A', B' and C'	coefficients for determination of saturation temperature
A_d	effective swept formation area, m^2
B	volume factor
C_{cap}	thermal capacity of the component, J/(kg·K)
f	fugacity, Pa
$f(t)$	transient heat-conduction time function
f_{perf}	friction factor of perforation roughness
f_{wall}	friction factor for pipe flow
g	acceleration of gravity, m/s^2
H	thickness of the reservoir, m
h	enthalpy of the superheated component, J/kg
H_L	liquid holdup
H_{vap}	vaporization enthalpy of the component, J/kg
HVR	coefficient of vaporization enthalpy, J/(mol·K)
I	volumetric outflow rate into the reservoir, m^3/s
I_r	injectivity ratio
J_{pi}	productivity index, m^3/(s·Pa)
K_h	horizontal permeability of the reservoir, μm^2
K_r	relative permeability
K_v	vertical permeability of the reservoir, μm^2
L	length of the PHW, m
ΔL	length of perforation unit, m
M	molecular weight, g/mol
m_{sol}	mass fraction of solvent at the heel position of PHW
n_{perf}	perforation density, m^{-1}
p	pressure, Pa
$\overline{p_r}$	average reservoir pressure, Pa
p_{sat}	saturation pressure, Pa
Q_{in}	energy come into the perforation unit, J/s
Q_{out}	energy come out of the perforation unit, J/s
R	universal gas constant
r_{ci}	inside radius of casing, m
r_{co}	outside radius of casing, m
r_{di}	inside radius of outer tubing in vertical well, m
r_{do}	outside radius of outer tubing in vertical well, m
r_{ph}	radius of perforation hole, m
r_{ti}	inside radius of inter tubing in vertical well, m
r_{to}	outside radius of inter tubing in vertical well, m
r_w	radius of horizontal wellbore, m
s	skin factor
$\underline{S_{wi}}$	initial water saturation of the reservoir
$\overline{S_w}$	average water saturation
T	fluid temperature in the PHW, K
T_c	critical temperature of the component, K
T_{deg}	superheat degree, K
T_{ei}	initial temperature of the formation in the vertical-well section, K
T_{sat}	saturation temperature, K
T_r	reservoir temperature, K
U_{co}	over-all heat transfer coefficient between fluid and cement/formation interface for PHW, J/(s·m^2·K)
U_{to}	over-all heat transfer coefficient between fluid and cement/formation interface for vertical wellbore, J/(s·m^2·K)
v_r	velocity of radial outflow from the PHW to the formation, m/s
v	velocity, m/s
v_{sg}	superficial gas velocity, m/s
w	mass rate of the mixed fluid, kg/s
X	steam/solvent quality
y	molar fraction of the component in one phase
z	reservoir depth, m
Z	compression coefficient

Greek letters

α_c, α_1 and α_2	coefficient for the calculation of molar density of solvent in oil phase
α	thermal diffusivity of the reservoir, m^2/h
β	unit conversion factor
μ	viscosity, mPa·s
λ_{cem}	thermal conductivity of cement, W/(m·K)
λ_e	thermal conductivity of the reservoir, W/(m·K)
λ_{ins}	thermal conductivity of the insulation materials, W/(m·K)
ϕ	porosity of the reservoir
θ	well angle from horizontal direction
ρ_L^0	reference molar density of liquid at the reference pressure and reference temperature, mol/m^3
ρ	density, kg/m^3
ρ_{ns}	no-slip density of steam/water/solvent mixed fluid, kg/m^3
$\overline{\rho}$	average density, kg/m^3
φ	fugacity coefficient
ε	roughness of casing wall, m
ω	ratio of the formation heat capacity to the wellbore heat capacity

Subscripts

m	mixture
i	index of component
j	index of perforation unit
k	index of phase
sol	solvent
s	steam
w	water component
superh	superheated state
G	gas phase
L	liquid phase
O	oil phase
W	water phase
acc	acceleration
pot	potential energy
r	reservoir
o	oil
ref	reference condition

quality and concentration are the key parameters that need to be predicted [21]. Therefore, one of the most important tasks in the design of hybrid solvent-steam injection projects is to estimate these thermophysical properties, which are directly associated with complex heat and mass transfer characteristics, before the mixed fluid inside the PHW enters the formation.

Modeling of wellbore heat transmission dates back to the late 1950's, when Lesem et al. [22] developed an analytical model for calculation of fluid temperature at the bottom of gas production wells. Ramey [23] presented a modified model to estimate heat loss rate for non-compressible and single-phase steam flow in vertical wellbores. Nevertheless, it is assumed that both of the kinetic