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Review article

Modeling of temperature distribution and oil displacement during thermal recovery in porous media: A critical review

Mohammad Islam Miah, Murtada A. Elhaj, Salim Ahmed, M. Enamul Hossain*

Department of Process Engineering (Oil and Gas Program), Memorial University of Newfoundland, St. John's, NL, Canada

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ABSTRACT

Thermal flooding is one of the most successful and widely used processes for heavy oil recovery. The memory-based fluid flow model is effective in characterizing reservoir heat transport mechanism, temperature profile, and predicting the performance of thermal recovery. Temperature has a substantial effect on the thermodynamic properties such as thermal conductivity of the formation. In addition, the influence of temperature on reservoir rock and fluid properties plays an important role in accurately predicting reservoir temperature distribution, oil displacement, and steam oil ratio. This paper presents a critical review and analyses to provide inclusive information on the state-of-the-art memory-based fluid flow modeling during the thermal displacement process. The review highlights the assumptions and limitations of the current models in the areas of thermal conductivity, temperature distribution, oil displacement, and steam oil ratio during the thermal flooding process in porous media. This paper also serves to provide an insight into future research opportunities to fill the knowledge gaps in the subject area by applying the memory concept and further improvement of the current and classical models for heavy oil recovery.

1. Introduction

1.1. Background and motivation

The current worldwide petroleum industry is facing a great challenge to produce hydrocarbon from mature reservoirs. The produced reserves from new discoveries have provided steadily declining replacement rate over the last few decades. For meeting the global energy demands by producing more oil from mature hydrocarbon reservoirs, enhanced oil recovery (EOR) is the most popular technique. EOR is accomplished by increasing the oil recovery after the primary recovery such as natural drive mechanisms, and secondary recovery such as water flooding techniques. This can be accomplished by many techniques such as thermal recovery, chemical or gas injection, ultrasonic stimulation and microbial injection. These EOR methods allow recovery of oil that was not economically recoverable earlier using conventional techniques. EOR methods involve the injection of substances and/or energy into the oil reservoir to unlock trapped oil, improve sweep and enhance production rates. Among the tertiary oil recovery methods, thermal techniques (i.e. cyclic steam stimulation, steam flooding and in-situ combustion) aim to reduce oil viscosity to increase its mobility through the application of heat into the reservoir formation. Among the EOR processes, thermal injection is the most successful and extensively used process that is applicable to a variety of heavy oil as well as bitumen reservoirs [1]. However, the achievement of a thermal flood is entirely dependent on understanding the mechanism of heat transfer within the reservoir and the complex interactions between the reservoir rock and fluid matrices, temperature-sensitive rock and fluid parameters, which govern the evolution of the temperature profile during the thermal EOR processes [2,3].

1.2. Fluid flow modeling

It is important to predict reservoir properties and rheology through the porous media during thermal flooding. The classical constitutive equation describing fluid flow in reservoir porous media is Darcy's law [4]. This equation is based on several assumptions such as single phase, isothermal laminar flow, no chemical reaction between rock and fluid, as well as constant permeability and viscosity [4]. When heat energy is introduced, thermal alterations of reservoir rock and fluid properties induce non-Darcy flow effects, which cannot be captured accurately by the Darcy equation. This type of modeling is a complicated research task in oil and gas engineering due to the complex nature of reservoir rock and fluid properties, and geological subsurface behavior. Rheology is the study of fluid flow and its deformation, which are related to the field of physics [5]. The study of rheology focuses on materials that

* Corresponding author.
E-mail address: dr.mehossain@gmail.com (M.E. Hossain).

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Nomenclature

List of symbols

A_{cD}	dimensionless steam zone size [fraction]
A (t)	cumulative heated area function of time [m^2]
a	Corey coefficient of the oil relative permeability curve
B_o	oil formation volume factor [rm^3/sm^3]
C_f	specific heat capacity of fluid [$J\,Kg^{-1}\,K^{-1}$]
CSS	cyclic steam stimulation
C_o	specific heat capacity of oil [$J\,Kg^{-1}\,K^{-1}$]
$CSOR$	cumulative steam oil ratio (fraction)
C_w	specific heat capacity of water [$J\,Kg^{-1}\,K^{-1}$]
C_r	specific heat capacity of rock [$J\,Kg^{-1}\,K^{-1}$]
c_F	non-dimensional form-drag constant
c_t	total compressibility in porous medium [1/Pa]
D	thermal diffusivity [m^2/s]
dt	time step [s]
E_H	heating efficiency [percentage]
$E_{h,s}$	overall reservoir thermal efficiency [percentage]
EOR	enhanced oil recovery
G	the body force term due to gravity [N]
g	acceleration due to gravitation force [N]
H_o	heat injection rate [J/s]
H_m	hermite polynomial of order m
h	reservoir thickness [m]
k	reservoir permeability [m^2]
M	volumetric (overall) heat capacity [$JK^{-1}m^{-3}$]
m	temperature/viscosity parameter
P	pressure of condensate [Pa]
P_r	reservoir pressure [Pa]
P_s	pressure of the system [Pa]
P_{st}	steam temperature [Pa]
Q_o	cumulative oil production rate [m^3/s]
q	oil flow (drainage) rate [m^3/s]
q_v	convective heat flux [W/m^2]
r	radial distance of reservoir in Eq. (1) [m]
$SAGD$	steam-assisted gravity drainage
SF	steam flooding
S_o	oil saturation [fraction]
S_g	gas saturation [fraction]
S_w	water saturation [fraction]
T	reservoir temperature [K]
T_{inj}	injection temperature [K]
T_{st}	steam temperature [K]
$T*$	temperature gradient [K/m]
T_D^*	dimensionless temperature distribution [dimensionless]
dt/dx	temperature gradient along direction of heat transfer [K/m]
t	time [s]
t_D	dimensionless time [dimensionless]
t_{cD}	dimensionless critical time [dimensionless]
U_x	velocity of the advancing front of steam chamber (m/s)
$\vec{u}$	velocity vector [m/s]
V_{oD}	volume of displaced oil produce [fraction]
V_{pD}	initial pore void filled with steam as water [fraction]
v_s	linear velocity of steam front [m/s]
W_k	a weighting function for the numerical integration
w_s	Steam zone half width [m]

Greek letters

∇P	pressure gradient [Pa/m]
ΔS_o	change in oil saturation before/after steam front passage [fraction]
Δx	size of grid block in x direction
$\nabla \varnothing$	fluid potential gradient [N]
ξ	a dummy variable for time i.e., real part in the plane of the integral [s]
ξ'	distance measured ahead of the front into the coder zone [m]
$d\xi$	dummy time step [s]
ϕ	porosity of fluid media [fraction]
μ	fluid dynamic viscosity at any temperature [Pa-s]
μ_o	oil (dynamic) viscosity [Pa-s]
μ_w	water (dynamic) viscosity [Pa-s]
ρ_c	condensate density [kg/m^3]
ρ_f	fluid density [kg/m^3]
ρ_o	oil density [kg/m^3]
ρ_r	dry rock density [kg/m^3]
ρ_w	dry rock density [kg/m^3]
λ	thermal conductivity [$Wm^{-1}\,K^{-1}$]
$\lambda_h(T)$	effective thermal conductivity function of temperature [$Wm^{-1}\,K^{-1}$]
λ_{hf}	thermal conductivity of fluid or formation [$Wm^{-1}\,K^{-1}$]
λ_{hR}	effective thermal conductivity of oil sand [$Wm^{-1}\,K^{-1}$]
λ_r	reservoir thermal conductivity [$Wm^{-1}\,K^{-1}$]
$\lambda_{h,s}$	thermal conductivity of steam [$Wm^{-1}\,K^{-1}$]
η	ratio of the pseudo-permeability of the medium with memory to fluid viscosity [$m^3s^{1+\alpha}/kg$]
η'	scaled dimensionless space variable
α	fractional order of differentiation (related to the time and space), dimensionless
α_1, α_2	derived variable for dimensionless thickness
α_c	simplified condensate (water) or convective diffusivity
$\alpha_{c'}$	volumetric conversion factor
β	coefficient of the classical darcy's law
β_c	transmissibility conversion factor
γ	fractional order derivative
Γ	euler gamma function
ξ	normal distance to the advancing front of the steam chamber [m]
θ	inclination of the draining surface from the horizontal plane [angle]
ω	dummy integral variable

Subscripts

e	effective
$erfc$	complementary error function
f	fluid
g	gas
m	confining layer
o	oil
r	rock (matrix)
v	convection
w	water

possess both viscous and elastic properties. Most underground reservoir fluids do not follow the Newtonian behavior [6]. Heavy crude oil is a non-Newtonian fluid at low temperatures [7]. Fluid rheology is an important issue for the prediction of rock-fluid interactions within a complex oil reservoir or any formation management. The subsurface structure and reservoir rock properties of a formation are not only dependent on the deposition, but also on the sedimentation process within the earth's interior with respect to geological age [8]. This subsurface