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Full Length Article

Analytical modelling of steam chamber rise stage of Steam-Assisted Gravity Drainage (SAGD) process

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ABSTRACT

When steam is injected continuously in a SAGD operation, a steam chamber starts to develop in three stages; rise, lateral spreading and confinement, as observed in the field and laboratory experiments. The physics of chamber development in the first and the two last stages is different and thus modelled separately. Nearly all of the available theoretical analyses of SAGD are concerned with the lateral spreading stage of the steam chamber development with the exception of a few works which aim to determine rise velocity and oil rate. The rate of the upward growth of the steam chamber has a profound effect on the SAGD performance, because as the chamber reaches the top of the reservoir heat loss starts to play a significant role in the thermal efficiency of the process.

During the rise period, as the steam chamber grows upwards, oil drains downwards and so the process at this stage must account for to the frontal instability between steam and the liquid phases in the system. Stability is affected by factors such as the flow direction, gravity, and viscosity difference between gas/steam and liquid phases. Steam condensation, on the other hand, has a stabilizing effect.

In the present model, the rise velocity and the steam chamber height were calculated by combining volumetric oil displacement with Darcy oil rate considering the indirect effect of frontal instability. The model is extended to predict oil production, heat or steam injection rate, heat consumption and CSOR during this phase. Moreover, estimates of injected steam sweep efficiency and the angle between the steam chamber and the horizon are achieved. The model results show an increase in rise velocity with temperature and permeability. Also, the calculated oil production rate increases and Cumulative Steam Oil Ratio (CSOR) declines with time. This theory is tested via comparison with several field data sets to show the adequacy of the model.

1. Introduction

Several analytical models have been proposed for predicting steam chamber rise velocity, and in a few cases, for computing oil production rate at early times. The rise velocity and uniform steam distribution along the well pair at the early time of the SAGD process are the key parameters for evaluating the performance and economics of SAGD projects [4,13]. Closmann and Smith [9] measured the rate of steam chamber rise above a horizontal fracture in a steam injection project in the Athabasca oil sands and recorded the resulting temperature profile. Temperatures above the injection point were much higher than could be described by heat conduction alone. It was proposed that a higher rate of temperature increase could be explained if the steam front were moving upwards with a constant velocity. The measured steam rise was 0.021 m/day (0.070 ft/day) for a heat source at 198 °C. It was suggested that conduction was the dominant mechanism of heat transfer above the rising steam zone. Also, the numerical and analytical analyses showed good agreement with the observed upward movement of the steam front. Butler [4] developed a model to predict the constant upward steam front velocity. Steam flow into steam fingers and downward movement of heated oil around these fingers were postulated. The predicted steam chamber rise velocity was proportional to reservoir permeability, steam temperature, and oil viscosity and it also depended on the width of the steam finger. The model predicted a considerably lower maximum velocity (0.0047 m/day) than the observations of Closmann and Smith. Chung and Butler [8] conducted an experimental study using a 2D visual scaled reservoir model. Two well configurations were designed to represent the Steam-Assisted Gravity Drainage process. In the first scheme, the injector was horizontal and close to the horizontal producer near the base of the reservoir model which was a typical SAGD configuration. The second scheme consisted of a single horizontal production well and vertical wells close to the top of the formation. The laboratory study showed that in the first scheme, steam chamber started to rise until it reached the reservoir top. The measured

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Nomenclature

A	= Area, m^2
A_o	= Available area for oil to drain down at chamber top interface, m^2/m
A_s	= Available area for steam to move upward at chamber top interface, m^2/m
A_t	= Total area at the chamber top interface, m^2/m
c	= Specific heat capacity, J/kg. °C
c_o	= Specific oil heat capacity, J/kg. °C
c_r	= Specific rock heat capacity, J/kg. °C
c_w	= Specific water heat capacity, J/kg. °C
D	= Vertical depth, m
E_a	= Sweep Efficiency, fraction
f_s	= Steam quality
g	= Acceleration due to gravity, m/d^2
H	= Reservoir thickness, m
L_{int}	= Steam-oil interface length, m
L_v	= Latent heat of condensation of steam, J/kg
K_{res}	= Reservoir thermal conductivity, J/m.d.°C
k	= Absolute permeability, m^2
k_o	= Effective oil permeability, m^2
k_{ro}	= Relative oil permeability, m^2
k_{st}	= Effective steam permeability, m^2
m	= Dimensionless viscosity-temperature coefficient
m	= Mass, kg
Q_{inj}	= Cumulative heat injection, J/m
Q_o	= Cumulative oil production, m^3/m
Q_{oz}	= Cumulative heat into oil zone, J/m
Q_{ozo}	= Cumulative heat into the overhead interface of chamber, J/m
Q_{ozs}	= Cumulative heat into the side interfaces of chamber, J/m
Q_{sz}	= Cumulative heat to raise rock and fluid temperature from T_r to T_s, J/m
q_o	= Oil production rate, m^3/d-m
q_{omax}	= Maximum oil production, m^3/d-m
q_{sz}	= Heat rate to expand steam chamber, J/d-m
S_{oi}	= Initial oil saturation of reservoir
S_{or}	= Residual oil saturation in steam chamber
S_{wir}	= Irreducible water saturation
t	= Time, d
t_r	= Time at which steam chamber reaches the reservoir top, d
T	= Temperature, °C
T_D	= Dimensionless temperature
T_r	= Reservoir temperature, °C
T_s	= Steam temperature, °C
V_{oD}	= Darcy velocity, m/day
x	= Distance from production well in x axis, m
y	= Distance from production well in y axis, m
α	= Reservoir thermal diffusivity, m^2/day
α_A	= Dimensionless coefficient, areal flow ratio of oil to steam
α_{LS}	= Dimensionless coefficient, Lateral Spreading Coefficient
δ	= Total available width for liquid streams at chamber top interface, m
η	= Moving coordinate in y direction, m
θ	= Angle of steam-oil interface to horizon
μ_o	= Dynamic oil viscosity, kg/d-m
ν_o	= Kinematic oil viscosity, m^2/day
υ_{os}	= Kinematic oil viscosity at steam temperature, m^2/day
ρ_o	= Oil density, kg/m^3
ρ_g	= Steam density, kg/m^3
ρ_r	= Reservoir rock density, kg/m^3
ρ_w	= Water density, kg/m^3
$(\rho c)_{res}$	= Volumetric heat capacity, J/ m^3. °C
$\Delta\rho$	= Density difference between steam and oil, kg/m^3
ψ	= Distance from the sides of the steam chamber, in normal direction, m

oil production rate showed an increasing trend during this period. The rise velocity was not reported. The chamber grew fast during the first 20 min of the experiment, but slowed down thereafter, until it reached the top.

Chow and Butler [7] performed a numerical study, using a commercial simulator (STARS), for the SAGD process during the rise and lateral spreading phases of the steam chamber. The objective was to match oil recovery and interface positions as reported in Chung and Butler [8] experimental data. The rising steam chamber could not be modelled properly even with relative permeability adjustments. It was concluded that the lack of built-in physics such as steam fingering, and water/oil emulsification in the simulator caused this mismatch. Birrell and Putnam [3] suggested a graphical method to estimate the location and growth rate of the steam chamber during the rise period based on thermocouple data above the steam chamber. Ito and Ipek [17] discussed steam fingering during the rise time through the numerical history matches of measured field data. It was believed that the dimension of steam fingers is of the order of a few metres, similar to what Butler [4] concluded. It was postulated that a geomechanical change of formation at the early times has a profound effect on the generation of the steam fingers in addition to viscosity and density differences. It was noted that as the operating pressure increased the rise velocity increased.

Gotawala and Gates [15] extended the Butler [4] theory of steam fingers and concluded that the length of steam fingers from their model was smaller compared to the results of [4]. Also, it was claimed that the rise rate from the model was closer to the reported field data compared to Butler model. The two-phase counter-current flow noted in Butler [4] work was extended by Dehghanpour, Murtaza, and He [12] to include water-oil coupling at the edge of steam fingers to find the steam rise velocity that was higher than predicted. Butler [5] developed a model for steam chamber rise velocity and oil production rate during the steam chamber rise period by use of the original oil rate equation. Two curve fitted parameters were introduced to match experimental oil rate and steam chamber height to the model responses. No model was proposed for evaluating the SAGD thermal efficiency during the rise period. Sasaki et al. [18] studied experimentally the expansion and vertical rise of the steam chamber, and drainage mechanism close to the chamber edge. The oil production rate and steam chamber shape were reported. Oil production rate was seen to increase during the rise period, reaching a maximum.

Baker et al. [2] conducted a numerical simulation study of the SAGD process for early times of the project. It was concluded that the steam chamber during the rise period was unstable and it was critical to control the volumetric sweep efficiency of the injected steam as it had a significant impact on project economics. Azad and Chalaturnyk [1] proposed a circular geometry for representing the steam chamber to model the steam chamber rise phase. The model results were validated against Chung and Butler [8] experimental data, showing a good match between the predicted oil rate from the model and the experimental results. The steam chamber geometry observed in Chung and Butler experiment is very close to an inverted triangle as noted by the authors.

There is currently no analytical model describing all aspects of the rise stage of the SAGD process. The new analytical approach proposed in this study predicts the rise velocity, oil production rate, steam injection rate, and CSOR for this period. In this approach, counter-current