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Using exponential geometry for estimating oil production in the SAGD process

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ABSTRACT

SAGD, a steam injection method, is known as one of the most effective ways of heavy oil recovery. In addition to existing numerical methods, a fast alternative for evaluation of heavy oil recovery from a porous media by SAGD is to use semi-analytical models, which in recent years have considerably progressed.

Along this evolution, this study is aimed at introducing a model based on that suggested by Reis. Therefore, a more accurate estimation of oil production rate, steam chamber expansion and the amount of steam required for the process can be made. In this model, the most important mechanism for heavy oil recovery by SAGD is heat conduction and consequently gravity drainage of heated oil. The innovation established in this work is representing the location of oil–steam interface by an exponential function to excel the linear assumption in Reis's model. The presented model is finally compared with experimental, numerical and field data to assess its quality.

1. Introduction

Undoubtedly as conventional oil reserves are running out, the global demand for more viscous and heavy oils is growing. The natural flow of heavy or viscous oils does not easily occur in the reservoir (Mozaffari et al., 2013). In fact, the main problem in these reservoirs is the high oil viscosity. From various thermal methods recently introduced for heavy oil recovery, SAGD and its modifications have been attended more as they have appeared effective in recovery of heavy oils and bituminous sands (Hashemi-Kiasari et al., 2014; Kamari et al., 2015). Thermal methods are popular mostly because of the large viscosity drop occurring by a temperature rise (Shin and Polikar, 2005). As Fig. 1 indicates, steam is injected through a horizontal well and the heated oil is produced through another horizontal well located in the reservoir bottom. Heat is often transferred to viscous oil by conduction, whereas the heat of convection plays its role in this heat transfer as well. As the oil becomes heated, its viscosity declines sharply and starts to flow downward along the steam–oil interface to the production well by gravity drainage mechanism.

It is very difficult to model the beginning of a SAGD process when the steam chamber is forming and most analytical and semi-analytical simulators forgo that part. Therefore, authors usually attempt to model the sidewise expansion of the chamber. Butler and Mac Nab (1981) were the first to find equations for the sidewise expansion of the steam chamber at steady state. Combining Darcy's law and Heat Conduction along with a mass balance in the reservoir bed helped them find the oil production rate and locate the interface at any time. Of course, estimating a higher production rate compared to the real rate and a non-physical (unreal) indication of the interface were among the shortcomings of their model. Although it was later modified by Butler et al. (1981), a proper equation to accurately estimate the production rate and to determine the exact whereabouts of the chamber was yet to be found. It was Butler (1985) again to suggest a method in 1985, which could predict the chamber's growth and the production rate under semi-steady state conditions. As he stated, the major problem in all preceding equations was assuming a steady temperature distribution along the interface. Such a matter occurs only in the center of the interface and assuming so in the two interface ends is quite non-physical and leads to illogical results. Thus, he divided the interface into several elements for each of which he embraced mass and energy balances. Consequently, every element

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Nomenclature

a	Coefficient of velocity
b	Coefficient of horizontal distance
C	Scale coefficient
C_R	Specific heat of formation
H	Height of reservoir
k	Permeability
L	Interface length
L_s	Latent heat of steam
m	Viscosity coefficient
M_R	Formation heat capacity
q_o	Dead oil drainage rate
$\acute{Q}_{inj}$	Rate of Latent heat injection
$\acute{Q}_{loss}$	Rate of energy loss through overburden
Q_R	Enthalpy required to heat oil ahead of the interface
$\acute{Q}_R$	Enthalpy rate required to heat oil ahead of the interface
$\acute{Q}_s$	Steam injection rate
$\acute{Q}_{sz}$	Enthalpy rate needed for expansion of steam chamber
ΔS_o	Initial oil minus residual oil saturation of system
SOR	Steam–Oil ratio
t	Time
ΔT	Temperature difference between steam and virgin oil temperature
U_m	Maximum horizontal velocity
U_v	Velocity perpendicular to the steam chamber edge
W_S	Half-width of steam chamber
x	Horizontal distance from wells
X	Steam quality

Greek symbols

α	Thermal diffusivity of reservoir
η	Coordinate parallel to interface
$\nabla\Phi$	Flow potential gradient
φ	Porosity
θ	Angle of interface respect to horizontal
μ	Dynamic oil viscosity
ν_{os}	Kinematic oil viscosity at steam temperature
ρ	Density
ρ_R	Density of formation
ρ_o	Density of oil
ρ_w	Density of water
ξ	Coordinate perpendicular to interface

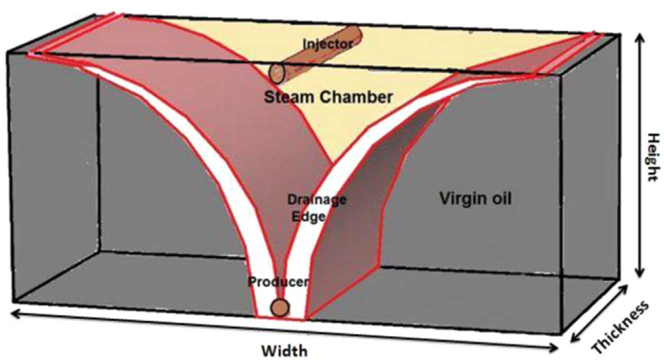

Fig. 1. Concept of the SAGD process.

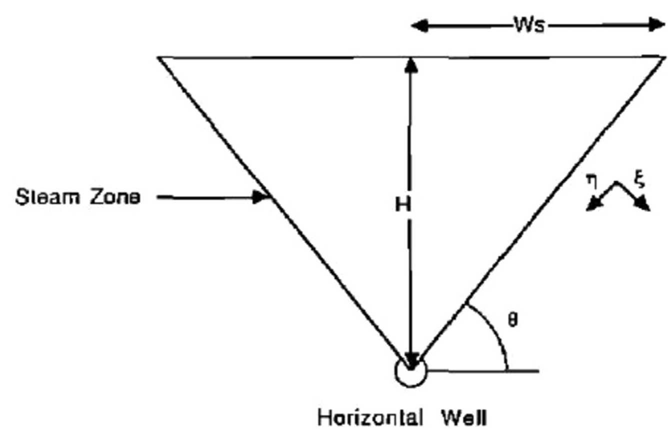

Fig. 2. Scheme of steam zone cross section in the Reis model (Reis, 1992).

separately moves toward the reservoir boundaries with oil drainage and indicates a specific location of the interface.

Years later, Reis (1992) defines a linear geometric model for locating the interface in which the interface is introduced as a straight line moving at an even pace in steady state conditions. Just as in Butler's work Darcy's law, heat conduction and the steady temperature distribution on the interface helped him calculate the oil production rate. Using these and the mass balance equation, he finally obtained the Eq. (1):

$$q_o = \sqrt{\frac{\varphi \Delta S_o k_o g H \alpha}{2 a \nu_{os} m}} \quad (1)$$

which evaluates the oil produced from one edge of the interface and:

q_o = oil production rate
φ = porosity
ΔS_o = initial oil minus residual oil saturation of system
k_o = oil permeability
H = reservoir height
α = thermal diffusivity of reservoir
a = coefficient of velocity
ν_{os} = oil viscosity at steam temperature
m = coefficient of viscosity

Furthermore, Reis (1992) found this relationship to describe the shape and location of the interface at each time of the SAGD process:

$$W_s = \sqrt{\frac{2 k_o g \alpha}{\varphi \Delta S_o a \nu_{os} m}}\, t \quad (2)$$

where W_s represents half of the chamber's width (half of the triangle's base Fig. 2). It is important to note that most analytical models assume a constant expansion velocity for the steam chamber, which is not well acknowledged by the physical reality. Anyhow, analytical and semi-analytical models are known as decent instruments for a faster estimation of the production rate, using the reservoir properties accessible.

Exploiting Butler's idea and the application of HIM (Heat Integral Method) in converting the energy balance PDE equation into a solvable ODE one and finding the heat diffusion depth ahead of oil–steam interface in semi-steady state conditions. Heidari et al. (2009) and Pooladi-Darvish et al. (1995) unveiled a semi-numerical method that could give a better estimation of the production rate and the interface locations. They assumed the temperature distribution profile ahead of the interface in an exponential or polynomial form. This helped them to calculate the heat penetration depth in each time interval.