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Prediction for steam chamber development and production performance in SAGD process

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A R T I C L E I N F O

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A B S T R A C T

Understanding steam chamber development of the steam assisted gravity drainage (SAGD) is important to predict SAGD production performance. In early research, a number of investigations have been conducted on the steam chamber development process and SAGD production performance separately. Although there must be some links between steam chamber development and SAGD production performance, as to our knowledge, few studies have been published to build a relationship between them. This paper proposes a new analytical model to predict steam chamber development process and SAGD production performance simultaneously. Comparisons have been made between the new model results and STARS (a mature commercial reservoir numerical simulator) results for a specific super-heavy oil reservoir case in Canada and similarity is observed. According to previous numerical and experimental research, we assume that the steam chamber shape is a combination of two symmetrical parabolas rather than an inverted triangle. The oil production rate is expressed by the steam chamber expansion rate as a function of reservoir properties as well as production and injection parameters. An energy balance equation is employed to connect the steam expansion rate and heat loss rate to surrounding formation (overburden, underburden, and formation ahead of steam chamber). With the parabola-shape assumption and energy balance equation, the steam expansion rate is calculated. Meanwhile, some key production parameters, such as oil production rate and steam oil ratio are predicted. With the help of the new model, a quick decision can be made for the SAGD production limit, such as the least reservoir thickness, or the least mobile oil saturation.

1. Introduction

Heavy oil resources play an important role in crude oil reserve replacement to meet the world's future energy needs. The heavy oil reserve is estimated to be 750 billion tons (4700 billion barrels), of which 160 tons (1000 billion barrels) are thought to be recoverable (http://www.total.com/, 2007). Despite its colossal potential, the super viscosity of heavy oil at initial reservoir conditions is a great challenge for heavy oil production. Up to now, two predominant in-situ recovery methods are cyclic-steam stimulation (CSS) and SAGD. The SAGD process was firstly introduced by Butler (Butler et al., 2009; Butler and Stephens, 1981) with two horizontal parallel wells. Since then, a lot of studies have been conducted on evaluating SAGD process.

In the research of SAGD process, great attention has been put into the description of steam chamber development and dynamic production performance. The steam chamber expansion theory is a basis for predicting SAGD production performance. Butler (Butler and Stephens, 1981) carried a series of experiments about SAGD. Steam was injected into the formation through the upper well and flew upwards until it touched the cold formation. Steam released its latent heat and condensed into water while as cold viscous oil was heated. Condensate water and heated oil flew downwards under the effect of gravity and more steam flooded into the formation to take up the void space and formed a region full of steam which was called steam chamber. During this process, the steam injection rate was controlled to balance the oil drainage rate so as to maintain the formation pressure within the steam chamber region approximately constant. Assuming that the temperature distribution outside the steam chamber was steady-state distribution corresponding to the instantaneous rate of interface advance, Butler derived the steam chamber movement rate and oil production rate. However, the SAGD oil production rate calculated by this model

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Nomenclature

q_o	oil mass production rate per well length, kg/(m.d)
ϕ	reservoir porosity
S_{oi}	initial oil saturation
S_{wc}	combined water saturation
t	SAGD production time, d
B	well space, m
q_{ht}	latent heat injection rate per well length, kJ/(m.d)
q_s	steam injection mass rate per well length, kg/(m.d)
q_{hloss}	heat loss rate to surrounding areas per length, kJ/(m.d)
ρ_r	the density of sand rock, kg/m^3
ρ_o	oil density, kg/m^3
H	vertical distance between production well and reservoir top, m
S_{lr}	residual liquid saturation
x_m	x-displacement of the steam chamber, m
t_b	required time for steam chamber reaching half well space, d
y_m	y-displacement of the steam chamber, m
ω_s	steam injection mass rate per well length, kg/(m.d)
H_v	steam latent heat per mass, kJ/(kg)
q_{heff}	required heat rate associated with steam expansion per length, kJ/(m.d)
ρ_w	the density of sand rock, kg/m^3
C_{pr}	the heat capacity of sand rock, kJ/(kg.°C)
C_{pw}	the heat capacity of water, kJ/(kg.°C)
T_r	initial reservoir temperature, °C
λ_{cap}	the thermal conduction coefficient of cap rock, kJ/(m.d.°C)
C_{cap}	the heat capacity of cap rock, kJ/(kg.°C)
$\Gamma(\cdot)$	gamma function
C_{po}	the heat capacity of oil, kJ/(kg.°C)
T_s	steam temperature, °C
$\overline{q}_{hloss}$	heat loss rate per area, kJ/(m^2.d)
ρ_{cap}	the density of cap rock, kg/m^3
s	a variable in Laplace space

was too optimistic to apply in field practice. In the same year, Butler (Butler et al., 2009) improved his theory by finding the tangent line of the original steam interface curve and the results showed a better agreement with scaled laboratory data. However, the two models were too complex to use, Reis (Reis, 1992) simplified Butler's model. By monitoring temperature distribution of scaled SAGD experiment, he claimed that the steam chamber could be approximated as an inverted triangle. Meanwhile, an empirically based temperature profile was employed to determine the oil viscosity ahead of the steam zone. Compared with Butler's model, Reis's model was easy to apply. In recent years, with the development of numerical algorithm and computer technology, non-isothermal reservoir numerical simulation becomes a popular method to predict steam chamber development process.

As for SAGD dynamic performance, the consumption of steam is a primary expense in the production period. Therefore, much attention is focused on cumulative steam oil ratio. Reis (Reis, 1992) calculated the heat loss rate to overburden and developed an equation for estimating steam oil ratio based on the triangle-shaped steam chamber assumption. Edmunds and Peterson (Edmunds and Peterson, 2008) supposed that the steam chamber was an inverted triangle and the steam chamber expansion rate was constant. Under such assumptions, Edmunds used energy balance equation and material balance equation to yield the steam oil ratio for the horizontal expansion period of steam chamber. On the basis of Edmunds and Peterson's work, Miura and Wang (Miura and Wang, 2010) extended the analytical model to the steam chamber developing downwards period. However, all the above research was based on a constant chamber expansion speed and didn't give a description for steam chamber development process.

In our research, we propose a new analytical model for predicting steam chamber development process and SAGD production performance. There are three main features compared with previous research: (1) the steam chamber is considered as a combination of two symmetrical parabolas rather than an inverted triangle; (2) the SAGD production performance parameters (oil production rate, steam oil ratio, and so on) are expressed as a function of both reservoir properties and operating parameters; (3) the steam chamber expansion rate is solved by energy balance equation instead of simple assumption.

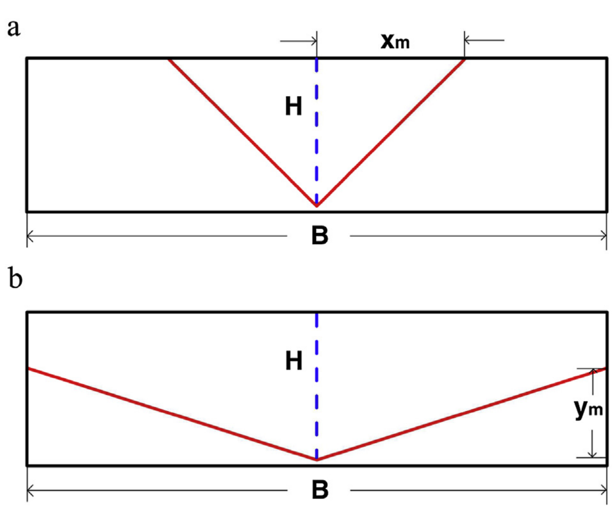

Fig. 1. Illustration of a triangle-shaped steam chamber: (a) steam chamber horizontal expansion and (b) steam chamber going downwards.

2. Model description and solutions

During SAGD production stage, steam is injected through the upper well and travels upwards until it contacts the cold formation and condenses into water completely. The condensate water and heated oil flow along the steam–fluid interface and are drained into the lower producing well. Steam is filled inside the interface and forms the so called steam chamber. As a result of the great gravity difference between water/oil and steam and the laterally parallel well pattern, the steam chamber tapers down. Chung and Butler (Chung and Butler, 1987) found that the steam chamber was much like an inverted triangle. Reis (Reis, 1992) assumed that the steam chamber was an isosceles triangle with its vertex fixed on the production well as is shown in Fig. 1. However, based on this assumption, the steam chamber expansion velocity, and the oil production rate are usually larger than field data. More Laboratory experiments were carried out by Joshi (1986) which revealed that the steam chamber shape was more like as a parabola. With the development of computer technology, numerical simulation became an important tool to reproduce oil-gas-water migration law. In 2007, Shako and Rudenko (Shako and Rudenko, 2007)