Energy 130 (2017) 76–85

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

A novel method to calculate consumption of non-condensate gas during steam assistant gravity drainage in heavy oil reservoirs

Zhan-xi Pang [a,*], Zheng-bin Wu [b], Meng Zhao [b]

[a] State Key Laboratory of Petroleum Resources and Engineering, China University of Petroleum, Beijing 102249, China
[b] Faculty of Petroleum Engineering, China University of Petroleum, Beijing 102249, China

A R T I C L E I N F O

Article history:
Received 22 June 2015
Received in revised form
7 March 2017
Accepted 14 April 2017

Keywords:
SAGD
Heavy oil reservoir
Nitrogen injection rate
Steam chamber
Material balance

A B S T R A C T

The thermal recovery technology, SAGD, shows unique advantages to develop heavy oil reservoirs. A certain volume of non-condensate gas injected along with steam can effectively decrease heat loss from steam chamber to top-layer. Also, gas can dissolve in heavy oil to decrease the saturation of residual oil in the steam chamber. According to the one dimensional steady heat transfer theory, a mathematical model was introduced to optimize the thickness of gas layer during steam-gas assisted gravity drainage in heavy oil reservoir. Aiming at the dissolubility of non-condensate gas into heavy oil, a mathematical model was established to calculate injection rate of gas phase according to SAGD theory when steam and nitrogen were simultaneously injected into reservoirs. According to some geology characteristics, such as top water, large thickness, high viscosity, of an actual reservoir in China, the minimum thickness of nitrogen layer is 12.06 m, and the volume of injected nitrogen is 47.86 $\times$ 10^4 m^3, and the injection rate of nitrogen is 5957.96 m^3/d when steam and nitrogen were simultaneously injected into reservoirs after SAGD stage.

1. Introduction

1.1. SAGD technology

Steam Assisted Gravity Drainage (SAGD) is a novel method for heavy oil development which combines horizontal well and steam injection [1–3]. This technology was first proposed by a Canadian professor named R. M. Butler [1]. A field test which gained great success was conducted in Alberta, Canada, and then a large-scale of industrial application was carried out. SAGD utilizes steam as heating medium, and relies on gravity to produce heavy oil. In SAGD processes, a horizontal production well is generally drilled close to the bottom of the reservoir, and steam is continuously injected by a parallel horizontal well or a series of vertical wells above [4–6]. A steam chamber gradually forms over the production well during steam injection. The injected steam contacts with the cold oil during rising up, and then the condensate water and the heated oil flow to production well under gravity [7,8]. The greatest advantage of this technology is to use steam overlay. As shown in Fig. 1, during the SAGD process, there are two stages of gravity drainage in steam chamber [6,8]. The first is a vertical drainage stage in which steam moves upwards to heat crude oil at the top of the reservoir. And then the heated crude oil flows directly downward under gravity [9]. The other is lateral drainage stage in which heat gradually transfers to cold reservoir laterally after steam chamber rises to the top of the reservoir. The heated crude oil flows downwards under gravity along the slope of steam chamber [7,8]. During SAGD, except for the driving force caused by the difference of fluid densities, there is no pressure difference between the injection well and the production well, that is, the drainage of crude oil is totally dependent on gravity [10,11]. If the density difference between steam and oil is greater, then the effect of gravity drainage is more obvious.

Butler et al. were the first ones to derive the classical mathematical model of SAGD by coupling Darcy's law and heat transfer theory [12]. Butler and Stephens modified the above study to account for drainage into a series of parallel wells, which considered an approximation of the interface curves by tangential connection to the production well. It was often referred to as the 'TANDRAIN' model [1]. Butler developed a semi-analytical approach to predict the location of interface and the oil drainage rate under unsteady-state conditions [13]. In this model, an ordinary differential equation (ODE) for the heat penetration depth of the interface was derived. Reis derived a similar theory for SAGD of vertical wells. In this model, the steam chamber is assumed to be an inverted cone [14]. Akin developed a theory of SAGD that accounted for steam distillation and asphaltene deposition effects [15]. The shape of

* Corresponding author.

http://dx.doi.org/10.1016/j.energy.2017.04.078
0360-5442/

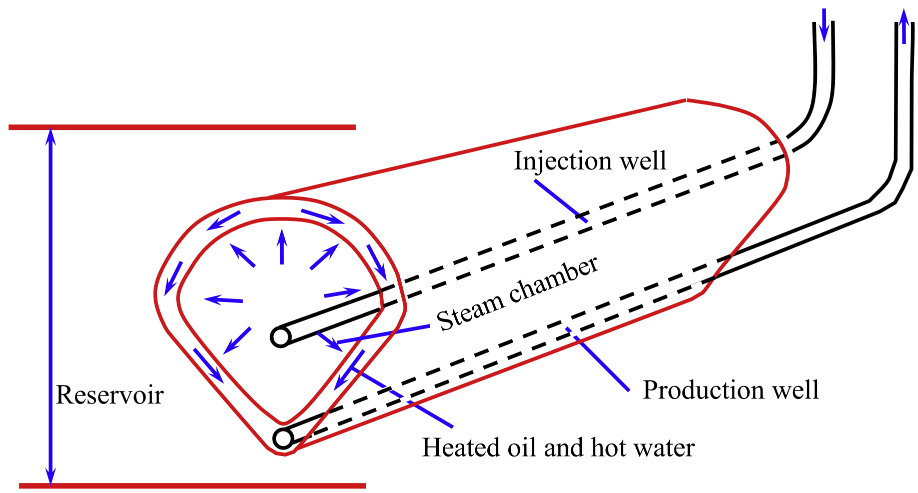

Fig. 1. The schematic diagram of SAGD.

steam chamber was approximated as an inverted triangle. Sharma and Gates considered the multiphase flow at the edge of a steam chamber during SAGD to derive a new theory to take into account the impact of oil saturation and relative permeability on the oil mobility [16]. The model revealed that the oil drainage rate was different from Butler's and other theories. The gamma function was introduced, which accounted for the viscosity parameter m and Corey parameter a. In addition, many researchers extended the theory of SAGD under the help of numerical simulation technology [17,18]. The theory summarization about SAGD are listed in Table 1.

1.2. SAGP technology

During SAGD, steam injection by adding non-condensate gas is called SAGP, which is an abbreviation of 'Steam and Gas Push' [19,20]. Non-condensate gas gathers above the injection well in the steam chamber to decrease heat loss of the cap rock [21,22]. The steam chamber maintains a low enthalpy to greatly decrease steam consumption. During co-injection of non-condensate gas and steam, steam chamber continues growing upwards and the temperature of the crude oil in the top of steam chamber gradually rises [21–25]. The heated crude oil flows along the boundary of steam chamber into the production well. Meanwhile, non-condensate gas gradually rises and gathers at the top of the reservoir, which can effectively decrease heat transfer between the steam chamber and the cap rock. Therefore, the rate of steam chamber expanding upwards gradually decreases to result in steam mainly heating oil sands on both sides of steam chamber [26–28]. So the vertical expanding rate of SAGP is less than that of SAGD, however the horizontal expanding rate of SAGP is greater than that of SAGD [29–32]. In SAGP process, steam chamber is ellipse in longitudinal section, however the steam chamber is inverted triangle in SAGD process, as shown in Fig. 2. The non-condensate gas plays a role in the maintenance of steam chamber pressure to decrease steam consumption. The fingering of non-condensate gas is also beneficial to increase the mobility of the steam front [24,25,31].

Butler considered the chamber defined by the inclined and vertical thick lines in Fig. 3 [19,20]. Then they derived an equation about the temperature distribution and oil production, as shown in following equation:

$$T_{Sy} = T_R + (T_S - T_R)\left[\frac{h-y}{\left(h-\frac{h_1}{2}\right)^2}\frac{m}{K_o g \alpha \Delta S_o}\left(\frac{q}{L}\right)^2\right]^{\frac{1}{m}} \tag{1}$$

The equation can be used to predict the oil drainage rate vs. different height that is corresponding to a certain temperature. However, it was no useful to calculate the gas consumption, especially for gas injection during SAGD.

Mohsen et al. presented a semi-analytical method for comparing oil drainage rates of SAGD during injecting steam and solvents [32]. They combined Darcy's law with the material balance method to deduce a new equation of oil drainage about steam-solvent co-injection during SAGD, as follows:

$$q_{o,coinj} = q_{o,SAGD}\sqrt{\frac{K_{rL,coinj}}{K_{rL,SAGD}}}\sqrt{\frac{\Delta S_{o,coinj}}{\Delta S_{o,SAGD}}}\sqrt{\frac{(U_m I_o)_{coinj}}{(U_m I_o)_{SAGD}}} \tag{2}$$

In addition, the numerical simulation technology can also be employed to optimize SAGD or SAGP. But the technology needs a large number of parameters about the reservoir geology and the production performance [25,28,31]. Therefore, it can hardly be used to resolve the oilfield questions in a short time.

1.3. Purpose of this study

The theory of SAGD has been mature, but SAGP is still at a state of qualitative analysis. On the basis of SAGD theory, a novel method to calculate the consumption of non-condensate gas during SAGD was introduced to decrease the heat loss from the cap rock. In this article, the material balance method and the heat conduction theory were employed to establish a new mathematical model to calculate some important parameters, such as the volume of steam-gas chamber, the volume of pre-injected gas, the injection rate of non-condensate gas and etc. The method deeply improves the theory system of SAGD or SAGP in the field of thermal recovery for heavy oil reservoirs.

2. Theory

SAGD has been proved as a perfect method to develop heavy oil reservoir. During the process of SAGD, steam overlay is used to drive heavy oil, which is unfavorable for the other thermal recovery technology, such as steam flooding, steam huff and puff. However, a large amount of heat will lose along the cap rock when steam chamber arrives at the top of oil layer. A certain amount of non-condensate gas, such as CO_2, N_2, CH_4 and flue gas, injected with steam can enlarge the volume of steam chamber and can decrease the residual oil saturation as well [21–25,31].