A novel model to investigate the effects of injector-producer pressure difference on SAGD for bitumen recovery

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Abstract: Steam-assisted gravity drainage (SAGD) provides many advantages compared to alternate thermal recovery methods for bitumen recovery. Nowadays, most of researchers believe that the gravity mechanism is the main drive in SAGD recovery, ignoring the injector-producer pressure difference, which makes the field prediction deviate from reality. To tackle this problem, this paper makes further investigation on the injector-producer pressure difference. A series of 2D numerical simulations are conducted on the basis of Mackay River reservoir in Canada to investigateon influence of injector-producer pressure difference. Meanwhile, a new mathematical model considering injector-producer pressure difference is established. The results indicate that when the injector-producer pressure difference exists, SAGD usually has better recovery. Pressure difference can effectively improve SAGD operating performance to achieve a high economic efficiency. More pressure difference does not necessarily lead to better recovery, for when the pressure difference increases to some certain degrees, it will cause steam breakthrough.
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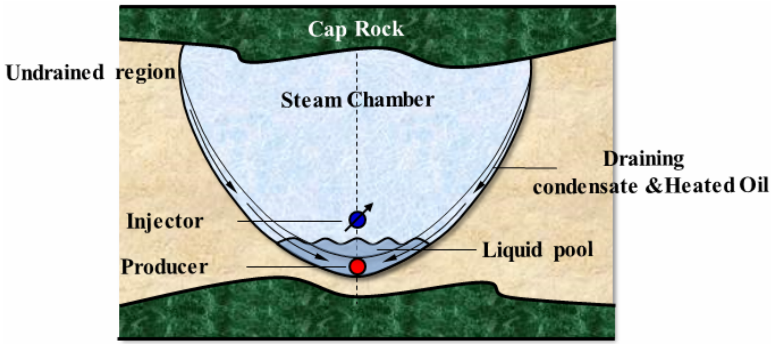
1 Introduction

As conventional oil reserves are running out, the global demand for more viscous and heavy oil is growing. However, because of the high viscosity of the heavy oil, the natural flow of heavy or viscous oils does not easily occur in the reservoir (Mozaffari et al., 2013). Nowadays, steam-assisted gravity drainage (SAGD) is considering as the most widely commercialised process for bitumen and heavy-oil recovery in most of the world. In SAGD, steam is injected through the top well, called the injector. When the steam enters into reservoir, it will heat the bitumen or heavy oil to decrease the viscosity and then the heated oil will flow to the lower well, called the producer (Butler et al., 1981; Butler, 1987). The concept of SAGD recovery process is shown in Figure 1. A variation on this recovery process is to inject steam into vertical wells and drain the oil to a lower horizontal well.

Figure 1 The concept of SAGD recovery process (see online version for colours)



Butler et al. (1981) assumed that the drive mechanism in SAGD recovery process was the gravity (Butler and Stephens, 1981). Based on this assumption, combining Darcy's law and Heat Conduction along with a mass balance in the reservoir bed help deduce the oil production rate. Later, lots of researchers have revised the model to make it more reliable. Reis (1992, 1993) stated that the limitation to the Butler's model was its complexity; and it required an iterative solution to a set of equations to calculate the production rate. He has provided linear and geometrical models for oil production where he introduced a dimensionless temperature coefficient to the denominator. However, his model does not predict production during the rise of the steam chamber. Wei et al. (2014) conducted a series of numerical simulations and found the shape of steam chamber was a combination of two symmetrical parabolas rather than an inverted triangle. Then, based on the new steam chamber shape, Wei proposed a new analytical model to predict steam chamber development process and SAGD production performance simultaneously, but Wei still did not consider the steam chamber rising stage. Butler assumed steam chamber along the horizontal well is uniform, but later researchers (Ong et al., 1990; Law et al., 2000; Das et al., 2005; Wei et al., 2010) regarded this assumption was unreasonable, for the steam non-conformance is rather common phenomenon in SAGD recovery process. And then Luo (2012) revised Butler's model by considering the steam non-conformance along the horizontal well.

Although Butler's model is considered more accurate, there are still some flaws in the model. For example, Butler assumed that gravity is the only drive mechanism in SAGD recovery process. Later researches find that it is not like Butler's thought and the drive mechanism is more complex. Adegbesan (1992) analysed the performance of a thermal horizontal well pilot. He used the analytical models to prove that pressure drive mechanisms dominated the early life of the well, with gravity drainage accounting for most of the production later in the well's life. Farouq-Ali (1997) questioned the recovery mechanism in SAGD. He mentioned that although gravity provided the drive in the processes, the processes are quite different from what Butler thought of. Then he used the field example-Tangleflags to support his conclusion. Ito and Suzuki (1996) noted that there were other displacements in the recovery, not just the gravity. Edmunds (2000) established an effective way to solve steam breakthrough – steam trap. Usually, if there is a steam trap, there will be pressure difference between injector and producer. Chen (2015) also raised questions on Butler's mathematical model. He mentioned that the pressure difference between injector and producer played an important role on recovery. If we ignore the pressure difference, the predicted outcomes are usually lower than the field data. Although these researchers stated the unreasonable assumption on driving mechanism, they just only characterised this oilfield phenomenon, and did not make further investigation.

Therefore, in this paper, a new predictive model which considers the differential pressure as a drive mechanism for the SAGD recovery process is presented based on the Butler's model. Meanwhile, a series of numerical simulations on different pressure difference are conducted. With the new proposed model, main production indexes (oil production rate, cumulative oil production) can be predicted quickly and conveniently. Besides, the validation of new mathematical model is testified by numerical simulations based on Mackay River and Dover reservoir in Canada.

2 Mathematical modelling

Basic assumption for the mathematical model:

1. steam condenses on the interface, mixes with the oil and makes them with the same characters
2. in the steam zone, identical pressure means the same temperature
3. the injector-producer pressure difference will not reach the threshold of the steam breakthrough
4. fluid flow obeys Darcy's law
5. in the process of SAGD, it has uniform steam chamber along the horizontal well (Butler and Stephens, 1981).

2.1 Oil production rate

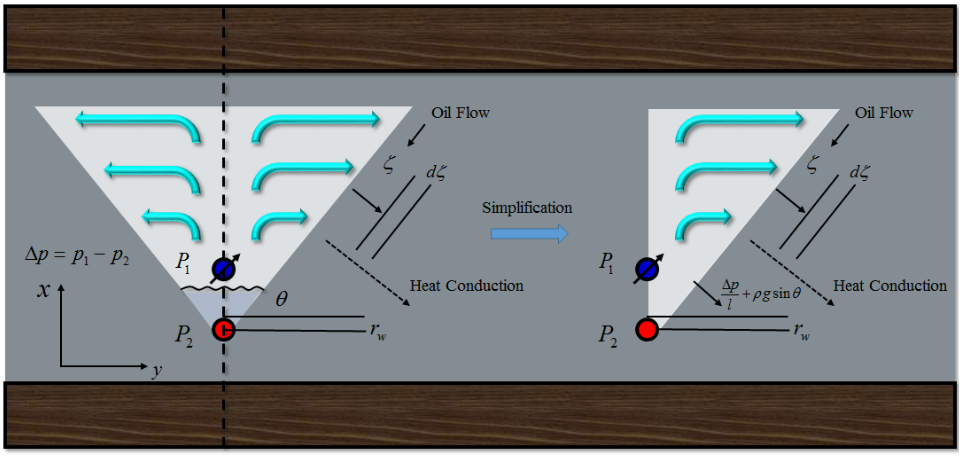
The model assumes that the steam zone shape is an inverted triangle with the lower vertex fixed at the production well (Reis, 1992). Configuration of SAGD process is illustrated in Figure 2.

According to Darcy' law, based on Butler's model, a section with unity thickness is written below (Butler, 1991)

$$dq_{lb} = \frac{\Delta \rho g K \sin \theta A}{\mu_o} = \frac{\left(\rho_0 - \rho_g\right) g K \sin \theta}{\mu_o} d\xi \tag{1}$$

where dq_{lb} is the rate of drainage per thickness without considering the pressure difference, m^2/d; ζ is the distance from the interface, m; μ_o is the viscosity of the oil, mPa•s; g is the gravity, m/s^2; Θ is the angle between steam/oil interface and production well; K is the permeability of the formation, 10–12 m^2; ρ_o and ρ_g are density of the bitumen and steam respectively, kg/m^3.

Figure 2 Small vertical profile of steam – reservoir transfer surface (see online version for colours)



When Butler's typical model considers the pressure difference between injector and producer, according to Darcy's law, a section with unity thickness could be written as equation (2):

$$dq_L = \frac{kA}{\mu_o l}\Delta p + \frac{\Delta\rho g k \sin\theta A}{\mu_o} = \left(\frac{k\sin\theta}{\mu_o y}\Delta p + \frac{(\rho_0 - \rho_g)gk\sin\theta}{\mu_o}\right)(1\times d\xi) \tag{2}$$

where dq_L is the rate of drainage per thickness considering the pressure difference, m^2/d; ΔP is the pressure difference between the injector and producer, kPa; y is the height of the steam chamber, m.

Because the ρ_g is so small compared with ρ_o, it can be ignored. Therefore, the above equation (2) can be simply written as:

$$dq_L = \left(\frac{\Delta p}{\rho_o y} + g\right)\frac{k\sin\theta}{\upsilon_s} d\xi \tag{3}$$

where υ_s is the kinematic viscosity of the oil, which is equal to $\frac{\mu_o}{\rho_o}$, m^2/d.

It is assumed that the heat transfer is by conduction only, and then the temperature ahead of the interface would be a steady-state advance. The temperature ahead of the interface for a steady-state advance is shown below (Butler, 1991):

$$\frac{T - T_R}{T_s - T_R} = e^{-U\xi/\alpha} \tag{4}$$

where T_R is the original temperature of the reservoir, °C; T_S is the temperature of the steam/oil interface, °C; U is the velocity of the interface, m/s; α is the thermal diffusivity of the tar sand, m^2/d.

There is an unknown variable U in the equation (4), but the velocity of the interface U is related to the term $\frac{\partial x}{\partial t}$, as in equation (5):

$$U = \left(\frac{\partial x}{\partial t}\right)_y \sin\theta \tag{5}$$

If the reservoir is unheated, then the corresponding differential flow can be shown by equation (6):

$$dq_R = \left(\frac{\Delta p}{\rho_o y} + g\right)\frac{k\sin\theta}{\upsilon_R}d\xi \tag{6}$$

where dq_R is the oil production rate of unheated reservoir; υ_R is the kinematic viscosity of unheated reservoir, m^2/d.

Equation (3) subtracts equation (6), then increased flow due to heating can be got by from equation (7):

$$dq_L - dq_R = k\sin\theta\left(\frac{\Delta p}{\rho_o y} + g\right)\left(\frac{1}{\upsilon_s} - \frac{1}{\upsilon_R}\right)d\xi \tag{7}$$

Redefining dq as $dq_L - dq_R$, and then integrating equation (7), as given in equation (8):

$$q = k\sin\theta\left(\frac{\Delta p}{\rho_o y} + g\right)\int_0^\infty\left(\frac{1}{\upsilon_s} - \frac{1}{\upsilon_R}\right)d\xi \tag{8}$$

Equation (8) cannot be integrated, so another way is applied.

The variation of viscosity with temperature depends upon the properties of the particular oil in the reservoir (Butler et al., 1981). One arbitrary form of temperature function that corresponds reasonably well to the performance of actual oils over the range of interest is given by equation (9):

$$\frac{\upsilon_s}{\upsilon} = \left(\frac{T - T_R}{T_S - T_R}\right)^m \tag{9}$$

Applying equation (4) and equation (9) to equation (8), as shown in equation (10):

$$\begin{gathered}\int_0^\infty\left(\frac{1}{\upsilon} - \frac{1}{\upsilon_R}\right)d\xi = \int_{T_R}^{T_S}\left(\frac{1}{\upsilon_S}\left(\frac{T - T_R}{T_S - T_R}\right)^m - \frac{1}{\upsilon_R}\right)\frac{\alpha}{U}\frac{dT}{T - T_R} == \frac{\alpha}{U}\frac{1}{m\upsilon_S} = \frac{\alpha}{\frac{\partial x}{\partial t}\sin\theta}\frac{1}{m\upsilon_S} \\ q = \left(\frac{\Delta p}{\rho_o y} + g\right)k\frac{\alpha}{\frac{\partial x}{\partial t}m\upsilon_s}\end{gathered} \tag{10}$$

In equation (10), there is an unknown variable $\frac{\partial x}{\partial t}$, it can be replaced by the material balance equation. The material balance equation is given below:

$$\left(\frac{\partial x}{\partial t}\right)_y = \frac{1}{\phi \Delta S_o}\left(\frac{\partial q}{\partial y}\right)_t \tag{11}$$

where ϕ is the porosity of the reservoir, %; ΔS_o is the difference between oil saturation and residual oil saturation, %.

Combine equation (10) and equation (11) to get a differential oil flow, as given in equation (12):

$$q = \left(\frac{\Delta p}{\rho y} + g\right)\frac{k\phi\alpha\Delta S_o}{m\upsilon_s}\left(\frac{\partial y}{\partial q}\right)_t \tag{12}$$

Equation (12) could be integrated by separating the variables, as written in equation (13):

$$\begin{gathered}\int_0^q q dq = \int_{r_w}^{y}\left(\frac{\Delta p}{\rho y} + g\right)\frac{k\phi\alpha\Delta S_o}{m\upsilon_s}dy \\ q = \sqrt{\frac{2k\phi\alpha\Delta S_o}{m\upsilon_s}\left(\frac{\Delta P}{\rho_o}\ln\frac{y}{r_w} + g\left(y - r_w\right)\right)}\end{gathered} \tag{13}$$

Because only part of y will be useful, so β is used to displace the constant 2 (Butler, 1991). Meanwhile, r_w is so small compared with y, so it also could be neglected. Finally, equation (13) is simplified as shown in equation (14):

$$q=\sqrt{\frac{\beta k\phi\alpha\Delta S_o}{m\mu_o}\left(\Delta P\ln\frac{y}{r_w} + \rho_o g y\right)} \tag{14}$$

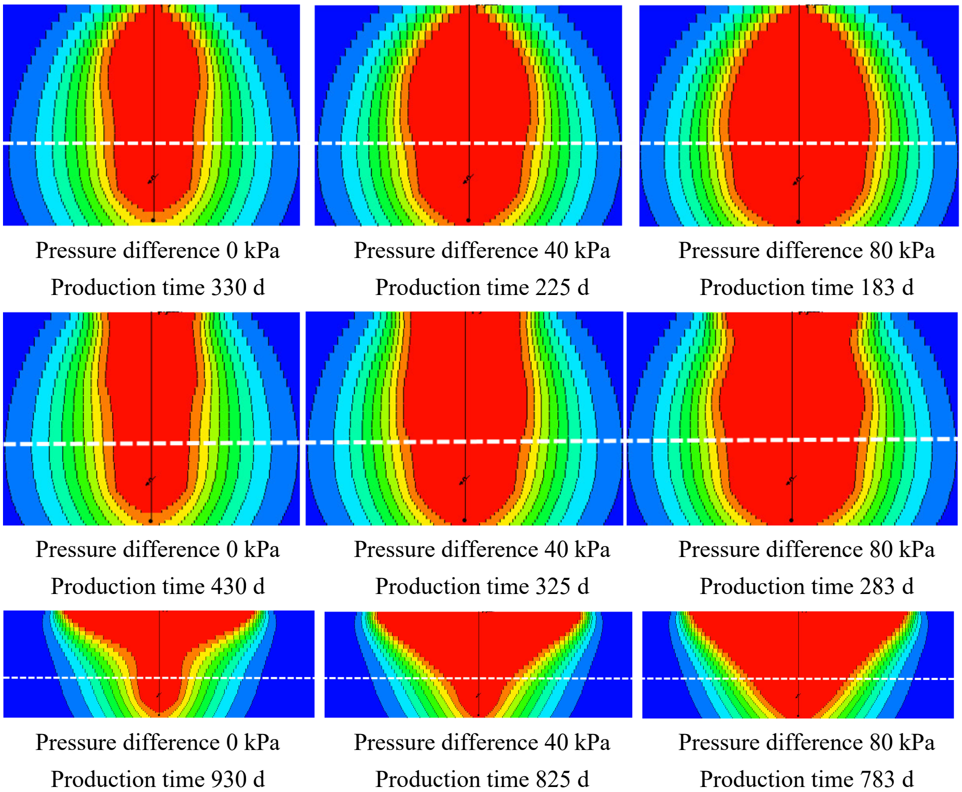
Equation (14) is the rate of drainage which considers the pressure difference between the injector and producer.

When the $\Delta P = 0$, equation (14) will become the Butler's oil drainage rate, as in equation (15):

$$q=\sqrt{\frac{\beta k\phi\gamma\alpha\Delta S_o g y\rho_o}{m\mu_o}} \tag{15}$$

In the process of SAGD recovery, it usually goes through three stages: the rising steam chamber, the lateral expansion of the steam chamber when it reaches cap-rock, and the declining steam chamber when it reaches the boundary (Huang et al., 2016). Figure 3 shows the steam chamber expansion on different pressure differences. Above the white dotted line, Figure 3 reveals that when the steam chamber reaches the cap-rock, the effect of pressure difference on steam chamber expansion is decreased. Therefore, in the second stage, the effect of pressure difference will become small. Meanwhile, this physical process also confirms Adegbesan's (1992) idea that pressure drive mechanisms dominated the early life of the well, with gravity drainage accounting for most of the production later in the well's life.

Figure 3 Steam chamber expansion on different pressure differences (see online version for colours)



2.2 Production model on the rising steam chamber

Butler's typical model assumes that the problem is a two dimension and that the shape of the steam chamber remains geometrically similar as it rises (Butler, 1991). The cumulative oil production will be proportional to the mobile oil per unit area multiplied by the square of the chamber height. The constant γ is determined by the shape of the chamber, and the area of the chamber is γy^2:

$$q_{cum} = \int_0^t q dt = \gamma \phi \Delta S_o y^2 \tag{16}$$

where γ is a constant number, which is equal to $\tan^2 \theta$.

Differentiating equation (16) with respect to time gives another expression for the rate of drainage, as in equation (17):

$$q = 2\gamma \phi \Delta S_0 y \frac{dy}{dt} \tag{17}$$

Making the right hand side of equation (15) multiplies 2 and it will be equal to the right hand side of equation (17), as shown in equation (18):

$$2\phi\Delta S_o\gamma y\frac{dy}{dt}=2\sqrt{\frac{\beta k\phi\alpha\Delta S_o}{m\upsilon_s}\left(\frac{\Delta P}{\rho_o}\ln\frac{y}{r_w}+gy\right)} \tag{18}$$

Assuming that $A=\phi\Delta S_o\gamma;\ B=\frac{\Delta P}{\rho};\ C=\sqrt{\frac{\beta\varphi\Delta S_o k\alpha}{m\upsilon_s}}$. Equation (18) is integrated by separating the variables, then equation (18) can be simplified to equation (19):

$$\int_{r_w}^{h}\frac{Ay}{C\sqrt{B\ln\frac{y}{r_w}+gy}}dy=\int_0^t dt \tag{19}$$

Though there is no analytical for equation (19), there is numerical solution by using MATLAB. Firstly, by applying the iterative method, the relationship between *y* and *t* can be obtained. Then by introducing *y* to equation (16) to achieve *q*, relationship between *y* and *q* will be got. As for the fact that *y* is in relation with *t*, so the relationship between *q* and t can be got, eventually.

3 Results and discussions

In this section, fine-scale numerical simulations on different pressure difference are applied to verify the validation of the new mathematical model.

Table 1 Main inputs for CMG simulation model

Property	*Unit*	*Value*
Reservoir dimensions	m	3 × 80 × 40
Reservoir temperature	°C	25.7
Oil saturation	%	83
Water saturation	%	17
Reservoir thickness	M	40
Lateral boundary	M	80
Horizontal permeability	mD	3,400
Vertical permeability	mD	2,000
Porosity	%	36
Rock heat capacity	kJ/(kg. °C)	1.138
Water heat capacity	kJ/(kg. °C)	4.2
Oil heat capacity	kJ/(kg. °C)	2.2
Overburden heat capacity	kJ/(m^3. °C)	2,530
Rock heat conductivity	kJ/(m.day. °C)	450
Water heat conductivity	kJ/(m.day. °C)	55.3
Oil heat conductivity	kJ/(m.day. °C)	8.035
Overburden heat conductivity	kJ/(m.day. °C)	148
Steam temperature	°C	250
Injection pressure	kPa	2,000
Steam quality		0.85

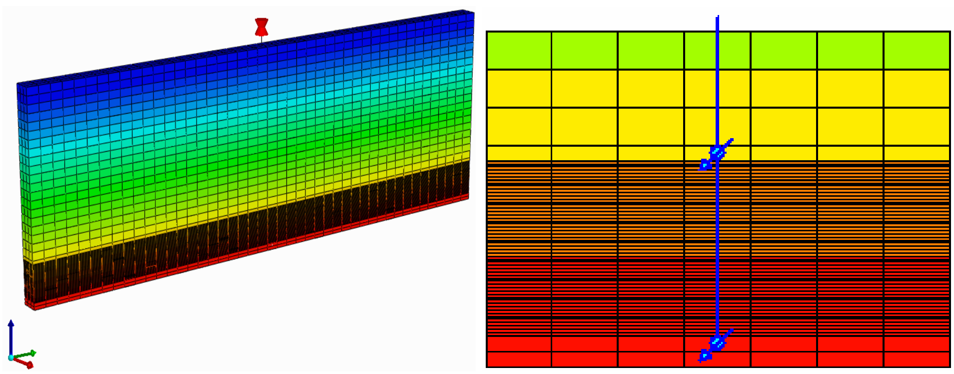
CMG STARS is applied to study the relationship between pressure difference and production rate. In order to avoid the influence of non-uniform steam injection along the horizontal well on SAGD performance, a 2D model is built, as is shown in Figure 4(a). The height of grids between injection well and production well is refined to 0.1 m, as shown in Figure 4(b). There is no bottom water or gas cap zone in the model. The injection well is located 5 m above the production well, which is 2.0 m above the bottom of the reservoir model. The initial oil saturation is 0.83. The aqueous (W) phase initially exists at its irreducible saturation of 0.17. Table 1 summarises the rock physical and thermal properties used in the numerical, and rel-perm curve and viscosity-temperature curve for CMG simulation are given in Figure 5. All of these data are acquired from Mackay River and Dover in Canada.

According to the results of numerical simulations mentioned above, the residual oil saturation is about 0.43, so difference between initial oil saturation and residual oil saturation is 0.40. Meanwhile, parameter m is a function of the viscosity-temperature characteristics of the oil, the steam temperature and the reservoir temperature (Butler, 1991). So, parameter m can be obtained by equation (9), which is also written below:

$$\log\left(\frac{\mu_s}{\mu}\right) = m\log\left(\frac{T - T_R}{T_S - T_R}\right) \qquad (20)$$
$$y = mx$$

where y is equal to $\log\left(\frac{\mu_s}{\mu}\right)$; x is equal to $\log\left(\frac{T - T_R}{T_S - T_R}\right)$; μ_S is the oil viscosity at steam temperature, which is equal to 2.5 m^2/d; T_R is the initial reservoir temperature, which is equal to 25.7°C. Meanwhile, statistics of viscosity-temperature can be acquired in Figure 5. Finally, the fitting curve is shown in Figure 6 and input parameters of mathematical model are shown in Table 2:

Figure 4 (a) Schematic diagram of CMG modelling (b) Grid refinement between two (see online version for colours)



(a) (b)

Figure 5 Rel-perm curve and viscosity-temperature curve for CMG simulation (see online version for colours)

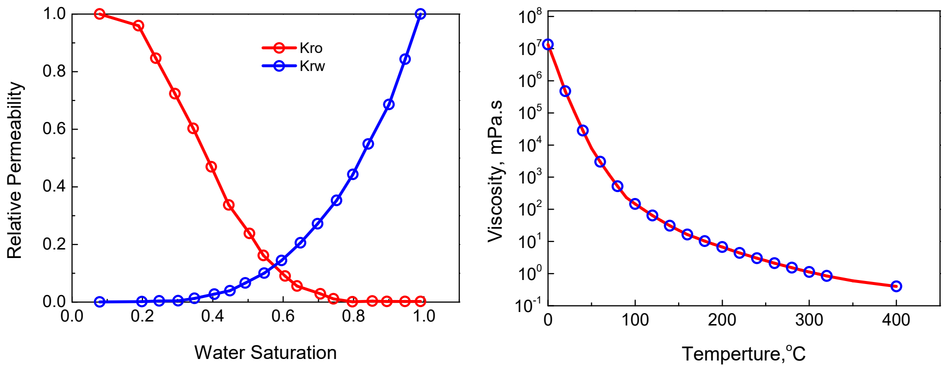
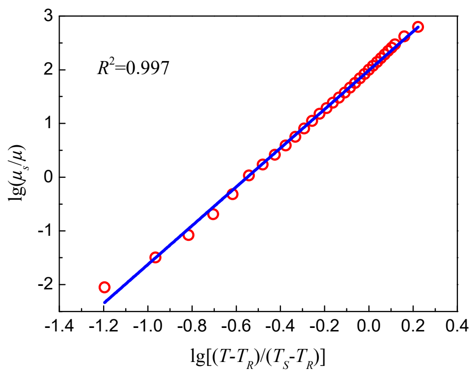


Figure 6 Fitting curve of parameter *m* (see online version for colours)



3.1 Analysis of Butler's model

In equation (19), when the $\Delta P = 0$, it would be simplified to equation (21):

$$y = \left(\frac{9}{4}\frac{\beta}{\gamma^2}\right)^{1/3}\left(\frac{kg\alpha}{m\upsilon_s\phi\Delta S_o}\right)^{1/3} t^{2/3} \tag{21}$$

According to the parameters in Table 2, combining equation (21) and equation (16), the relationship between cumulative oil production and production time can be acquired. In this way, comparison has been made between Butler's model results and STARS results. The outcome is shown in Figure 7. Meanwhile, the relationship between oil production rate and time can be obtained by using the equation (15) and equation (21). Compared with the CMG data. The outcome is shown in Figure 8.

Table 2 Main inputs for new mathematical model

Property	*Unit*	*Value*
Reservoir height	m	40
Pressure difference	kPa	0 to 80
Permeability	mD	1,800
Porosity	%	36
Lateral boundary	m	80
Bitumen viscosity exponent, m	-	3.616
Oil kinematic viscosity at steam temperature	m^2/d	0.20
Thermal diffusivity 'α',	m^2/d	0.04
Difference in oil saturation, ΔS_o	-	0.4
Oil density	gm/cc	0.98

Figure 7 Comparison of calculated cumulative oil production with CMGs results (see online version for colours)

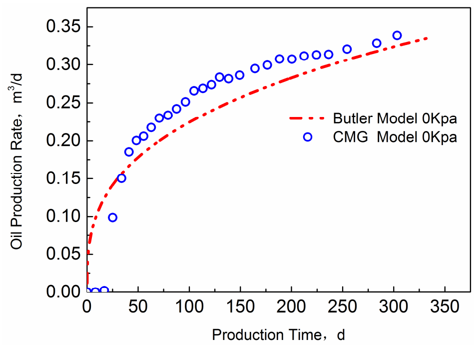


Figure 8 Comparison of calculated oil rate production with CMGs results (see online version for colours)

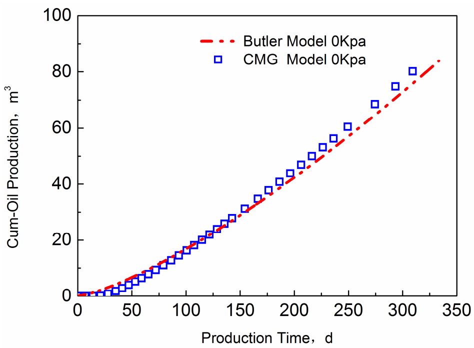


Figure 7 and Figure 8 reveal that the calculated cumulative oil production and oil production rate are very satisfactory with STARS results. In other words, if there is no pressure difference between injector and producer in SAGD recovery process, Butler's model is also rather reliable. But unfortunately, as it mentioned before, pressure difference often plays a significant role in the process of SAGD, especially at the stage of rising steam chamber. Therefore, if we still use Butler's model to predict the production, the outcome could not be satisfactory with the field data.

3.2 Analysis of the model that considers pressure difference

To make Butler's model more practical, it is vital to consider pressure difference between injector and producer, which is the reason proposing the new mathematical model. When the pressure difference is not equal to 0, the relationship between oil production rate and production time can be obtained by using equation (14) and equation (19). Figure 9 to Figure 12 show comparison of calculated oil rate production with CMG's results when ΔP = 20 Kpa, ΔP = 40Kpa, ΔP = 60 Kpa and ΔP = 80 Kpa, respectively. Figure 13 shows the relationship between oil production rate and production time on different pressure difference. Meanwhile, the relationship between cumulative oil production and production time can be acquired by combining equation (16) and equation (19). Figures 14 to 17 show comparison of calculated cumulative oil production with CMGs results when ΔP = 20 Kpa, ΔP = 40 Kpa, ΔP = 60 Kpa and ΔP = 80 Kpa, respectively. Figure 18 shows the relationship between cumulative oil production and production time on different pressure difference.

Figure 9 Comparison of calculated oil rate production with CMGs results when ΔP = 20 Kpa (see online version for colours)

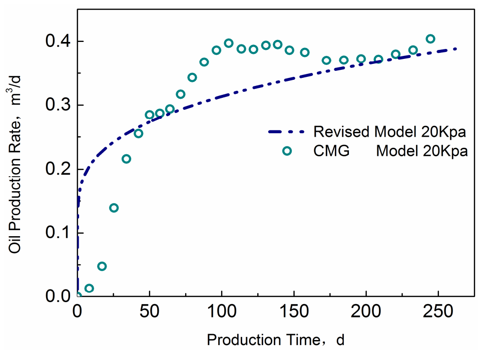


Figure 10 Comparison of calculated oil rate production with CMGs results when ΔP = 40 Kpa (see online version for colours)

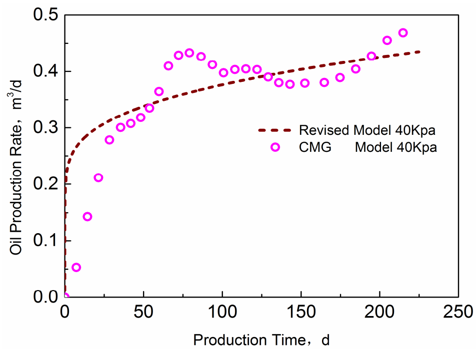


Figure 11 Comparison of calculated oil rate production with CMGs results when ΔP = 60 Kpa (see online version for colours)

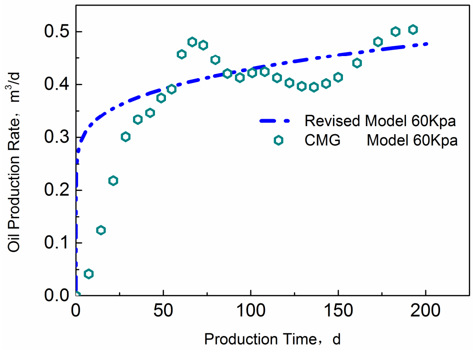
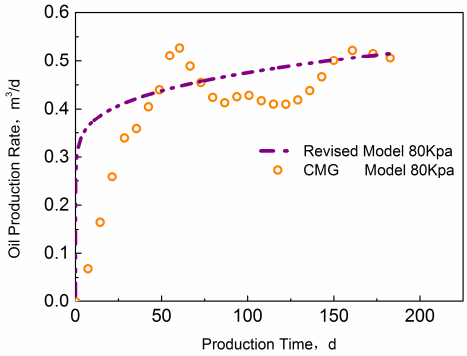


Figure 12 Comparison of calculated oil rate production with CMGs results when ΔP = 80 Kpa (see online version for colours)



Figures 9 to 12 show that the simulated results agree very well with the calculated values. Meanwhile, in Figure 13, when the time is 150 day, the oil production rate of these curves '①②③④⑤' are 0.25994 m^2/d, 0.341871 m^2/d, 0.403714 m^2/d, 0.455709 m^2/d and 0.501641 m^2/d, respectively. Therefore, it could be concluded that with increasing of the pressure difference, the oil production rate increases as well. However, the increasing range decreases as pressure difference increases, which are 0.00409655 m^2/(d•kPa), 0.00309215 m^2/(d•kPa), 0.00259975 m^2/(d•kPa), and 0.0022966 m^2/(d•kPa), respectively. What causes this phenomenon? The reason may be that on the one hand, when there is no pressure difference, some heated bitumen cannot be moved by gravity, but when the pressure difference exists, the pressure difference can drive this heated bitumen to the production well, which increases the oil production rate. On the other hand, when the pressure difference continues increasing, some unheated bitumen still cannot move because of its high viscosity, for which the increasing range is decreased with the increasing of pressure difference.

Figure 13 The relationship between oil production rate and production time on different pressure difference (see online version for colours)

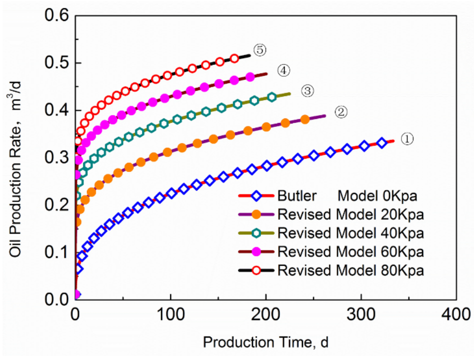


Figure 14 Comparison of calculated cumulative oil production with CMGs results when ΔP = 20 Kpa (see online version for colours)

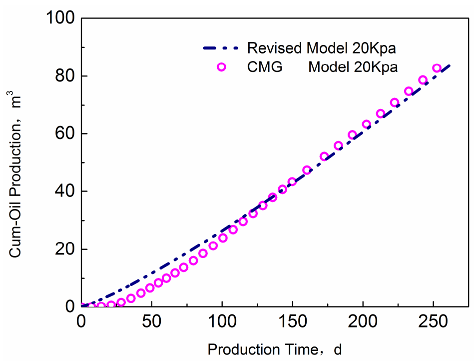


Figure 15 Comparison of calculated cumulative oil production with CMGs results when ΔP = 40 Kpa (see online version for colours)

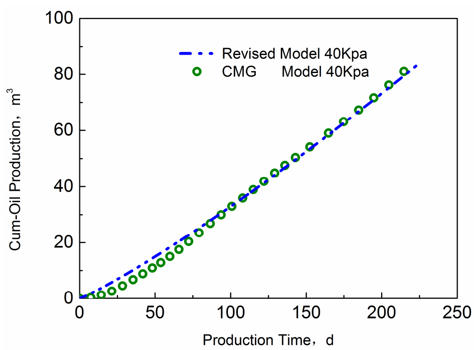


Figure 16 Comparison of calculated cumulative oil production with CMGs results when ΔP = 60 Kpa (see online version for colours)

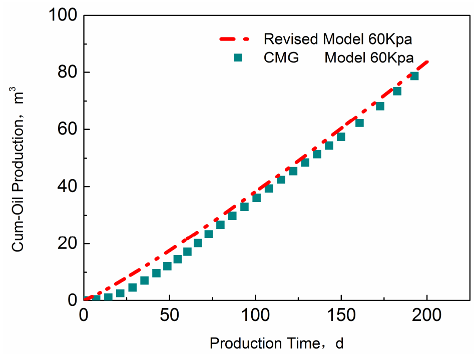


Figure 17 Comparison of calculated cumulative oil production with CMGs results when ΔP = 80 Kpa (see online version for colours)

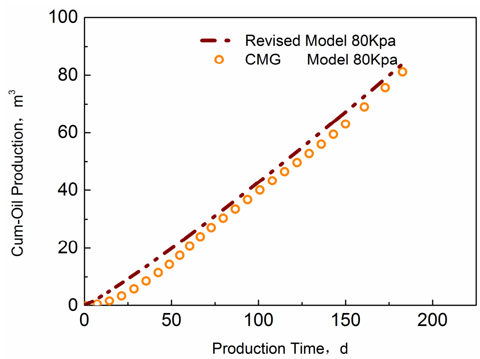
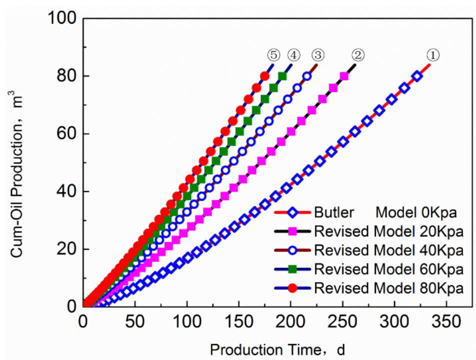


Figure 18 The relationship between cumulative oil production and time on different pressure difference (see online version for colours)



Figures 14 to 17 show that calculated cumulative oil productions are extremely satisfactory with numerical simulation results. Besides, Figure 18 reveals that in the SAGD recovery process, when there is the pressure difference, the effect of recovery would be better. What is more, Figure 18 also presents that the time of steam chamber reaching the cap-rock (①330 days, ②260 days, ③225 days, ④200 days, ⑤183 days) decreases with the increasing of the pressure difference. In other words, steam chamber will use less time to enter expansion of steam chamber, which the oil production rate is the largest (Butler, 1981, 1985). In this way, field can collect more oil in shorter time.

However, Figure 17 shows that when the pressure difference is equal to 80 KPa, the new mathematical model's results are higher than CMGs results. This is because when the pressure difference increases to certain point, it will cause steam breakthrough, which can damage the oil production rate. That is to say, it cannot be concluded that the higher the pressure difference is, the better recovery will get.

4 Conclusions

1. A new insight and greater understanding are herein provided for drive mechanism in SAGD. In the SAGD recovery process, when there is pressure difference between injector and producer, the effect of recovery would be better.
2. An innovative mathematical model is presented which considers the pressure difference between injector and producer is presented.
3. In the phase of the rising-chamber, when there is pressure difference between injector and producer, Butler's production model usually underestimates the production. Meanwhile, the pressure difference between injector and producer would increase the production oil rate and decrease the time that steam reaches the cap-rock. Therefore, pressure difference between injector and producer can effectively improve SAGD operating performance to achieve high economic efficiency.
4. When the pressure difference between injector and producer is higher than the threshold of the steam breakthrough, it has negative effect on the production. Therefore, it is not necessary that higher pressure difference means more production.

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Nomenclature

dq_{lb}	Rate of drainage per thickness without considering the pressure difference, m^2/d
Z	The distance from the interface, m
μ_o	the viscosity of the oil, mPa•s
g	The gravity, m/s^2
Θ	The angle between steam/oil interface and production well
K	The permeability of the formation, μm^2
ρ_o	Density of the bitumen, kg/m^3
ρ_g	Density of the steam, kg/m^3
dq_l	The rate of drainage per thickness considering the pressure difference, m^2/d
ΔP	The pressure difference between the injector and producer, kPa
y	The height of the steam chamber, m
υ_s	The kinematic viscosity of the oil, which is equal to $\frac{\mu_o}{\rho_o}$, m^2/d
T_R	The original temperature of the reservoir, °C
T_S	the temperature of the steam/oil interface, °C
U	the velocity of the interface, m/s
α	the thermal diffusivity of the tar sand, m^2/d
dq_R	the oil production rate of unheated reservoir
υ_R	the kinematic viscosity of unheated reservoir, m^2/d
ϕ	the porosity of the reservoir, %
ΔS_o	the difference between oil saturation and residual oil saturation, %
β	Determined by the shape of steam chamber
γ	A constant number, which is equal to $\tan^2 \theta$

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