Geomechanical coupling simulation in SAGD process; a linear geometry model

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ABSTRACT: SAGD (Steam Assisted Gravity Drainage) is an in-situ oil recovery technique for heavy oil reservoirs. The technique has been successfully applied to many projects in the past 25 years and the process has been, now, well understood. It is now believed that geomechanics plays an important role in SAGD and should be considered in numerical or analytical modeling. Currently, geomechanics is numerically modeled through combining a multi-phase flow and a geomechanical simulator. Numerical modeling is, however, time consuming, need lots of input data, and could not be used for quick decision-making purposes. To decrease the modeling time, this study based on a new version of the Reis drainage model, proposes coupled mathematical model and reserves the effect of geomechanics in the process. Results showed a perfect match with the past experimental and numerical data.

1 INTRODUCTION

The fundamental concept of SAGD is to heat the oil sand by steam and to reduce the viscosity of oil. This concept, however, is the principal of any thermal recovery process in petroleum engineering. SAGD is a continuous process of oil production for heavy oil reservoirs. Figure 1 shows the basic elements of a SAGD project.

SAGD consists of two boreholes that are drilled horizontally one on the top of the other. Both boreholes are drilled close to each other and close to the bottom of the oil sand layer and steam is injected through the top borehole. An initial startup phase is completed, typically after several months of steam circulation in both the upper and lower horizontal wells, when a clear communication between two boreholes is identified. The upper well is converted to steam injection and the lower well is converted to a production well. While steam is injected into the formation, a zone all around the injector will be affected by steam and heat transfer mechanism causes the oil to flow and causes the steam chamber to grow.

Once the steam chamber grows vertically and reaches the upper barrier, lateral growth becomes the dominant mechanism for steam chamber growth. Butler model that was originally proposed by Butler et al. (1981) originally proposed a model (the “Butler” model) which provided an elegant analytical solution for SAGD when the steam chamber has reached the caprock at the top of the oil sand layer. Experimental modeling has been also carried out to prove the feasibility of SAGD such as Chung and Butler (1988). The theory for the Butler model, however, does not consider the effect of geomechanics. Geomechanics describes the process in which stress-induced deformations and mechanical failures change the initial properties of the reservoir. Considering geomechanics in modeling can define why permeability and porosity increases. This is also true for the many subsequent models developed based on the original Butler theory such as Reis (1992 and 1993), Akin (2005), Liang (2005) and Nukhaev et al. (2006).

All the models above have used small-scale lab test data or numerical flow simulators to check the accuracy and to validate the model. The problem with flow simulators is clear; they solve hydro-thermal equations and geomechanics is ignored. Therefore, those models that have been validated with flow simulators can be used as a replacement of a flow (not full physics) simulator. But why those models that have been verified with lab tests are not strong enough to capture full physics? By other words, why these models could not predict SAGD process in a real reservoir? An important reason lies on lab test preparation. Lab tests conducted to verify the analytical models were not configured to include geomechanical effects and so, can not be used to infer the relevance of geomechanical processes on SAGD physics. The simulated oil sand that is synthetically reproduced in laboratory does not have the natural interlocked structure reported by Dusseault and Morgenstern (1978). Also, surcharge effects and test rate are not included in the experimental models. Therefore, the geomechanical effect does not exist in both model and data set and so flow models alone can successfully match lab tests.

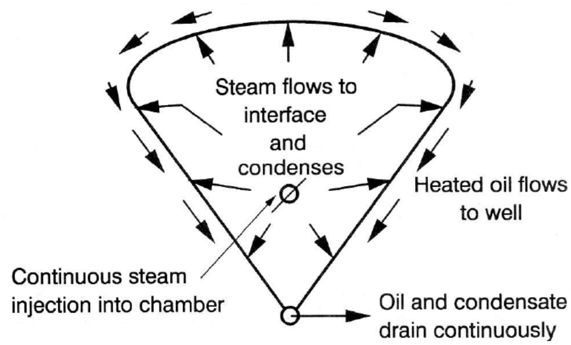

Figure 1. Steam Assisted Gravity Drainage (SAGD) process, from Butler (1991)

The importance of considering geomechanics in modeling and designing SAGD has been confirmed in many researches (e.g. Chalaturnyk, 1996, Li, 2006, and Collins, 2007). A very common solution to consider the effect of geomechanics for modeling a SAGD problem is numerical modeling. Coupling methodologies are usually suggested. In general, these iteratively coupled or sequentially coupled reservoir-geomechanical models have very long run times which make then currently unsuitable for inclusion in closed-loop reservoir management workflows for SAGD projects. Ideally, a fast model with a low level of complexity that is able to capture the important or most relevant geomechanical physics and its impact on the SAGD process would valuable. In the next section, the first stage of including geomechanics in an analytical Butler-type SAGD model (a version of the Reis model) is described.

2 MODIFIED DRAINAGE MODEL

2.1 *Butler and Reis Models*

Reis (1992) proposed a mathematical model for a linear geometry. The model was basically the same as the original theory by Butler and his colleagues (1981) for a triangular shape of steam chamber (linear geometry). Both theories predict a constant rate of oil production and hence the cumulative oil is a linear function of time. Figure 2 illustrates geometry and the proposed formulation to calculate oil rate for both models.

The models, of course, do not consider geomechanics in their formulation. Their approach is to solve the drainage rate of oil regarding to material balance in the reservoir. In addition, an average velocity parameter 'a' has been added in the Reis theory. Both the Reis and Butler theories consider an integration band for ξ from zero to infinity (see Fig. 1). Such integration simplifies the theory and results in a final, straight-forward equation. This equation, however, is not physically correct because of the geometry of the oil sand layer. Oil sand formation has a limited thickness and integration should be applied only where oil exists.

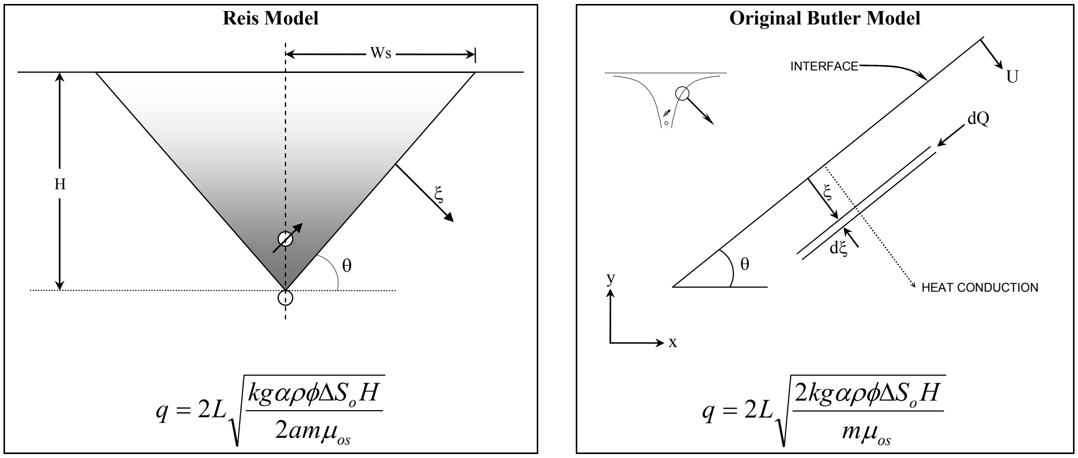

Figure 2. SAGD mathematical models and formulations.

2.2 *Heterogeneity*

Unlike the simplicity of the analytical model, real reservoirs possess varying degrees of heterogeneity with parameters such as permeability, porosity and geomechanical parameters. As a modification to Reis theories, the current model incorporates heterogeneity of permeability using a simple assumption of elliptical anisotropy.

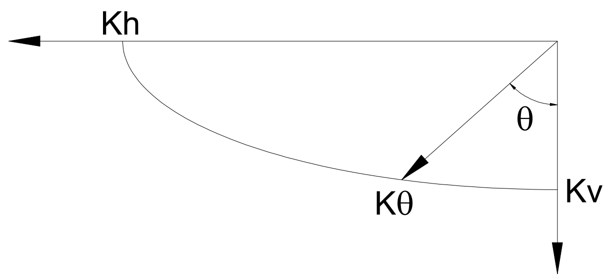

Figure 3. Elliptical relation between horizontal and vertical permeability

Based on Figure 3 and defining $K_h=nK_v=K_o$, permeability on any arbitrary angle, θ, can be calculated as follows:

$$K_\theta^2 = \frac{K_o^2}{(\sin\theta)^2 + (n\cos\theta)^2} \tag{1}$$

2.3 *Geomechanical Azad Butler (GAB) model*

In this study, the Reis model has been modified to solve the flow equation. The derivation obeys the same concept as in Reis model, but heterogeneity and correction of integration (bands of integral) have been also applied to the solution.

Assume that the steam chamber is growing laterally with a certain velocity. At any time, t, (which corresponds to a particular angle θ), Darcy's law can be written as:

$$dq_t = \frac{K_\theta \rho_o}{\mu(X)} \nabla\Phi dA \tag{2}$$

$$dq_t = \frac{K_\theta \rho_o}{\dfrac{\mu_o}{(T^*)^m}} (g\cos\theta) dX \cos\theta \tag{3}$$

$$(T^*)^m = \exp\left(\frac{-am(U_{\max}\cos\theta)X}{\alpha}\right) \tag{4}$$

$$dq_t = \frac{K_\theta \rho_o g(\cos\theta)^2}{\mu_o} \exp\left(\frac{-am(U_{\max}\cos\theta)X}{\alpha}\right) dX \tag{5}$$

Equation 5 expresses the relation between the differential flow rate and the steam chamber position. Combining equation 5 and 1 and integrating from zero to infinity (on X) yields equation 6 where ρ_o is oil density, μ_o is oil viscosity at steam temperature, and α is reservoir thermal diffusivity. This equation shows that the differential flow rate is varying as a function of steam chamber angle and the maximum velocity.

$$q_t = \frac{2K_o \rho_o g \alpha \cos\theta}{\mu_o am U_{\max}\left[(\sin\theta)^2 + (n\cos\theta)^2\right]^{0.5}} \tag{6}$$

Using a material balance approach, the following relationship between velocity and oil production rate at each specific time (or steam chamber shape) can be developed:

$$q_t = 2\frac{d}{dt}\left[(\phi\Delta S_o)(\frac{1}{2}H_t B)\right] = (\phi\Delta S_o)(H_t U_{\max}) \tag{7}$$

where ϕ is the reservoir porosity and ΔS_o is the difference between initial and residual oil saturation. Recalling $U_{max} = dX/dt$ allows both Equation 6 and 7 to be solved simultaneously.

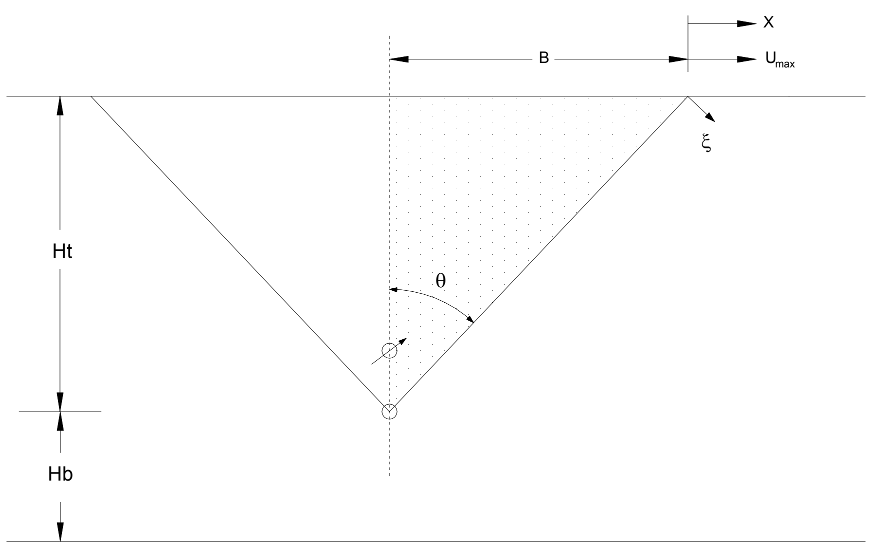

Figure 4. Geometry of steam chamber and its growth

3 ENERGY BALANCE

Based on the law of conservation of energy, Reis (1992) proposed a method to calculate SOR (Steam/Oil Ratio). The same approach was adopted for our model and although similar approaches were used, the modifications described above for the drainage model result in a model that differs from the Reis model and are described below. Equation 8 solves the rate of thermal energy that are divided into three categories; (i) the energy inside the steam chamber, Q_{in}, (ii) the energy lost to the overburden, Q_{top}, and (iii) the energy required to preheat the area in front of the steam chamber, Q_{sides}. Total steam injection rate (q_s in Eq. 9) is then calculated by dividing Equation 8 by the latent heat preserves in unit volume of steam.

$$\frac{dQ}{dt} = \frac{d(Q_{in} + 2Q_{side} + Q_{top})}{dt} \tag{8}$$

$$SOR = \frac{q_s}{q_t} = \left(\frac{dQ/dt}{\rho_w L_s}\right) / q_t \tag{9}$$

In Equation 8 and 9, Q is the total thermal energy loss, ρ_w is density of water, and L_s is the latent heat capacity of steam.

4 PROPOSED METHOD TO CONSIDER GEOMECHANICS

4.1 *Classic geotechnical engineering concept*

For coupling geomechanics and flow simulation, as shown in Figure 5, we have assumed that there exists a geomechanical shear zone which is moving in front of the steam chamber. The idea comes from this fact that permeability changes do not necessarily occur inside the steam chamber. Comparing the results of some limited studies such as Chalaturnyk (1996) and Collins (2007) supports that permeability changes due to geomechanics is not limited to the area inside or very close to the area with the steam temperature. For simplicity, the shear zone is assumed to be linear and effective stresses on the triangular regions (SC and SZ in Figure 5) are bounded by a surcharge force (overburden stress) from the top and the lateral pressure on the sides. Symmetry of the zones about the wells creates a zero displacement boundary condition along the left boundary of the steam chamber (SC). Equilibrium within the model is assumed to satisfy a limit equilibrium condition, a common approach to the solution of geotechnical problems (e.g. Duncan, 1996).

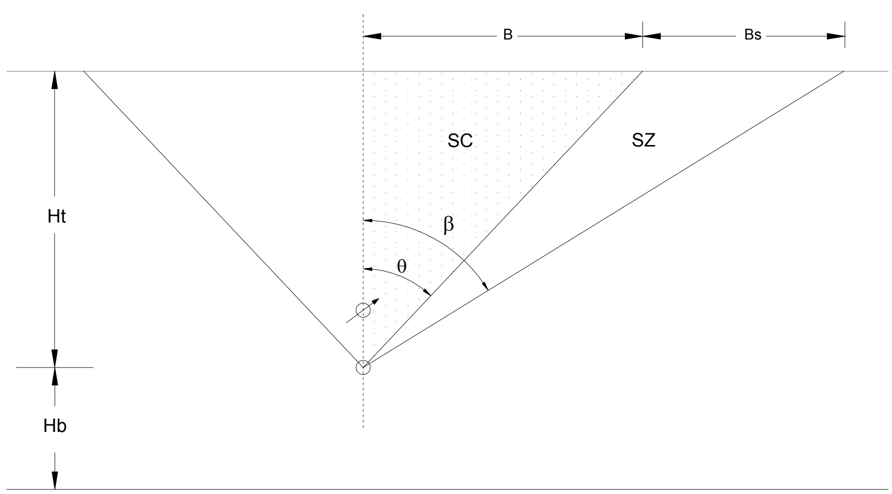

Figure 5. Moving shear zone in front of steam chamber

4.2 *Formulation*

The source of the thermal stress that is acting on the wedge in Figure 6 is the temperature difference between two sides of the triangle. On the left side, temperature is constant and is equal to the steam temperature. However, temperature on the right side is varying from the steam temperature at the bottom and it decreases along the edge. The maximum temperature difference would occur on both sides of the line shown in Figure 6 by L-bar. Assuming ΔT as the maximum temperature difference, average thermal stress on a specific wedge is calculating by theory of thermo-elastic in Equation 10.

$$P_{thermal} = \frac{1}{2}(\alpha \Delta T) E H_t / \cos\beta \tag{10}$$

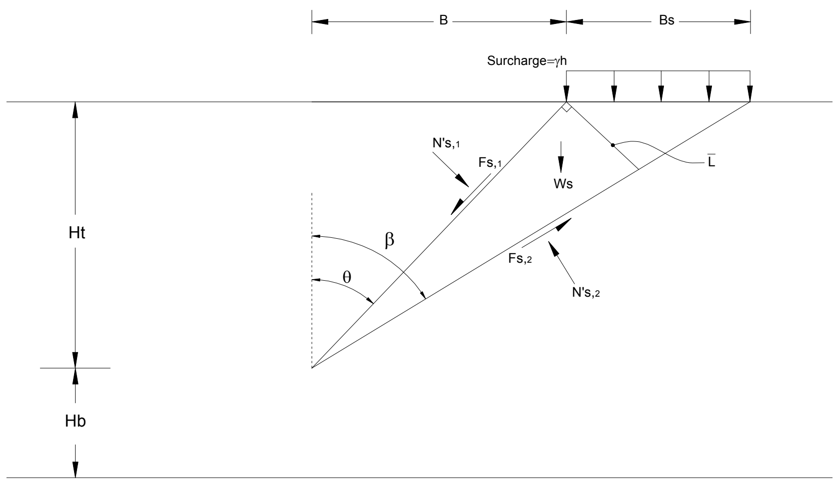

Figure 6. Effective forces on the wedge

Once thermal stress is calculated, force equilibrium equations on two major directions (Eq. 11) and Mohr-Coulomb's failure criteria on both sides provide the geomechanical solution.

$$\sum F_x = \sum F_y = 0 \tag{11}$$

$$F_{s,1} = N'_{s,1} \tan\phi' \tag{12}$$

$$F_{s,2} = N'_{s,2} \tan\phi'_r \tag{13}$$

$$N'_{s,1} = \frac{\left(\dfrac{P_{thermal,x}}{\cos\beta - \sin\beta\tan\phi'}\right) - \left(\dfrac{P_{thermal,y} - W_s - P_{surcharge}}{\sin\beta + \cos\beta\tan\phi'}\right)}{\left(\dfrac{\cos\theta - \sin\theta\tan\phi'_r}{\cos\beta - \sin\beta\tan\phi'} - \dfrac{\sin\theta + \cos\theta\tan\phi'_r}{\sin\beta + \cos\beta\tan\phi'}\right)} \tag{14}$$

Equation 14 can now be used to compute the force resulting from SAGD thermal process on the edge of the wedge. Searching for the angle at which the maximum force will act on the wedge, establishes a unique wedge for each steam chamber shape. Therefore, at each time step, there is a unique shear zone where the total volumetric strain occurs. This procedure provides the methodology for determining a deformation boundary condition and if the total reservoir expansion is determined, one can easily calculate the average volumetric strain since the boundary of expansion is now known.

4.3 *Total Reservoir Expansion*

The method proposed by Wong and Lau (2006) has been modified here for calculating the total reservoir expansion. Total reservoir expansion of an oil sand reservoir is equal to the influence of heating process and steam injection. Total volume is equal to the volume of steam injected, V_s, thermal expansion due to latent heat, V_{LH}, volume change due to cooling of the injected fluid, V_h, and the extracted oil out of the reservoir, V_p:

$$V_s = q_s \Delta t \tag{15}$$

$$V_{LH} = (q_s \Delta t) L_s \left[\frac{(1-\phi)\alpha_s + \phi S_w \alpha_w + \phi S_o \alpha_o}{(1-\phi)c_s + \phi S_w c_w + \phi S_o c_o} \right] = (q_s \rho_w \Delta t) L_s [\Gamma] \tag{16}$$

$$V_h = (q_s \Delta t) \Delta T' \left\{ \left[\frac{(1-\phi)\alpha_s + \phi S_w \alpha_w + \phi S_o \alpha_o}{(1-\phi)c_s + \phi S_w c_w + \phi S_o c_o} \right] c_w - \alpha_w \right\} \tag{17}$$

$$V_p = q_t \Delta t \tag{18}$$

$$V_{total,\Delta t} = (q_s \Delta t)\left[L_s \Gamma + \Delta T' (\Gamma c_w - \alpha_w) + 1 \right] - q_t \Delta t \tag{19}$$

In Equations 15 to 19, q_s is the rate of injected steam, Δt is time differential, $\Delta T'$ is the temperature difference in equilibrium, $\alpha_s/\alpha_o/\alpha_w$ are thermal expansion coefficient of sand, oil and water, and $c_s/c_o/c_w$ are heat capacity of solid grains, oil, and water.

4.4 *Permeability and porosity changes*

Permeability and porosity are influenced by any changes in stain field. Tortike and Farouq Ali (1993) suggested an equation to consider the effect of volumetric changes on permeability:

$$k / k_0 = \left(1 + \varepsilon_v / \phi_0\right)^3 / (1 + \varepsilon_v) \tag{20}$$

For porosity Li and Chalaturnyk (2003) proposed a linear relationship to take volumetric changes into account as follows:

$$\phi = \frac{(\phi_0 + \varepsilon_v)}{(1 + \varepsilon_v)} \tag{21}$$

In this study, volumetric strain that is changing during the process will modify both porosity and permeability at each time step.

4.5 *Solution process*

The flowchart illustrated in Figure 7 shows how geomechanical processes will influence the flow solution. Once each critical shear zone is picked, volumetric strain will modify permeability and porosity and the loop with be repeated till the end of the process. However, it is meaningless to consider the end of the process to be 90 degrees (the limit of the steam chamber angle) and so the simulation is stopped at 80-85 degrees. Subsequent developments will consider economic factors, such as SOR, as a determinant of when to conclude a simulation. The model has been coded using visual basic.

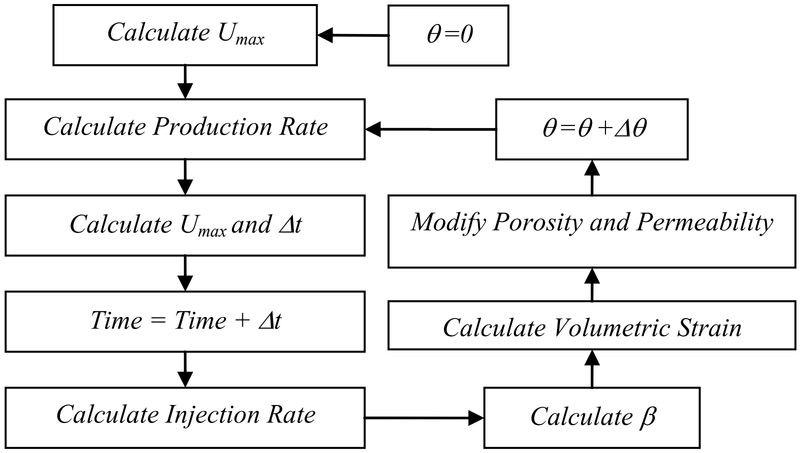

Figure 7. Solver flowchart

5 VALIDATION OF DRAINAGE MODEL

To test the validity of the drainage model component of the GAB model, the results of two lab tests have been compared here with the results of the GAB model and the original Butler and Reis models. In these two runs geomechanical effects are assumed to be negligible for the following three reasons; (1) no surcharge force was applied to the top of the model, (2) the material is synthetic (mixture of crud oil and glass beads) and would likely not have behaved as a natural geo-material and (3) the experimental run time was fast. Consequently, just the drainage model should be sufficient to match the experimental results. Properties of the model have been listed in Table 1.

Table 1. Experimental parameters

Properties	Test 1 (Butler et. al, 1981)		Test 2 (Chung and Butler, 1988)	
	Value	Unit	Value	Unit
Porosity	40	%	39	%
Initial Oil Saturation	100	%	100	%
Residual Oil Saturation	0	%	5	%
Absolute Permeability	15000	Darcy	2930	Darcy
Relative Permeability	0.48	-	0.48	-
Oil Density	0.98	gm/cc	0.98	gm/cc
Model Height	0.1	m	0.21	m
Thermal Diffusivity	0.0557	m^2/day	0.0507	m^2/day
Constant ‘a’	0.4	-	0.4	-
Constant ‘m’	3.9	-	3.6	-
Oil Viscosity	12.15	m^2/day	9	m^2/day
Model Thickness	0.025	m	0.03	m

Figure 8 compares the results of four models with the experimental data. The first model is the model proposed by Butler et al. (1981) and is usually called original Butler model (see Fig. 1). Butler and Stephens (1981) then revised the original model and proposed a modified version in which the ‘2’ in the denominator under the square root sign was changed to ‘1.5’ (see Fig. 2). The results of these two models, the Reis model and the method proposed in this study have been plotted in Figure 8.

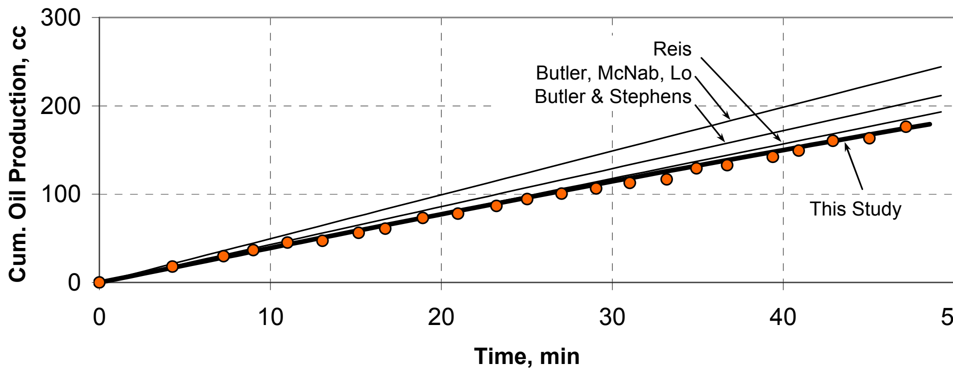

Figure 8. Comparison of measured and calculated model (Test 1)

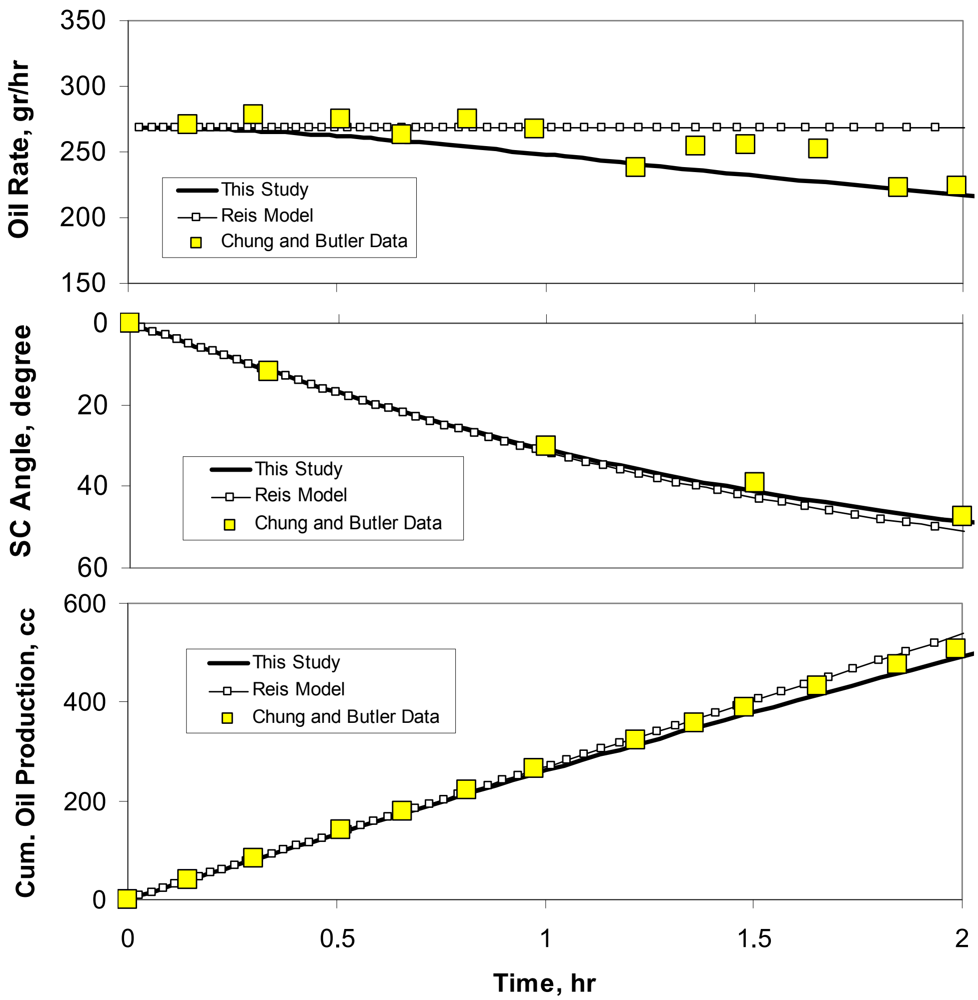

Figure 9. Comparison of measured and calculated model (Test 2)

Although the Reis model provides reasonable results, it has difficulty predicting the nonlinear trend of the oil production at late times. Since all of the models other than the GAB are linear, they can be replaced by each other using a constant multiplier. It means that setting the constant parameters such as ‘m’ or ‘a’ can provide a better fit and none of them is superior. For the same input parameters as the Reis model, the model proposed in this study is to capture the nonlinearity in oil production throughout the full time scale of the experiment. Figure 9 illustrates a comparison between the proposed model and the Reis model and the results from test 2. The nonlinearity in oil production is matched reasonably well by both models as well as the steam chamber movement, as defined by steam chamber angle. The comparisons illustrated in Figures 8 and 9 provide confidence that the drainage model component of the GAB model is functioning properly.

6 VALIDATION OF A COUPLED PROBLEM

Li (2006) proposed a methodology for coupling a flow simulator and a geomechanical simulator and validated the results with the results of Phase A of the Underground Test Facility (UTF) project (Li and Chalaturnyk, 2009). Data of a numerical uncoupled and coupled model of his study is used in the current study as a reference for comparison and a test of the validity of the GAB model.

Table 2. Parameters of the geomechanical model

Property	Value	Unit
Horizontal/vertical Permeability	2	-
Horizontal Permeability	1100	*mD*
Average Relative Oil Permeability	0.2	-
Oil Density	1008	kg/m^3
Gravity Acceleration	9.81	m/s^2
Ht	50	*m*
Surcharge Height	317	*m*
Dynamic Viscosity at steam temperature	0.007	*Pa.s*
Porosity	34	%
Oil Saturation Difference	68	%
Reservoir Thermal Diffusivity	0.0000006	m^2/s
Reservoir Temperature	11	℃
Steam Temperature	240	℃
Equilibrium Temperature	100	℃
Formation Heat Capacity	2100000	$J/ (m^3. ℃)$
Latent Heat of Steam	1740000	*J/Kg*
Steam Quality	98	%
Water Density	1000	kg/ m^3
Formation Density	21950	N/ m^3
Linear Thermal Expansion Coefficient	0.000001	1/℃
Young's Modulus	756000000	*Pa*
Oil-Sand Friction Angle, Peak	45°	-
Oil-Sand Friction Angle, Residual	20°	-
Sand Thermal Expansion	0.00005	1/℃
Water Thermal Expansion	0.00045	1/℃
Oil Thermal Expansion	0.00062	1/℃
Specific Heat capacity of Water	4200	J/(kg. ℃)
Specific Heat capacity of oil	1658	J/(kg. ℃)
Specific Heat capacity of sand	735	J/(kg. ℃)
Coefficient of viscosity change, m	3.9	-
Coefficient of average velocity, a	0.4	-
Initial Oil Saturation	85	%
Initial water Saturation	15	%
Injector/Collector Length	700	*m*

6.1 *Parameters of the model*

The constructed model is run on a 50-meter thick oil sand layer. Injector and producer are located right at the bottom of the model and their length is assumed to be 700 meters. On top of the oil sand layer, some other formations make 317 meters of overburden. Other specific parameters of the model as long as needed to run our proposed model have been listed in Table 2. All the parameters are selected from the original study by Li (2006). It means that no attempt to fit the history has been done.

6.2 *Comparison of uncoupled results*

The parameters of Table 2 were used to run two models; the model proposed in the current study and Reis model. As the first stage, an uncoupled modeling was performed. It means that permeability and porosity were kept constant. Therefore, only a part of parameters is needed to be used for this step. Results are shown in Figure 10.

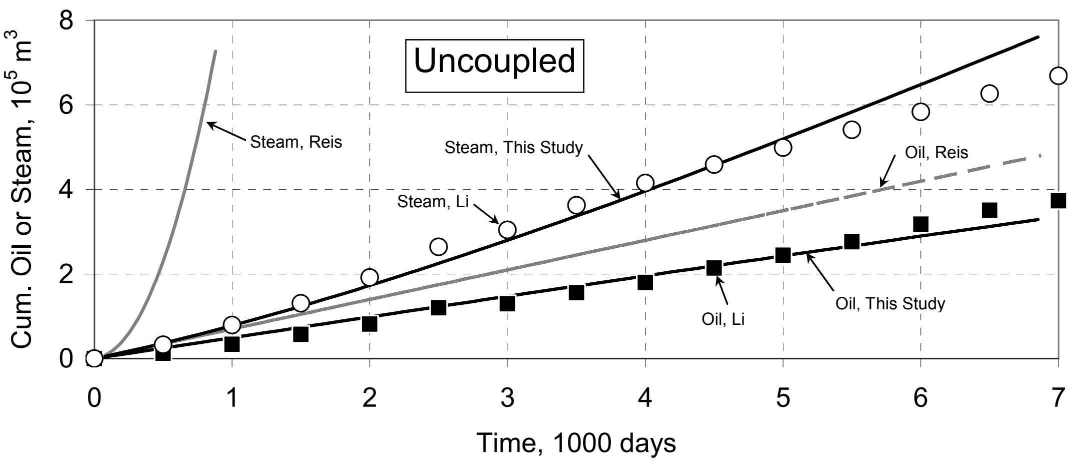

Figure 10. Comparison of numerical modeling results with two analytical uncoupled models

Figure 10 shows that the GAB model was reasonably successful at matching the numerical results reported by Li (2006), including both cumulative oil production and cumulative steam injection. Note however that the original Reis model does not closely follow the numerically generated data. It has reproduced the production trend and could be improved by empirically changing some model parameters. The predicted steam injection by the Reis model, however, is not capable of matching the simulation data, even with changing parameters in the model. This invalidity has been also reported by Reis (1992) who stated that the energy model that calculates the steam injection rate should be used with caution because the model has not been validated for high angles of steam chamber.

6.3 *Comparison of coupled results*

After comparing the uncoupled simulation and validating the drainage model, the proposed GAB model was run fully coupled and the results plotted against the results of the numerical modeling by Li (2006). In Figure 11 predicted oil production and steam injection (cumulatively) have been illustrated versus time.

Other than generating the same trend, oil production predicted by the coupled model has been perfectly fitted the numerical data in a fully coupled simulation process. The match of injected steam is not as good as oil production, but still very close and in an acceptable range. Recalling the geometry of the model confirms that at the end of a SAGD process, an infinite oil sand reservoir will be recovered. Hence, the increasing slope trend in both oil production and steam injection curves is quite predictable due to the foundation of the model.

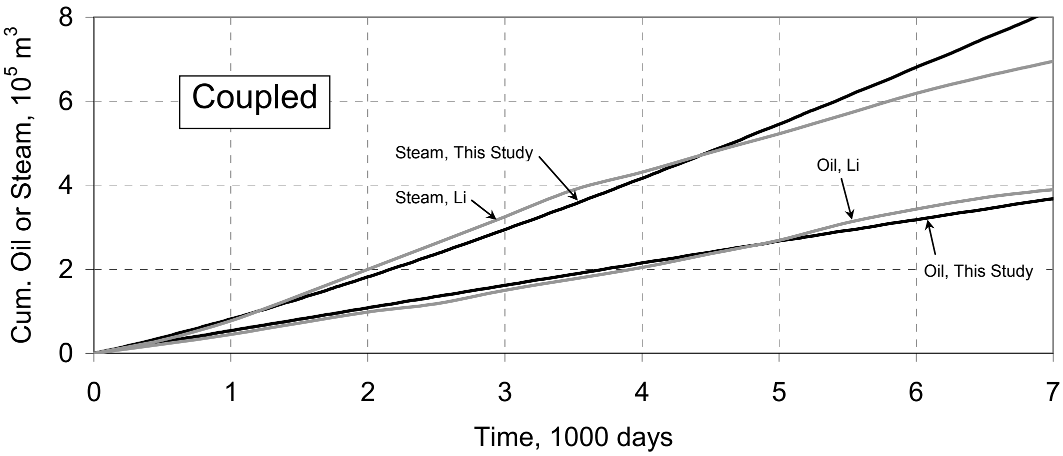

Figure 11. Comparison of coupled numerical modeling with the current study

7 CONCLUSIONS

In this paper a modified version of Reis model was proposed to simulate the drainage process occurring in SAGD. Modifications were applied to modify two concerns; (i) the physical inaccuracy of the mathematical solution and (ii) heterogeneity of permeability. The modified model was compared with two lab tests results and a validated numerical modeling. In both cases results showed an improvement in fitting the data especially in actual size data. It was also showed that the energy balance that firstly proposed by Reis has been effectively improved in the modified model.

The proposed geomechanical modeling (coupled with the drainage model) which is the main goal of this study was tested against the available numerical data. The results confirm an excellent agreement more for cumulative oil production and less for injected steam.

Regardless of the limited available data for supporting the validity of the model, the proposed methodology presented in this paper has shown that the GAB model may capture sufficient reservoir-geomechanical processes inherent in the SAGD process to warrant the use of the model in smart field or closed-loop reservoir management studies of the SAGD process.

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