Calculating an Improved Connected Hydrocarbon Volume with Line-of-Sight for Ranking Realizations by SAGD Performance

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Ranking realizations is important for reducing the professional and computational time required to understand uncertainty in production performance. The ranking measure should be tailored to the flow characteristics of the production method used. The SAGD method of production is gravity driven and dependent on the connectivity of the steam chamber. Various ranking measures based on connectivity have been applied for ranking realizations for SAGD. The method proposed herein extends the calculation of connectivity to account for various influences on production such as the presence and location of flow barriers, the proximity of bitumen to the production well, and the direction the bitumen must flow to reach the production well. Accounting for these factors can lead to a ranking measure which better correlates with true production performance.

Introduction

Geological heterogeneity and connectivity is impossible to exactly predict between wells. Geostatistics can be used to quantify uncertainty in the geological model. This is done by constructing multiple equally probable realizations of reservoir properties. These realizations are used to quantify the uncertainty in production performance due to geological uncertainty. Production performance is assessed by flow simulation, but flow simulation is too computationally expensive to perform on all available realizations due to the required level of geological detail and complex heat transfer equations. This computational expense necessitates reducing the geological input to flow simulation. A subset of realizations must be isolated for flow simulation. Determining a subset of realizations by randomly choosing geological realizations does not accurately represent uncertainty. Ranking is a superior method that selects cases that span production uncertainty (Deutsch & Srinivasan, 1996).

Numerous methodologies have been applied to the ranking of multiple realizations. These include volumetric measures such as the calculation of original-oil-in-place (OOIP) or net oil-in-place (McLennan & Deutsch, 2005). These also include statistical measures such as the calculation of net-to-gross ratio, net pore volume, or average permeability (Deutsch & Srinivasan, 1996). Static measures of continuity have also been applied for ranking. These have been applied both locally (McLennan & Deutsch, 2005; Fenik, Nouri, & Deutsch, 2009) and globally (Deutsch & Srinivasan, 1996). There are also dynamic continuity measures which measure continuity between injecting and producing locations such as tracer simulation, simulation based on a network of 1D streamtubes, and waterflood simulation. Applying the correct physics to upscaled coarse resolution geological models could also be done.

Steam assisted gravity drainage (SAGD) is a popular insitu heavy oil recovery process. It is applied to multiple horizontal wells up to 1000m long. An upper injection well and lower production well are nominally parallel and are separated by approximately 5m of elevation. To initiate inter-well connectivity, steam is injected through both wells for the first 3 to 6 months. Steam circulation then continues to be injected through the upper injection well forming a cone-shaped steam chamber anchored at the production well. As new reservoir is heated, bitumen lowers in viscosity and flows downward along the outside of the steam chamber boundary via gravity into the production well.

It is well known that a particular ranking measure must be highly correlated to production response and that this correlation is achieved when the calculation procedure is tailored to the flow process. The SAGD flow process is unique in that gravity is the main driver. Reservoir geology and heterogeneity affect SAGD production performance. Although there are many factors that affect SAGD production performance, prediction, connectivity, and the spatial distribution of facies, porosity, water saturation, and permeability are the most significant. Conventional ranking measures may not be acceptable. The SAGD process depends on the efficient connection of the steam chamber to the surrounding reservoir; therefore the ranking measures must somehow account for connectivity.

McLennan and Deutsch (2005) formulated several SAGD ranking measures with varying complexity. In particular they define global connectivity which is an important indicator of SAGD production performance. They also extend the global connectivity method by limiting the calculation of connectivity to local windows. Fenik, Nouri, and Deutsch (2009) extended the work of McLennan and Deutsch (2005) to consider those net locations outside of the local window which are visible from the producer by line-of-sight.

This work proposes a new method for calculating connected hydrocarbon volume (CHV) based entirely on line-of-sight. The CHV can be modified based on the expected time and likelihood of production. The result is a ranking measure that correlates well with flow response over a large time period. The methodology can be broken down into two main steps: determine connected cells and modify CHV.

Determining Connected Cells

The procedure of determining which cells are connected begins the same as other implementations of CHV. The first step is to classify each cell in the model as net or non-net. A cell is considered net if it satisfies some combination of facies, porosity, saturation, and permeability cutoff criteria. A net cell is coded as $i^l_{x,y,z} = 1$ while a non-net cell is coded as $i^l_{x,y,z} = 0$ where $i^l_{x,y,z}$ represents the coding for a particular cell in a particular realization, *l* ranges from 1,…,*L, L* is the number of realizations, and *x, y, z* indicates a 3D cell location.

The procedure of determining the connected cells is illustrated by a number of schematics in Figure 1. A 2D slice perpendicular to the wells is shown. The white cells are net while the black cells are non-net or barrier. The black circle near the bottom represents the location of the production well. The method proceeds by identifying all the cells which are visible between the producer and the cells at the left-hand margin of the slice. The cells which are visible are identified by dark gray. Next, the visible cells between the top of the slice and the producer are identified. Finally, the visible cells between the right-hand margin of the slice and producer are identified. This identifies all the cells which are visible from the producer. The visible cells represent the steam chamber. Note that cells which are lower than the producer are not considered visible.

The methodology continues by next identifying all of the cells which are visible from the current steam chamber. This necessitates identifying all the cells which fall at the boundary of the current steam chamber. These are identified by a dark gray color in the middle plot on the third row. A cell is considered to fall at the boundary if it is visible from the producer and is adjacent to a net cell which is not visible. The invisible net cell must be either beside or above the visible cell for it to be identified as a boundary.

The procedure of identifying the visible cells is repeated considering each boundary cell as the production well. The sides and top are scanned to identify all visible cells from each boundary cell. A new set of boundary cells is then identified. The process of identifying visible cells from the boundary cells and then identifying new boundary cells is repeated until no more boundary cells can be found. When this occurs, all of the cells that are connected to the production well have been identified.

At this stage, the steam chamber is nearly identical to that identified by calculating the connected geoobjects. The only difference is that the cells below the production well are not considered connected. The next step is to calculate CHV.

CHV Calculation

Once the cells which are connected to the production well have been identified, CHV can be calculated. Consider a connectivity indicator, $c^l_{x,y,z}$, which indicates for each cell in each realization whether that cell is connected to the producer. This connectivity indicator is binary where $c^l_{x,y,z} = 1$ indicates that the cell is connected and $c^l_{x,y,z} = 0$ indicates that the cell is not connected. CHV is calculated as:

$$CHV^l = \sum_{z=1}^{Z}\sum_{y=1}^{Y}\sum_{x=1}^{X} c^l_{x,y,z} \cdot V_{x,y,z} \cdot \left(1 - S^l_{x,y,z}\right) \cdot \phi^l_{x,y,z}, \quad l = 1, \dots, L$$

where *X, Y, Z* are the number of cells in each dimension of the model, *V* is the volume of the cell, *S* is the water saturation, and ϕ is the porosity.

The calculation of CHV shown above does not take into account the location of the cell relative to the producer, nor does it account for the presence and position of any barriers. It also does not account for the quality of sand along the flow path. This work presents various means for accounting for these considerations. Means for modifying the CHV calculation are suggested which aim to better relate to the true production at multiple time intervals.

Number of Steps

The first consideration is the number of flow steps required for the bitumen to travel from its original location to the production well. The number of steps is illustrated in Figure 2 and is controlled by the location of any barriers that may lie between the bitumen and the production well. More flow steps means longer time or reduced probability of production. The calculation of CHV is modified by a factor based on the number of steps. This factor, ${f_s}^l_{x,y,z}$, is calculated from the number of steps required to reach each cell, $s^l_{x,y,z}$, as follows:

$${f_s}^l_{x,y,z} = 1 - r \cdot s^l_{x,y,z}$$

where *r* is a non-negative parameter which would be calibrated to true production performance. The calculation of CHV is modified to account for this factor:

$$CHV^l = \sum_{z=1}^{Z}\sum_{y=1}^{Y}\sum_{x=1}^{X} {f_s}^l_{x,y,z} \cdot c^l_{x,y,z} \cdot V_{x,y,z} \cdot \left(1 - S^l_{x,y,z}\right) \cdot \phi^l_{x,y,z} \ , \qquad l = 1, \dots, L$$

A value of *r* = 0 would mean that the number of steps is not considered and the calculation of CHV would be equivalent to that shown previously.

Angle from Vertical

Another consideration in the calculation of CHV is the angle made between the original location of the bitumen and the production well as measured from vertical. Bitumen with an original location whose angle from vertical is quite large will take a long time to be produced, if it is produced at all. This is illustrated in Figure 3 where the angle from vertical is calculated for two locations. The angle from vertical for location 2 is greater than the angle from vertical from location 1 corresponding to the fact that the bitumen at location 2 would be produced later than the bitumen at location 1. The calculation of CHV is modified by a factor based on the angle from vertical. This factor, ${f_a}^l_{x,y,z}$, is calculated from the angle from vertical made by each cell, $a^l_{x,y,z}$, as follows:

$${f_a}^l_{x,y,z} = 1 - t \cdot a^l_{x,y,z}$$

where *t* is a non-negative parameter which would be calibrated to true production performance. The calculation of CHV is modified to account for this factor:

$$CHV^l = \sum_{z=1}^{Z}\sum_{y=1}^{Y}\sum_{x=1}^{X} {f_a}^l_{x,y,z} \cdot c^l_{x,y,z} \cdot V_{x,y,z} \cdot \left(1 - S^l_{x,y,z}\right) \cdot \phi^l_{x,y,z} \ , \qquad l = 1, \dots, L$$

A value of *t* = 0 would mean that the angle from vertical is not considered and the calculation of CHV would be equivalent to that shown initially.

For cells which require more than one step to be connected to the producer, the angle from vertical is calculated for the boundary cell which minimizes the angle from vertical. This is illustrated in Figure 4. The cell under consideration is highlighted. This cell is visible from multiple boundary cells. Therefore, there are multiple values that the angle from vertical could take. For example, the angle from vertical could be either α_2 or α_3 among other values. α_2 is selected as this is the minimum possible angle from vertical.

Permeability Along Flow Path

Another consideration in the calculation of CHV is the permeability of the material along the flow path. Bitumen which must flow through material with low permeability to reach the producer will take more time to be produced than bitumen which flows through material with high permeability. This can be accounted for in the calculation of CHV. This is done by taking the harmonic average of the permeability of the cells along the flow path. The harmonic average is appropriate for capturing flow properties. The calculation of CHV is modified by a factor based on the average permeability along the flow path. This factor, ${f_p}^l_{x,y,z}$, is calculated from the harmonic average permeability along the flow path, $p^l_{x,y,z}$, as follows:

$$ {f_p}^l_{x,y,z} = \left(\frac{p^l_{x,y,z}}{p_{max}} \right)^{\omega_p} $$

where p_{max} is some user-specified maximum permeability and ω_d is a parameter which would be calibrated to true production performance. The calculation of CHV is modified to account for this factor:

$$ CHV^l = \sum_{z=1}^{Z} \sum_{y=1}^{Y} \sum_{x=1}^{X} {f_p}^l_{x,y,z} \cdot c^l_{x,y,z} \cdot V_{x,y,z} \cdot \left(1 - S^l_{x,y,z}\right) \cdot \phi^l_{x,y,z} \ , \qquad l = 1, \dots, L $$

A value of ω_d = 0 would mean that the permeability along the flow path is not considered and the calculation of CHV would be equivalent to that shown initially herein. ω_d typically takes values between 0 and 2.

Distance from Producer

Another consideration in the calculation of CHV is the length of the flow path. Bitumen farther from the production well will be produced later than bitumen closer to the production well. This is illustrated in Figure 5. The length of the flow path is the sum of the lengths of each flow step, in this case, $d_1 + d_2 + d_3$. The length of the flow path can be accounted for in the calculation of CHV by a modifying factor based on the length of the flow path. This factor, ${f_d}^l_{x,y,z}$, is calculated from the length of the flow path, $d^l_{x,y,z}$, as follows:

$$ {f_d}^l_{x,y,z} = \left(\frac{d^l_{x,y,z}}{d_{max}} \right)^{\omega_d} $$

where d_{max} is the maximum distance observed and ω_d is a parameter which would be calibrated to true production performance. The calculation of CHV is modified to account for this factor:

$$ CHV^l = \sum_{z=1}^{Z} \sum_{y=1}^{Y} \sum_{x=1}^{X} {f_d}^l_{x,y,z} \cdot c^l_{x,y,z} \cdot V_{x,y,z} \cdot \left(1 - S^l_{x,y,z}\right) \cdot \phi^l_{x,y,z} \ , \qquad l = 1, \dots, L $$

A value of ω_d = 0 would mean that the length of the flow path is not considered and the calculation of CHV would be equivalent to that shown initially herein. ω_d typically takes values between 0 and 2.

All four modifying factors discussed could be used simultaneously in the calculation of CHV. The calculation of CHV would be as follows:

$$ CHV^l = \sum_{z=1}^{Z} \sum_{y=1}^{Y} \sum_{x=1}^{X} {f_s}^l_{x,y,z} \cdot {f_a}^l_{x,y,z} \cdot {f_p}^l_{x,y,z} \cdot {f_d}^l_{x,y,z} \cdot c^l_{x,y,z} \cdot V_{x,y,z} \cdot \left(1 - S^l_{x,y,z}\right) \cdot \phi^l_{x,y,z} \ , \ \ l = 1, \dots, L $$

Calibration with Production Data

Each of the four modifying factors requires calibration with production data. Calibration requires an objective function where some measure of goodness is maximized or some measure of difference is minimized. One type of calibration that could be performed is to maximize the correlation between CHV and some production parameter. The relationship between correlation and the calibration parameters would likely have one of the two relationships shown in Figure 6. Behavior like the first calibration response would indicate that the calibration parameter is meaningful and that there is a calibration parameter value where the correlation between CHV and production is maximized. Behavior like the second calibration would indicate that the calibration parameter is not meaningful and that correlation is maximized if that factor is not considered.

The optimization space can be quite large, particularly when all four modifying factors are used. In order to find the optimum set of parameters, the optimization space must be thoroughly explored. Fortunately, the response surface of the objective function has been found to be quite stable and free from local maxima/minima. This enables the recursive use of one-dimensional search strategies to be employed in determining the optimal parameters. To do this, all parameters but one are held constant. The space occupied by the one free parameter is explored until a maximum is found. This parameter is then fixed at that optimal value and the next parameter is considered as the free parameter. The space occupied by this parameter is explored searching for a maximum. This procedure is repeated cycling through all of the parameters until no further improvement can be made. The stability of the objective function response surface suggests that the global optimum will be identified.

Conclusions

The size and connectivity of the steam chamber is the primary control on SAGD production performance. The calculation of the static connected hydrocarbon volume aimed to approximate the production performance, however, there was no way to account for the location of bitumen and barriers relative to the production well. Determining the connected reservoir using line of sight provides a number of measures which can summarize the performance of a SAGD reservoir. These are the number of steps to reach the producer, the angle from vertical, the permeability along the flow path, and the length of the flow path. The influence given to each of these factors can be calibrated to true production performance in order to provide a reasonable measure for ranking realizations. Accounting for these factors can increase the correlation between the ranking measure and true performance giving a better assessment of uncertainty in production performance with reduced professional and computational effort.

References

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McLennan J and Deutsch C, 2005. Ranking geostatistical realizations by measures of connectivity. Society of Petroleum Engineers (SPE), Paper 98168.

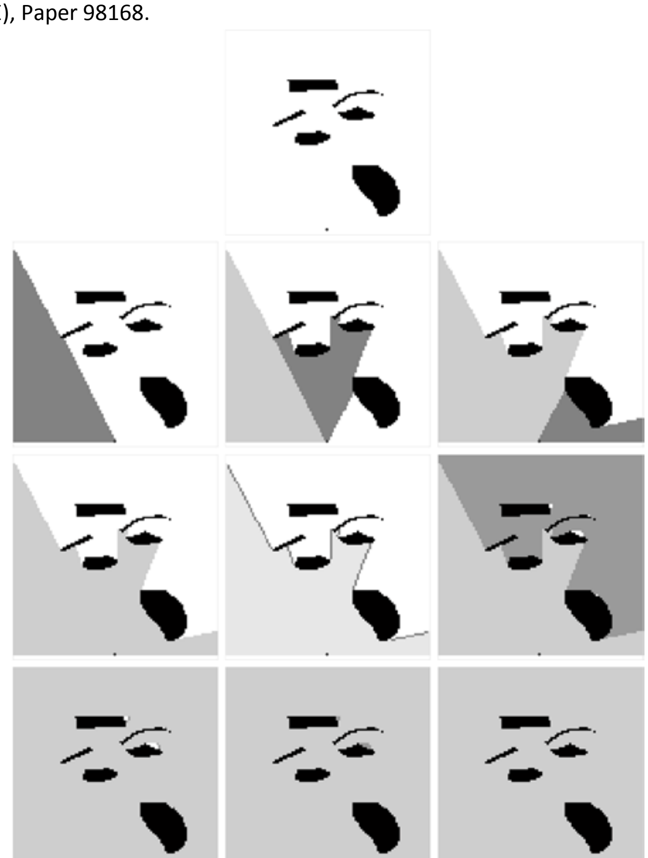

Figure 1: Schematics illustrating the process of determining the connected cells using line-of-sight. Black cells are non-net, white cells are net which have not been identified as visible. Varying shades of gray indicate visible cells, boundary cells, and the stages of steam chamber growth.

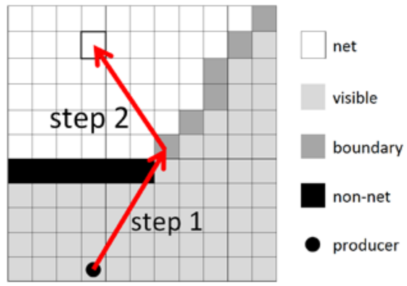

Figure 2: Illustration of the number of steps required for the bitumen to travel to the production well.

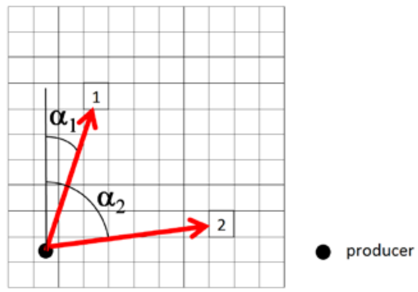

Figure 3: Illustration of the measure angle-from-vertical.

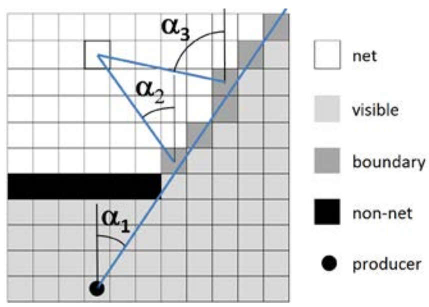

Figure 4: Illustration of angle-from-vertical for locations requiring more than one step to reach the producer.

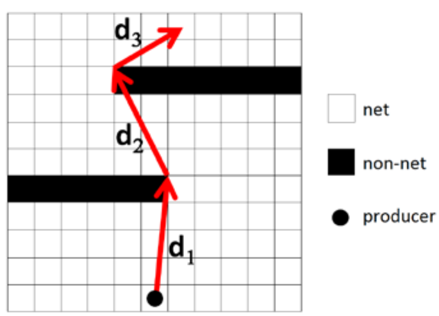

Figure 5: Illustration of the calculation of the length of the flow path.

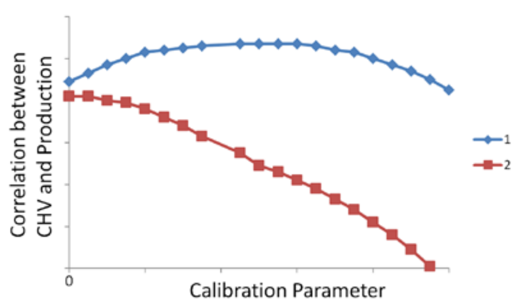

Figure 6: Typical calibration responses when calculating correlation between CHV and production.