Numerical Investigations into Oil Drainage Rates during Vapour Extraction (VAPEX) of Heavy Oils

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Abstract
Heavy oil recovery using the Vapour Extraction (VAPEX) process is of great interest as it is more energy-efficient compared to thermal recovery processes. An analytical VAPEX model was first proposed by Butler and Mokrys (1989) as a solvent analogue of Steam Assisted Gravity Drainage (SAGD). This model however was found to underestimate the oil production rates in porous media despite accurately predicting the oil rates in experiments using Helé-Shaw cells. This thesis reviews the assumptions made in the original Butler-Mokrys model and proposes a modified expression of the analytic model by considering the end point density difference between solvent and oil.

A validated numerical simulation model was used to investigate the oil drainage rate sensitivity to reservoir thickness, length, permeability, well placement, density difference and viscosity ratio. Simulation results were compared against the predicted rates using both the original and modified Butler-Mokrys models. The impact of using dispersion rather than molecular diffusion coefficients in the analytic model was also investigated. Predictions using end point density difference combined with longitudinal dispersion coefficient were found to be in good agreement with simulated results. Predictions using the original Butler-Mokrys model meanwhile were consistently lower than the simulated rates.

Simulation results showed that drainage rates have a lower than square root dependency on reservoir height. The results also found that the Butler-Mokrys model breaks down at high height/length aspect ratios where the underlying assumptions no longer apply. Analysis on oil rate sensitivity to well placement found that in reservoirs with low height/length aspect ratios the spacing between injector and producer does not affect the stabilised oil drainage rate and cumulative production significantly.

Introduction
The decline in conventional oil reserves has encouraged the industry to explore alternatives to meet the ever increasing world oil demand. Heavy oil and bitumen is an area of particular interest as it is understood that there is a global deposit exceeding 5,000 billion barrels in place (World Energy Council, 2007). The high viscosities of these resources however make it difficult to recover using conventional techniques, with recovery factors seldom exceeding 10% (Roopa and Dawe, 2007). The typical method to produce these resources is through thermal processes such as Cyclic Steam Stimulation (CSS) and Steam Assisted Gravity Drainage (SAGD). Although effective, thermal processes have low energy efficiency due to excessive heat losses to the overburden and underburden (Das and Butler, 1998). In addition, treatment and disposal of effluent water and the related environmental problems are the other important concerns associated with heavy oil recovery through thermal processes (Das and Butler, 1998).

An alternative to the thermal process, the vapour extraction (VAPEX) process was first proposed by Butler and Mokrys (1989) as a solvent analogue of the Steam-Assisted Gravity Drainage (SAGD) method. In the VAPEX process, a vapour solvent is injected into a heavy oil reservoir to reduce its viscosity sufficiently for the oil to drain by gravity. VAPEX is more economical than thermal processes as it is more energy efficient and requires less capital costs compared to SAGD (Yazdani and Maini, 2005; Upreti et al, 2007; Vargas-Vasquez and Romero-Zerón, 2007). Carbon dioxide may also be injected together with the vapourised solvent, making VAPEX an attractive option for carbon dioxide sequestration projects (Talbi and Maini, 2003).

A schematic of the VAPEX process is shown in Fig. 1. Two parallel horizontal wells are drilled; one above the other, in the reservoir section of interest. Vapour is injected through the upper well and spreads upwards and laterally into the reservoir, forming a V-shaped chamber with the production well at the point of the ‘V’. During this spreading phase, the vapour comes into contact and diffuses into the oil, reducing its viscosity sufficiently for it to drain along the vapour-oil interface by gravity to the lower production well. The interface between solvent vapour and heavy oil is also known as the mixing layer. Das and Butler (1998) highlighted that the use of vapourised, rather than liquid solvent, produces a higher driving force due to the higher density difference between the oil and solvent vapour.
Butler and Mokrys (1989) derived an analytical model using analogies between the SAGD and VAPEX process to show that the stabilised oil drainage rate is determined from:

\[
q = \sqrt{2 \, k \, g \, h \, \phi \, N_i \, \Delta S_o}
\]  

(1)

where \( k \) is permeability (m\(^2\)), \( g \) is the acceleration due to gravity (m/s\(^2\)), \( h \) is the reservoir thickness (m), \( \phi \) is the porosity and \( \Delta S_o \) is the initial mobile oil saturation. \( N_i \) is a dimensionless parameter dependent only on the oil and vapour properties and is defined as:

\[
N_s = \int_{c_{\text{min}}}^{c_{\text{max}}} \frac{\Delta \rho \, D_s \, (1-c) \, dc_s}{\mu \, c_s}
\]  

(2)

where \( \Delta \rho \) is the density difference between the draining oil-vapour mixture and vapour (kg/m\(^3\)), \( D_s \) is the effective molecular diffusion coefficient between the vapour and oil (m\(^2\)/s), \( c_s \) is the concentration of the solvent, \( \mu \) is the viscosity of the solvent-oil mixture (Pa s), \( c_{\text{max}} \) and \( c_{\text{min}} \) are the maximum and minimum solvent concentration in the solvent-oil layer respectively.

The analytical model accurately predicted the oil drainage rates from experiments in Hele-Shaw cells (Butler and Mokrys, 1989) but significantly under-predicted the rates from subsequent experiments in porous media (Dunn et al., 1989; Das and Butler, 1998; Boustani and Maini, 2001; Karmaker and Maini, 2003; Yazdani and Maini, 2005; Yazdani and Maini, 2008).

Most of the researchers have proposed increasing the diffusion coefficient, in some cases, up to 2 or 3 orders of magnitude (Lim et al., 1996; Boustani and Maini, 2001) to match the higher rates observed in the experiments (Dunn et al., 1989, Das and Butler, 1998; Kapadia et al., 2006). The increased level of mixing observed in porous media were attributed to various reasons such as a larger interfacial contact area for mass transfer (Das and Butler, 1998) and enhanced solvent-oil mixing by convective dispersion (Boustani and Maini, 2001; Das, 2005). Das and Butler (1998), Cuthiell et al. (2006) and Frauenfeld et al. (2006) suggested that capillary imbibition of the original crude oil into oil films on the sand grains in the mixing layer would maintain a large concentration gradient between solvent and oil and thus increase diffusion. Das and Butler (1998) also hypothesized that counter-current flow during solvent chamber rise was a possible reason for increased solvent-oil mixing. Other researchers (Karmaker and Maini, 2003; Yazdani and Maini, 2008; Alkindi et al., 2010a) meanwhile have postulated that the increased drainage rates observed in the experiments are a result of a different dependency on reservoir height than that given in Eq. 1.

Several numerical simulation studies have also been performed to replicate the VAPEX experiments and predict the oil drainage rate. Das (2005) found that artificially high diffusion coefficients were required to match the experimental values when simulating the VAPEX experiment using a fully compositional simulator. Even so, the simulator was still unable to simultaneously match the thickness of the boundary layer as it predicted a much wider interface than observed in experiments. Kapadia et al. (2006) developed their own numerical model to determine the dispersion of butane in Cold Lake bitumen during VAPEX. They found that the dispersion coefficient required to match experimental rates was four orders of magnitude higher than molecular diffusion. Simulations using commercial thermal simulators, in contrast, were more successful. For example, Wu et al. (2005) were able to match the experimental results of Mokrys and Butler (1993) while Cuthiell et al. (2003) managed to history match the results from a series of 5 VAPEX experiments performed in a laboratory sand-pack.

Numerical simulations, in some cases, produced consistent results with experimental observations whereas predictions using the analytical model of Butler and Mokrys (1989) appear to always under-predict the oil rates. The consistent under-prediction of oil rates using the Butler-Mokrys analytical model raises some questions regarding the validity of some of the assumptions made during its derivation. Alkindi et al. (in press) suggested that a systematic experimental study which
replicates all the simplifying assumptions in the analytical model (Butler and Mokrys, 1989) is performed to investigate possible causes of this lower prediction. Alkindi et al. (in press) performed a set of VAPEX experiments with first contact miscible analogue fluids (ethanol and glycerol) to study the displacement and oil recovery process. They also performed experiments to independently determine the longitudinal and transverse dispersion coefficients of the ethanol and glycerol pair. Other fluid parameters such as density and viscosity were either measured directly in the laboratory or in the case of molecular diffusivity, taken from literature (Tominaga and Matsumoto, 1990). These parameters were then used as input into numerical simulation in a commercial thermal simulator.

The predicted oil rates from numerical simulation and analytical model were then compared with experimental results. They found that the VAPEX simulation model produced a good match with the experiments as it was able to predict the oil drainage rates and mixing layer thickness accurately. The analytical model, in contrast, still under-predicted the oil rates although they noted that there was an improvement in the prediction when the measured longitudinal dispersion coefficient was used instead of molecular diffusion.

This thesis aims to check the consistency of the Butler-Mokrys analytical model with the validated numerical simulation model from Alkindi et al. (in press). The simplifying assumptions made in deriving the analytical model were reviewed and an improvement on the expression was proposed. Multiple simulation runs were performed to study the sensitivity of oil drainage rates to several key parameters such as reservoir thickness, length, permeability, well location, density difference and viscosity ratio. The simulation output was then compared against predicted rates from the original and modified analytic Butler-Mokrys models. The thesis also investigates the impact of alternative well placement and fluid properties on the oil recovery by VAPEX and highlights the relevant areas for consideration for a field scale implementation.

**Analytical Model Review**

The assumptions made by Butler and Mokrys (1989) in deriving their analytic prediction of oil drainage rate during VAPEX were as follows:

1. The solvent chamber has been established but the solvent-oil interface has yet to reach the edges of the reservoir
2. Flow is essentially two dimensional in the vertical plane perpendicular to the horizontal wells
3. The undiluted oil is immobile and oil can only move once it is diluted by the solvent
4. The density difference between the solvent and oil is so large and the solvent injection rate is very slow that the flow is gravity dominated and there is vertical equilibrium. The oil and solvent are segregated completely except for the mixing at the interface.
5. The solvent and oil are first contact miscible so that the mixing at the interface is controlled by the effective molecular diffusion. Relative permeability and capillary pressure effects can be ignored.
6. Oil is recovered by a thin layer of oil diluted by the injected solvent draining down the solvent-oil interface to the production well.

Since the flow of solvent is gravity dominated and the reservoir is in vertical equilibrium (Assumption 4), there is no vertical Darcy flow in the reservoir. The spreading of solvent into the reservoir is essentially an unstable displacement under segregated flow conditions and is characterised by a gravity tongue. This type of displacement was first studied by Dietz (1953) and later extended by Fayers and Muggeridge (1990). During the gravity unstable spreading phase, the flow of solvent into the reservoir is governed by pressure gradient in the horizontal direction. Using the same approach of Dietz (1953) and Fayers and Muggeridge (1990), and ignoring any capillary pressure effects, it could be shown that the horizontal solvent velocity is then only a function of end point density difference between the solvent and oil. (Muggeridge, private communication)

Assuming that the fluids are incompressible, the introduction of solvent must be balanced by an outflow of oil or solvent-oil mixture to maintain mass balance. As the oil is immobile and can only move once diluted (Assumption 3), the conservation of mass is achieved through gravity drainage of diluted oil solvent mixture in the mixing layer. The flow rate of draining oil is then \( q_{oil} = q_{mixture} (1-c_s) \) where \( q_{oil} \) is the oil flow rate, \( q_{mixture} \) is the solvent-oil mixture flow rate in the mixing layer and \( c_s \) is the solvent concentration.

Butler and Mokrys (1989) assumed that the gravity driving force gradient was due to the density difference between the solvent-mixture and pure solvent in the mixing layer, and thus was concentration-dependent. However, from the above analysis, it is proposed that the driving force is due to the end point density difference between solvent and oil and is not concentration dependent. Butler and Mokrys (1989) also assumed that diffusion rate between solvent and oil in the mixing layer was a function of concentration-dependent diffusion coefficients. In this study, it is suggested that the mutual diffusion coefficient at infinite dilution is used instead as the analogue fluids selected are first contact miscible. Taking all this into account, the Butler-Mokrys expression for \( N_t \) can then be re-written as:

\[
N_t = \Delta \rho \ D_m \int_{c_{min}}^{c_{max}} \frac{(1-c_s)}{\mu c_s} \ dc_s
\]

(3)
Eq. 3 shows that since $D_m$ is constant for specific solvent-oil mixtures, the stabilised oil rate prediction using $N_e$ in the Butler-Mokrys model will be constant regardless of the solvent injection rate. Experiments by various researchers (Alkindi et al., 2010a; Cuthrell et al., 2003) however have shown that the stabilised oil rate increases with an increase in solvent injection rate and have proposed that convective dispersion, rather than molecular diffusion as the main mixing mechanism in the VAPEX process. Alkindi (2009) performed experiments to independently measure the longitudinal ($K_L$) and transverse dispersion ($K_T$) coefficients of the fluid pair (ethanol and glycerol) in his study and matched them to correlations proposed by Perkins and Johnston (1963). The measured coefficients were then used in the Butler-Mokrys model to predict the stabilised oil drainage rate.

Table 1 shows the predicted oil drainage rates using solvent-oil end point density difference ($\Delta \rho_{end}$) and concentration dependent solvent-mixture density difference ($\Delta \rho_{m}$) to calculate $N_e$. The influence of dispersion was studied by incorporating the longitudinal dispersion coefficient ($K_L$) instead of molecular diffusion ($D_m$) in $N_e$ calculations using both $\Delta \rho_{end}$ and $\Delta \rho_{m}$ methods. The predicted rates from analytical models were then compared against measured stable oil rates from the experiments (Alkindi, 2009).

<table>
<thead>
<tr>
<th>Injection Rate</th>
<th>Oil rate predicted using $\Delta \rho_{end}$ and molecular diffusion, $D_m$</th>
<th>Oil rate predicted using $\Delta \rho_{m}$ and longitudinal dispersion, $K_L$</th>
<th>Oil rate predicted using $\Delta \rho_{end}$</th>
<th>Oil rate predicted using $\Delta \rho_{m}$ and longitudinal dispersion, $K_L$</th>
<th>Measured stable oil rate (Alkindi et al.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(cm$^3$/hr)</td>
<td>(cm$^3$/hr)</td>
<td>(cm$^3$/hr)</td>
<td>(cm$^3$/hr)</td>
<td>(cm$^3$/hr)</td>
<td>(cm$^3$/hr)</td>
</tr>
<tr>
<td>0.6</td>
<td>0.32</td>
<td>0.36</td>
<td>0.52</td>
<td>0.55</td>
<td>0.48</td>
</tr>
<tr>
<td>1.2</td>
<td>0.45</td>
<td>0.41</td>
<td>0.63</td>
<td>0.63</td>
<td>0.75</td>
</tr>
</tbody>
</table>

The $\Delta \rho_{end}$ approach over-predicted the oil rate by 8% for the 0.6 cm$^3$/hr injection rate case but under-predicted the rate by 31% as the solvent injection rate is doubled to 1.2 cm$^3$/hr. The $\Delta \rho_{m}$ approach meanwhile, under-predicted the oil rate by 33% in the 0.6 cm$^3$/hr injection rate case and 57% for the 1.2 cm$^3$/hr case. There was an improvement in the oil rate prediction using $\Delta \rho_{m}$ at low injection rates but the error in prediction increased significantly when the injection rate was doubled. Incorporation of the measured longitudinal dispersion coefficient ($K_L$) improved the predicted oil rates in both approaches. For example, the $\Delta \rho_{end}$ method for the 1.2 cm$^3$/hr solvent injection rate case was under-predicted the oil rate by 16%, which was a 48% improvement over the prediction using molecular diffusion coefficient ($D_m$).

From this analysis it can be observed that using the end point density difference is an improvement over the original $N_e$ expression which used a concentration-dependent density difference. Alkindi (2009) highlighted that the use of longitudinal dispersion coefficients resulted in a better analytical oil rate prediction and as seen in Table 1, combining this with the end point density difference approach further improved the prediction. However, it is also noted that at lower solvent injection rates, this approach overpredicted the stabilised oil rate.

**VAPEX Physical Model**

Alkindi (2009) performed laboratory experiments of the VAPEX process using analogue fluids in his study to investigate the influence of dispersion mixing on oil drainage rate. The VAPEX experiments were performed in a bead pack constructed within a Perspex box which measured 30 cm high, 15 cm wide and 0.5 cm thick. Grade 11 Ballotini glass beads (212-250μm diameter) were used as the porous medium. The pack porosity and permeability were measured to be 40% and 43 Darcies respectively. Injection and production ports were located at the middle and bottom of the 30 cm and 15 cm vertical sides of the model to represent the upper injector and lower producer. The model could be rotated counter-clockwise 90 degrees to allow for VAPEX experiments to be performed at a lower height/length aspect ratio. A schematic of the bead pack model is shown in Fig. 2.

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Fig. 2 – Schematic of the bead pack model used for the VAPEX experiments (Alkindi, 2009)
Ethanol and glycerol were chosen as analogue fluids for solvent and heavy oil respectively. The density and viscosity contrast between the fluids were deemed sufficiently similar to that found between typical solvent and heavy oil in the VAPEX process. Physical properties of ethanol and glycerol are summarised in Table 2. Further description of the physical bead back model and analogue fluids chosen are provided in Alkindi (2009).

**Table 2 – Physical properties of ethanol and glycerol at 20 °C and 1 atm (Alkindi, 2009)**

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Density (kg/m³)</th>
<th>Viscosity (mPa s)</th>
<th>Molecular Weight (kg/kmol)</th>
<th>T_c (°C)</th>
<th>P_c (kPa)</th>
<th>Diffusion coefficient (m²/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethanol</td>
<td>790</td>
<td>1.2</td>
<td>46.1</td>
<td>240.75</td>
<td>6140</td>
<td>6.0×10⁻¹⁰</td>
</tr>
<tr>
<td>Glycerol</td>
<td>1261</td>
<td>1390</td>
<td>92.1</td>
<td>452.85</td>
<td>6680</td>
<td></td>
</tr>
</tbody>
</table>

**Numerical Simulation Model**

The VAPEX experiments were numerically simulated and the simulation predictions were compared against experimentally measured parameters of solvent and oil distribution, oil rate, solvent breakthrough time and solvent/oil ratio. Simulations were performed using a semi-compositional simulator, CMG-STARS (Computer Modelling Group, Canada) to simplify modelling of the liquid system. A fully compositional simulator would add complexities into the simulation as additional fitting is required to obtain an adequate equation of state description of the fluids (Alkindi, 2009).

The reference case for this work was based on Alkindi’s (2009) numerical simulation model of his VAPEX experiment set up. The model had a grid size of 60×1×150 grid cells with thickness of 0.25, 0.5 and 0.2 cm in the x, y and z-directions respectively. The model represented a 2D vertical cross section of half of a reservoir being subjected to the VAPEX process. This grid size was selected after a grid sensitivity study by Alkindi (2009). The grid size was sufficiently fine to ensure that physical dispersion dominated over numerical dispersion at all times while keeping the computing time to a minimum.

The porosity and permeability were set constant in all cells. Straight line relative permeability curves were applied and no capillary pressure data was used since the fluids were first contact miscible. Mixing between oil and solvent was modelled by explicitly specifying the total dispersion coefficient in the x and y-directions. The dispersion coefficients used in the simulations were calculated from experimentally measured interface velocities using correlations proposed by Perkins and Johnston (1963). Longitudinal dispersion was defined as dispersion in the vertical direction and transverse as horizontal in the simulation model.

The production and injection wells were modelled as high permeability blocks to represent the point source injection used in the experiments. The producer was placed at the bottom of the first column while the injector was placed at the mid-point height of the same column. The injector and producer were operated under constant injection rate and constant bottom-hole pressure (BHP) constraints respectively. The system pressure was set at 101 kPa (atmospheric pressure) and temperature to 20 °C which were equal to experiment conditions. A summary of the base case model properties is shown in Table 3.

Results of the base case model were in excellent agreement with experimental results. The simulation was able to predict the stabilised oil rate and solvent breakthrough time very well. The key physical features in the VAPEX process such as development of a spreading solvent chamber and a mixing interface layer between pure solvent and oil were also replicated accurately by the simulator (Alkindi, 2009). This is illustrated in Fig. 3. The simulated solvent concentration profiles at different pore volume injected (PVI) agreed very well with the solvent distribution observed in the experiment. The good match between the model and experiments in terms of oil drainage rate, breakthrough time and solvent-oil interface shape enhanced the confidence in using the numerical simulation model. This model was then used to run different sensitivity runs to test and validate the Butler-Mokrys model in lieu of further lab experiments.

**Table 3 – Key properties of base case simulation model**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid type</td>
<td>Cartesian</td>
</tr>
<tr>
<td>Grid size</td>
<td>60×1×150</td>
</tr>
<tr>
<td>Aspect Ratio (Height : Length)</td>
<td>2:1 and 1:2</td>
</tr>
<tr>
<td>Porosity</td>
<td>0.4</td>
</tr>
<tr>
<td>Permeability</td>
<td>43.3 D</td>
</tr>
<tr>
<td>Reference Pressure</td>
<td>101 kPa</td>
</tr>
<tr>
<td>Reservoir Temperature</td>
<td>20 °C</td>
</tr>
<tr>
<td>Number of injection wells</td>
<td>1</td>
</tr>
<tr>
<td>Number of production wells</td>
<td>1</td>
</tr>
<tr>
<td>Injection rate</td>
<td>0.6 cm³/hr and 1.2 cm³/hr</td>
</tr>
<tr>
<td>Longitudinal Dispersion Coefficient</td>
<td>8.9×10⁻¹⁰ m²/s</td>
</tr>
<tr>
<td>Transverse Dispersion Coefficient</td>
<td>4.8×10⁻¹⁰ m²/s</td>
</tr>
</tbody>
</table>
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The sensitivity of oil drainage rate to reservoir height, length, permeability, well placement and density difference were investigated in this study. The impact of each parameter on the solvent concentration distribution, mixing interface shape and oil viscosity profile was also analysed to study VAPEX performance under different conditions. The simulation results were then compared against the Butler-Mokrys analytical model and the consistency between both numerical and analytical predictions were reviewed. This will be further discussed in the following section. Table 4 shows the parameters that were investigated in the sensitivity analysis.

### Table 4 – Sensitivities investigated in this study

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sensitivity Run</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aspect Ratio (Height : Length)</td>
<td>3:1, 4:1, 6:1, 8:1, 1:1, 1:2, 1:4</td>
</tr>
<tr>
<td>Permeability</td>
<td>0.5, 1, 6, 12, 23.5 D</td>
</tr>
<tr>
<td>Injector Location</td>
<td>Middle and Top of Reservoir</td>
</tr>
<tr>
<td>Density difference ($\Delta \rho$)</td>
<td>118, 235, 940, 1400, 2350 kg/m³</td>
</tr>
<tr>
<td>Viscosity ratio ($M$)</td>
<td>500, 2000, 10000, 20000</td>
</tr>
</tbody>
</table>

### Simulation Results

**Aspect Ratio**

Fig. 4 shows a plot of oil rate vs PVI for different reservoir heights which correspond to aspect ratios of 2:1, 3:1, 4:1, 6:1 and 8:1. It is noted that some convergence issues were observed as the reservoir height was increased. Due to a limitation on the number of grid cells in the software license, it was not possible to further refine the model to reduce these numerical problems. However, this was still deemed acceptable as the simulation produced a stable trend oil rate from which the average oil drainage rate could be estimated.

Initial observation of Fig. 4 showed that the oil rate was proportional to reservoir height but to further analyse whether the height dependency was square root as proposed by Butler and Mokrys, a sensitivity analysis of oil rate vs height was plotted and shown in Fig. 5. Neither the $\Delta \rho_{sw}$ nor $\Delta \rho_{sm}$ Butler-Mokrys model was found to provide a good match with the simulation results. Incorporating longitudinal dispersion coefficient in place of molecular diffusion improved the predictions slightly but the match was still quite poor. Karmaker and Maini (2003), Yazdani and Maini (2008) and Alkindi et al (2010a) have argued that the oil rate has a different dependency on reservoir height than square root and have proposed different dependency factors. These different height dependency factors were also plotted in Fig. 5 and it can be observed that neither of these factors matched the simulated oil rates. The simulation results from this study were best matched using $\Delta \rho_{so}$ with longitudinal
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dispersion coefficient and a height dependency of 0.28. Even so, the match was only good up to a height of 0.6 cm (aspect ratio 4:1) and at larger reservoir heights, the match became increasingly poor.

Fig. 4 – Oil rate vs PVI for different reservoir heights (Aspect ratio 2:1, 3:1, 4:1, 6:1 and 8:1) and constant reservoir length of 15 cm

Fig. 5 – Sensitivity analysis of oil rate vs height comparing simulation results with the Butler-Mokrys model. Reservoir length was kept constant at 15 cm in all cases.

The solvent chamber development for the 2:1 and 4:1 aspect ratio cases are shown in Fig. 6 to further study and visualise the displacement process. The solvent concentration profile of the 4:1 aspect ratio model shows that as the reservoir height increased, the solvent-oil mixing interface shape became more vertical and did not maintain the characteristic V-shaped profile, except near the top of the reservoir where a gently sloping shape can still be observed. The solvent flow into the reservoir appeared to follow an unstable gravity tongue similar to one described by Dietz (1953). In addition, vertical equilibrium is also less likely to be established in this thicker reservoir, as highlighted by Coats (1971). Based on these observations, it is very probable that the underlying assumptions in the Butler-Mokrys no longer apply for thick reservoirs, resulting in the analytical model breaking down at these conditions. It is hypothesized that most of the mixing in the 4:1 aspect ratio model occurs along the vertical section of the solvent-oil mixing layer where the oil drainage velocity is much greater compared to the velocity along the sloped section. The higher drainage velocity reduces the time available for diffusion to mix the solvent and oil perpendicular to the interface. The rate of mixing does not increase and therefore remains the same. This results in the oil rate reaching a plateau at reservoir aspect ratios greater than 4:1.
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Fig. 6 – Solvent concentration profiles for reservoir with aspect ratios of 2:1 and 4:1

The effect of reservoir length on oil rates was also analysed and the oil rate vs time for aspect ratios of 1:1, 1:2 and 1:4 is presented in Fig. 7. The results show that the stabilised oil drainage rate was the same for all cases and the reservoir length only influenced the duration of stabilised production. The start of stabilised production occurred at approximately the same time for the three cases, which is expected as all three cases have the same reservoir thickness, well location and solvent injection rate. The duration of stabilised oil drainage in the 1:2 aspect ratio case was much longer compared to the 1:1 case as the solvent chamber needed to travel a greater distance before reaching the edge of the reservoir. The oil rate then began to drop after the solvent chamber has reached the reservoir boundary. The drop in oil rate was due to the reduction in the interface height and gravity head available for drainage as the solvent chamber moved downwards. However, in the 1:4 aspect ratio case, the stabilised oil rate was not significantly longer than the 1:2 case. In fact, the oil rate started to follow the same declining profile as the 1:2 case after approximately 8000 minutes. Fig. 8 shows the solvent-concentration profile in the 1:4 case at this time. It can be seen that the solvent chamber had yet to reach the edge of the reservoir when a drop in oil rate is observed. This earlier than expected end to the stabilised oil drainage period in the 1:4 case suggests that the reservoir aspect ratio may have an influence on oil drainage profile. This is consistent with the earlier argument that the oil rate has a dependency on the reservoir aspect ratio although in this case, the cause of Butler-Mokrys model breakdown is uncertain, as the mixing layer still maintained the sloping V-shaped profile.

Fig. 7 – Oil rate vs time for different reservoir lengths (aspect ratio 1:1, 1:2 and 1:4) at a constant reservoir height of 30 cm
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Fig. 8 – Solvent concentration profile for the 1:4 aspect ratio case (reservoir height 30cm) after 8000 minutes

Injector Location

The sensitivities of oil drainage rate to injector location and the injector-producer spacing were also investigated in this study. Simulations of cases with an alternative injector located at the top of the reservoir were performed to analyse the impact of this new well location on stabilised oil rate, cumulative oil production, solvent/oil ratio (SOR) and injector bottomhole pressure (BHP). Sensitivities were run for cases with reservoir aspect ratios of 1:2 and 1:4 to study how reservoir length influences the oil drainage rates with different injector locations.

Fig. 9 shows the stabilised oil rate and cumulative oil production for cases where the injector is located at mid-height and top of the reservoir respectively, for a 1:2 aspect ratio (30 cm height) model and 1.2 cm³/hr solvent injection rate. The top injector case had a longer initial high oil production rate compared with the middle injector case as it took a longer time to establish communication between the injector and producer due to the increased distance. The initial high rates resulted from the viscous-dominated displacement process while communication between the upper and lower wells was being established (Alkindi et. al., in press). At 0.4 PVI, the oil drainage in both cases reached approximately the same rate. The cumulative oil production in the top injector case was 14% higher than the middle injector case. The solvent/oil ratio (SOR) and injector BHP for both cases are shown in Fig. 10. For the top injector case, there was no solvent breakthrough until 0.15 PVI, at which communication between the injector and producer had been established. Once solvent had broken through, the SOR increased dramatically, and this is more pronounced in the middle injector case as an almost instantaneous step-change in SOR from 0 to 0.65 was observed as soon as breakthrough was achieved. After initial communication between the injector and producer was established, the displacement changed from a viscous to a more gravity dominated process. Consequently, the bottomhole pressure of the injector dropped as there was no longer viscous flow of solvent towards the lower producer.

Fig. 9 – Oil rate and cumulative production profile trend for top and middle injector cases (aspect ratio 1:2 and height 30 cm)
Numerical Investigations into Oil Drainage Rates during Vapour Extraction (VAPEX) of Heavy Oils

Fig. 10 – BHP and SOR trends for top and middle injector cases (aspect ratio 1:2 and height 30 cm)

Fig. 11 - Oil rate and cumulative production profile trends for top and middle injector cases (aspect ratio 1:4 and height 30 cm)

Fig. 12 – BHP and SOR trends for top and middle injector cases (aspect ratio 1:4 and height 30 cm)
Numerical Investigations into Oil Drainage Rates during Vapour Extraction (VAPEX) of Heavy Oils

The same plot of oil rate and cumulative oil production for a reservoir with an aspect ratio of 1:4 is shown in Fig. 11. It shows a similar profile as Fig. 9 but in this case the oil drainage for both cases reached the same rate much earlier at 0.25 PVI, and the difference in cumulative oil production now was 9%. **Fig. 12** shows the SOR and injector BHP for both cases, which also displayed a similar trend with the 1:2 aspect ratio reservoir. However, the initial displacement period was shorter and the breakthrough time was earlier in the 1:4 case. The SOR for both top and middle injectors approached the same value at approximately 0.4 PVI.

From these observations, it could be concluded that as the reservoir length is increased, the impact of injector placement becomes insignificant as placing the well either at mid-height or at the top of the reservoir will result in approximately the same stabilised oil rate and cumulative oil production. However, there is an opportunity for production strategy optimisation especially during the initial displacement period, where the top injector can provide higher rates at a longer plateau. The cost of the prolonged high pressure period required to maintain this high rate should also be part of the consideration when selecting the best strategy to develop a field using VAPEX.

**Permeability**

**Fig. 13** compares the relationship between stabilised oil rate and square root of permeability predicted from numerical simulation and the analytic Butler-Mokrys model. The effect of using $\Delta \rho_{so}$, $\Delta \rho_{sm}$ molecular diffusion and longitudinal dispersion coefficients in the Butler-Mokrys model to predict the stabilised oil rates was analysed. The Butler-Mokrys predictions show a good match with simulation results, especially when $\Delta \rho_{so}$ and longitudinal dispersion coefficient were used. This is consistent with the findings of previous researchers (Das and Butler, 1998; Karmaker and Maini, 2003; Yazdani and Maini, 2005) that the oil rate is dependent on the square root of permeability and confirmed the relationship originally proposed by Butler and Mokrys (1989). Stabilised oil drainage rate calculation using $\Delta \rho_{so}$ in comparison, was found to consistently under-predict the oil rate.

**Fig. 13** – Stabilised oil rate vs square root of permeability sensitivity plot for 1.2 cm$^3$/hr injection rate case (aspect ratio 2:1, reservoir height 30 cm)

**Fig. 14** presents the sensitivity plot when the solvent injection rate was reduced to 0.6 cm$^3$/hr. The influence of a more gravity stable displacement at this lower injection rate on the stabilised oil rate predicted by numerical simulation and the analytical Butler-Mokrys model was observed. The sensitivity analysis showed that applying the longitudinal dispersion coefficients in the analytic model did not influence the Butler-Mokrys predictions significantly as the measured dispersion coefficient at this injection rate was only 12% higher than the molecular diffusion coefficient (Alkindi et. al., in press). This observation agrees with findings of several researchers (Jiao Hotzl, 2004; Flowers and Hunt, 2007) who asserted that the dispersion mechanism in porous media reduces to molecular diffusion when the displacement becomes more gravity stable. This provides an explanation why there is little difference in using dispersion or diffusion coefficients in the Butler-Mokrys calculation in this case. Predicted oil rates using $\Delta \rho_{so}$ was also plotted and again, the results showed that this approach under-predicted the oil rate.

**Density Difference ($\Delta \rho$)**

Understanding the impact of density difference on the oil drainage rate is important when selecting a suitable solvent for VAPEX of a heavy oil reservoir. **Fig. 15** shows how changing the density difference ($\Delta \rho$) affects the oil drainage profile. The stabilised oil rate increased with a higher $\Delta \rho$ but the stabilisation period was significantly reduced. The increased rate was due to the higher driving force associated with a high density difference (Butler and Mokrys, 1989) while the shorter stabilisation period was attributed to a more rapid spreading of the solvent chamber. **Fig. 16** presents a sensitivity analysis of oil rate vs
square root of $\Delta \rho$ to compare the simulation results with predicted rates from several variations of the Butler-Mokrys analytical model.

Fig. 15 – Oil rate vs PVI for density difference 118, 235, 470, 940, 1400 and 2350 kg/m$^3$ (aspect ratio 2:1, reservoir height 30 cm)

Fig. 16 – Stabilised oil rate vs square root of density difference ($\Delta \rho$) for base case model (aspect ratio 2:1, reservoir height 30 cm) and 1.2 cm$^3$/hr injection rate

Findings from Fig. 16 showed consistency with previous observations where the use of $\Delta \rho_{so}$, coupled with the measured longitudinal dispersion coefficients provided the best match with simulation results. At higher $\Delta \rho$, where the process is more gravity stable, the results closely match that of the Butler-Mokrys model with molecular diffusion, which is also consistent with the previous assertion that convective dispersion reduces to molecular diffusion as the process becomes more gravity stable.

**Viscosity Ratio ($M$)**

The relationship between stabilised oil rate and viscosity ratio was analysed and shown in Fig. 17. The mixture viscosity was calculated using the ideal mixing rule:

$$
\mu_m = \mu_o \cdot e^{(\ln M) \cdot c_s}
$$

where $\mu_m$ is the mixture viscosity, $\mu_o$ is the oil viscosity, $M$ is the viscosity ratio and $c_s$ is the solvent concentration. This correlation was within reasonable agreement with the empirical ethanol-glycerol viscosity correlation from Alkindi’s (2009) experiments. Predictions using $\Delta \rho_{so}$, together with longitudinal dispersion again was the best match with simulation results. The model under-predicted the oil rates at low viscosity ratios but at viscosity ratios where we expect VAPEX to be applied ($M > 1000$), the match between Butler-Mokrys predictions and simulation results was very good.

A spider plot illustrating the sensitivity of the oil drainage rate to changes in the viscosity ratio, $M$ and density difference, $\Delta \rho$ is shown in Fig. 18. Changes in $M$ and $\Delta \rho$ were found to have contrasting effects on the predicted oil rate. This analysis could be helpful during solvent selection process to determine the optimum solvent properties for application in heavy oil recovery by VAPEX.

Fig. 17 – Stabilised oil rate vs viscosity ratio sensitivity plot for the base case model (aspect ratio 2:1, reservoir height 30 cm) and 1.2 cm$^3$/hr injection rate

Fig. 18 – Spider plot showing sensitivity of stabilised oil drainage rate to changes in viscosity ratio ($M$) and density difference ($\Delta \rho$)
Discussions

From the simulation results and analysis using the Butler-Mokrys model, it can be seen that using the end point density difference ($\Delta\rho_{po}$) and measured dispersion coefficients in calculating $N_t$ consistently provide the best match with simulation results. It appears that using concentration-dependent density difference ($\Delta\rho_{pot}$) in calculating $N_t$ as originally proposed by Butler and Mokrys is the reason the model predicted a lower oil drainage rate. Also, applying the longitudinal dispersion coefficients ($K_l$) in the calculations instead of molecular diffusion coefficients ($D_m$) was found to further improve the accuracy of the predictions. However, since the dispersion rate is a dynamic parameter which is directly related to the mixing layer velocity and is influenced by displacement stability, the use of a constant dispersion coefficient is only valid within a limited range. Beyond this range, the analytical model was unable to provide a good prediction of the stabilised oil rate. Selection of a dispersion coefficient that represents the mixing process more accurately therefore is important to improve the accuracy of the Butler-Mokrys prediction under different displacement conditions. The stabilised oil rate dependency on height is still uncertain; as in this study, it was found to best match a factor of 0.28 when $\Delta\rho_{po}$ and $K_l$ were used in the Butler-Mokrys model. This is inconsistent with findings from other researchers such as Yazdani and Maini (2008) and Alkindi et. al. (2010a) who reported the dependency to be 1.13 and 0.67 respectively, although it is noted that these exponents were determined using $\Delta\rho_{pot}$ in the $N_t$ calculations.

The oil drainage rate is argued to also have a dependency on the reservoir aspect reservoir as the sensitivity analyses of height and length showed that there is a limiting condition where further increase in either parameter resulted in deviation from the expected VAPEX behaviour. The simulation results show that the stabilised drainage rate reached a plateau when the reservoir aspect ratio is greater than 4:1. This is speculated to be due to less time being available for diffusion mixing between solvent and oil perpendicular to the mixing layer as the interface velocity in the vertical direction increases. In cases with low height/length aspect ratios, the period of stabilised drainage in the simulation was found to be significantly shorter than expected. The cause of this is unclear as inspection of the solvent distribution and viscosity profiles do not highlight any significant change from a typical VAPEX process. Further studies on the influence of aspect ratio on the oil drainage profiles should be undertaken to provide an improved explanation for this.

The simulation results from the base case model were found to be in good agreement with experimental results. This was the basis of using numerical simulation to study various parameter sensitivities and test the Butler-Mokrys model in lieu of further experimental work. In this study, sensitivity studies were performed so that the variation of any parameter was limited up to 400% of the base case value. This was done to ensure all the results were within an acceptable range in view of the grid cell size limitation in the software. Other limitations of the numerical simulation model may also influence the accuracy of the results. For example, the dispersion coefficient was modelled as a constant in the x and y-directions using experimentally measured values, whereas in reality, the dispersion coefficient varies as a function of interface velocity (Perkins and Johnston, 1963; Das, 2005; Alkindi. et. al, in press). Furthermore, the influence of gravity as shown by Alkindi et. al. (in press) in reducing the longitudinal dispersion in gravity stable displacements was also not accounted for. Therefore, validation of these simulation results, especially the results of the extreme cases (highest and lowest change from base model) with lab experiments is highly recommended to improve confidence in using the numerical model.

Quantifying the dispersion and diffusion rates is the main uncertainty in upscaling the lab scale model to field scale. Applying a velocity dependent dispersion coefficient should improve the estimation of the stabilised oil drainage rate. It is important to be able to quantify the average interface velocity so that the dispersion coefficients could be determined using the correlation proposed by Perkins and Johnston (1963). As the dispersion rate is also affected by gravity, calculation of the dispersion rate must also consider other factors influencing the displacement stability such as solvent injection rate and reservoir thickness. A systematic approach to quantify the average interface layer velocity has not yet been fully established and thus at present, determination of dispersion coefficients will still require experimental lab measurements. This presents a huge challenge in modelling the VAPEX process at a field scale.

Well placement is one of the few parameters within our control when developing a field. Thus, understanding the impact of well location on oil rate is important when designing a VAPEX development plan. As highlighted earlier, for a realistic reservoir aspect ratio where the length is much greater than the height, the location of the injector does not influence the stabilised oil rate and cumulative recovery significantly. However, during the initial period where the oil is produced through a displacement-type process, there is a major difference in the production profiles between the top injector and middle injector cases. This is most likely where any optimisation of field development or operating strategy should be considered. Having the injector further away from the producer allows for high oil rates at a longer plateau but the cost of maintaining higher pressures for this period must also be evaluated. Placing the injector much closer to the producer results in earlier solvent breakthrough and the cost of handling high solvent production will be incurred much earlier but this may be offset by the reduced compression cost as it will take a shorter period to establish communication between the upper injector and lower producer. The cost of compression may become significant especially for a field scale VAPEX process, as the injection rates and pressures are much higher. Apart from this operational consideration; for a real field, reservoir geometry and heterogeneity may well have a greater influence on well placement. The presence of shale layers for example, would dictate the placement and number of wells to be drilled over any operationally-optimised design.

Selection of a suitable solvent is also important as the sensitivity analysis of density difference and viscosity ratio shows that the oil rate is directly related to density difference but inversely related to the viscosity ratio. Solvent selection therefore must balance between selecting a low density and high viscosity solvent to optimise the oil production rate from VAPEX. The
selection is more complicated when using real fluids in real reservoirs as the effects of sub-miscibility, capillary pressure and relative permeabilities would also influence the solvent-oil mixing process.

Conclusions
The original Butler-Mokrys analytical model was reviewed and a modified expression to calculate the dimensionless parameter \(N_r\) was proposed. This modified expression suggested that the end point density difference \(\Delta \rho_{wp}\) is used instead of a concentration-dependent density difference \(\Delta \rho_{pm}\). Incorporation of longitudinal dispersion coefficients in place of molecular diffusion is also proposed, consistent with findings from Alkindi et al. (2010a) and Boustani Maini (2001) who have highlighted that longitudinal dispersion is the dominant mixing mechanism between the solvent and oil in porous media.

Numerical simulation of the VAPEX process with analogue fluids were performed to investigate the sensitivities of reservoir aspect ratio, permeability, injector location, density difference and viscosity ratio on the stabilised oil drainage rate. The results showed that numerical simulation using a semi-compositional simulator was able to reproduce the key features of the VAPEX process such as the spreading solvent chamber and oil drainage by gravity along the mixing interface layer. The simulated results for the base case model were compared against experimentally measured rates and were found to be in excellent agreement. This base case model was then used to run further simulations with different reservoir properties and dimensions in lieu of further lab experiments.

In general, using the modified \(N_r\) and longitudinal dispersion coefficient in the Butler-Mokrys model provides a good match with the simulated oil rates. This is an improvement over the concentration-dependent density difference \(\Delta \rho_{pm}\) method in the original \(N_r\) expression. The height dependency in this study was found to best match an exponent of 0.28 which is significantly lower than what was proposed by previous researchers (Yazdani and Maini, 2008; Alkindi et al., 2010a). The analytic model was also found to over-predict the stabilised oil drainage rates in reservoirs with large height/length aspect ratios. It is hypothesized that this over-prediction is due to oil drainage rate having a dependency on aspect ratio which was not accounted for in the original Butler-Mokrys model.

Sensitivity analyses show that the injector location does not affect the oil drainage rate and cumulative production significantly when the length of the reservoir is much greater than the height. However, for a field scale development; although the well placement does not affect the VAPEX performance, selection of a suitable well location is nevertheless important to optimise field development and operating strategy. In addition, selection of an optimum solvent should also be given careful consideration as the viscosity ratio and density difference between the solvent and oil have contrasting effects on the stabilised oil drainage rate.

It is highly recommended that the simulated oil rates from extreme cases be compared against lab experiments to verify whether the model still produces results consistent with physical models. Future work should strongly consider development of methods to quantify average interface velocity and dispersion coefficient. Studies of the impact of reservoir aspect ratio on the stabilised oil drainage rate and period would also be beneficial. Ultimately, the simulation should be scaled up to realistic reservoir dimensions and geometries to study the VAPEX process at the field scale. This shall incorporate realistic rock and fluid models with high viscosity ratios, high density difference, multi-contact miscibility and consideration of relative permeability and capillary pressure effects.

Nomenclature

\[
\begin{align*}
BHP &= \text{Bottom hole pressure, } \text{m}/\text{L}^2, \text{kPa} \\
c_m &= \text{Solvent concentration in the mixture, fraction} \\
D_s &= \text{Solvent diffusion coefficient in the mixture with concentration } c_m, \text{L}^2/\text{t}, \text{m}^2/\text{s} \\
D_m &= \text{Molecular diffusion coefficient, L}^2/\text{t}, \text{m}^2/\text{s} \\
g &= \text{Acceleration due to gravity, L}/\text{t}^2, \text{m}/\text{s}^2 \\
h &= \text{Drainage height, L, m} \\
k &= \text{Permeability of physical model, L}^2, \text{m}^2, \text{D} \\
K_L &= \text{Longitudinal dispersion coefficient, L}^2/\text{t}, \text{m}^2/\text{s} \\
K_T &= \text{Transverse dispersion coefficient, L}^2/\text{t}, \text{m}^2/\text{s} \\
M &= \text{Viscosity ratio, dimensionless} \\
N_r &= \text{Dimensionless parameter defined by Eq. 2} \\
P_c &= \text{Critical pressure, m}/\text{L}^2, \text{kPa} \\
q &= \text{Stabilised oil drainage rate, L}^3/\text{t}, \text{m}^3/\text{s} \\
q_{mixture} &= \text{Solvent-oil mixture drainage rate, L}^3/\text{t}, \text{m}^3/\text{s} \\
SOR &= \text{Solvent-Oil Ratio, fraction} \\
T_c &= \text{Critical temperature, } \text{T}, \text{°C} \\
\Delta S_o &= \text{Oil saturation change, fraction} \\
\Delta \rho &= \text{Density difference between pure solvent and oil, M}/\text{L}^3, \text{kg}/\text{m}^3 \\
\Delta \rho_{pm} &= \text{Concentration-dependent density difference between pure solvent and mixture used in calculating } N_r, \text{M}/\text{L}^3, \text{kg}/\text{m}^3
\end{align*}
\]
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\[ \Delta \rho_{so} = \text{End point density difference between pure solvent and pure oil used in calculating N_s, M/L}^3 \text{, kg/m}^3 \]

\[ \mu_m = \text{Mixture viscosity with concentration c_s, M/L_t, Pa s} \]

\[ \mu_o = \text{Oil viscosity, M/L_t, Pa s} \]

\[ \phi = \text{Porosity of model, fraction} \]

References


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### Appendix A

#### Milestones in Heavy Oil Recovery by VAPEX

<table>
<thead>
<tr>
<th>Source</th>
<th>Year</th>
<th>Title</th>
<th>Authors</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>JCPT</td>
<td>1991</td>
<td>“A New Process (VAPEX) for Recovering Heavy Oils Using Hot Water and Hydrocarbon Vapour”</td>
<td>R.M Butler, I.J Mokrys</td>
<td>First to introduce the term VAPEX and further expanded the earlier developed concept of VAPEX with more representative experiments.</td>
</tr>
</tbody>
</table>
2. Compared the performance of wet VAPEX and dry VAPEX.                                                                                     |
2. Modified the Butler-Mokrys model by introducing effective diffusivity coefficient in place of apparent diffusion coefficient for predicting oil rates in porous media. |
<p>| JCPT                            | 2001 | “The Role of Diffusion and Convective Dispersion in Vapour Extraction Process” | A. Boustani, B.B Maini        | Highlighted that dispersion effects need to be incorporated into the mass transfer model to improve the match between experimental results and analytical models.   |
| JCPT                            | 2003 | “Investigation of the VAPEX Process Using CT Scanning and Numerical Simulation” | D Cuttiell, C. McCarthy, T. Frauenfeld, S. Cameron, G. Kissel | Highlighted the factors affecting the accuracy of numerical models in simulating experimental conditions.                                      |</p>
<table>
<thead>
<tr>
<th>Journal/Thesis</th>
<th>Year</th>
<th>Title</th>
<th>Authors</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPE 84199</td>
<td>2003</td>
<td>“Experimental Investigation of Oil Drainage Rates in the VAPEX Process for Heavy Oil and Bitumen Reservoirs”</td>
<td>Karmaker, K, Maini, B.B</td>
<td>Experimentally showed that VAPEX oil drainage rate prediction is not valid using the transmissibility scale up method</td>
</tr>
<tr>
<td>SPE 89409</td>
<td>2005</td>
<td>“Effects of Drainage Height and Grain Size on the Convective Dispersion in the VAPEX Process: Experimental Study”</td>
<td>A. Yazdani, B.B Maini</td>
<td>Highlighted that a higher dependency exponent for drainage height is required to improve prediction of oil rates.</td>
</tr>
<tr>
<td>SPE 97924</td>
<td>2005</td>
<td>“Diffusion and Dispersion in the Simulation of VAPEX Process”</td>
<td>S.K Das</td>
<td>Presented the results of a 2D field scale simulation model and performed sensitivity analysis of diffusion coefficient.</td>
</tr>
<tr>
<td>Energy &amp; Fuels</td>
<td>2008</td>
<td>“Modeling of the VAPEX Process in a Very Large Physical Model”</td>
<td>A. Yazdani, B.B Maini</td>
<td>Experimentally showed the consistency of results between a small scale model and a large scale physical model</td>
</tr>
</tbody>
</table>
| Imperial College London PhD Thesis | 2009 | “Experimental and Numerical Investigation of the Vapour Extraction (VAPEX) Process for Heavy Oil Recovery” | A.S Alkindi                  | 1. Independently measured transverse and longitudinal dispersion coefficients  
2. Performed numerical simulation that were in good agreement with experimental results |
| SPE 129169    | 2010 | “Experimental Investigation into the Influence of Convective Dispersion and Model Height on Oil Drainage Rates during VAPEX” | A. Alkindi, A.H Muggeridge, Y. Al-Wahaibi | 1. Showed that an improved analytical drainage rate prediction is achieved by using measured dispersion coefficients.  
2. Speculated that drainage rates have a higher than the square root dependency originally proposed by Butler and Mokrys. |
Appendix B

Critical Literature Review

SPE 480

A Review of Diffusion and Dispersion in Porous Media

Authors:

Perkins, T.K & Johnston, O.C

Contribution to the understanding of VAPEX:

Described the mechanism of diffusion and dispersion in porous media

Objective of the paper:

To summarise and review the studies of diffusion and dispersion in porous media by different workers

Methodology used:

Literature review of experimental work studying diffusion and dispersion in porous media undertaken by different workers.

Conclusion reached:

Developed mathematical expression describing longitudinal and transverse dispersion. Concluded that for fluids flowing through porous medium, dispersion may have greater influence than molecular diffusion.

Comments:

This paper summarises the key discoveries in studies of diffusion and dispersion in porous media up to the early 1960’s.

Solvent Analog Model of Steam-Assisted Gravity Drainage

Authors:
Butler, R.M & Mokrys, IJ

Contribution to the understanding of VAPEX:

Introduced an analytical model for a solvent analogue of the Steam Assisted Gravity Drainage (SAGD) process.

Objective of the paper:
To develop an analytical model of a solvent analogue of SAGD and experimentally validate the proposed model.

Methodology used:
Analytical study and derivation of a mathematical expression for a solvent-leaching process that is analogous to the well-established SAGD model. Performed experiments in Hele-Shaw cells using toluene (solvent) to recover Athabasca and Suncor bitumen. Experimental results were compared against rates predicted from the analytical model.

Conclusion reached:
Solvent assisted gravity drainage is a direct theoretical and experimental analogue of SAGD. Drainage rate is a linear function of square root of permeability at low permeabilities but is non-linear and approaches a constant value at high permeabilities.

Comments:
This is a milestone paper in VAPEX as it was the first to propose the recovery mechanism, which was based on SAGD. Assumed that dispersion in the interface layer is only due to molecular diffusion. In Hele-Shaw experiments, the porosity and change in oil saturation = 1, thus it may not be representative of the process in porous media.
A New Process (VAPEX) for Recovering Heavy Oils Using Hot Water and Hydrocarbon Vapour

Authors:
Butler, R.M & Mokrys, IJ

Contribution to the understanding of VAPEX:
First to introduce the term VAPEX and further expanded the earlier developed concept of VAPEX with more representative experiments.

Objective of the paper:
Develop relationship between VAPEX recovery rates and temperature.
Qualitatively demonstrate the VAPEX recovery mechanism.

Methodology used:
Experiments of simultaneous hot water and propane vapour injection in a bead packed cell with back-pressure control to limit excess vapour bypass. The experiments were performed at various temperatures and pressures ranging from 32 - 55 C and 145 - 250 psia respectively.

Conclusion reached:
Oil production rate increases with temperature up to a critical value where further increase in temperature will not result in increased oil production.
Established a description of the VAPEX recovery mechanism which consists a spreading vapour chamber, dilution of viscous oil, counter-current evaporation of propane and gravity draining along propane-oil interface.

Comments:
This paper is an extension to the earlier published paper by the same authors (1989). It describes further into detail the recovery process of VAPEX and proposed that VAPEX could be an alternative to Steam Assisted Gravity Drainage (SAGD) in thin heavy oil reservoirs.
Numerical Investigations into Oil Drainage Rates during Vapour Extraction (VAPEX) of Heavy Oils


Recovery of Heavy Oils Using Vapourized Hydrocarbon Solvents: Further Development of the Vapex Process

Authors:
Butler, R.M & Mokrys, IJ

Contribution to the understanding of VAPEX:

3. Further experimental investigation of the effects of heavy oil upgrading due to asphaltene precipitation during the Vapex process.
4. Compared the performance of wet VAPEX and dry VAPEX.

Objective of the paper:

1. To investigate the performance of hot water-solvent (wet) and dry VAPEX process.
2. To study the mechanism and effects of asphaltene precipitation in both processes.

Methodology used:

Lab measurements of wet and dry VAPEX oil rates using a bead packed cell filled with Lloydminster heavy oil. Visual observation of the vapour spreading front and profile of asphaltene deposits on the packed cell.

Conclusion reached:

Performance of dry VAPEX is comparable to wet VAPEX and is more economically attractive. In the VAPEX process, propane mixes with the oil and preferentially mobilises the lighter ends, leaving the heavier ends (asphaltenes) as deposits.

Comments:

1. Use of a more realistic experimental set-up compared to previous Hele-Shaw cells.
2. Qualitatively describes the mechanism of asphaltene deposition as observed in lab experiments.
3. Discussion mainly focused on the effect of propane mixing in reducing the oil viscosity as the primary factor in oil recovery.
4. No discussions about diffusion/ dispersion mixing mechanism.
Numerical Investigations into Oil Drainage Rates during Vapour Extraction (VAPEX) of Heavy Oils


Mechanism of the Vapour Extraction Process for Heavy Oil and Bitumen

Authors:
Das, S.K & Butler, R.M

Contribution to the understanding of VAPEX:
3. Experimentally verified that oil production is proportional to square root of permeability as proposed by the Butler-Mokrys analytical model.
4. Modified the Butler-Mokrys model by introducing effective diffusivity coefficient in place of apparent diffusion coefficient for predicting oil rates in porous media.

Objective of the paper:
3. To visualise and study the mechanism of VAPEX.

Methodology used:
Performed experiments using Hele Shaw and scaled bead packed cells filled with Peace River and Lloydminster crude. Visual observation of cells during VAPEX process to study asphaltene deposition and solvent (butane)-oil interface profiles.

Conclusion reached:
Analytical model under-predicts flow rate compared to experimental results. Effective diffusivity coefficient is used in the Butler-Mokrys model to account for increase in interfacial contact area in porous media.

Comments:
The paper also qualitatively discussed other mechanisms for the increased mixing observed in porous media such as the effects of capillary imbibition, continuous undiluted oil surface renewal and counter-current flow of the rising solvent chamber. These mechanisms are not considered in the analytical model, thus it is speculated that this was the cause of lower predicted rates.

The Role of Diffusion and Convective Dispersion in Vapour Extraction Process

Authors:
Boustani, A & Maini, B.B

Contribution to the understanding of VAPEX:
Highlighted that dispersion effects need to be incorporated into the mass transfer model to improve the match between experimental results and analytical models.

Objective of the paper:
To study the role of diffusion and convective dispersion in the VAPEX process.

Methodology used:
Performed Hele Shaw cell experiments with butane as solvent and two heavy oil types (Dover and Panny). Compared the back-calculated $N_s$ values obtained from experiments with analytically-calculated $N_s$ based on molecular diffusion coefficient and $N_s$ based on convective dispersion coefficient.

Conclusion reached:
The Hayduk and Minhas (1982) correlation to determine molecular diffusion coefficient is a more reliable estimate of the true diffusive characteristics of solute/solvent pair in the VAPEX process compared to the correlation developed by Das and Butler (1996).
The use of dispersion coefficient rather than molecular diffusion coefficient in the analytical model gives a better match with experimental results.

Comments:
The authors used the Taylor dispersion theory for capillary tubes in calculating the dispersion coefficients and they acknowledged that utilisation of this dispersion formulation is completely different than in porous media. However, they highlighted that it did serve as a good example of the importance of incorporating dispersion effects into the analytical model.
Compositional Simulation of the VAPEX Process

Authors:
L.X Nghiem, B.F Kohse & P.H Sammon

Contribution to the understanding of VAPEX:
Modelled asphaltene precipitation, molecular diffusion and convective dispersion in the VAPEX process using a fully compositional simulator.

Objective of the paper:
To apply finite-difference equations in a numerical simulator to model asphaltene precipitation and fluid mixing.

Methodology used:
Applied Sigmund (1976) correlation to calculate the molecular diffusion coefficient. Modelled the asphaltene precipitation phenomena as suspended solids and also deposits on rock surface, and incorporated these into the finite-difference equation. Phase behaviour of the selected Lindbergh oil was modelled using the Peng-Robinson EOS. Performed sensitivity analysis on the dispersing coefficient (α) in the total dispersion calculation to analyse the extent of convective dispersion effects.

Conclusion reached:
Showed that asphaltene precipitation can be modelled reasonably well in numerical simulators by applying suitable EOS. The mixing mechanism in the VAPEX process is primarily driven by convective dispersion.

Comments:
The authors did not highlight the extent of numerical dispersion and effects of grid size selection on their simulation.

Reference:
SPE 77459 (2002)

An Integrated Experimental and Numerical Approach to Assess the Performance of Solvent Injection into Heavy Oil.

Authors:
C. Dauba, L. Quettier, J. Christensen, C. Le Goff, P. Cordelier

Contribution to the understanding of VAPEX:
Not much. Described how an integrated experimental and numerical approach is useful to study the VAPEX process.

Objective of the paper:
To perform numerical and experimental studies in assessing the performance of solvent vapour injection into heavy oil.

Methodology used:
Tuned Peng Robinson EOS from PVT experiments to establish a fluid model. Performed numerical simulation using semi-compositional and fully-compositional simulators to design a core-flood experiment of vapour injection into heavy oil. Conducted core-flood experiments and compared results against predicted from simulations.

Conclusion reached:
Basic fluid measurements must be carried out on several oil-solvent mixtures at different solvent concentrations to enable EOS tuning and correctly predict heavy oil behaviour under solvent injection. Numerical simulations can optimise the design of core-flood experiments and enable selection of suitable injection rates to ensure stable displacement. Asphaltene precipitation is only observed when very high solvent fractions in heavy oil are reached. The main mechanism of oil-upgrading is by viscosity reduction due to solvent dilution.

Comments:
The paper does not extend much further the current knowledge of the VAPEX process but does highlight the approach to be undertaken in conducting any VAPEX studies. The integrated PVT, numerical and experimental approach is useful in understanding the potential of VAPEX recovery for a specific reservoir.

Investigation of the VAPEX Process Using CT Scanning and Numerical Simulation

Authors:
D Cuthiell, C. McCarthy, T. Frauenfeld, S. Cameron & G. Kissel

Contribution to the understanding of VAPEX:
Highlighted the factors affecting the accuracy of numerical models in simulating experimental conditions

Objective of the paper:
To perform numerical simulation that is able to reproduce key experimental observations using physical mechanism available in a commercial reservoir simulator.

Methodology used:
Lab experiments using sand of varying grain size and at different injection rates were performed. Solvent and mixing interface profiles were observed using a computed tomography (CT) scanner. A numerical model was set up and ran to simulate the lab experiments and the results were compared.

Conclusion reached:
Viscous fingering observed in lab experiments, which characterised the unstable displacement during high injection rates could be matched using numerical simulators by incorporating random permeability variations and a proper amount of physical dispersion.

Comments:
Numerical dispersion was estimated from a correlation between square root of oil rate and the explicit physical dispersion. A novel “quasi-pore scale” (QPS) grid to represent “sand grains” was proposed as a useful approach to simulate the mixing process at pore level. However, this may come at a higher cost of computing time.
SPE 84199 (2003)

Experimental Investigation of Oil Drainage Rates in the VAPEX Process for Heavy Oil and Bitumen Reservoirs

Authors:
Karmaker, K & Maini, B.B

Contribution to the understanding of VAPEX:
Experimentally showed that VAPEX oil drainage rate prediction is not valid using the transmissibility scale up method

Objective of the paper:
To investigate the validity of transmissibility scale up method to predict VAPEX oil drainage rates in porous media

Methodology used:
Performed VAPEX experiments using models of different heights and permeability. Analysed the effects of grain size and height on drainage rate. Compared experimental results with scaled up predictions using analytical methods.

Conclusion reached:
1. Effect of grain size distribution on dispersional mixing is not pronounced
2. Model height significantly increases the magnitude of convective dispersion incurred in the VAPEX process
3. The transmissibility matching scale up method does not apply to the VAPEX process

Comments:
The authors suggested that another scale up method is considered and indirectly speculated that the height dependency of VAPEX oil drainage rates is not square root as previously proposed.
SPE 89409 (2005)

Effects of Drainage Height and Grain Size on the Convective Dispersion in the VAPEX Process: Experimental Study

Authors:
Ali Yazdani & Brij B. Maini

Contribution to the understanding of VAPEX:
Highlighted that a higher dependency exponent for drainage height is required to improve prediction of oil rates.

Objective of the paper:
To develop an improved scale-up method for the VAPEX process using physical model experiments of different sizes.

Methodology used:
Performed lab experiments in cylindrical packed cell of different grain sizes and oil types, with butane as the solvent. Measured the oil drainage rates and compared with previous work by Karmaker & Maini (2003) to validate the results of the cylindrical cell with the previously built rectangular model. Used the results to study the relationship between flow rate, permeability and drainage height.

Conclusion reached:
Confirmed that flow rate is dependent on square root of permeability. Suggested that a higher exponent of height dependency (between 1.1 – 1.3) is required to improve the Butler-Mokrys oil drainage prediction. Speculated that the additional height effect is related to convective dispersion mechanism which was not accounted for in the original analytical model.

Comments:
The higher exponents for height dependency require further validation but it does point out that the original mathematical model may require modification. This finding is also consistent with later work by Alkindi et al who also found a higher than square root dependency for drainage height.
SPE 97924 (2005)
Diffusion and Dispersion in the Simulation of VAPEX Process

Authors:
Das, S.K

Contribution to the understanding of VAPEX:
Presented the results of a 2D field scale simulation model and performed sensitivity analysis of diffusion coefficient.

Objective of the paper:
To investigate the sensitivity of diffusion and dispersion coefficients during history match with experimental data

Methodology used:
Performed 2D numerical simulation on a 75 x 1 x 50 grid block model using a fully compositional simulator. Used different diffusion coefficients (which were varied by order of magnitude) for each simulation run. Compared the production rate and diffusion interface layer thickness between simulation model and experiments.

Conclusion reached:
Conflicting results in numerical simulation were achieved (i.e. higher diffusion coefficients give high production rates but results in unrealistically thick diffusion interface layers).
Concluded that it may be difficult to model the VAPEX process using bulk diffusion coefficient.

Comments:
The paper did not state the extent of numerical dispersion observed in the simulation runs.
Qualitatively described the difficulties encountered in performing 2D simulation of the VAPEX process.
**SPE 117555 (2008)**

The Influence of Diffusion and Dispersion on Heavy Oil Recovery by VAPEX

**Authors:**
Abdullah Alkindi, Ann Muggeridge, Yahya Al-Wahaibi

**Contribution to the understanding of VAPEX:**
Highlighted that the use of total measured dispersion in the Butler-Mokrys model improved prediction of oil drainage rates.

**Objective of the paper:**
To investigate the role of convective dispersion in VAPEX through lab experiments and numerical simulation.

**Methodology used:**
Measured longitudinal dispersion ($K_L$) and transverse dispersion ($K_T$) coefficients using analogue fluid pair (ethanol-glycerol) in a packed bead cell. Performed VAPEX experiments using the same fluid pair and compared the experimental oil drainage results with Butler-Mokrys model which incorporated the earlier measured $K_L$ and $K_T$ dispersion coefficients. Performed numerical simulation and compared results with lab experiments.

**Conclusion reached:**
Improved predictions were obtained when the measured dispersion coefficients were used in the Butler Mokrys analytical model. Numerical simulation with dispersion coefficients improved prediction but still under-predicts drainage rates. However, it did satisfactorily predict solvent breakthrough time.

**Comments:**
The fluid pair selected was first contact miscible which eliminated other possible mixing influencing factors such as capillary effects and increased surface area due to formation of oil films. The solvent injection rates in the VAPEX experiments were selected to give a gravity to drainage ratio $> 1$ to ensure that the process is gravity dominated.

Modeling of the VAPEX Process in a Very Large Physical Model

Authors:
Yazdani, A & Maini, B.B

Contribution to the understanding of VAPEX:
Experimentally showed the consistency of results between a small scale model and a large scale physical model

Objective of the paper:
To study the VAPEX process in a large scale model and history match the results using a numerical simulator

Methodology used:
Performed lab experiments in a large scale model using butane as solvent and Frog Lake heavy oil. Compared results with previous work on smaller scale models. Developed a 2D numerical simulation model to history match experimental results. Assigned the dispersivity value as the tuning parameter to match lab results.

Conclusion reached:
1. The large scale experimental results are consistent with small scale experiments
2. Numerical dispersion is inherent in simulation and requires careful consideration
3. Higher than square root dependency (between 1.13 and 1.17) is proposed in the Butler Mokrys model to obtain a more accurate oil drainage prediction.

Comments:
The finding of a higher dependency on model height is consistent with the authors' previous work. Grid size selection is important as it affects dispersion coefficient, interface layer thickness and breakthrough time matching.
Imperial College London PhD Thesis 2009

Experimental and Numerical Investigation of the Vapour Extraction (VAPEX) Process for Heavy Oil Recovery

Authors:
Abdullah Alkindi

Contribution to the understanding of VAPEX:
Demonstrated that the use of measured longitudinal ($K_L$) and transverse ($K_T$) dispersion coefficients in the Butler-Mokrys model improves oil drainage rate predictions. Suggested that model height dependency is higher than square root as originally proposed.

Objective of the paper:
To perform experimental and numerical studies in assessing the performance of the VAPEX process using analogue fluids.

Methodology used:
Performed two sets of experiments using analogue solvent/oil pair (ethanol & glycerol) to measure the dispersion coefficients and oil drainage rates. The results from the VAPEX experiment were compared with the predicted rates from original Butler-Mokrys model (using molecular diffusion coefficient) and one from a Butler-Mokrys model using dispersion coefficients. Developed a numerical simulation model using a commercial semi-compositional simulator to reproduce experimental results.

Conclusion reached:
The incorporation of longitudinal dispersion in place of molecular diffusion in the Butler-Mokrys model improved the oil drainage rate predictions. The stabilised oil drainage rate had a higher dependency on the model height than the square root dependency proposed by Butler and Mokrys. The study indicate that the rate is proportional to the model height with exponent of 0.64-0.68. The predictions from numerical simulations of oil rate, solvent rate and concentration distribution compared very well with those obtained from lab experiments, and it is proposed that numerical simulation is used to assess the viability of a VAPEX recovery scheme on a field scale as the analytical models appear to make systematically pessimistic predictions.

Comments:
The integrated approach of experimental and numerical studies resulted in the development of a representative 2D model. Use of first contact miscible analogue fluids confine the study to analysing the effects of diffusion and dispersion, eliminating any other possible mixing mechanisms that have been proposed by others.

Pitfalls and Solutions in Numerical Simulation of VAPEX

Authors:
Ali Yazdani & Brij B. Maini

Contribution to the understanding of VAPEX:
Highlighted the key challenges in performing numerical simulation of VAPEX process

Objective of the paper:
To investigate the influence and effect of different parameters in the numerical simulation of the VAPEX process

Methodology used:
Performed numerical simulation using a fully compositional model simulator and conducted sensitivity analysis of various parameters to history match earlier experimental results.

Conclusion reached:
Validated PVT and fluid models specific for each solvent/oil pair must be used to properly model the mixing process. Selection of very fine grid size is required to properly capture the physics involved in the mixing interface layer. The finite difference methods used in numerical simulators lead to numerical problems and suggested that other numerical simulation methods are considered to improve reliability and accuracy.

Comments:
The big uncertainty involved in numerical simulation is the magnitude of convective dispersion coefficient selected in modelling the VAPEX process. The permeability for grid cells near the wells were increased by 50 – 100 to account for wall effect in the packed cell and also to give a better match with experimental results.
SPE 129169 (2010)

Experimental Investigation into the Influence of Convective Dispersion and Model Height on Oil Drainage Rates during VAPEX

Authors:

Abdullah Alkindi, Ann Muggeridge & Yahya Al-Wahaibi

**Contribution to the understanding of VAPEX:**

Showed that an improved analytical drainage rate prediction is achieved by using measured dispersion coefficients. Speculated that drainage rates have a higher than the square root dependency originally proposed by Butler and Mokrys.

**Objective of the paper:**

To investigate the influence of diffusion and convective dispersion in predicting oil drainage rates.
To study the effect of model height on oil drainage rates.

**Methodology used:**

Lab measurements of transverse and longitudinal dispersion coefficients in bead packed cells with analogue fluids (solvent – ethanol) and (oil – glycerol). Performed VAPEX experiments followed by oil drainage rate measurements, observation of solvent chamber profile and analysis of the effect of different model heights.

**Conclusion reached:**

Use of measured longitudinal ($K_L$) and transverse ($K_T$) dispersion coefficients in place of molecular diffusion coefficient in the Butler-Mokrys analytical model improved the oil drainage rate predictions.
The height dependency for oil rate prediction in the Butler-Mokrys model is higher than square root. Proposed a height dependency exponent of 2/3.

**Comments:**

Analogue fluids chosen are first contact miscible thus eliminating any other mechanisms that can influence oil drainage rates such as capillary imbibition and asphaltene precipitation.
Appendix C

1. The following correlations were used to calculate mixture viscosity ($\mu$) and density ($\rho$) for any volume percent of ethanol ($c$) (Alkindi et al. in press)

$$\mu = 1.376 \times e^{-0.0715c}$$

$$\rho = -9.3 \times 10^{-3} c^2 - 3.9c + 1266.4$$

2. The longitudinal dispersion coefficients used to calculate the oil drainage rate in the Butler-Mokrys models were taken from experimentally measured values as below (Alkindi et. al, in press)

<table>
<thead>
<tr>
<th>Model height cm</th>
<th>Injection rate cm$^3$/hr</th>
<th>Rate based on molecular diffusion cm$^3$/hr</th>
<th>Measured stable oil rate (average) cm$^3$/hr</th>
<th>Longitudinal Dispersion $K_L$ cm$^2$/sec</th>
<th>Stable rate based on $K_L$ cm$^3$/hr</th>
<th>Recovery at 1 PVI</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0.6</td>
<td>0.32</td>
<td>0.48</td>
<td>6.7x10$^{-6}$</td>
<td>0.41</td>
<td>76%</td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td></td>
<td>0.75</td>
<td>8.9x10$^{-6}$</td>
<td>0.47</td>
<td>63%</td>
</tr>
<tr>
<td>15</td>
<td>0.6</td>
<td>0.23</td>
<td>0.40</td>
<td>6.3x10$^{-6}$</td>
<td>0.28</td>
<td>59%</td>
</tr>
</tbody>
</table>

Reference
Appendix D

An example of CMG-STARS input file for Base Case Model.
(Aspect Ratio 2:1, Reservoir Height: 30 cm, Injection Rate: 1.2 cm³/hr)

*CASEID 'Dispersion'
*INUNIT *LAB
TITLE1 'Simulation of Vapex Experiments'
TITLE2 'Grid Size 150 1 60'
TITLE3 'Rate = 0.02 cc/min'

**If Ctrl+C are pressed then stop the run
*INTERRUPT *STOP

**frequency of writing restart record in the o/p restart file
**this stores a snapshot of the reservoir at a particular time
*WRST 300

**frequency of writing to the o/p print file i.e. OUTPRN
**e.g. write grid results every 400 time steps
*WPRN *GRID 400
*WPRN *SECTOR 400
*WPRN *ITER 400

**frequency of writing to the simulation o/p file i.e. SR2 file
*WSRF *WELL 1
*WSRF *GRID *TIME
*WSRF *SECTOR 1

**what items are printed in o/p print file at the frequency defined by *WPRN
*OUTPRN *GRID *PRES *SO *SG *X
*OUTPRN *WELL *WELLCOMP
*OUTPRN *RES *ALLSMALL
*OUTPRN *ITER *NEWTON

**what items are written in simulation results file
OUTSRF GRID PRES VELOCSC VISO Z
OUTSRF WELL COMPONENT ALL
OUTSRF WELL LAYER ALL
**OUTSRF SPECIAL BLOCKVAR SO 130 60 1
**OUTSRF SPECIAL MATBAL CURRENT
**OUTSRF SPECIAL MATBAL OLEIC

*XDR *ON
*PRNTORIEN 2 0
*PRINT_REF *ON
*OUTSOLVR *OFF
*MAXERROR 20
*SR2PREC *DOUBLE

**$ Distance units: cm
RESULTS XOFSSET 0.0000
RESULTS YOFFSET 0.0000
RESULTS ROTATION 0.0000 **$ (DEGREES)

**$
Numerical Investigations into Oil Drainage Rates during Vapour Extraction (VAPEX) of Heavy Oils

***************************************************************************
**$ Definition of fundamental cartesian grid
**$ ***********************
GRID VARI  60  1 150  
KDIR DOWN  
DI IVAR  60*0.25  
DJ JVAR  0.5  
DK ALL  9000*0.2  
DTOP  60*0  
**$ Property: NULL Blocks Max: 1 Min: 1  
**$ 0 = null block, 1 = active block  
NULL CON  1  
**$ Property: Porosity Max: 0.4 Min: 0.4  
POR CON  0.4  
PERMI CON  47000  

*MOD  
   1:1     1:1     75:75     = 100000  
   1:1     1:1    150:150    = 100000  
   1:1     1:1     1:75     = 75000  
**$ Property: Permeability J (md) Max: 47000 Min: 47000  
PERMJ CON  47000  
**$ Property: Permeability K (md) Max: 47000 Min: 47000  
PERMK CON  47000  
**$ Property: Pinchout Array Max: 1 Min: 1  
**$ 0 = pinched block, 1 = active block  
PINCHOUTARRAY CON  1  
END-GRID

ROCKTYPE 1  
CPOR 0.00000000001  
PRPOR 101  
**$ Model and number of components  
MODEL 3 3 3 1  
COMPNAM 'water' 'glycerol' 'ethanol'  
CMM 0 0.092095 0.046069  
PCRIT 0 6680 6140  
TCRIT 0 452.85 240.75  
KV1 0.000E+0 0.0E+0 0  
KV2 0.000E+0 0.000E+0 0  
KV3 0.000E+0 0.000E+0 0  
KV4 0.0 1024.3 0  
KV5 0.0 273.15 0  
PSURF 101.325  
PRSR 101.325  
TSURF 20  
MASSDEN 0 0.001261 0.0007  
CP 0 0 0
Numerical Investigations into Oil Drainage Rates during Vapour Extraction (VAPEX) of Heavy Oils

CT1
0 0 0
** T, deg F     'WATER'   'glycerol'   'ethanol'
**

VISCTABLE
**$
\text{temp} & 0 & 0 & 12070 & 1.785 \\
10 & 0 & 3900 & 1.456 \\
20 & 0 & 1390 & 1.2 \\
30 & 0 & 612 & 0.996 \\
40 & 0 & 284 & 0.833 \\
50 & 0 & 142 & 0.701 \\

ROCKFLUID
RPT 1 WATWET
SWT
**$
\text{Sw} & \text{krw} & \text{krow} \\
0 & 0 & 1 \\
1 & 1 & 0 \\

SLT
**$
\text{Sl} & \text{krg} & \text{krog} \\
0 & 1 & 0 \\
1 & 0 & 1 \\

** Property: Oil Dispersion Coef. I(glycerol) ((cm*cm)/min)  Max: 0.000285  Min: 0.000285
DISPI_OIL 'glycerol' CON 0.000285
** Property: Oil Dispersion Coef. I(ethanol) ((cm*cm)/min)  Max: 0.000285  Min: 0.000285
DISPI_OIL 'ethanol' CON 0.000285
** Property: Oil Dispersion Coef. J(glycerol) ((cm*cm)/min)  Max: 0.000285  Min: 0.000285
DISPJ_OIL 'glycerol' CON 0.000285
** Property: Oil Dispersion Coef. J(ethanol) ((cm*cm)/min)  Max: 0.000285  Min: 0.000285
DISPJ_OIL 'ethanol' CON 0.000285
** Property: Oil Dispersion Coef. K(glycerol) ((cm*cm)/min)  Max: 0.000535  Min: 0.000535
DISPK_OIL 'glycerol' CON 0.000535
** Property: Oil Dispersion Coef. K(ethanol) ((cm*cm)/min)  Max: 0.000535  Min: 0.000535
DISPK_OIL 'ethanol' CON 0.000535

INITIAL CONDITIONS

*INITIAL
VERTICAL DEPTH_AVE

*REFPRES 101
*REFBLOCK 1 1 150

INITREGION 1
** Property: Pressure (kPa)  Max: 101.325  Min: 101.325
PRES CON 101.325
** Initial Temp
** ++++++++ \\
** Property: Temperature (C)  Max: 20  Min: 20
TEMP CON 20
** Initial Composition
** ++++++++ \\
** Property: Oil Mole Fraction(glycerol)  Max: 1  Min: 1
MFRAC_OIL 'glycerol' CON 1 \\
** Property: Water Mole Fraction(water)  Max: 0  Min: 0
MFRAC_WAT 'water' CON 0 \\

NUMERICAL CONTROL

*Numerical
Numerical Investigations into Oil Drainage Rates during Vapour Extraction (VAPEX) of Heavy Oils

MAXSTEPS 9999999
NORTH 300
ITERMAX 300
NCUTS 40
MAXPRES 350

RUN  **Centigrade  

*********************************************************
** ============== RECURRENT DATA ==============**
*********************************************************
DATE 2008 1 1
DTWELL 0.01
DTMAX 20

WELL 'injector'
INJECTOR MOBWEIGHT IMPLICIT 'injector'
INCOMP OIL 0. 0. 1.
TINJW 20.
OPERATE MAX STO 0.02 CONT REPEAT

GEOMETRY K 0.002 0.37 1. 0.
PERF GEO 'injector'

WELL 'producer'
PRODUCER 'producer'
OPERATE MIN BHP 101. CONT REPEAT

GEOMETRY K 0.002 0.37 1. 0.
PERF GEO 'producer'

TIME 80
TIME 100
TIME 130
TIME 200
TIME 300
TIME 400
TIME 500
TIME 700
TIME 900
TIME 1000
TIME 1600
TIME 1800
TIME 2000
TIME 2600
TIME 2700
TIME 2750
TIME 2850
TIME 2940
TIME 3200
TIME 3500
TIME 4000
TIME 4500
TIME 4560
TIME 4670

STOP
Appendix E

Oil rate vs PVI plots for various sensitivity parameters.

Fig. E.1 – Oil drainage rate vs PVI for different reservoir permeability (Reservoir height : 30 cm and injection rate 1.2 cm³/hr)

Fig. E.2 – Oil drainage rate vs PVI for different reservoir permeability (Reservoir height : 30 cm and injection rate 0.6 cm³/hr)
Numerical Investigations into Oil Drainage Rates during Vapour Extraction (VAPEX) of Heavy Oils

Fig. E.3– Oil rate vs PVI for middle and top injector cases in a 2:1 aspect ratio reservoir (reservoir length = 15 cm)

Fig. E.4– Oil rate vs PVI for different viscosity ratio cases in a 2:1 aspect ratio reservoir (reservoir length = 15 cm)
Numerical Investigations into Oil Drainage Rates during Vapour Extraction (VAPEX) of Heavy Oils

Fig. E.5– Oil rate vs PVI for different permeability in a 2:1 aspect ratio reservoir (reservoir length = 15 cm)
Appendix F

Solvent Distribution and Oil Viscosity Profiles of Several Simulation Cases

Fig. F.1 – Solvent concentration profile at 0.2 PVI for reservoir aspect ratio 2:1 with injector located at mid-height

Fig. F.2 – Viscosity profile at 0.2 PVI for reservoir aspect ratio 2:1 with injector located at mid-height
Numerical Investigations into Oil Drainage Rates during Vapour Extraction (VAPEX) of Heavy Oils

Fig. F.3 – Solvent concentration profile at 0.2 PVI for reservoir aspect ratio 2:1 with injector located at the top of reservoir

Fig. F.4 – Viscosity profile at 0.2 PVI for reservoir aspect ratio 2:1 with injector located at the top of reservoir
Fig. F.5 – Solvent concentration profile at 0.4 PVI for reservoir aspect ratio 2:1 and solvent injection rate of 1.2 cm³/hr

Fig. F.6 – Viscosity profile at 0.4 PVI for reservoir aspect ratio 2:1 and solvent injection rate of 1.2 cm³/hr
Numerical Investigations into Oil Drainage Rates during Vapour Extraction (VAPEX) of Heavy Oils

Fig. F.7 – Solvent concentration profile at 0.4 PVI for reservoir aspect ratio 2:1 and solvent injection rate of 0.6 cm³/hr

Fig. F.8 – Viscosity profile at 0.4 PVI for reservoir aspect ratio 2:1 and solvent injection rate of 0.6 cm³/hr