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# Estimation of effect of diffusion and dispersion parameters on VAPEX process

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ABSTRACT

Recent developments in heavy oil extraction have heightened the need for a promising vapor extraction process in problematic reservoirs. Due to the high energy efficiency and suitability for the latter reservoirs, it is believed that VAPEX has had a great deal of interest compared to the thermal methods in recent years. The present study aims to develop a method based on a compositional simulation in the VAPEX process to study the effect of mass transfer coefficients on production rate. This model can simulate VAPEX with different diffusion and dispersion coefficients and is validated against the experimental data. Simulation results show a challenge between mass transfer and gravity drainage process; hence, if drainage is the dominant step, a high diffusion coefficient has a reverse impact on production rate. Instead, a high dispersion coefficient almost has a positive effect on oil production.



## 1. Introduction

The vapor extraction (VAPEX) process was reported (Butler and Mokrys, 1991, 1993) as a new and convenient synthetic procedure for the recovery of heavy oil and bitumen in 1991. Because of many advantages of VAPEX (James et al., 2008), this promising process has received so much interest in recent years. In the VAPEX process, two horizontal wells are drilled inside reservoirs for solvent injection and oil production. Solvent is injected through an upper horizontal well and dissolves and diffuses in the heavy crude oil to reduce its viscosity and makes it mobile, then can be easily extracted from the production bore. The concept of VAPEX described above was drawn in Fig. 1 by Das and Butler (1998). Accordingly Das and Butler (1998) describe the major mechanisms of the VAPEX process: (1) dissolution of solvent at the vapor–oil interface, (2) diffusion of the dissolved solvent through the thick oil, (3) reduction of oil viscosity, (4) gravity drainage of the diluted oil into the production well (also deasphalting at higher solvent concentration).

Within early time, several attempts have been made to model the process (Butler and Mokrys, 1989; Nghiem et al., 2001; Kapadia et al., 2006; Nourozieh et al., 2011). A large and growing body of literature has been focused on the solvent diffusion through the ahead of gas–liquid interface as well as the sideway expansion of the vapor chamber after the solvent has reached to the top of the reservoir (Pourabdollah et al., 2012). Butler and Mokrys (1989) developed a model for steady state conditions based on molecular diffusion and gravity drainage of the thin oil. They predicted the volume flow rate of live oil produced at the production well:

$$Q = L\sqrt{2Kg\phi\Delta S_o N_s h} \tag{1}$$

In Eq. (1), $L$ is the length of wells, $K$ is permeability, $g$ is gravity, $\varphi$ is porosity, $h$ is effective height, $\Delta S_o$ is change in oil saturation and $N_s$ is a dimensionless number which is defined by

$$N_s = \int_{c_{s,\,\min}}^{c_{s,\,\max}} \frac{\Delta\rho D_s(1-c_s)}{\mu c_s} dc_s \tag{2}$$

where, $c_s$ is the volume fraction of the solvent, $\Delta\rho$ is density difference, $D_s$ is solvent diffusivity and $\mu$ is mixture viscosity. Years later, Das and Butler (1998) modified the aforementioned model for porous media, but experimental oil production is higher than Das and Butler's estimation. These findings imply to wide dispersion

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**Nomenclature**

| | |
|---|---|
| $c$ | solvent volume fraction |
| $dp$ | particle diameter (m) |
| $F$ | formation resistivity factor |
| $g$ | gravity acceleration ($m^2/s$) |
| $h$ | height of model (m) |
| $k_r$ | relative permeability |
| $q$ | molar flow rate per unit volume (mole/$m^3$ s) |
| $t$ | time (s) |
| $\boldsymbol{u}$ | velocity vector (m/s) |
| $u$ | horizontal velocity (m/s) |
| $v$ | vertical velocity (m/s) |
| $x$ | hydrocarbon mole fraction of liquid phase |
| $y$ | hydrocarbon mole fraction of vapor phase |
| $z$ | overall hydrocarbon mole fraction |
| $C_F$ | compressibility factor of molar density (1/kPa) |
| $C_R$ | compressibility factor of porosity (1/kPa) |
| $D$ | molecular diffusion ($m^2/s$) |
| $\boldsymbol{K}$ | matrix permeability ($m^2$) |
| $K_m$ | equilibrium ratio of hydrocarbon component |
| $L$ | length of well (m) |
| $P$ | pressure (kPa) |
| $Q$ | molar flow rate ($mol^3/s$) |
| $S$ | saturation |
| $T_\alpha$ | transmissibility |
| $X$ | horizontal direction |
| $Z$ | vertical direction |

*Greek symbols*

| | |
|---|---|
| $\delta$ | heterogeneity index for porosity distribution |
| $\sigma$ | surface tension ($kg/s^2$) |
| $\gamma$ | gradient of fluid phase (kPa/m) |
| $\phi$ | porosity |
| $\mu$ | viscosity (Pa s) |
| $\nu$ | kinematic viscosity ($m^2/s$) |
| $\rho$ | density ($kg/m^3$) |
| $\xi$ | molar density (kmol/$m^3$) |
| $\Delta$ | differential operator |
| $\mathbf{K}$ | total dispersion coefficient ($m^2/s$) |
| $K$ | total dispersion coefficient for $X$ or $Z$-axis ($m^2/s$) |
| $\Omega$ | cementation factor |

*Subscripts*

| | |
|---|---|
| $\alpha$ | index for fluid phase |
| $g$ | gas |
| $m$ | index of hydrocarbon component |
| $o$ | oil |
| $s$ | solvent |
| $w$ | water |

*Special definitions*

| | |
|---|---|
| $T_\alpha$ | $\frac{\xi_\alpha k_{r\alpha}}{\mu_\alpha}\boldsymbol{K}$ |
| $\nabla.$ | divergence operator |
| $\nabla$ | gradient operator |

effect over effective diffusion coefficient. Nghiem et al. (2001) attempted to model the VAPEX process by computer modeling group (CMG) software. They simulated a VAPEX process by generalized equation-of-state at compositional reservoir simulator with regard to fluid mixing through dispersion and asphaltene precipitation as the major mechanisms in VAPEX, then convective dispersion was identified as a major contributing factor for mixing in VAPEX process. Kapadia et al. (2006) planned a mathematical model to determine the dispersion coefficient on a laboratory scale model. They considered a rectangular bed, which is divided into blocks of bitumen. One side of the bed is initially exposed to a solvent, then live oil is drained since the solvent diffuses and is absorbed by the medium. They used the convective dispersion mechanism and the Darcy's Law for gravity drainage to simulate the VAPEX process. Although they could reach to a dispersion correlation, but in the mathematical model, several simplification were assumed to be

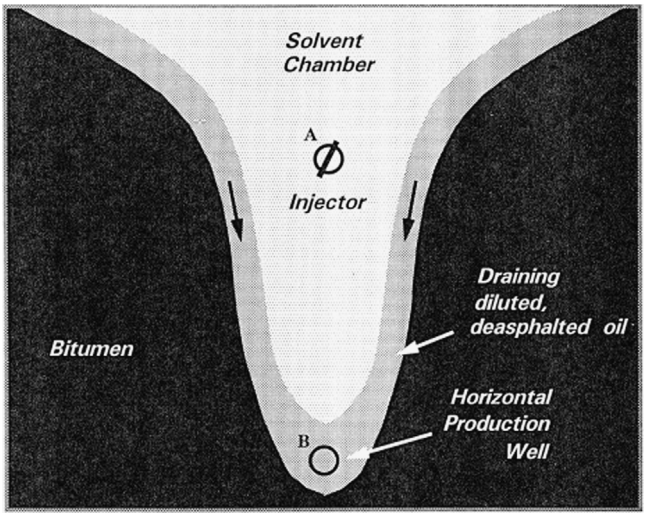


**Fig. 1.** Schematic diagram of the VAPEX process (Das and Butler, 1998).

**Table 2**
Relative permeability of water and oil phase in the studied core sample.

| $S_w$ | $K_{rw}$ | $K_{row}$ |
|---|---|---|
| 0 | 0 | 0.893 |
| 0.22 | 0 | 0.893 |
| 0.3 | 0.09 | 0.721 |
| 0.4 | 0.202 | 0.439 |
| 0.5 | 0.33 | 0.234 |
| 0.6 | 0.556 | 0.05 |
| 0.65 | 0.65 | 0 |
| 1 | 0.65 | 0 |

**Table 1**
Properties of rock and fluid in the studied core sample.

| Property | Permeability (mDarcy) | Porosity (%) | Reservoir pressure (kPa) | Oil density (g/cm$^3$) | Initial oil viscosity (cp) | Residual oil saturation | Initial water saturation |
|---|---|---|---|---|---|---|---|
| Value | 226 | 12.6 | 4000 | 0.725 | 2.24 | 0.35 | 0.22 |