Introduction

Steam drive is an economical way of producing oil and is used worldwide for heavy oil. Steam drive is also considered an efficient method to clean polluted sites [3][24], [38]. During the steam drive, however, a certain amount of oil is left behind in the steam swept zone [6]. In the late seventies Dietz [6] proposed to add small amounts of volatile oil to the steam to reduce the oil left behind. The volatile oil co-injected with the steam in almost infinitesimal amounts would ideally condense at the same location where the steam condenses. The condensed volatile oil acts as a solvent for the heavy oil. As such it pushes the oil away from the steam swept zone leaving no oil behind (see Fig. 1). The model we used carries three important simplifications. Firstly, the diffusion mixing between volatile oil and heavy oil in the liquid phase and between volatile oil vapor and water vapor in the gaseous phase are disregarded. The model is not valid for extremely low injection rates, where capillary diffusion dominates convection, because we ignore capillary effects. Finally, we do not specify a detailed model for the kinetics of the condensation process.

Physical model

Our interest is confined to (1) three-phase flow, i.e., flow of the aqueous (w), oleic (o) and gaseous (g) phases in the steam zone and (2) two-phase flow, i.e., flow of the aqueous and oleic phases in the liquid zone. For liquids, we distinguish between an aqueous (water-like) phase and an oleic (oil-like) phase because they do not mix. We use the following convention: the first subscript (w,o,g) refers to the phase, the second subscript (w,v,d) refers to the component, i.e., water, volatile oil and dead oil. Capital subscripts (W,V,D) are used to denote phases consisting of a single component. The densities of the pure liquids are denoted as $\rho_{OW}$, $\rho_{OD}$, $\rho_w$.

Thermodynamic model

Using the notion of partial molar volumes equation of state reads

$$\sum_{i=1}^{N} \bar{V}_i c_i = \sum_{i=1}^{N} \bar{V}_i \rho_{io} x_i = 1$$

(1.1)

where $\bar{V}_i$ is the partial molar volume, which we assume to be the inverse density of the pure phase components. Hence it follows that the molar density of oil is

$$\bar{\rho}_o = \frac{1}{\sum_{i=1}^{N} \bar{V}_i x_i}$$

(1.2)
Therefore

\[
\rho_{ov} = \frac{x_{ov}}{x_{ov} + 1 - x_{ov}}, \quad \rho_{od} = \frac{1 - x_{ov}}{x_{ov} + 1 - x_{ov}}
\]  

(1.3)

We use a combination of the Clausius-Clapeyron equation and Raoult’s law to close the thermodynamic model. The vapor phase consists of a mixture of steam and volatile oil vapor at pressures \(P_w\) and \(P_v\) respectively and we obtain

\[
P_w = P_{\text{atm}} \exp \left( \frac{\Lambda_w (T_w^\circ)}{R} \left( \frac{1}{T_w^\circ} - \frac{1}{T} \right) \right), \quad P_v = P_{\text{atm}} \times \rho_{ov} \exp \left( \frac{\Lambda_v (T_v^\circ)}{R} \left( \frac{1}{T_v^\circ} - \frac{1}{T} \right) \right)
\]  

(1.4)

where \(P_{\text{atm}}\) is the atmospheric pressure, \(\Lambda_w, \Lambda_v\) are the heats of evaporation at the indicated boiling points of water and volatile oil, \(R\) is the gas constant. \(P_v + P_w\) is the total pressure. The ratio’s \(P_w/(P_v + P_w)\) and \(P_v/(P_v + P_w)\) are the mole fraction of water and volatile oil in the vapor phase.

The mole fraction of volatile oil in the vapor phase is given by

\[
x_{ov} = \frac{P - P_{\text{atm}} \exp \left( \frac{\Lambda_w (T_w^\circ)}{R} \left( \frac{1}{T_w^\circ} - \frac{1}{T} \right) \right)}{P_{\text{atm}} \exp \left( \frac{\Lambda_v (T_v^\circ)}{R} \left( \frac{1}{T_v^\circ} - \frac{1}{T} \right) \right)}
\]  

(1.5)

**Mass/Energy balance equations**

For the three components, water, volatile oil and dead oil we have three mass conservation laws.

\[
\phi \partial_t \left( \rho_{gw} S_g + \rho_{hw} S_w \right) + \partial_i u \left( \rho_{gw} f_g + \rho_{hw} f_w \right) = 0
\]

\[
\phi \partial_t \left( \rho_{gw} S_g + \rho_{ov} S_o \right) + \partial_i u \left( \rho_{gw} f_g + \rho_{ov} f_o \right) = 0
\]

\[
\phi \partial_t \left( \rho_{od} S_o \right) + \partial_i u \left( \rho_{od} f_o \right) = 0
\]

(1.6)

where the gas phase densities are given by \(\rho_{gw} = M_w P_w/(RT)\), \(\rho_{gw} = M_v P_v/(RT)\). The fractional flow functions are in the absence of gravity and capillary forces: \(f_w = k_{rw}/k_{ro} + k_{rw}/k_{ro} + k_{rg}/k_{rg}\) in conventional notation. We use relative permeabilities described by a fourth power fourth power of the irreducible saturations ((\(S - S_w\))/(1-\(S_w\))^2, \(S_o^4, S_g^4\)).

Finally we need the energy balance equation

\[
\partial_t \left( H_w + \rho_{gw} h_w + \phi S_g \left( \rho_{gw} h_w + \rho_{rov} h_{ov} + \rho_{rov} h_{od} \right) \right) + \partial_i u \left( \rho_{gw} h_w + \rho_{gw} h_w + \phi f_g \left( \rho_{gw} h_w + \rho_{gov} h_{ov} + \rho_{gov} h_{od} \right) \right) + \partial_i u \left( \rho_{gw} h_w + \phi f_g \left( \rho_{gw} h_w + \rho_{gov} h_{ov} + \rho_{gov} h_{od} \right) \right) + \phi f_g \left( \rho_{gw} h_w + \rho_{gov} h_{ov} + \rho_{gov} h_{od} \right) = 0
\]

(1.7)

It is tedious but straightforward to find the appropriate thermodynamic relations (see, however, Bell et al. (2014)). In the two phase region \(f_o = S_o = 0\).

The problem with solving the equations, is that you need to anticipate whether you are in the three-phase or two phase region.
Fig. 2. Steam displacement of a dead-oil/heptane mixture. The water saturation, oil saturation and steam saturation are shown as the dashed, solid and dashed-dotted curves. The volatile oil fraction in the oil phase and the reduced temperature are shown as the dotted and filled-square curves. (obtained from reference 3)

Fig. 3. Pressure vs. carbon number domain for low-, medium-, and high boiling temperature alkanes. The structure of the solution changes at the curves separating the L, M, and H regions.
Coincidence of the steam condensation front and the volatile oil bank leads to the best recovery results, like in the M-region of Fig. 3.

**ERoEI analysis and conclusions**

The exergy return on exergy invested analysis shows how much exergy was used to recover the oil. In the case of water injection the pumping costs to circulate the water can towards the end of the project exceed the recovered exergy. This analysis can be carried out to various degrees of sophistication. In practice the most important contributors to the exergy invested are the pumping exergy required to circulate the fluids. For one cubic meter of oil to be carried towards the production well we use that an estimate can be obtained, by assuming that an order of magnitude is that the pressure drop is given by 50 bar, which means that the exergy required to displace one cubic meter of fluids (let us assume that it is all oil) is $50 \times 10^5 \text{[Pa]} \times 1\text{[m}^3\text{]} = 5 \text{MJ}$. Such an amount costs in terms of fossil fuels $5/0.324 = 15.4 \text{MJ}$.

The energy content of oil is typically 10.7 kWh/liter (MacKay (2008)). Once combusted one m$^3$ of oil delivers 10.7 MWh/ m$^3$, or 38.5 GJ/ m$^3$.

The exergy of steam is given by

$$Ex = \Delta H - T_0 \Delta S$$

(1.8)

This value has to be divided again by 0.324, to obtain the practical energy required to generate the steam.

The main conclusion is that for steam apart from the circulation costs $Q\Delta P$ and the drilling costs (100 MJ/m) the energy to generate the steam needs to be taken into account. This method can help to choose the optimal recovery method with the smallest carbon footprint.

**References**


5. A. Eftekhari, H. van der Kooi, J. Bruining, Exergy analysis of underground coal gasification with simultaneous storage of carbon dioxide, Energy, Volume 45, Issue 1, September 2012, Pages 729-745,

