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TÍTULO DO TRABALHO:

Co-injeção de óleo volátil em vapor para maximizar a recuperação de óleo.

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MAXIMAL OIL RECOVERY BY STEAM ALKANE CO-INJECTION

Abstract

Steam injection is a cheap and widely used method for enhanced oil recovery. However, some portion of oil remains trapped in the pores of the reservoir after the passage of steam injection wave, unrecovered. To increase recovery efficiency, Dietz proposed at the end of the 70 the co-injection of a small fraction of volatile oil. His intention was that the volatile oil injected ideally would condense with the steam, forming a bank of light oil capable of dissolving and displacing the heavy oil contained in reservoir, improving the recovery. The mechanism that describes this gain is therefore related to the reduction in the oil viscosity resulting from the effects of mixing and heating.

We use a model capable of capturing these effects. It allows describing the behavior of the flow of oil by a uniform porous medium in local thermodynamic equilibrium. Thus the interaction at the interface between different configurations of components and phases can be modeled by shock waves, where the upstream thermodynamic configuration of the physical wave is allowed to differ from the downstream one. Therefor it is natural to try to understand the mechanisms that allow the improvement in oil recovery through the solution of Riemann problems for the conservation laws governing the injection of volatile oil in the reservoir. This has a direct interpretation in terms of laboratory experiments: if we have a long and thin sample of porous rock, which means that the area of its cross section is small in comparison to its length, containing oil, the so called Riemann problem corresponds to constant injection through one side of this rock. Its solution provides a family of waves, built from some basic ones: namely the shocks and rarefactions waves that describe the recovery process and can also be used as tools for construction of solutions to conservation laws modeling more complex flows. The Riemann problems can also be used as a tool to test complex numerical simulators.

We checked the computational results comparing the simulated shock speeds with calculated analytical expressions. The injection of volatile oil can also be considered in off-shore production when it is not practical to distribute the produced gas. In this case, knowing the structure of the Riemann problem can help predict the gain in the recovery factor.

Introduction

Steam drive recovery of oil continues to be an economical way of producing oil and is used world wide. An overview of the last forty years of steam drive recovery in California is given in reference [5]. The main challenges are to improve sweep efficiency and to improve recovery from the steam swept zone. Our interest focusses on the latter issue.

In the late seventies Dietz [1] proposed to add small amounts of volatile oil to the steam. His view was that the volatile oil co-injected with the steam in almost infinitesimal amounts would displace the dead oil ahead of the steam condensation front leaving no oil behind in the steam swept zone. The stability of the steam displacement would guarantee an even distribution of volatile oil along the steam condensation front. Experiments investigating the mechanism are described in references [1], [2], [4]. Similar ideas were put forward independently by Farouq-Ali [4].

At the time the main criticism towards this idea was that volatile oil is also present naturally and therefore the virtue of adding additional volatile oil is not clear. What was required was a theoretical description of the displacement process such that the results could be upscaled from the laboratory scale to the field scale. The theoretical model must be able to establish the difference between steam drive recoveries with co-injection of volatile oil with respect to the recoveries from oil

that contains a fraction of volatile oil. In spite of this fact these ideas have already found their way to field applications [6] where propane is used as low volatile hydrocarbon.

Due to the preliminarily stage of this work we will focus in the subproblem of volatile oil gas injection into a porous medium containing a mixture of oil and gas. The comprehension gathered with this simplification constitute a key step of the co-injection problem. Also the sole alkane injection posses a relevance of it's own: during off-shore production it is not always possible to store the produced gas. Therefore, this gas can be reinjected into the reservoir raising the reservoir pressure and so increasing the recovery factor. Our approach is to follow [3] and so simplify the model equations in such a way that the essential elements are retained and yet avoids the complexities of solving the pressure equation.

In Section 2 the model for the flow of oil with volatile oil gas injected is presented. The thermodynamical phase relationships and fluid densities are described. The hydrodynamical and energy equations that govern the flow are also discussed in Section 3. The numerical scheme for the governing equations is presented in Section 4. Section 5 introduces the Riemann problem. The resulting solution is discussed in Section 6. Appendices A and B contain a plethora of empirical relationships needed.

Physical Model

Flow of fluids and qualitative behavior: We consider the injection of volatile oil into a linear horizontal core with constant porosity. The core is originally filled with oil. The oil consists of a mixture of dead oil and volatile oil.

Physical quantities are evaluated at a representative constant pressure throughout the core. Thermal expansion of liquids will be disregarded. All fluids are considered incompressible. We assume Darcy's law of multiphase flow. The tube diameter is considered sufficiently small so that gravity segregation does not occur and temperature is homogeneous radially.

Thermodynamic fundaments: Let us describe the phase behavior. We always assume local thermodynamic equilibrium. We have two phases, i.e. gaseous and oleic. There are two components viz. volatile oil (v) and dead oil (d). We define dead oil as an oil with zero vapor pressure and volatile oil as an oil with finite nonzero vapor pressure.

We use the following convention for subscripts: the first subscript (o, g) refers to the phase, the second subscript (v, d) refers to the component. The pure phase densities of liquid volatile oil and liquid dead oil are denoted ρ_V and ρ_D respectively. The pure phase densitie of volatile oil vapor is denoted by ρ_{gV}.

Gibbs' phase rule $(f = c - p + 2)$ gives two degrees of fredom to the thermodynamic variables. As in our model we fix the pressure at which the displacement is conducted, we get that all concentrations are functions of the temperature only.

We derive a simple model for the thermodynamic behavior. We disregard any heat of mixing between volatile oil and dead oil. Moreover we disregard any volume contraction effects resulting from mixing. The concentration $[kg/m^3]$ of (dead) volatile oil in the oleic phase is denoted as (ρ_{od}) ρ_{ov}. In the same way we define the concentration of the volatile oil in the gaseous phase as ρ_{gv}. For ideal fluids we obtain

$$\frac{\rho_{ov}}{\rho_V} + \frac{\rho_{od}}{\rho_D} = 1. \tag{1}$$

The pure liquid densities ρ_V, ρ_D [kg/m^3] are considered to be independent of temperature, and the pure vapor density is considered to obey the ideal gas law, i.e., $\rho_{gV} = M_V P/RT$, where M_V denote the molar weight of volatile oil. P is pressure and the gas constant is $R = 8.31[J/mol/K]$.

Two-phase behavior: We assume that the volatile oil vapor pressure P_v is determined by the Clausius-Clapeyron equation with Raoult's law (see [7]), which states that the vapor pressure of volatile oil is equal to its pure vapor pressure times the mole fraction x_{ov} of volatile oil in the oil phase. Therefore we obtain

$$P_v(T) = x_{ov} P_o \exp\left(\frac{-M_V \Lambda_V\left(T_b^v\right)}{R}\left(\frac{1}{T} - \frac{1}{T_b^v}\right)\right), \tag{2}$$

where T_b^v is the normal boiling temperature of volatile oil, $\Lambda_V\left(T_b^v\right)$ is the evaporation heat of volatile oil at the normal boiling temperature T_b^v of volatile oil and M_V is the molar weight of volatile oil. Furthermore we assume that the total pressure is the volatile oil vapor pressures, i.e. $P^{tot} = P_v$.

Finally we need to derive an equation that relates the oleic phase densities to the mole fraction x_{ov}. From the definition of the mole fraction (moles volatile oil / total moles)

$$x_{ov} = \frac{\rho_{ov}/M_V}{\rho_{ov}/M_V + \rho_{od}/M_D}, \tag{3}$$

where M_D is the molar weight of the dead oil. Combining Eq. 3 with the first ideal mixing rule of Eq. (1) we find after some algebraic manipulation

$$\rho_{ov} = \frac{x_{ov}\rho_D\rho_V M_V}{x_{ov}\rho_D M_V + (1-x_{ov})\rho_V M_D}, \quad \rho_{od} = \frac{(1-x_{ov})\rho_D\rho_V M_D}{x_{ov}\rho_D M_V + (1-x_{ov})\rho_V M_D}. \tag{4}$$

The pure phase densities ρ_V, ρ_D have been given in table A.

Balance equations

Heat balance equations : The conservation of enthalpy is given as

$$\frac{\partial H}{\partial t} + \frac{\partial}{\partial x}\left(uf_o H_o + uf_g H_g\right) = 0, \tag{5}$$

Capital H is used for enthalpies per unit volume. It is convenient to define $H_o = \rho_{ov} h_{oV} + \rho_{od} h_{oD}$, $H_g = \rho_{gV} h_{gV}$.

The enthalpies h are all per unit mass and depend on temperature (see Appendix A). The enthalpy of volatile oil in the gaseous phase is h_{gV}. Furthermore h_{oV} and h_{oD} are the enthalpies of liquid volatile oil and dead oil. Hence $H = H_r + \varphi(s_o H_o + s_g H_g)$.

The saturation of oleic and gaseous phases are denoted as s_o, s_g and f_o, f_g are the Buckley-Leverett fractional flow functions. We use u to denote the total Darcy flow velocity and φ the constant rock porosity.

Rock enthalpy H_r is a function of temperature. It can be shown that if the heat capacities with respect to volume of volatile and dead oil are equal then H_o is linear in temperature and independent of composition. In this case we can reduce the liquid equation to a much simpler equation that can be solved explicitly in our numerical scheme. This excellent approximation simplifies the dependence of the total enthalpy $H = H(s_g, T)$, i.e. H does not depend on the composition of the oleic phase.

Conservation equations: We can write for the mass conservation volatile oil and dead oil respectively as:

$$\begin{aligned} \varphi \frac{\partial}{\partial t}\left(\rho_{gV} s_g + \rho_V s_o\right) + \frac{\partial}{\partial x} u\left(\rho_{gV} f_g + \rho_V f_o\right) &= 0, \\ \varphi \frac{\partial}{\partial t}(\rho_{od} s_o) + \frac{\partial}{\partial x} u(\rho_{od} f_o) &= 0. \end{aligned} \tag{6}$$

Notice that f_g and f_o are functions of the variables s_g and T. The independent variables of Eq. (6) are s_g, T and u. The equations (6) and (5) can be rewritten in condensed form as:

$$\frac{\partial G_l}{\partial t} + \frac{\partial u F_l}{\partial x} = 0, \quad \text{for} \quad l = v, d, T; \tag{7}$$

where we use the subscript l to denote the components (v, d) and the temperature T.

Numerical method

We discretize (7) with an implicit, backward in time, backward in space method on a uniform mesh. We write:

$$G_l^k(t+\Delta t) = G_l^k(t) - \frac{\Delta t}{\Delta x}\left(u^k(t+\Delta t) F_l^k(t+\Delta t) - u^{k-1}(t+\Delta t) F_l^{k-1}(t+\Delta t)\right), \tag{8}$$

where the superscript denotes the k^{th} grid cell. The unknowns are $u^k(t+\Delta t)$ and $\mathsf{V}^k(t+\Delta t)$ where $\mathsf{V} = (s_g, T)$. To shorten the notation we rewrite (8), $u^k(t+\Delta t)$ as u and $\mathsf{V}^k(t+\Delta t)$ as V. We obtain

$$G_l(\mathsf{V}) + \frac{\Delta t}{\Delta x} u F_l(\mathsf{V}) = R_l^{k,k-1}, \tag{9}$$

where $R_l^{k,k-1} = G_l^k(t) + u^{k-1}(t+\Delta t) F_l^{k-1}(t+\Delta t)\Delta t/\Delta x$. Note that all unknows lie in the left side.

We solve this system of non-linear implicit equations by the Newton-Raphson method. Given a solution at the n^{th} iteration V^n and u^n of (9) we want to guess an approximation to the solution in the $(n+1)^{th}$ iteration, in order to use the Newton-Raphson method to correct it. Substituting

$\mathbf{V}^{n+1} = \mathbf{V}^n + \Delta\mathbf{V}$, $u^{n+1} = u^n + \Delta u$ and neglecting second order terms we obtain a first order approximation

$$\left(\frac{\partial G_l}{\partial \mathbf{V}}(\mathbf{V}^n) + \frac{\Delta t}{\Delta x} u^n \frac{\partial F_l}{\partial \mathbf{V}}(\mathbf{V}^n)\right)\Delta\mathbf{V} + \frac{\Delta t}{\Delta x} F_l(\mathbf{V}^n)\Delta u = -\mathbf{R}_l^n \tag{10}$$

where $\mathbf{R}^n = G_l(\mathbf{V}^n) + u_l F(\mathbf{V}^n)\Delta t/\Delta x - R_l^{k,k-1}$. The system will be solvable if $u\Delta t/\Delta x$ is not a characteristic speed, which can be achieved by controlling the time step.

The Riemann Problem

The building blocks for solutions of conservation laws are shocks and rarefactions [8]. They arise in a very important class of initial value problems, the so called Riemann problems. Mathematically, a Riemann problem is a powerful tool that can be used to solve more general problems or to test new numerical methods. For the oil industry Riemann problems can be interpreted as constant injection problems in very thin and large reservoirs.

To validate the present simulation, we will utilize the structure of shocks in the equations (6). We write from the Rankine-Hugoniot conditions [8]:

$$\sigma = u^- \frac{F_v(\mathbf{V}^+)F_d(\mathbf{V}^-) - F_d(\mathbf{V}^+)F_v(\mathbf{V}^-)}{F_d(\mathbf{V}^+)[G_v(\mathbf{V}^+) - G_v(\mathbf{V}^-)] - F_v(\mathbf{V}^+)[G_d(\mathbf{V}^+) - G_d(\mathbf{V}^-)]}, \tag{11}$$

where σ is the shock speed and $\mathbf{V}^{\pm} = (s_g^{\pm}, T^{\pm})$, $u^{\pm}$ are the left$(-)$ and right$(+)$ states. A change of variables $x \to x/u^-$ shows that the total Darcy velocity at injection only rescales the speed of waves, retaining its shape, and so for purpose of visualization we can assume $u^- = 1$.

Numerical Results

All simulations use an equidistant grid with 1000 grid blocks. The initial reservoir temperature is $T^{ref} = 350K$. All simulations were run at atmospheric pressure.

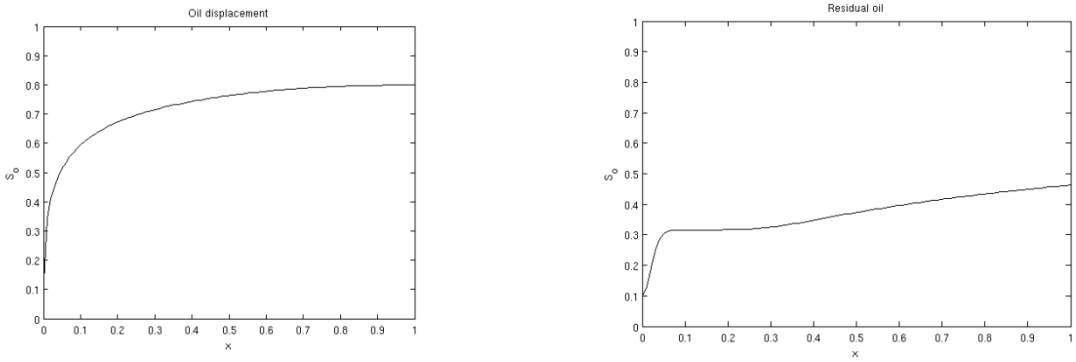

Figure 1

We simulate the displacement of oil in two cases. First, we consider a reservoir containing initially 20% of gas saturation *i.e* $s_g^{ref} = 0.2$. In all simulations we suppose that the reservoir pressure is sufficient to condensate a small fraction of the gas. So we impose a constant injection rate of volatile gas $s_g^{inj} = 0.9$ at temperature $T^{inj} = 440K$ into the well.As shown in figure (1-a), there is a continuous displacement of dead oil, which gives rise to a Buckley-Leverette rarefaction wave

joining the pair of states $(s_g^{inj} = 0.9, T^{ref} = 440K)$ and $(s_g^{ref} = 0.2, T^{ref} = 350K)$. After long times, the simulation produces a constant state, the residual oil saturation due to injection, as shown in figure (1-b).

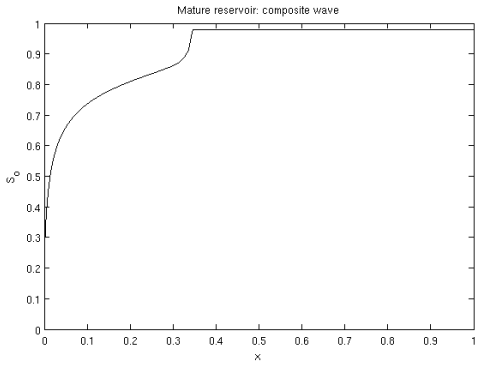

Figure 2

In the second case we consider a mature reservoir, in which the gas saturation is almost zero $s_g^{res} = 0.02$. This case contains the type of wave necessary to validate the model. Figure (2) shows a classical Buckley-Leverett shock/rarefaction composite wave. We have compared shock speeds calculated by simulations and analytically by (11). They agreed very well.

Conclusion

We focused on the problem of the volatile oil injection into a porous medium containing a mixture of oil and gas. Following [3] we used a simplified model in such a way that the key physical aspects were retained and yet the complexities of solving the pressure equation were avoided. We used an implicit numerical scheme to solve the problem assuming constant injection. The oil displacement was due a Buckley-Leverett rarefaction wave, and we observed a good recovery. The simulation of mature reservoirs generated composite waves. The simulated shock speeds were used to validate the model by comparison with explicit formulas. This comparison showed a very good agreement between the simulated and the analytical shock speeds.

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Appendix A: Physical quantities, symbols and values

In this appendix we summarize the values and units of the various quantities used in the computation and empirical expressions for the various parameter functions. For convenience we express the heat capacity of the rock C_r in terms of energy per unit volume of *porous medium* per unit temperature *i.e.* the factor $1-\varphi$ is already included in the rock density. All other densities/concentrations are expressed in terms of mass per unit volume of the phase. All enthalpies per unit mass are with respect to the enthalpies at the reference temperature of the components in their standard form. All heat capacities are at constant pressure. All enthalpies in their standard form are zero at the reference temperature.

Table A. Summary of physical input parameters and variables

Physical quantity	*Symbol*	*Value*	*Unit*
Porous rock permeability	k	1.0×10^{-12}	[m^2]
Molar weights	M_V, M_D	0.10021,0.4	[kg/mole]
Total pressure	p^{tot}	1.0135×10^5	[Pa]
Injection saturation	s_g^{inj}	input	[m^3/m^3]
Reservoir, injection temperature	T^{ref}, T^{inj}	350, 440	[K]
Boiling point of volatile, dead oil	T_b^v, T_b^d	371.57, ∞	[K]
Volatile, dead oil heat capacities	c_{oV}, c_{oD}	2121, $c_{oV}\rho_V/\rho_D$	[J/kg/K]
Volatile oil (log) viscosity	μ_{ov}	$-11.145+981.25/T$	[Pa s]
Dead oil (log) viscosity	μ_{od}	$-13.80+3780/T$	[Pa s]
Gas constant	R	8.31	[J/mole/K]

Pure vol-oil, dead oil densities	ρ_V , ρ_D	683, 800	[kg/m^3]
Rock porosity	φ	0.38	[m^3/m^3]

Temperature dependent variables. We use references [9] and [10] to obtain all the temperature dependent properties below.

The rock enthalpy C_r can be expressed as

$$H_r = (1-\varphi)C_r(T-\overline{T}),\ C_r = (1-\varphi)\times 3.274\times 10^6 = 2.03\times 10^6 \quad J/m^3/K. \tag{12}$$

A conventional choice for the reference temperature is $\overline{T} = 298.15K$. The volatile oil enthalpy $h_{oV}[J/kg]$ and the dead oil enthalpy $h_{oD}[J/kg]$ as a function of temperature is approximated by $h_{oV}(T) = c_{oV}(T-\overline{T}),\ h_{oD}(T) = c_{oD}(T-\overline{T})$. The values of c_{oV} and c_{oD} can be found in Table A. The enthalpies are chosen so that the enthalpy of oil per unit volume is independently of composition. Therefore the heat capacity of the oleic phase per unit volume can also be defined indepent of composition.

The volatile oil vapor enthalpy $h_{gV}[J/kg]$ as function of temperature is approximated by $h_{gV}(T) = c_{gV}(T-\overline{T}) + \Lambda_V(\overline{T})$. The enthalpies $h_{oV}(T),\ h_{oD}(T)$ vanish at the reference temperature $\overline{T} = 298.15K$. For the evaporation heat $\Lambda_V(T)[J/kg]$ we use Trouton's rule

$$\Lambda_V(T) = 88.0\times T_b^v/M_V - (c_{oV}-c_{gV})(T-T_b^v). \tag{13}$$

The viscosities of liquid volatile oil μ_{ov}, and liquid dead oil μ_{od} can be found from Table A. The viscosity of the oil mixture is approximated by $\mu_{mix} = (\rho_{ov}/\rho_V)\mu_{ov} + (\rho_{od}/\rho_D)\mu_{od}$. We assume that that the viscosity of the gas is independent of composition $\mu_g = 1.8264\times 10^{-5}(T/300)^{0.6}$.

Appendix B: Relative permeabilities for three-phase flow

We assume Darcy's law for multi-phase flow. Without the gravity terms and ignoring capillary effects it is

$$u_\alpha = \frac{k_\alpha}{\mu_\alpha}\frac{\partial P}{\partial x},\quad \alpha = o, g. \tag{14}$$

The total Darcy flow velocity is written $u = u_o + u_g$. The simplest expressions for relative permeability functions are power functions of their respective saturations i.e. $k_o = s_o^2,\ k_g = s_g^2$. Considering the mobilities for the oleic phase and the gaseous phase as given by $\lambda_o = k_o/\mu_{mix}$ (where μ_{mix} is in (19)) and $\lambda_g = k_g/\mu_g$ we can express the Buckley-Leverett fractional flow functions as $f_\alpha = \lambda_\alpha/(\lambda_o+\lambda_g)$, $\alpha = o, g$.