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Modeling of Thermally Enhanced Oil Recovery by In-Situ Combustion for Heavy Oil reserves.

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Abstract

The present work describes the application of equations of state in modeling of in-situ combustion of crude oil in porous reservoirs. The model incorporates the heat and mass flow through porous reservoirs. A finite difference based numerical model is used to solve the mass and energy conservation equations. The conservative equations are developed by considering advective-reactive flow of mass and advective-diffusive-reactive flow of heat through porous medium. The model considers Peng-Robinson (PR) Equation of State (EoS) to estimating properties such as compressibility and phase equilibrium compositions of pseudo-components. The numerical model is efficient enough in investigating the nature of combustion mechanism within the reservoir, predicting the propagation of thermal front and the key parameters affecting the performance of in-situ combustion process.

Introduction

Global energy consumptions are estimated to increase from 524 quadrillion Btu in 2010 to 630 quadrillion Btu in 2020 [6]. With easy-to-produce oil unable to fulfil the energy demand, heavy to extra heavy oils that are difficult to produce, but, untapped yet are expected to take major share in fulfilling the world energy demands. Enhanced Oil Recovery (EOR) methods especially In-Situ Combustion (ISC) technology aims to recover these heavy oil reserves and have the potential to reclassify the unrecoverable and contingent reserves. Thermal recovery by ISC process is characterized by the input of thermal energy into the reservoir through in-situ chemical reaction between crude oil and oxygen [4], which will make the oil flow more easily with their viscosity thermally lowered. Heavy fractions separate from lighter fractions due to distillation in vaporization zone (as shown in figure 1) and thermal cracking breaks large molecules into lighter hydrocarbons, resulting in up-gradation of heavy oil with respect to its original state; it will have a lower density and be less viscous.

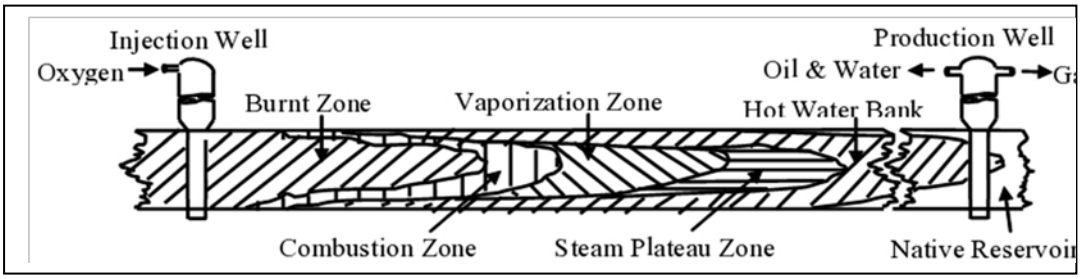

Figure 1 – Representation of zones in ISC process.

When a reservoir that is amenable to thermal recovery techniques as to which process to pursue if both steam and in-situ combustion are technically feasible, In-situ combustion shows a clear advantage over steam drive, when the thermal efficiency of each process is analysed [9]. Although thermal efficiency favours in-situ combustion, field scale in-situ combustion projects represent about 3% of the oil produced by thermal-recovery processes. This is because the difficulty in understanding

complex phenomena which occur during in-situ combustion and lack of reliable methods for predicting their performance. Numerical modeling is a powerful tool which can help in understanding this complex ISC process. Such a modeling and simulation can provide a means to predict the performance of a reservoir and which can be used to make intelligent decisions regarding future reservoir operations. The purpose of the present work is to develop a simplified numerical model incorporating an equation of state model to estimate phase behaviour characteristics and rigorously model the complex multiphase multi-component heat and mass transport taking place in ISC process.

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Model Description

The present physical model is based upon one-dimensional combustion process taking place in typical porous media, and the reservoir properties are presented in Table 1 [2].

Table 1: Characteristics of the reservoir and reservoir fluids

Property	value	Property	value
Porosity	0.38	Permeability [m^2]	1E-11
Reservoir temperature [K]	367	Reservoir pressure [kPa]	455
Reservoir length [m]	50	Initial oil saturation	0.5
Oil density ^{0}API	26	Initial water saturation	0.2

The mathematical model considers the mass conservation of 6 components: heavy oil, light oil, oxygen, water, inert gas and coke represented by equation (1) and energy conservation represented by equation (2) which are similar to those used by [11]. The model also takes in to account the advective and reactive flow of the reaction products and capillary pressures are used. Heat transfer is assumed to take place by both conduction and convection.

$$\varphi \frac{\partial}{\partial t}\left(\sum \rho_j S_j Y_i\right) + \frac{\partial}{\partial X}\left(\sum \rho_j V_j Y_i\right) = Q_i + \sum S_r Y_r \tag{1}$$

$$(1-\varphi)\frac{\partial}{\partial t}\left(\sum \rho_R U_R\right) + \varphi \frac{\partial}{\partial t}\left(\sum\left(\rho_j S_j Y_i U_i + \rho_C U_C\right)\right) + \frac{\partial}{\partial X}\left(\sum \rho_j V_j Y_i h_i\right) = \frac{\partial}{\partial X}\left(\mathrm{K}_r \frac{\partial T}{\partial X}\right) + Q_i \dot{h}_i + \sum (S_r Y_r \mathrm{H}_r) \tag{2}$$

Where i, j and k denote components, phases and reactions respectively.

The phase flow velocities are calculated using Darcy's law. The injection/production rates are estimated using well flow conditions described by [10]. Heat loss by conduction to the adjacent formations is considered [12]. The minimal kinetic model [7] developed by [5] is used to represent the reactions taking place in process. The Arrhenius expressions for temperature dependency are used in developing reaction rates.

The model assumes the system to be under thermal equilibrium expressed by equality between component fugacity in oil and gas phases. PR EoS for mixtures [8] is used to obtain the fugacity as shown in Eqs. (3) to (8).

$$P = \frac{RT}{V - b_m} - \frac{a_m}{V(V + b_m) + b_m(V - b_m)} \tag{3}$$

$$a = \frac{0.45724 R^2 T_c^2}{P_c}\alpha \tag{4}$$

$$b_i = \frac{0.07780\, RT_c}{P_c} \tag{5}$$

$$\alpha_i = (1 + (0.37464 + 1.54226\omega - 0.26992\omega^2)(1 - \sqrt{T_r}))^2 \quad (6)$$

where,

$$T_r = \frac{T}{T_c} \text{ and } P_r = \frac{P}{P_c} \quad (7)$$

Eq. (3) can be written for compressibility factor as Eq. (8).

$$Z^3 - (1-B)Z^2 - (A - 3B^2 - 2B)Z - (AB - B^2 - B^3) = 0 \quad (8)$$

The terms A and B are evaluated using Eqs. (9) to (13). Eq. (8) yields three roots of which only the positive real roots are considered. The largest root is considered as the compressibility factor of vapour and the smallest as the liquid phase compressibility factor.

$$A = \sum_i \sum_k x_i x_k A_{ik} \; or \; \sum_i \sum_k y_i y_k A_{ik} \quad (9)$$

$$B = \sum_i x_i B_i \; or \; \sum_i y_i B_i \quad (10)$$

$$A_i = 0.45724\, a_i \frac{P_{r_i}}{T_{r_i}^2} \quad (11)$$

$$B_i = 0.07780 \frac{P_{r_i}}{T_{r_i}} \quad (12)$$

$$A_{ik} = \sqrt{(A_i A_k)}(1 - \delta_{ik}) \quad (13)$$

where the binary interaction parameter δ_{ik} is calculated using Eq. (14) [3] and the equilibrium constant K_i is then calculated using Eq. (15)

$$\delta_{ik} = 1 - \left(\frac{2\sqrt{T_{c_i} T_{c_j}}}{T_{c_i} + T_{c_j}} \right)^n \quad (14)$$

$$\mathrm{K}_i = \frac{\phi_i^l}{\phi_i^v} \quad (15)$$

where ϕ_i^v is fugacity coefficient of component *i* in vapour phase and is obtained from Eq. (16) [8]. A similar expression can be obtained for the liquid phase fugacity coefficient by replacing the gas phase compressibility factor with its liquid phase counterpart.

$$\phi_i^j = Exp\left[(Z_j - 1)\frac{B_i}{B} - \ln(Z_j - B) - \frac{A}{2\sqrt{2}B}\left(\frac{2\sum_k y_k A_{ik}}{A} - \frac{B_i}{B} \right) \ln\left(\frac{Z_j + (1+\sqrt{2})B}{Z_j + (1-\sqrt{2})B} \right) \right] \quad (16)$$

Block centre based implicit finite difference approximation is used to discretize the partial differential equations (1) and (2) for the 6 pseudo components. A FORTRAN code based on Quasi-Newton/secant iteration solver with LU decomposition method has been developed to solve the resulting non-linear algebraic equations using the data in Tables 1 and 2. Validation of the developed model is presented in [11].

Table 2 – Data for ISC model

Component	Phase	Mol.wt.	T_C(K)	P_c(KPa)	ω
Light oil	L&G	44	369.1	4246.48	0.1517
Heavy oil	L&G	170	657.9	1824.35	0.5752
Water	A&G	18	647.1	22058.4	0.5824
Oxygen	G	32	154.4	5033.17	0.021
Inert Gas	G	44	304.2	7398.07	0.225
Coke	S	13	---	---	0.6978

Results and Discussion

The equation of state based ISC model is run with data shown in Table 2 [1] and [2]. Figure 2 shows the spatial distribution the temperature profile after 75 days. The profile reflects a typical combustion profile projected by combustion tube experiments consisting of various zones. Oxygen flowing through the reservoir propagates the combustion front from injection well through burnt zone. The temperature in the burnt zone linearly increases from injection temperature. The oxygen entering the combustion zone reacts with oil available in the reservoir producing gases, water and heat. The heat is generated from exothermic oxidation reactions between hydrocarbon and oxygen. The temperature reaches a peak value within the combustion zone. Heavy oil under goes thermal cracking producing coke and the temperature falls drastically. The coke produced/deposited by heavy oil oxidation acts as the main fuel source for stable propagation of combustion front. The peak temperature at any location in the reservoir is a function of fuel available. As the combustion front moves downstream combustion zone oil and water is vaporized. The rate of temperature drop starts to decrease. As the combustion front propagates through vaporization zone, the temperature drops to steam saturation temperature. The steam condensation begins at the leading edge of steam plateau zone. Downstream the steam plateau zone, temperature further decreases below the steam saturation temperature. Most of the water vapor gets condensed here, giving rise to the formation of hot water bank zone. The temperature continues to decrease in this zone to reach the reservoir original temperature. The combustion front is estimated to propagate with a velocity of about 0.3 m/day and the average reservoir temperature is found to be about 765K.

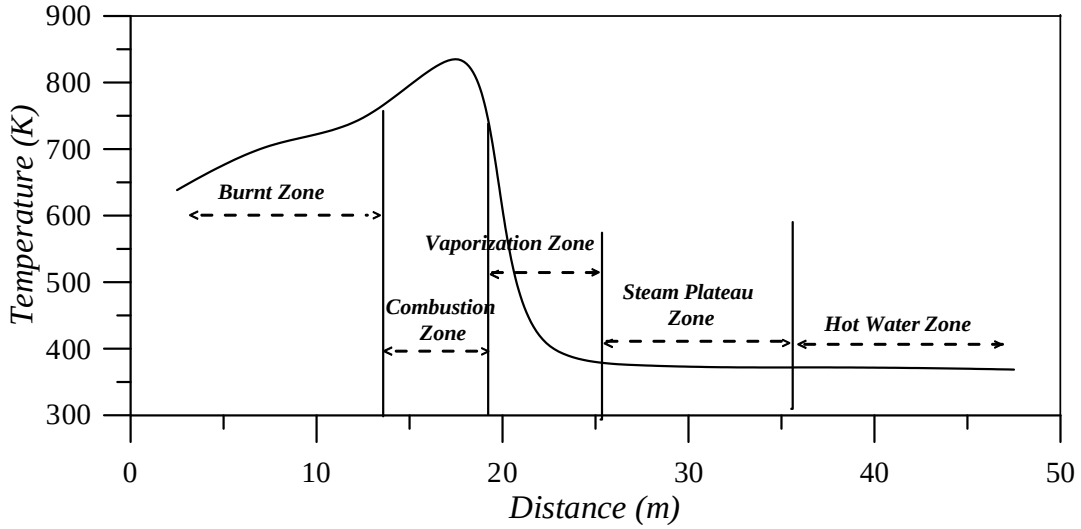

Figure 2 – Spatial distribution of Temperature profiles

Figure 3 presents the spatial distribution of oil saturation profiles predicted by the ISC model. As the oxygen flows in to the reservoir, it initiates low temperature oxidation reaction. This reaction consumes a part of heavy oil in the vicinity of injection well. As the temperature in the reservoir reaches a maximum, most of the heavy oil remaining in the reservoir is consumed in cracking and high temperature oxidation of heavy oil. These processes result in minimum oil saturation in the vicinity of injection well. Greater amounts of heat energy generated from exothermic combustion reactions of heavy oil and coke decrease the viscosity of Heavy oil. This reduction in viscosity

enhances the mobility (k/μ) of heavy oil towards the production well. The light oil produced from heavy oil cracking mixes with this mobilized heavy oil, resulting in a gradual increase in oil saturation. Away from injection well, where the temperature reaches a minimum, most of the oil vapors condense and mixes with mobilized heavy oil phase. This total oil further mixes with heavy oil initially present in the reservoir, resulting in maximum oil saturation towards the production well.

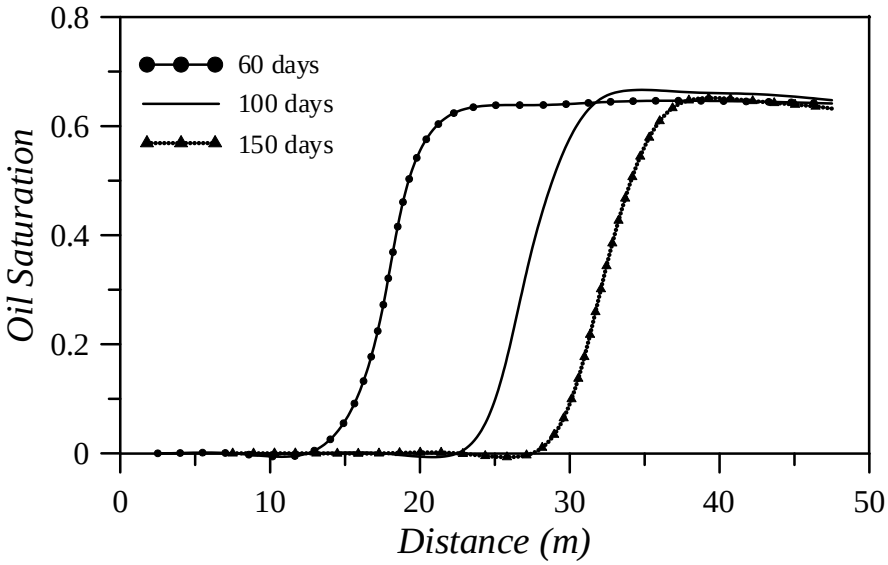

Figure 3 – Spatial distribution of oil saturation profiles

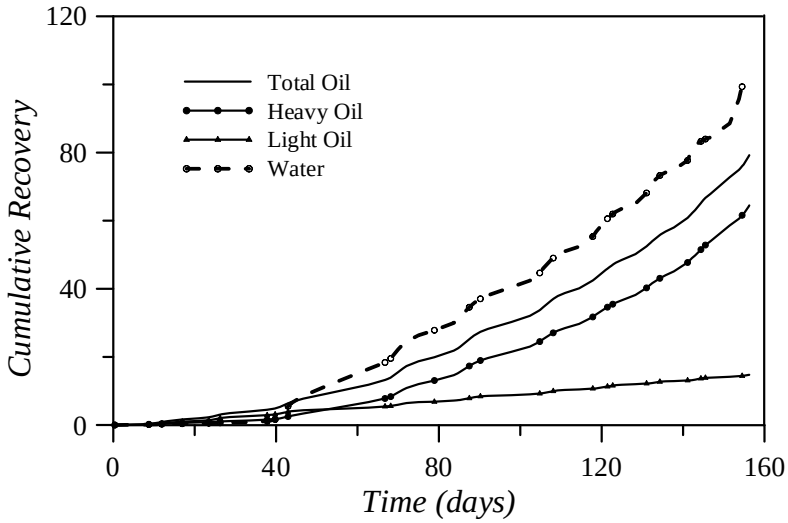

Figure 4 – Cumulative oil and water production profile.

Figure 4 provides the cumulative oil and water recovery profile by the present numerical model. Cumulative oil recovery is volumetric oil recovery expressed as a percentage of the original oil in place (OIIP). The total oil recovery is the sum of heavy oil and light oil production both in liquid and vapour phase. The numerical results report a total oil recovery of about 80% in about 160 days. A heavy oil recovery of about 68% and light oil recovery of about 12% are reported. The numerical results project a cumulative water recovery of about 100%. Cumulative water recovery is volumetric water recovery expresses as a percentage of the original water in place (OWIP). Water recovery is the sum of water originally present and the water generated form combustion reactions.

Conclusions

An equation of state based in-situ combustion model is developed incorporating PR EoS taking into account the compositions in estimating the phase behaviour at equilibrium condition. Based on the study, the following conclusions can be drawn.

- The model predicts the combustion front profiles similar to those reported by typical combustion tube tests.
- The model projects an average reservoir temperature of 765 K with a combustion front propagating at a velocity of 0.3 m/day.
- A cumulative oil recovery of 80% of OOIP and a water recovery of 100% OWIP is estimated.

Nomenclature

φ	Porosity
ρ	Density, gmol/m3
μ	Viscosity, KPa/day
H	Heat of reaction, KJ/gmol
h	Phase enthalpy, KJ/gmol
K	Thermal conductivity, KJ/day-m-K
P	Pressure, KPa
P_c	Critical pressure, KPa
P_r	Reduced Pressure
S	Saturation
T	Temperature, K
T_c	Critical temperature, K
T_r	Reduced temperature
t	Time, day
U	Internal Energy, KJ/gmol
x	Composition in liquid phase
y	Composition in vapor phase

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