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Numerical modelling of enhanced oil recovery by microbial flooding under non-isothermal conditions

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ABSTRACT

In the present paper an attempt has been made to develop an improved numerical model in order to simulate the oil recovery by microbial flooding under non-isothermal conditions. The proposed model simulates the coupled heat and mass transfer resulting from the mobility of microbes along with its nutrients in a typical petroleum reservoir against the conventional isothermal conditions. The model results have been verified with the existing analytical and experimental results. The present model evaluates the optimum mean fluid velocity in order to achieve the maximum oil displacement under different reservoir temperature conditions. The model also investigates the change in relative permeability of oil and water during microbial flooding within the reservoir under non-isothermal conditions and subsequently estimates the residual oil recovery. The model results suggest that the microscopic oil displacement efficiency increases with the increase in mean fluid velocity and reaches a threshold maximum oil displacement just before the water breakthrough at a relatively lower temperature. In addition, it is observed that the maximum oil displacement efficiency of 82.75% is achieved at a reservoir temperature of 60 °C and at an optimum mean fluid velocity of 1.68 m/day in a sandstone reservoir of length 50 m.

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1. Introduction

Crude oil forms the source for numerous products which serve the needs of human. In addition, the crude oil also plays a key role in defining the economy and GDP of many oil exporting as well as importing countries (Fatai et al., 2004; Narayan and Popp, 2012). The demand for oil continues to grow globally but the supply of oil from the current mature oil fields is on a decline (Chuanjin et al., 2012) and in addition, the exploration of new economically viable fields have also declined in recent times. Moreover, the production of oil from the existing fields by primary and secondary oil recovery processes only produces up to two thirds of initial recoverable oil-in-place. In order to have a sustained economic development in oil exporting and importing countries, and also to overcome the shortfall in oil supply, it is necessary to increase the production of oil from existing matured fields in an economical way. Implementing Enhanced Oil Recovery (EOR) techniques in an existing pressure declined mature field has been proved to be more cost effective than exploring new fields. Among the existing EOR methods like chemical EOR, miscible carbon-di-oxide flooding, microbial EOR and thermal EOR; microbial EOR method possesses economical, operational and environmental advantages over other EOR methods (Ghadimi and Ardjamand, 2006). In microbial EOR (MEOR) method, the microbes are used to produce the metabolites within the reservoir which in turn helps to recover the residual oil from the petroleum reservoirs (Bryant and Douglas, 1988; Murray et al., 2008). Though, MEOR process possesses many advantages, it involves complex mechanism which requires the application of microbiology and reservoir engineering practices with a better understanding of key parameters for its successful field implementation. The key parameters which impact the MEOR process are the type of indigenous bacteria; the type of nutrients fed into the reservoir; the characteristics of microbial metabolism; and the microbial growth as well as decay rate as a function of pH, salinity, temperature, which eventually influences the enhanced oil recovery from the petroleum reservoirs.

Earlier, to understand the MEOR process, laboratory studies (Desouky et al., 1995; Sidsel, 2010) have been carried out in order to evaluate the influence on the type of bacteria and nutrients and its sensitivity under different pH and salinity conditions on the resulting oil recovery process under isothermal conditions. However, during the field practice, non-isothermal condition exists in the reservoir because the temperature of the injected fluid (water mixed with microbes) through the injection well is relatively

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Nomenclature

b, c	Ratkowsky constants
$C_{microbes}$	concentration of microbes, mg/ml
C_o	injected microbe concentration, mg/ml
$C_{bio-surfactant}$	concentration of biosurfactants, mg/ml
d_r	microbial decay rate, day^{-1}
D_{mean}	mean hydrodynamic dispersion coefficient for microbes & nutrients, m^2/day
D_m	reservoir matrix dispersion co-efficient, m^2/day
D_t	longitudinal thermal dispersion in the reservoir, m
$H_{nutrients}$	Monod half growth constant, mg/ml
$K_{microbes}$	concentration of sandstone in microbial water, mg/ml
K_d	equilibrium distribution coefficient, ml/mg
k^*_{rw}	relative permeability of water at endpoint residual oil saturation, dimensionless
k_{rw}	relative permeability of water, dimensionless
k^*_{ro}	relative permeability of oil at endpoint residual oil saturation, dimensionless
k_{ro}	relative permeability of oil, dimensionless
NP	injected nutrient concentration, mg/ml
N^0_{ca}	initial capillary number before microbial flooding, dimensionless
N^*_{ca}	capillary number after microbial flooding, dimensionless
$N_{nutrients}$	concentration of nutrients, mg/ml
g_1, g_2, g_3	constants
Q_{max}	maximum specific microbial growth rate, day^{-1}
m_1, m_2, m_3	biosurfactant constants
R	sorption retardation factor
R_s	Monod kinetics, dimensionless
S_{iw}	irreducible water saturation, fraction
S	total fluid saturation, fraction
S_e	effective water saturation, fraction
s_{or}	initial residual oil saturation (i.e. after water flooding)
s^*_{or}	residual oil saturation after the microbial flooding process
T_{max}	maximum temperature at which the microbe sustain, °C
T_{min}	minimum temperature at which the microbe sustain, °C
T_{nw}	temperature near wellbore, °C
T_{res}	reservoir temperature, °C
T_r	relative temperature in the reservoir, fraction
T	time variable, day
u_{mean}	mean fluid velocity, m/day
x	space coordinate along the flow direction in reservoir, m
Y	microbial yield coefficient

Greek symbols

α	Corey constant
α_l	longitudinal dispersivity, m
β_t	thermal dispersivity, m
γ_{API}	specific gravity of crude oil, API
σ	initial interfacial tension between oil and water before microbial flooding, mN/m
σ^*	change in interfacial tension between oil and water after microbial flooding, mN/m
μ_0	viscosity of crude, Ns/m^2
μ_w	viscosity of water, Ns/m^2
ϕ	porosity, fraction

lower than the initial reservoir temperature. As a result, the injected fluid at a relatively lower temperature starts gaining the heat energy during its mobility within the high temperature reservoir, and subsequently a non-isothermal condition of injected fluids prevails within the reservoir. Such a varying temperature of the injected fluid, which essentially contains microbes along with its nutrients yields varying spatial and temporal distribution of the resultant biosurfactants within the reservoir. And subsequently, the rate at which the viscosity and Interfacial Tension (IFT) of the fluid gets reduced varies spatially as well as temporally as against its behaviour under isothermal conditions. Thus, before its implementation at a larger field scale, an understanding on the fundamental behaviour of microbes along with its nutrients under non-isothermal conditions at a relatively smaller scale becomes very critical. In this context, mathematical models are generally preferred to been excellent artifact as the amount of cost and time involved in developing these models is relatively nothing when compared to that of complex experimental as well as field investigations, which require heavy initial investment as well as significant time period to successfully conduct those experiments. Relatively, few mathematical models (Yao et al., 2012; Murphy and Timothy, 1999; Li et al., 2011; Lacerda et al., 2012; Sidsel, 2010) have been developed to simulate the transport of microbes and nutrients in porous media in order to predict the enhanced oil recovery under isothermal conditions. However, the growth of microbes and its metabolism is significantly affected by temperature of the reservoir during the MEOR process (Donaldson et al., 1989). Since, the metabolic (growth) rate of bacteria is a function of temperature, the resultant microbial concentration within the reservoir, and in turn, the biosurfactant production also varies as a function of temperature, and subsequently, it affects the residual oil saturation of the reservoir. Not many attempts have been made in this context to study the MEOR processes under different temperature conditions (Jinfeng et al., 2005) and no modelling work has been carried out to investigate the influence of reservoir temperature on residual oil recovery during the MEOR process atleast to the author's knowledge. Hence, the objective of the present work is to develop a numerical model in order to investigate the MEOR process under non-isothermal conditions and its associated recovery efficiency.

In the present numerical study, a one dimensional finite difference numerical model has been developed to simulate the microbial enhanced oil recovery mechanism under different reservoir temperature conditions and at various flood velocity/mean fluid velocity within the reservoir. The one dimensional model developed in the present study is easier to implement and produces faster result with relatively lower computational cost which helps in making quick decision before the application of the MEOR process in the field. Thus, the present one dimensional model helps in evaluating the performance and feasibility of MEOR implementation in the field and acts as a substitute against the complex multi-dimensional simulation studies. In the present model, the growth of microbes is coupled with the thermal distribution in the reservoir. The developed MEOR model simulates the transport of heat, nutrients and microbes within the reservoir. It further estimates the influence of mean fluid velocity and reservoir temperature on relative permeability of water and oil. The present numerical model also evaluates the suitable mean fluid velocity required to achieve maximum oil displacement efficiency for different reservoir temperature conditions. The robustness of

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