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Coupling heat and mass transfer for a gas mixture–heavy oil system at high pressures and elevated temperatures

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ABSTRACT

A generalized methodology has been developed to couple heat and mass transfer of a gas–heavy oil system and a gas mixture–heavy oil system at high pressures and elevated temperatures. Theoretically, the Peng–Robinson equation of state (PR EOS) incorporating with a one-way heat and mass transfer model has been developed to couple heat and mass transfer from either a hot gas or a hot gas mixture into heavy oil. Experimentally, diffusion tests have been conducted with a PVT setup for a hot CO_2–heavy oil system and a hot C_3H_8–CO_2–heavy oil system under a constant pressure, respectively. Both the gas-phase volume and liquid-phase swelling effect are simultaneously recorded during the measurement. The gas chromatography method is employed to measure compositions of the C_3H_8–CO_2 mixture at the beginning of the diffusion measurement. The heat transfer is found to proceed faster than mass transfer, leading to that the thermal equilibrium is achieved more quickly than mass equilibrium. The heavy oil expands rapidly at the initial stage of the coupled heat and mass transfer, and then swells gradually in the subsequent stage of mass transfer. The diffusion coefficient is determined by minimizing the discrepancy between the measured and calculated swelling factors of heavy oil during the diffusion tests. Adding C_3H_8 to CO_2 stream is found to not only improve mass diffusion, but also accelerate the heat diffusion and consequently an enhanced swelling effect of heavy oil.

1. Introduction

Adding alkane solvent(s) (e.g., C_3H_8 or n-C_4H_{10}) into CO_2 stream has been found to be a promising method for enhancing heavy oil recovery through an immiscible process [1–3]. Meanwhile, the hot solvent injection technique has attracted considerable attentions since it is particularly effective for improving heavy oil recovery due to the incremental benefits of heat transfer together with mass transfer from solvent(s) into heavy oil. It has been well-recognized that a steam–solvent process enhances oil mobility and thus a higher oil production rate compared to the steam-only process [4,5]. Hot solvent-enriched CO_2 flooding might be able to significantly further improve heavy oil recovery by combining advantages of both enriched CO_2 flooding process and hot solvent injection process. Three distinct benefits arise from the hot solvent-enriched CO_2 flooding process. Firstly, the existence of CO_2 in the injected gas mixture is able to maintain a high reservoir pressure, which is critically important for developing heavy oil reservoirs [6]. Secondly, the solvent-enriched CO_2 stream has a much higher solubility in heavy oil compared to pure CO_2, resulting in enhanced viscosity reduction and swelling effect of heavy oil [7]. Thirdly, the heat transfer from gas mixture to heavy oil contributes to the further reduction of heavy oil viscosity [8]. Therefore, it is of fundamental and practical importance to study the coupled heat and mass transfer of solvent–CO_2–heavy oil system so that the underlying mechanisms associated with dissolution of hot solvent(s)–CO_2 mixture into heavy oil can be better understood and quantified.

Numerous efforts have been made to study mass transfer from either a gas [9–12] or a gas mixture [13–15] into heavy oil. Fick's diffusion law is generally employed to describe the mass transfer process, while the volume change of heavy oil is usually considered due to the dissolution of a gas solvent. As a critical parameter in the diffusion equation, diffusion coefficient is generally determined by matching a theoretically calculated parameter to its experimentally measured value. The diffusion coefficient of a solvent has been assumed to be a constant [11,12,14,15], a function of the concentration of solvent in heavy oil [10,16] or viscosity of heavy oil [17,18], and even a multi-parameter equation associated with pressure, temperature, and viscosity of liquid [19], respectively. Since the convective mixing due to a high initial mass transfer rate together with surface tension-driven instability plays an important

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Nomenclature

A	cross-sectional area of the PVT cell, cm^2
a	attraction parameter in the PR EOS model, kPa m^3/kmol
a_c	factor in correlation of attraction parameter in the PR EOS model
b	van der Waals volume, m^3/kmol
c_i	concentration of ith solvent in heavy oil, mol/m^3
$c_{i,sat}$	saturated concentration of ith solvent in heavy oil, mol/m^3
$c_{p,g}$, $c_{p,l}$	heat capacity of gas and liquid phase, J/(kg K)
D_i	diffusion coefficient of ith solvent, m^2/s
H	updated height of heavy oil, cm
H_0	initial height of heavy oil, cm
H^*	updated height of heavy oil at last time step $t - \Delta t$, cm
MW_i	molecular weight of ith component, g/mol
m	the mth node along the diffusion direction
$m_{g,i}$	mass of ith component in gas phase, kg
N_{exp}	number of data obtained from the experiment
n	the nth time step during the numerical calculation
ng	number of gas component
nc	number of components in the diffusion system
$O(SF)$	objective function
p	pressure, kPa
p_c	critical pressure, kPa
R	universal gas constant, kPa m^3/(K kmol)
S_E	energy input to the gas phase from the environment, W/m^3
S_m	mass loss due to the mass transfer from gas phase to liquid phase, kg/s
S_T	energy loss due to the heat transfer from gas phase to liquid phase, W/m^3
SF_X	swelling factor
SF^i_{cal}	calculated swelling factor of the ith data point
SF^i_{exp}	measured swelling factor of the ith data point
SG	specific gravity
T_c	critical temperature, K
T_g, T_l	temperature of gas and liquid phase, K
$T_{l,0}$	initial temperature of liquid phase, K
T_r	reduced temperature, K
t	time, s
V	molar volume, m^3/kmol
$V_{corrected}$	corrected molar volume, m^3/kmol
V_1	molar volume of heavy oil at test pressure and initial temperature, m^3/kmol
V_2	molar volume of solvent-diluted heavy oil at test pressure and temperature, m^3/kmol
x_i, x_j	composition of the ith and jth component in liquid phase, respectively, mole fraction
y	coordinate direction of liquid phase, cm
y_g	coordinate direction of gas phase, cm
Z_{RA}	Rackett parameter

Greek symbols

α	alpha function in PR EOS model, constant in Eq. (12)
β	constant in Eq. (12)
Δt	time interval
Δy	space interval
δ	BIP matrix
λ	thermal conductivity, W/(m K)
μ	dynamic viscosity, cP
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
τ	dimensionless time
ϕ	volume fraction
ω	acentric factor

Subscripts

0	initial state
cal	calculated
exp	experimental
g	gas
l	liquid
o	heavy oil
s	solvent
sat	saturated

role at the early stage of diffusion [10], diffusion coefficient may be underestimated at the initial stage of the mass transfer process if it is assumed to be constant. Consequently, it may be more reasonable to assume that diffusion coefficient is dependent on the solvent concentration and/or viscosity of the liquid, though its accuracy relies on the forms of representation functions.

A hot solvent such as methane, ethane, propane, butane, and their combinations have been tested to examine their effectiveness for enhancing heavy oil recovery. Experimentally, effects of temperature, gravity, permeability, pore size, asphaltene precipitation, pressure, and solvent type on heavy oil recovery have been extensively studied [5,8,20–24]. Theoretically, thermal reservoir models have been developed for numerically simulating steam injection and other thermal processes [25–27]. The swelling of heavy oil contributes to an increase in mobile oil saturation as well as an increase in relative permeability of heavy oil, and hence heavy oil recovery is improved [28,29]. Nonetheless, few attempts have been made to develop a generalized framework for accurately not only quantifying the swelling effect, but also determining the diffusion coefficient due to the coupled heat and mass transfer.

In this study, a generalized methodology has been developed to couple heat and mass transfer from a gas and its mixture to heavy oil at a constant pressure. Theoretically, the Peng–Robinson Equation of State (PR EOS) [30] incorporating a coupled heat and mass transfer model has been developed to describe the heat and mass transfer from a gas or a gas mixture to heavy oil at high pressure and elevated temperatures. Experimentally, PVT tests are conducted to measure the decaying volume of gas phase and the swelling volume of liquid phase during the heat and mass transfer for a hot CO_2–heavy oil system and a hot C_3H_8–CO_2–heavy oil system under a constant pressure, respectively. The diffusion coefficient of the gas or gas mixture in heavy oil is determined once the discrepancy between the measured and calculated swelling factor of heavy oil during the diffusion measurement has been minimized. Also, the temperature profile and concentration profile can be correspondingly determined.

2. Mathematical formulations

2.1. PR EOS model

Due to its wide application in the petroleum and chemical industries, the PR EOS is chosen as the equation of state for describing phase behavior of solvent(s)–CO_2–heavy oil systems. The PR EOS model can be described as [30,31],

$$p = \frac{RT}{V - b} - \frac{a}{V(V + b) + b(V - b)} \tag{1}$$

$$a = a_c \alpha(T_r, \omega) \tag{2a}$$