Determination of individual diffusion coefficients of alkane solvent(s)–CO_2–heavy oil systems with consideration of natural convection induced by swelling effect

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ABSTRACT

By both coupling heat and mass transfer and characterizing heavy oil as multiple pseudocomponents, a new and pragmatic technique has been developed to determine individual diffusion coefficient of each component in alkane solvent(s)–CO_2–heavy oil mixtures with consideration of natural convection induced by swelling effect. Experimentally, diffusion tests of alkane solvent(s)–CO_2–heavy oil systems are conducted with a visualized PVT cell under elevated temperatures and a constant pressure. Theoretically, the Peng-Robinson equation of state, heat transfer equation, and diffusion-convection equation are coupled to form a mathematical matrix where diffusion coefficient and viscosity of the mixture are considered to be concentration-dependent. Diffusion coefficients of each component of a gas mixture in liquid phase are respectively determined once either the deviation between the experimentally measured and theoretically calculated mole fraction of CO_2 and/or solvent(s) or the deviation between the experimentally measured dynamic swelling factors and the theoretically calculated ones has been minimized. Also, effects of heat and natural convection on the mass transfer of CO_2 and/or solvent(s) in heavy oil have been examined. The individual diffusion coefficient of each component in a mixture is found to be larger than those documented in the literature, while thermal equilibrium is able to achieve much faster than mass transfer for the entire system. A higher temperature is beneficial to enhance the mass transfer rate in a certain range, while natural convection induced by swelling effect results in a fluid flow direction opposite to that of the mass transfer, and thus decreasing the mass transfer rate under the same conditions.

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1. Introduction

In recent years, combining solvent(s) and heat has been considered as a promising method for enhancing oil recovery from heavy oil reservoirs [1–3]. Compared with heat-alone or solvent-alone approach, such hybrid thermal-solvent processes can take advantages of both solvent and heat [4]. As alkane solvents are expensive, CO_2 has been considered as an effective agent for enhancing heavy oil recovery, though its solubility in heavy oil is limited. Addition of alkane solvents to the CO_2 stream leads to enhanced viscosity reduction and swelling effect of heavy oil [5]. During a hybrid solvent-thermal process, it has been proved that the energy efficiency can be significantly increased with the injection of solvent(s), while the cost of heat is greatly reduced [6,7]. Not only can the heat carried by a hot CO_2/solvent remarkably decrease

the viscosity of oleic phase [8], but also its mass transfer in heavy oil can be effectively accelerated due to the quick heat transfer with a larger swelling factor [2,3]. Physically, both heat and mass transfer make a CO_2/solvent(s)-assisted process extremely complicated in the presence of multiple gaseous diffusion and natural convection induced by oil swelling. As such, it is of practical and fundamental importance to accurately quantify the mass transfer rate for each solvent of a gas mixture during a CO_2/solvent(s)-assisted thermal recovery process.

As for a solvent-assisted recovery technique, mass transfer rate is important to evaluate the feasibility for recovering heavy oil [9], while diffusion coefficient is a key parameter required to quantify the mass transfer process. Numerous efforts have been made to experimentally and theoretically determine diffusion coefficients for solvent(s)–heavy oil systems [9–12]. In general, diffusion coefficient can be obtained indirectly by minimizing the deviation between the experimental measurements and theoretical calculations from various mathematical models. As for such an indirect

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Nomenclature

A	constant in Eq. (7)
A_c	cross-sectional area of the PVT cell, m^2
A_{li}	constant to the ith component of liquid mixture in Eq. (9a)
B	constant in Eq. (7)
B_{li}	constant to the ith component of liquid mixture in Eq. (9a)
c_i	i^{th} solvent or CO_2 concentration in the liquid phase, mol/m^3
c_{pl}	heat capacity of the liquid phase, J/(kg·K)
c_{sat}	solvent concentration at the gas-liquid interface, mol/m^3
D_i	i^{th} solvent or CO_2 diffusion coefficient, m^2/s
l_0	initial height of the liquid phase, m
$l(t)$	height of the liquid phase at time t, m
n_g	the number of gas solvent component
N_m	the number of experimental data
N_n	the number of gas-phase component
P	pressure, kPa
ΔP	pressure deviation from atmospheric pressure, MPa
P_c	critical pressure, kPa
R	universal gas constant, kPa·m^3/K·mol
S	swelling factor
s_i^{cal}	calculated dynamic swelling factor
s_i^m	measured dynamic swelling factor
T	temperature, K
T_c	critical temperature, K
T_h	temperature of the PVT chamber, K
T_l	temperature of liquid phase, K
T_{li}	initial temperature of liquid phase, K

T_r	reduced temperature
u	velocity of natural convection, m/s
V_M	molar volume, m^3/kmol
V_{Mx}^0, V_{Mx}^t	molar volume of oleic phase at initial stage and time t, respectively, m^3/kmol
ΔV	total increased volume of the liquid phase, m^3
$\overline{V}$	corrected molar volume, m^3/kmol
V_c	critical volume of each component
V_i^p	i^{th} component corrections
W_i	i^{th} component mass fraction in the liquid phase
x_{gi}	composition of the ith gas solvent in the liquid phase
x_i	composition of the ith component in the liquid phase
x_i^{cal}	calculated mole fraction of the ith component in liquid phase
x_i^m	measured mole fraction of the ith component in liquid phase
z_{RA}	Rackett parameter
$\alpha(T_r, \omega)$	alpha function
α_l	viscosibility parameter of liquid mixture
α_i	viscosibility parameter of the ith component in the liquid phase
δ_{ij}	binary interaction parameter between the ith and j^{th} components
λ_l	thermal conductivities of the liquid phase, W/(m·K)
μ	viscosity, cP
$\mu^0(T)$	dynamic viscosity of mixture at temperature T and atmospheric pressure, cP
ρ_l	density of the liquid phase, kg/m^3
ω	acentric factor

determination, PVT tests, X-ray method, and NMR approach are found to be effectively experimental approaches for quantifying mass transfer of solvent(s) in heavy oil [12–14]. Physically, mass transfer is dominated by the diffusion mechanisms under various initial and boundary conditions as well as solvent transport processes associated with corresponding experimental procedures. Thus, Fick's second law is usually utilized to theoretically quantify the solvent mass transfer processes from the solvent–heavy oil interface to the heavy oil phase. Both analytical and numerical solutions of mathematical models have been used to determine diffusion coefficients, depending on the complexity of history matching experimental processes [15–17].

During diffusion experiments, fluids flow or convection cannot be completely avoided due to existing experimental procedures or swelling effect induced by either the heat or dissolution of gas component in crude oil. Since numerical solutions associated with mass transfer models for accurately describing the fluid flow are complicated, it is difficult to isolate the contribution of convection to the mass transfer, which has been vaguely combined with diffusion mechanisms as stated in the literature [13,17–19]. Such a vague combination can cause the to-be-measured diffusion coefficient deviated from its true value up to two orders of magnitude [18]. To examine effects of heat or natural convection, Farajzadeh et al. [20] initiated a study on diffusion coefficients of the CO_2–water systems with consideration of the density-driven natural convection. As for CO_2–n-$C_{16}H_{34}$ systems, Li and Dong [21] calculated the velocity resulted from the swelling effect in porous media and thus indirectly determined the corresponding diffusion coefficient, accounting for both convection and diffusion. By treating heavy oil as one pseudocomponent [4] and multiple pseudo-components [22–24], generalized methods have been developed to determine diffusion coefficients for solvent(s)–heavy oil systems

at high pressures and elevated temperatures without considering convection. So far, few attempts have been made to quantify the preferential dissolution of each component in a solvent(s)–CO_2–heavy oil system with consideration of both natural convection and heat contribution [8,25].

In this study, by coupling the heat and mass transfer as well as characterizing heavy oil as multiple pseudocomponents, a new and pragmatic technique has been developed to determine the individual diffusion coefficient of each component in solvent(s)–CO_2–heavy oil systems with consideration of natural convection induced by oil swelling effect. Peng-Robinson equation of state (PR-EOS), one dimensional (1D) heat transfer equation, and 1D convection-diffusion equation are integrated to quantify both mass and heat transfer. The diffusion coefficient considering the effect of convection between each component of a gas mixture and liquid phase can be respectively obtained as a function of viscosity once either the deviation between the experimentally measured mole fractions of CO_2 and/or solvents and the calculated ones or the deviation between the experimentally measured dynamic swelling factors and theoretically calculated ones from the newly developed mathematical model is minimized. Furthermore, the effects of heat and natural convection induced by swelling effect on mass transfer rate are evaluated and discussed.

2. Experimental

2.1. Materials

Heavy oil sample used in the experiments was collected from Lloydminster area in Saskatchewan of Canada. The specific density and molecular weight are measured to be 0.9997 and 482 g/mol,