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Research paper

Sensitivity analysis of hydrate dissociation front conditioned to depressurization and wellbore heating

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ABSTRACT

A gas hydrate reservoir can be divided by a dissociation front into a dissociated zone and a hydrate zone during production. The advance of such a dissociation front greatly affects both the energy recovery potential and geological hazards prevention. In this paper, the advance of hydrate dissociation front has been elaborately investigated by means of numerical simulation. More specifically, depressurization and wellbore heating methods are used as development strategies in the reservoir simulation models, which are characterized by various geological and production parameters. Quantitative sensitivity analyses have been conducted through 14 simulation models representing diversified configurations of boundary condition, intrinsic hydrate reaction rate, intrinsic permeability, initial hydrate saturation, overall heat conductivity, wellbore heating temperature, and bottom-hole pressure. It has been found that the velocity of hydrate dissociation front is positively proportional to intrinsic hydrate reaction rate, intrinsic permeability, overall heat conductivity, wellbore heating temperature, and heat supply from the boundary. In contrast, increasing initial hydrate saturation and bottom-hole pressure reduce the velocity of hydrate dissociation front. Furthermore, the shape of dissociation front advance curve also varies with the aforementioned parameters. A concave shape of dissociation front advance curve is transformed into a convex one as the intrinsic permeability increases, which reveals the effect of fluid-flow controlling mechanism on the variation of dissociation front. From the sensitivity view of point, the average velocity of the dissociation front is strongly dependent on the overall heat conductivity, initial hydrate saturation, and bottom-hole pressure and weakly dependent on intrinsic hydrate reaction rate and intrinsic permeability. Quantitatively, the average velocity of hydrate dissociation front can be increased by 47% when the overall heat conductivity increases from 3.1 W/(m·K) to 8.0 W/(m·K), whereas it is rarely affected by the wellbore heating temperature.

1. Introduction

Tremendous methane hydrate reservoirs deposited in seabed and permafrost have been considered as the most promising unconventional energy sources (Sloan and Koh, 2007). Depressurization and heat injection techniques are commonly applied to produce the methane from hydrate reservoirs (Chong et al., 2015). The emergence of a dissociation front during the methane production splits the hydrate reservoir into two zones, i.e., a dissociated zone and a hydrate zone, which are characterized by different geological properties, e.g., hydrate saturation and overall heat conductivity. (Yousif et al., 1990; Tsypkin, 1991). Since the advance of dissociation front plays a significant role in the production performance of hydrate reservoirs (Makogon, 1997), it is essential to identify the advance of dissociation front for not only optimizing the methane production in fields but also preventing potential geological hazards resulted from hydrate reservoir exploitations (Zhang et al., 2012; Bhade and Phirani., 2015; Fujii et al., 2015).

Based on self-similarity, theoretical models have been derived by assuming the position of dissociation front is in proportion to the square root of time (Verigin et al., 1980; Selim and Sloan, 1990; Yousif et al., 1991; Makogon, 1997; Ji et al., 2001, 2003; Yu et al., 2004; Li et al., 2006; Tang et al., 2006; Ahmadi et al., 2007; Zhao, 2013; Li et al., 2015a; Azizi et al., 2016). A comparison of mechanisms considered in the theoretical models has been implemented by Yin et al. (2016). However, there is no consensus on the variation of dissociation front velocity among experimental and theoretical results. Zhou et al. (2007) experimentally measured the advance of dissociation front during hot water injection in a one-dimensional (1D) reactor and found the velocity of dissociation front declined gradually. Zhang et al. (2010) found that the velocity of dissociation front was reduced under a constant heat

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source condition. Li and Fan (2012) observed a constant velocity of dissociation front in a heat injection experiment. Liu et al. (2013) demonstrated that the velocity of dissociation front was proportional to the square root of time via a 1D experimental reactor adopting depressurization method. They also observed similar relationships from experiments using both depressurization and heat injection.

Theoretically, Selim and Sloan (1985) found that the dissociation front advanced linearly with time through a model based on heat balance integral method. By considering the effect of heat conduction and kinetics of hydrate dissociation in a 1D model, Jamaluddin et al. (1989) indicated that the dissociation front advanced linearly with time and the velocity of dissociation front decreased with increasing activation energy and initial reservoir pressure. Yousif et al. (1991) integrated water and gas two-phase flow as well as kinetics of hydrate dissociation in a 1D model and found the velocity of dissociation front decreased with time. Briaud and Chaouch (1997) proposed a heat conduction model with finite element method and indicated that the velocity of dissociation front was proportional to the square root of time and increased with the radius of oil pipe. Sung et al. (2000) concluded that the dissociation front advanced linearly in the 1D model and gradually slowed down in the three-dimensional (3D) model. Moreover, the hydrate dissociation front velocity was reduced with an increase in hydrate saturation and a decrease in intrinsic permeability. Hong et al. (2003) found that the velocity of dissociation front decreased with increasing porosity by using a semi-infinite model. Yu et al. (2004) concluded that the velocity of dissociation front increased with decreasing bottom-hole pressure and increasing initial reservoir temperature. According to numerical simulation studies of gas hydrate production by depressurization, Li et al. (2005) found that the velocity of dissociation front increased with intrinsic permeability but decreased with initial hydrate saturation and bottom-hole pressure. By investigating the production performance of heat injection in seafloor hydrate reservoirs using mathematical models based on Selim and Sloan (1990), Tsimpanogiannis and Lichtner (2007) reported that the velocity of dissociation front increased with heat injection rate and heat conductivity of the dissociated zone but decreased with porosity, heat conductivity, and thermal diffusivity. Su et al. (2011) established a mathematical model solely considering the heat conduction. They concluded that the advance of dissociation front is more sensitive to hydrate saturation and heat conductivity and less sensitive to wellbore heating temperature and temperature difference between equilibrium and initial conditions of the hydrate reservoir. Long and Tjok (2016) investigated hydrate reservoir production by depressurization with a numerical simulator, i.e., HydrateResSim (Moridis et al., 2005). It was addressed that the average velocity of dissociation front increased with intrinsic permeability.

The differences in the effects of various parameters on the advance of dissociation front are attributed to the following two facts. First, various mechanisms are considered in models proposed by different researchers. For instance, only heat transfer was included in the model of Selim and Sloan (1985), whereas both heat transfer and kinetics of hydrate dissociation were considered by Jamaluddin et al. (1989). On the other hand, different definitions of the dissociation front are used in the aforementioned studies. The dissociation front has been defined as the position where the temperature becomes larger than the equilibrium one or the pressure decreases to be lower than the equilibrium one (Sun et al., 2005; Ji et al., 2003; Sakamoto et al., 2007). In addition, the hydrate saturation of zero was also used to define the dissociation front (Kowalsky and Moridis, 2007; Yousif et al., 1991). Although numerous investigations have been carried out on the dependence of dissociation front velocity on intrinsic permeability, heat conductivity, bottom-hole pressure, and hydrate saturation, few efforts have been made to systematically analyze the sensitivities of these geological and production parameters on the dissociation front velocity.

In this paper, the effects of geological and production parameters on dissociation front are synergistically evaluated to better understand the mechanisms of hydrate dissociation during production by depressurization and wellbore heating. A hydrate reservoir simulator has been utilized to build simulation models associated with five geological parameters (i.e., thermal boundary conditions, intrinsic reaction rate of hydrate, intrinsic permeability, initial hydrate saturation, and overall heat conductivity) and two production parameters (i.e., wellbore heating temperature and bottom-hole pressure). Subsequently, the sensitivity of dissociation front to each individual parameter is quantitatively analyzed, which yields ranked contributions of each one to the average velocity of dissociation front.

2. Numerical modeling

Compared to other numerical simulators (Sun et al., 2005; Su et al., 2011; Hong and Pooladi-Darvish, 2003), HydrateResSim, i.e., an open source code developed by Lawrence Berkeley National Laboratory (LBNL), can comprehensively simulate phase transition, fluid flow, and heat transfer in complicated hydrate reservoirs (Moridis et al., 2005; Gamwo and Liu, 2010; Zheng et al., 2015). As such, HydrateResSim is applied in this work to investigate the advance of dissociation front. In this section, the mathematical models of mass and energy conservation in HydrateResSim are briefly introduced for equilibrium and kinetic models, respectively. Then, the simulation models in this work is elaborately described followed by introduction of the approach to perform the sensitivity analyses of dissociation front velocity.

2.1. Mathematical models

2.1.1. Equilibrium model

The hydrate dissociation is assumed to take place while the pressure is lower or the temperature is higher than corresponding equilibrium conditions in the equilibrium model where three components of water, methane and inhibitor denoted by superscripts of *w*, *m* and *i* are distributed in four phases, i.e., gas, aqueous, hydrate, and ice phases indicated by subscripts of G, A, H and I, respectively (Hong and Pooladi-Darvish, 2003; Li et al., 2014; Zheng et al., 2015). Mass conservation of water component is represented by

$$\frac{d}{dt}\left(\varphi S_A\rho_A x_A^w + \varphi S_G\rho_G x_G^w + \varphi S_I\rho_I + \frac{NM^w}{M^h}\varphi S_H\rho_H\right) = \nabla\cdot\left[-k\frac{k_{rA}\rho_A}{\mu_A}x_A^w(\nabla P_A - \rho_A g) - k\left(1+\frac{b}{P_G}\right)\frac{k_{rG}\rho_G}{\mu_G}x_G^w(\nabla P_G - \rho_G g)\right] + q_A x_A^w + q_G x_G^w + \frac{q_I\rho_A}{LWH} \quad (1)$$

where the left-hand-side term is mass accumulation; the first term on the right-hand side is mass flux; the second term on the right-hand side is sink/source. Similarly, mass conservation of methane component and inhibitor component can be written as

$$\frac{d}{dt}\left(\varphi S_A\rho_A x_A^m + \varphi S_G\rho_G x_G^m + \frac{M^m}{M^h}\varphi S_H\rho_H\right) = \nabla\cdot\left[-k\frac{k_{rA}\rho_A}{\mu_A}x_A^m(\nabla P_A - \rho_A g) - k\left(1+\frac{b}{P_G}\right)\frac{k_{rG}\rho_G}{\mu_G}x_G^m(\nabla P_G - \rho_G g)\right] + q_A x_A^m + q_G x_G^m \quad (2)$$

$$\frac{d}{dt}\{[\varphi S_A + (1-\varphi)\rho_R K_d^i]\rho_A x_A^i\} = \nabla\cdot\left[-k\frac{k_{rA}\rho_A}{\mu_A}x_A^i(\nabla P_A - \rho_A g)\right] + q_A x_A^i \quad (3)$$