



Using similarity theory to design natural gas hydrate experimental model



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ABSTRACT

Experimental simulation is an important approach to study the gas hydrate dissociation mechanism, and similarity theory is an effective tool for the design of experimental model. Based on hydrate kinetic reaction model in HydrateResSim, seventy-three similarity numbers are derived by means of inspectional analysis and dimensionless analysis. Gas production from the natural gas hydrate reservoir is controlled by two mechanisms, namely dissociation-controlled mechanism and flow-controlled mechanism. Two groups of schemes are put forward for the design of experimental model of natural gas hydrate according to these two mechanisms respectively: for flow-controlled hydrate reservoir the scale of injection rate of heat and water, and parameters associated with size is the same with that of length, the scale of time is the square of length scale; for dissociation-controlled hydrate reservoir, the scale of parameters associated with size is the same with that of length, the scale of absolute permeability is 4/3 times square of length scale, the scale of time is 2/3 times square of length scale, the scale of injection rate of heat and water is 7/3 times square of length scale.

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1. Introduction

Gas hydrate is formed with gas molecules and water molecules under the condition of low temperature and high pressure. There are abundant gas hydrate resources in the seafloor and permafrost zone and it is estimated (Burshears et al., 1986) that the resources of natural gas hydrate all over the world are two times more than that of fossil fuels. As a new source of energy with adequate resources and wide distribution, natural gas hydrate not only has high combustion value, but also is very environment-friendly. Nowadays, commercial exploitation of natural gas hydrate has gradually become of primary interest.

In the past decades, researches on gas hydrate have made great progress and lots of experimental models have been made at home and abroad. For example, Yousif and Sloan (1991) designed a consolidated sandstone experiment system to study hydrate formation/dissociation in Berea sandstone cores; Buffett and Zatsepina (2000) designed an experimental device to simulate hydrate formation in natural porous media; researchers in USGS (Booth et al., 1999), NETL (Charles E. Taylor., 2004), China University

of Petroleum (Donghai and Jian, 1997), and so on, also designed their own experimental devices.

Quantities of laboratory experiments have been carried out to study gas hydrate dissociation (Yousif et al., 1991; Moridis, 2002; Bai and Li, 2010a, 2010b; Kono et al., 2002; Yuhu et al., 2008), but they are not based on the similarity theory, so that the conclusions could not be applied for the field directly. In this study, we would link the laboratory experiment with the field exploitation by means of similarity theory (Ishii and Kataoka, 1983; Ishii and Jones, 1977).

2. Mathematical models of hydrate exploitation

At present, the most comprehensive model for gas hydrate exploitation is the Tough + Hydrate (Moridis et al., 2008) model, which considers four phases and nine components. It is thought that the Tough + Hydrate model is too complicated to use, therefore, we base our work on HydrateResSim (Moridis et al., 2005), which assumes that the gas hydrate system is formed with four phases (water, gas, hydrate and ice) and four components (hydrate, water, gas and inhibitor).

Two kinds of models are proposed to simulate the gas hydrate dissociation, namely equilibrium model and kinetic model (Kowalsky and Moridis, 2007). The equilibrium model assumes that

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hydrate dissociation is an instantaneous process, that is to say the hydrate dissociation rate is limitlessly fast when the hydrate equilibrium condition is met. While for kinetic model, the hydrate dissociation rate is limited by dissociation kinetics. According to Kowalsky and Moridis (2007) and Liang-Guang et al. (2007), kinetic model is more accurate, and especially for hydrate dissociation in laboratory dissociation, kinetics can not be neglected. Therefore, we deduce the similarity numbers with the kinetic model.

The relationship between phase and components (β denotes phase, k denotes component) in HydrateResSim is shown in Table 1.

2.1. Mass and energy conservation equation

Water component:

$$\frac{d}{dt} (\phi S_A \rho_A x_A^w + \phi S_G \rho_G x_G^w + \phi S_I \rho_I) = \nabla \cdot \left[k \frac{k_{rA} \rho_A}{\mu_A} x_A^w (\nabla P_A - \rho_A g) + k \left(1 + \frac{b}{P_G} \right) \frac{k_{rG} \rho_G}{\mu_G} x_G^w (\nabla P_G - \rho_G g) \right] + q_A x_A^w \delta(x - x_p) \delta(y - y_p) + q_G x_G^w \delta(x - x_p) \delta(y - y_p) + \frac{q_I \rho_A}{LWH} \delta(x - x_I) \delta(y - y_I) + \frac{NW^w}{W^h} \dot{m}_H \quad (2.1)$$

Methane component:

It is assumed that methane is the only gas that forms the gas hydrate.

$$\frac{d}{dt} (\phi S_H \rho_H) = -\dot{m}_H \quad (2.4)$$

Energy conservation equation:

$$\frac{d}{dt} (\phi S_A \rho_A x_A^m + \phi S_G \rho_G x_G^m) = \nabla \cdot \left[k \frac{k_{rA} \rho_A}{\mu_A} x_A^m (\nabla P_A - \rho_A g) + k \left(1 + \frac{b}{P_G} \right) \frac{k_{rG} \rho_G}{\mu_G} x_G^m (\nabla P_G - \rho_G g) \right] + q_A x_A^m \delta(x - x_p) \delta(y - y_p) + q_G x_G^m \delta(x - x_p) \delta(y - y_p) + \frac{W^m}{W^h} \dot{m}_H \quad (2.2)$$

Inhibitor component:

The effect of heat conduction and heat convection is considered, and also heat transfer caused by vaporization and dissolution, hydrate and ice dissociation.

$$\begin{aligned} & \frac{d}{dt} \left\{ \left(1 - \phi \right) \rho_R C_R T + \phi S_A \rho_A \left[x_A^w u^w + x_A^m \left(u^m + u_{sol}^m \right) + x_A^i u_{sol}^i \right] + \phi S_G \rho_G \left(x_G^w u_G^w + x_G^m u_G^m + U_{dep} \right) + \phi S_I \rho_I u_I + \phi S_H \rho_H u_H + \phi \Delta S_I \rho_I \Delta H^f \right\} \\ & = \nabla \cdot \left\{ \left[\left(1 - \phi \right) K_R + \phi S_H K_H + \phi S_I K_I + \phi S_A K_A + \phi S_G K_G \right] \nabla T \right\} + \nabla \cdot \left\{ k \left(1 + \frac{b}{P_G} \right) \frac{k_{rG} \rho_G}{\mu_G} \left(\nabla P_G - \rho_G g \right) \left(x_G^w h_G^w + x_G^m h_G^m + H_{dep} \right) \right. \\ & \quad + k \frac{k_{rA} \rho_A}{\mu_A} \left(\nabla P_A - \rho_A g \right) \left[x_A^w h^w + x_A^m \left(H^m + H_{sol}^m \right) + x_A^i H_{sol}^i \right] \left. \right\} + \frac{q_I \rho_A h^w}{LWH} \delta(x - x_I) \delta(y - y_I) + \frac{q_d}{LHW} + \left\{ q_G \left(x_G^w \cdot h_G^w + x_G^m \cdot h_G^m \right. \right. \\ & \quad \left. \left. + H_{dep} \right) + q_A \left[x_A^w \cdot h^w + x_A^m \cdot \left(H^m + H_{sol}^m \right) + x_A^i \cdot H_{sol}^i \right] \right\} \cdot \delta(x - x_p) \delta(y - y_p) + \dot{m}_H \Delta H^o \end{aligned} \quad (2.5)$$

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