The sensitivity analysis of scaling criteria in gas hydrate reservoir physical simulation

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ABSTRACT

A numerical approach of sensitivity analysis of dimensionless parameters in gas hydrate reservoir physical simulation is proposed by analyzing the sensitivity factor defined as the relative variation ration of a target function with respect to the relative variation of dimensionless parameter. With this approach, the dominance degree of all the dimensionless parameters can be quantitatively evaluated and the dominant ones can be singled out conveniently. Taking a 1-D experiment of gas production from hydrate reservoir by depressurization as an example, we find that the order of sensitivity factors ranges from 10^{-5} to 10^0. The most dominant dimensionless parameter is the dimensionless initial temperature of hydrate reservoir and the dimensionless phase equilibrium pressure of gas hydrate, which just reflects that the consumed energy for hydrate dissociation comes from the energy contained in formation and the driving force for hydrate dissociation is very important in hydrate dissociation by depressurization.

1. Introduction

Gas hydrate is regarded as a kind of future energy due to its tremendous reserve [1] and widespread deposition [2]. With the continuous researching development on gas hydrate, the commercial production of gas hydrate is probably becoming a reality. Some theoretical and experimental works were carried out on how to exploit nature gas from hydrate reservoir by the safe, commercial and efficient methods. A lot of laboratory experiments have been carried out to study gas hydrate dissociation [3–8]. However few literatures have reported experiment based on the principle of similarity. The reasons may be that the hydrate dissociation process involves some complex mechanism which now cannot be clearly explained. Therefore, most experiments intended to reveal those kinds of unknown mechanisms. On the other hand, few institutes can obtain the nature samples of gas hydrate. Moreover, the measurement values for the same parameter may be with the difference of several orders which implies the lack of common view. Physical simulation obeying the principle of similarity is an important approach to reveal mechanism of gas hydrate dissociation which is helpful for filed design and optimization of development programs. Compared with field tests, physical simulation seems to be cheaper, time-saving and easier to implement.

There are so many dimensionless parameters in physical simulation of hydrate reservoir exploitation because gas hydrate dissociation associates with such complicated factors as multiphase fluid flow in porous media, kinetic and endothermic process of hydrate dissociation, heat convection and conduction. According to the similarity of principle [9], each field prototype should theoretically exist a fully similar model which satisfies all the dimensionless parameters. However, it is very difficult or sometimes even impossible to keep all the dimensionless parameters identical in the laboratory experiment. To tackle this kind of problems, an efficient and practical way out is to single out the dominant parameters and to relax the secondary ones in laboratory experiments. Theoretical and experimental arranging all the dimensionless parameters in the orders of importance is not easy or even impossible to realize. In our work, a set of scaling criteria of gas production from hydrate reservoir by depressurization is firstly derived from the mathematical models. Then a numerical approach of sensitivity analysis of dimensionless parameters is proposed based on the scaling criteria of gas hydrates exploitation. With this approach, the dominance degree of the dimensionless parameters can be quantitatively evaluated and the dominant ones can be singled out conveniently.

2. Sensitivity analysis of dimensionless parameters

It is not realistic for us to estimate the role of each dimensionless parameter on experimental results by physical simulation,

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because too many dimensionless parameters are involved in gas hydrates exploitation experiment. Therefore, we propose a numerical approach to evaluate the effect of each dimensionless parameter on a target function. The sensitivity factor of a given dimensionless parameter π_i is firstly defined as follows

$$S_i = \frac{\partial(f/f_p)}{\partial(\pi_i/\pi_{ip})} \quad (1)$$

It denotes the relative variation ratio of a target function with respect to that of the dimensionless parameter π_i. Here π_{ip} is the theoretical value of the given dimensionless parameter; f is the target function of the physical model of gas hydrate reservoir which is defined as the function of all the dimensionless parameters and the dimensionless time T_D. The detail expression can be written as follows

$$f = \int_0^T R(\pi_1, \pi_2, \ldots, \pi_i, \ldots, \pi_n, T_D)dT_D \quad (2)$$

in which $R(\pi_1, \pi_2, \ldots, \pi_i, \ldots, \pi_n, T_D)$ is the dissociation ratio of gas hydrate defined as the ratio of dissociated gas hydrate to all hydrate bearing in formation. So the f means the surrounding area of the axis of the dimensionless time and the dissociation ratio of gas hydrate as the dashed line shown in Fig. 1.

f_p is the target function of the hydrate reservoir prototype and can be defined as

$$f_p = \int_0^T R(\pi_1, \pi_2, \ldots, \pi_{ip}, \ldots, \pi_n, T_D)dT_D \quad (3)$$

in which subscript p denotes the gas hydrate reservoir prototype. So the f_p denotes the surrounding area of the axis of the dimensionless time and the dissociation ratio of gas hydrate as the solid line shown in Fig. 1. In numerical scheme, the sensitivity factor can be written as in the following form

$$S_i = \frac{\Delta f_i/f_p}{|w_i|} \quad (4)$$

in which

$$w_i = \frac{\pi_i - \pi_{ip}}{\pi_{ip}} \quad (5)$$

representing for the relative distortion of the ith dimensionless parameter.
$\Delta f_i = \int_0^T |R_i(\pi_1, \pi_2, \ldots, \pi_i, \ldots, \pi_n, T_D) - R_p(\pi_1, \pi_2, \ldots, \pi_n, T_D)|dt$ means the difference of dissociation ratio of gas hydrate between
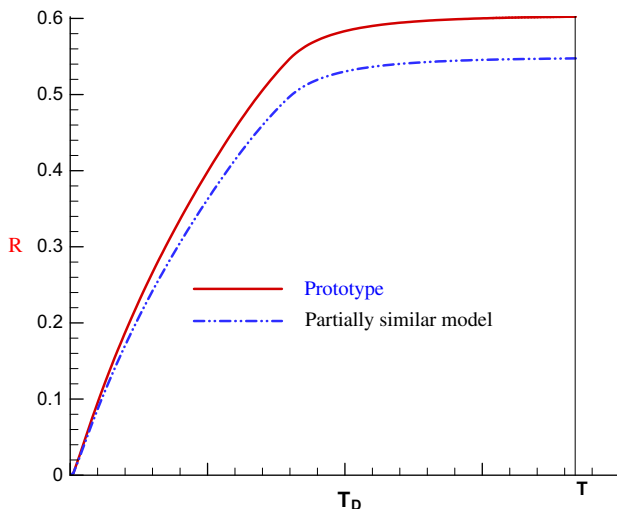

Fig. 1. The comparison of dissociation ratio of gas hydrate dissociation of a prototype with a partially similar model, in which the ith dimensionless parameter is given a small deviation from the prototype.

partially similar physical model that the ith dimensionless parameter is relaxed and prototype.

3. Mathematical model

Let us consider one-dimensional hydrate-bearing porous medium of length L. The production well is located at $x = 0$, where the bottom pressure is fixed below the phase equilibrium pressure of gas hydrate. To reasonable simplify the physical problem some assumptions are introduced as follows: (1) gas hydrate in our assumed reservoir is methane hydrate; (2) water phase contains only water, gas phase contains only methane; (3) Darcy's law is valid for water and gas phases; and (4) the diffusion and the dispersion are neglected in mass transportation. With these concerned, the transport equations governing hydrate dissociation and the flow of gas and water in the porous media are

$$\frac{\partial}{\partial x}\left(\frac{\rho_g k_g}{\mu_g}\frac{\partial p_g}{\partial x}\right) + \dot{m}_g = \frac{\partial(\phi \rho_g s_g)}{\partial t} \quad (6)$$

$$\frac{\partial}{\partial x}\left(\frac{\rho_w k_w}{\mu_w}\frac{\partial p_w}{\partial x}\right) + \dot{m}_w = \frac{\partial(\phi \rho_w s_w)}{\partial t} \quad (7)$$

$$-\dot{m}_h = \frac{\partial(\phi \rho_h s_h)}{\partial t} \quad (8)$$

The energy conservative equation is written as

$$\frac{\partial}{\partial t}(C_t T) = \frac{\partial}{\partial x}\left[\left(\rho_w C_w \frac{k_w}{\mu_w}\frac{\partial p_w}{\partial x} + \rho_g C_{pg}\frac{k_g}{\mu_g}\frac{\partial p_g}{\partial x}\right)T\right]$$
$$+ \frac{\partial}{\partial x}\left(K_t\frac{\partial T}{\partial x}\right) - \dot{m}_h \Delta H \quad (9)$$

in which

$$C_t = \phi(\rho_w s_w C_w + \rho_g s_g C_{Vg} + \rho_h s_h C_h) + \rho_r C_r(1-\phi)$$
$$K_t = \phi s_w K_w + \phi s_g K_g + \phi s_h K_h + (1-\phi)K_r$$

The relationship of saturations satisfy

$$s_w + s_g + s_h = 1 \quad (10)$$

The water and gas pressures are related by the following expression

$$p_c = p_w - p_g \quad (11)$$

The water and formation state equations are as follows when considering the slight compressibility.

$$\rho_w = \rho_{w0}(1 + c_w(p_w - p_{w0})) \quad (12)$$

$$\phi = \phi_0\left(1 + c_\phi\left(\frac{p_w + p_g}{2} - \frac{p_{w0} + p_{g0}}{2}\right)\right) \quad (13)$$

With the boundary conditions

$$x = 0, \quad p = p_{gp}, \quad T = T_{gp}$$
$$x = L, \quad \frac{\partial p_g}{\partial x} = 0, \quad \frac{\partial T}{\partial x} = 0 \quad (14)$$

and the initial conditions

$$p(x,0) = p_i, \quad s_h(x,0) = s_{hi}, \quad s_{wi}(x,0) = s_{wi}, \quad T(x,0) = T_i \quad (15)$$

the governing equations are closed.

Here ρ_g, ρ_w and ρ_h are gas, water and hydrate densities, respectively; ϕ the porosity; s_g, s_w and s_h the saturations of gas, water and hydrate phases, respectively; p_w and p_g the water and gas pressures, respectively; k_g and k_w the gas and water phase permeabilities, respectively; $\dot{m}_h$, $\dot{m}_g$ and $\dot{m}_w$ the mass rates of gas hydrate dissociation, gas and water production per unit formation volume, respectively; C_w, C_h, C_r, C_{Vg} and C_{pg} the specific heats of water, hydrate, rock, the constant volume and pressure specific heats,