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NUMERICAL SIMULATION STUDY OF THE INFLUNCE OF ICE ON GAS PRODUCTION FROM HYDRATE DISSOCIATION IN POROUS MEDIA

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ABSTRACT

A 3D model was established to study the influence of ice formation on the process of gas production during gas hydrate dissociation by depressurization. Considering effects of ice, the temperature field and absolute permeability of the reservoir were analyzed. Additionally, the cumulative gas production was compared with and without ice formation. The results indicated that the temperature change is a process of repeated fluctuations because ice affected the heat transfer in the reservoir. Meanwhile ice formation can reduce the absolute permeability near the production boundary significantly. And then, the permeability can recover from the boundary because of the constant temperature boundary. Moreover, compared to the condition without ice effects, the cumulative gas production with ice formation is more in the initial stage, and then it will become much less. And the gas production rate fluctuates with freezing and melting.

Keywords: hydrate dissociation, ice effects, temperature, permeability, gas production

1. INTRODUCTION

Natural gas hydrate is a great potential energy resource, which is mainly found in permafrost regions and ocean sediments [1]. Although the hydrates exploitation method is developing for effective commercial production, it basically reaches a consensus that depressurization is one of the least energy intensive and most promising gas production method until now [2]. And this method has been used and validated in some production tests in the field [3]. For hydrates exploitation, in recent decades, the mechanisms that hydrate dissociation in porous media were studied in depth [4, 5]. However, the process of gas production from hydrates with ice formation is still poorly understood. On the one hand, ice film generated decreases the hydrate dissociation specific surface area and increases mass transfer resistant [6]. On the other hand, in some experiment, there was no evidence that ice film formed around individual hydrate grains [7]. And the latent heat released by ice formation can strongly enhance the hydrate dissociation rate [8]. In this research, besides the ice influence on the hydrates dissociation, as a solid phase, the ice can affect the permeability of porous media.

The coupling of heat and mass conservation equations, kinetic model and geomechanical model has been used in macroscopic simulation. However, the influence of ice phase were overlooked in most the simulators. This research set a 3D program, which considered four phases (hydrate, water, gas and ice), to study the influence of ice on the change of temperature field, permeability of reservoir and gas production.

2. MODEL

2.1 Control equation

In this research, a 3D model was established to describe the process of gas production from hydrate dissociation by depressurization in porous media. The control equations are mainly composed of mass and energy conservation, fluid flow equation in porous media and kinetic model of hydrate dissociation. The total mass conservation equation is shown below.

$$-\nabla(\rho_w \vec{v}_w) - \nabla(\rho_g \vec{v}_g) + \dot{m}_w + \dot{m}_g + \dot{m}_i - \dot{m}_h = \frac{\partial}{\partial t}\left(\phi S_w \rho_w + \phi S_g \rho_g + \phi S_i \rho_i + \phi S_h \rho_h\right) \quad (1)$$

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where ρ_k $(k = w, g)$ is the density of water and gas, which is calculated by Dranchuk-Purvis-Robinson method. $\vec{v}_k$ $(k = w, g)$ is the velocity of water and gas. $\dot{m}_k$ $(k = w, g, i, h)$ is the reaction quality of each phase per unit volume per second. ϕ is the porosity of reservoir. t is the time. And S_k $(k = w, g, i, h)$ is the saturation of each phase.

Here, the heat transfer process contains not only the heat absorbed by hydrate dissociation but also the latent heat released by ice formation. So the energy conservation equation is given as follows.

$$\nabla\left\{\left[(1-\phi)\lambda_s + \phi S_w \lambda_w + \phi S_g \lambda_g + \phi S_i \lambda_i + \phi S_h \lambda_h\right]\nabla T\right\} - \nabla\left(\rho_w c_w v_w T\right) - \nabla\left(\rho_g c_g v_g T\right) - \dot{m}_h \Delta H_h + \dot{m}_i \Delta H_i = \frac{\partial}{\partial t}\left\{\left[(1-\phi)\rho_s c_s + \phi S_w \rho_w c_w + \phi S_g \rho_g c_g + \phi S_i \rho_i c_i + \phi S_h \rho_h c_h\right]T\right\} \quad (2)$$

where λ_k $(k = s, w, g, i, h)$ is the heat conductivity coefficient of skeleton and each phase. T is the temperature. c_k $(k = s, w, g, i, h)$ is the specific heat capacity of skeleton and each phase. ΔH_h is the heat absorption per unit mass of hydrate dissociation and ΔH_i is the latent heat per unit mass released by ice formation.

$\dot{m}_k$ $(k = w, g, h)$ can be calculated based on the kinetic model published by Kim et al.[9]. It can be described as follows.

$$\dot{m}_g = k_0 \exp\left(-\Delta E / RT\right) A_s \left(P - P_e\right) \quad (3)$$

where k_0 the kinetic constant, here it is 3.6×10^4 mol/m^{2}Pa s. ΔE is the activation energy (81084.19722 J/mol) [9]. R is the universal gas constant. A_s is the hydrate dissociation specific surface area. P is the actual pressure and P_e is the balance pressure based on the methane hydrate phase equilibrium equation [10].

2.2 Influence of ice

According to our previous research [11], ice formation would affect the hydrate dissociation rate through changing the dissociation specific surface area. It assumes that ice generated adheres to the surface of the hydrate. The dissociation surface covered by the ice is related to the ice saturation and the thickness of ice. Therefore, the hydrate specific surface area with ice formation can be described as follows.

$$A_s = \sqrt{\frac{\left[\phi\left(1-S_h\right)\right]^3}{2K}} - \phi S_i \left[\frac{2\lambda_i \int_0^t \left(T_i - T\right)dt}{\rho_i \Delta H_i}\right]^{-0.5} \quad (4)$$

where K is the absolute permeability of reservoir. T_i is the freezing temperature and T is the actual temperature.

Moreover, as solid phase, ice can block some flow channel and change the permeability in the porous media. The absolute permeability of reservoir with ice can be written as [12]:

$$K = K_0\left(1 - S_h - S_i\right)^N \quad (5)$$

where K_0 is the initial absolute permeability of reservoir, and N is the permeability decline index.

Using the model above, we set a $8\times8\times8$ m cube as the computational domain, in which the initial saturation of water, gas, hydrate and ice is 0.2, 0.3, 0.5 and 0 respectively. The initial pressure and temperature is 2.84 MPa and 275.45 K respectively. And the production pressure is 0.8 Mpa. Thus, the temperature in reservoir could reduce below 273.15 K during hydrate dissociation and gas production.

3. RESULTS

3.1 Temperature field

A constant temperature for each boundary was set in this model. The boundary temperature equaled to the initial reservoir temperature (275.45K). There was one face with a low boundary pressure (0.8MPa) for gas production. As shown in Fig 1, because of the low production pressure, at the beginning (10min) the hydrates near the low pressure boundary have dissociated and absorbed heat. When the process reached to 30min, the temperature near production boundary was below freezing point. Whereas, the temperature near the opposite boundary was higher than before. This was because that the ice formation near the production boundary impeded the flow of fluid to some extent and reduces the heat transfer in the reservoir. So, the temperature near the underside increased due to the constant boundary temperature. The ice also reduced the hydrate dissociation rate, so the absorbed heat decreased and the boundary temperature caused the temperature near the production boundary increasing again. Thus, ice started to melt and the heat transfer intensity recovers. It led to the temperature near the underside decreasing as shown in the temperature field at 600min. As time goes on, the temperature near the top decreased again due to hydrates dissociation. However, the decreasing of

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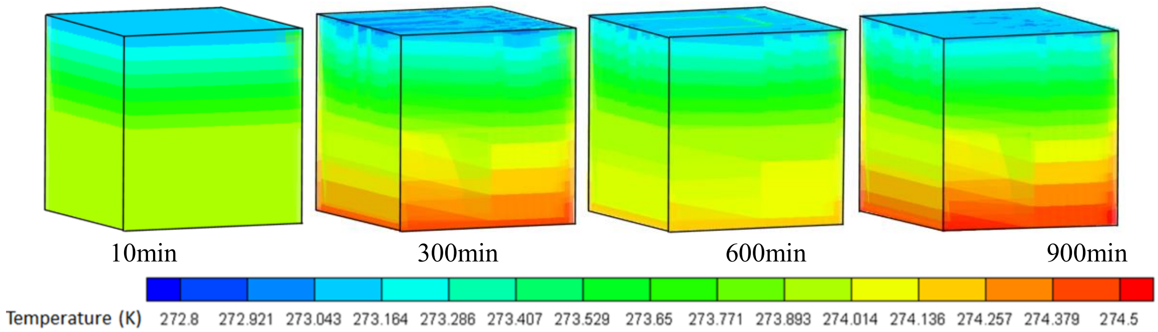

Fig 1 The temperature field change over time

hydrate saturation made the dissociation rate decrease and the heat consumption becomes less. Therefore, the average temperature in the reservoir was higher at 900min as the last one in the Fig 1. Above all, under the combined action of boundary temperature, hydrates dissociation and ice formation, the temperature field change was a process of repeated fluctuations.

3.2 Absolute permeability change

In this model, the absolute permeability of the reservoir was related to hydrate and ice saturation. So the absolute permeability change also can show the change of hydrate and ice distribution. Fig 2 shows the absolute permeability change over time. At 300min, because the ice forms near the production boundary, where the solid phase saturation rises greatly and the permeability decreased sharply. Therefore, the gas production rate would drop at this time because of the

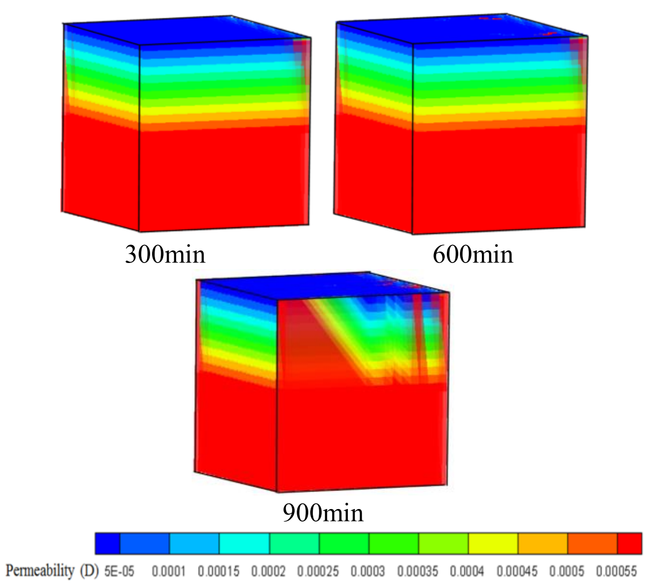

Fig 2 The absolute permeability change over time

higher flow resistance. As the analysis in 3.1, at 600min there was some ice melting. Additionally, more hydrates dissociated especially at the location near the boundary. So the permeability started to increase at the top boundary as shown in red points at the top of the second cube in Fig 2. Then, under the influence of constant boundary temperature, the absolute permeability recovered from boundary to inside. However, this process was slow, when the time went to 900min, only at some parts of boundary, the permeability rose. Moreover, in Fig 2, there was about half volume of the reservoir without permeability change. It indicated that hydrates in these regions almost cannot dissociate.

3.3 Gas production

As our previous study [11], the final total gas production strongly depended on the initial hydrate saturation. However, the gas production rate was affected by the hydrate dissociation rate and fluid flow capacity. So, the influence of ice formation cannot be ignored. Fig 3 shows a comparison of the cumulative gas production with and without ice formation. It shows that cumulative gas production grew smoothly over time. The slope of the curve of cumulative gas production means the gas production rate. When the ice effects were not considered, the gas production rate decreased with the hydrate saturation decreasing. If the ice effects were considered in the model, as the red curve shown in Fig 3, the change of gas production became complicated. In initial stage, the gas production with ice was more than that without ice because the latent heat released from ice formation enhanced the hydrate dissociation rate. And then, because the hydrate dissociation surface covered by ice increased and the permeability decreased due to the blockage of ice, the gas production rate dropped and the cumulative gas production was much less than that without ice effects. Specifically, as shown in Fig 4, in stage ① the ice formation promoted hydrate dissociation and enhances gas production. When there was enough ice formation to block the fluid channel and prevented hydrate dissociation from surface, the gas production rate dropped to very low as stage ②.

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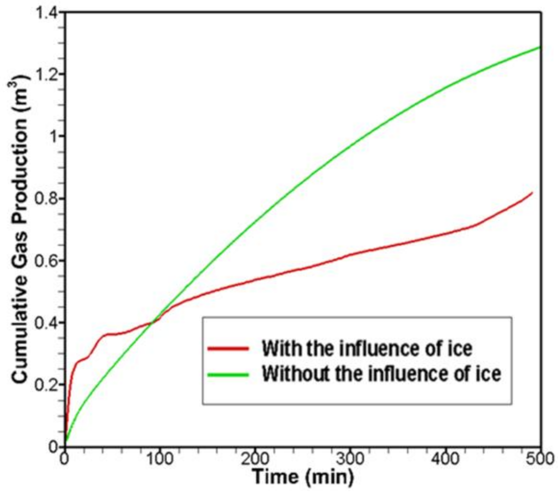

Fig 3 Comparison of the cumulative gas production over time with and without ice effects

During stage ③, some ice melted because of the constant temperature boundary. Thus, hydrate dissociation rate increased and more heat was absorbed. Therefore, similar to stage ①, ice formed again and the hydrate dissociation rate was further improved in stage ④. Finally, enough ice covered the hydrate and blocked the fluid channel again in stage ⑤. This process was similar to a cycle. Moreover, the trend of fluctuation gradually moderated. It indicated that the melting and crystallization of ice was more intense in the initial stages.

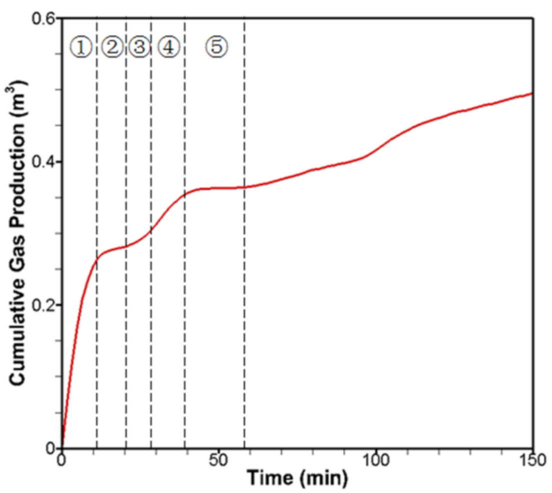

Fig 4 The different stages of ice effects

3.4 Conclusions

The influence of ice on temperature field, absolute permeability and gas production during gas hydrate dissociation in porous media was studied by a 3D model. Because of the ice formation, temperature field change is a process of repeated fluctuations. As a solid phase, ice formation reduces the absolute permeability significantly. And due to the constant temperature boundary, the ice would melt and the permeability can recover gradually. Moreover, the ice formation makes the gas production rate drop even though it can enhance gas production in initial stage. And the gas production rate fluctuates with ice melting and crystallization.

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