Study on hydrate decomposition under microwave heating

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Abstract. The decomposition of hydrates is a complex process involving three phases (gas phase, water phase, solid phase) and components (gas, water, hydrate). It is based on the numerical simulation of mass conservation and energy conservation equations for natural gas hydrates. The simulation results indicate that microwaves can effectively transfer energy from the feed, thus significantly improving the heating effect in the near-well area.

Keywords: Hydrate decomposition; Microwave heating; Numerical simulation.

1. Numerical simulation of hydrate heating by microwave

Hydrate decomposition is a decomposition process involving three phases (gas phase, water phase, solid phase) and components (gas, water, hydrate). Mass conservation equations and energy conservation equations are used in numerical simulations. In the process of hydrate decomposition, there is a complex heat and mass transfer process, so the research model is completed on the basis of uniform reservoir distribution, gas-liquid two-phase flow in accordance with the law, without considering the dissolution of gas in water, and only methane gas in the hydrate[1,2,3].

1.1. Energy conservation equation of hydrate decomposition[4]

In the one-dimensional case, a small unit is taken in the formation, and according to the conservation relationship of physical energy of the unit (incoming heat - outgoing heat + injected heat - reaction heat = heat increment), the change of heat in the unit includes four parts: heat convection, heat conduction, internal heat source and reaction heat. The energy exchange between the cell and the surrounding environment is carried out through heat convection and heat conduction[5].

In Δt time: The heat flowing into the unit body is: $\left(Au_{ex}\right)_x \Delta t + \left(A\rho_l H_l u_x\right)_x \Delta t$

The heat that flows out of the cell is: $\left(Au_{ex}\right)_{x+\Delta t} \Delta t + \left(A\rho_l H_l u_x\right)_{x+\Delta t} \Delta t$

The heat produced by the heat source is: $E\Delta t$

The heat absorbed by hydrate decomposition is: $E_H \Delta t$

The heat increment of the unit is:

$$\bar{A}\Delta x\left[\phi\rho_{l+H}H_{l+H} + (1-\phi)\rho_R H_R\right]_{t+\Delta t} - \bar{A}\Delta x\left[\phi\rho_{l+H}H_{l+H} + (1-\phi)\rho_R H_R\right]_t$$

The energy conservation expression is:

$$\begin{aligned}&\left(Au_{ex}\right)_x \Delta t + \left(A\rho_l H_l u_x\right)_x \Delta t - \left(Au_{ex}\right)_{x+\Delta x} \Delta t - \left(A\rho_l H_l u_x\right)_{x+\Delta} + E\Delta t - E_H \Delta \\ &= \bar{A}\Delta x\left[\phi\rho_{l+H}H_{l+H} + (1-\phi)\rho_R H_R\right]_{t+\Delta t} - \bar{A}\Delta x\left[\phi\rho_{l+H}H_{l+H} + (1-\phi)\rho_R H_R\right]_t\end{aligned} \tag{1}$$

In the formula, H_l 、 H_R is *l* phase fluid, rock enthalpy, J ; ρ_R is the density of rock, hydrate, gas and water, g/cm^3 ; E is the heat produced by the heat source per unit time, J/s.

1.2. Mass conservation equation of hydrate decomposition

The mass conservation equations (1-2) to (1-4) describe the mass migration of gas, water and hydrate in hydrate decomposition[6]:

$$-\frac{1}{r}\frac{\partial}{\partial r}(r\rho_g \upsilon_{gr}) - \frac{\partial}{\partial x}(\rho_g \upsilon_{gx}) + q_g + m_g = \frac{\partial}{\partial t}(\phi\rho_g S_g) \tag{2}$$

$$-\frac{1}{r}\frac{\partial}{\partial r}(r\rho_w\upsilon_{wr})-\frac{\partial}{\partial x}(\rho_w\upsilon_{wx})+q_w+m_w=\frac{\partial}{\partial t}(\phi\rho_w S_w) \quad (3)$$

$$\dot{m}_h=\frac{\partial}{\partial t}(\phi\rho_h S_h) \quad (4)$$

In the formula, r is the radial distance; ρg, ρw, ρh are the densities of gas, water and hydrate; νgr, νgx are the radial and axial velocities of gas; Sg, Sw, Sh are gas, water, hydrate saturation; ∅ is the porosity of the reservoir. mh is the mass change of hydrate[7].

2. Establishment and analysis of the basic model of hydrate heating by microwave

2.1. Software simulation setup

Operating conditions include 2.45GHz frequency, 283.15K temperature, and 100atm pressure with a power input of 1kW through six feedports. The feeder arrangement consists of two layers, each layer distributing three feeders at a 120-degree angle. In the development of a hydrate vertical well, the microwave heating system is constructed with several heating joints measuring 400×400×800mm in size, an outer cylinder diameter of 190mm, and a height of 800mm. Therefore, this study focuses on simulating the heating joints to investigate the impact of reservoir temperature and feed length on the heating effect.

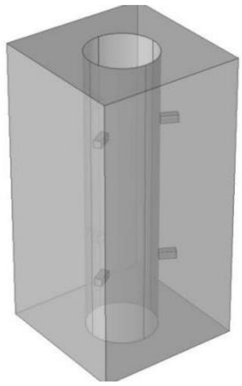


Figure 1 The heating nipple model was fabricated.

The initial parameters in this article are established as follows: $T=T_0$; $S_h=S_{H0}$; $S_W=S_{W0}$; $S_G=S_{g0}(0\le r\le R,\ 0\le x\le L)$

The initial boundary conditions are set as follows: $P=P_0(x=0)$; $\partial P/\partial x=0(x=0)$; $\partial P/\partial r=0(r=0,R_0)$; $\partial T/\partial r=0(r=0)$; $\partial T/\partial x=0(x=0,L)$.

2.2. The factor analysis of the model's influence

Table 1 physical parameters of hydrate simulation

Molecular weight (kg·mol^{-1})	0.119	Permeability (mD)	300
Molar density(kg·m^{-3})	919.7	Temperature (℃)	5
Molar volume (m^{3}·mol^{-1})	7696	Porosity (%)	30
Reaction enthalpy (dimensionless)	1.071×10^{13}	Pressure (MPa)	8
Reaction frequency factor (J·mol^{-1})	81084.2	Water saturation	0.5
Specific heat (J·g^{-1}·℃$^{-1}$)	51858	Hydrate saturation	0.5

(1) reservoir temperature field[8]

Fig 2 to Fig 7 show the temperature profile of the microwave heating system at 600, 1800 and 3600s when the inlet and the reservoir center are in the preset working conditions. As can be seen from the figure, the center of the wellbore was not affected by the microwave for a short time, and the temperature did not increase significantly. However, during the longer heating process, the temperature gradually rises due to the influence of heat conduction. After one hour of heating, the maximum temperature near the well wall reached 294K, while the temperature around the feed port exceeded 310K.

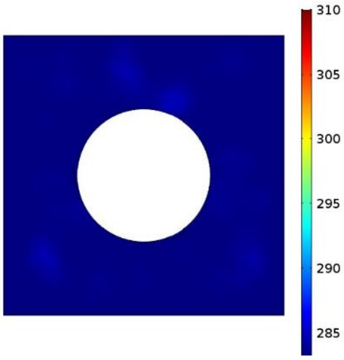


Figure 2 Tangent plane of temperature field during central of reservoir 600s

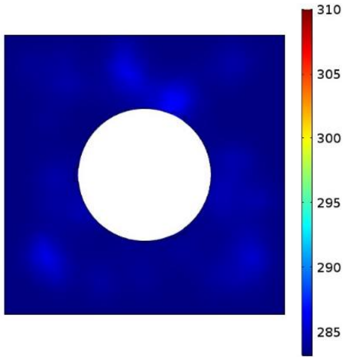


Figure 3 Tangent plane of temperature field during central of reservoir 1800s

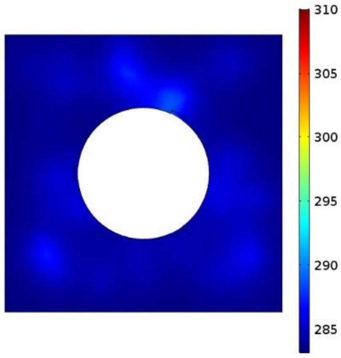


Figure 4 Tangent plane of temperature field in the center of reservoir 3600s

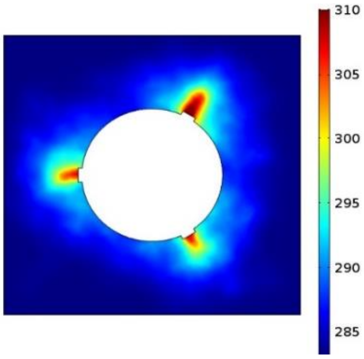


Figure 5 Tangent plane of the temperature field at the feed center 600s

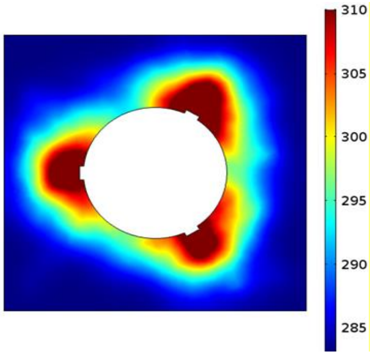


Figure 6 Tangent plane of the temperature field at the feed center 1800s

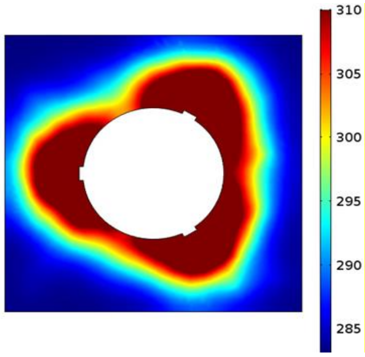
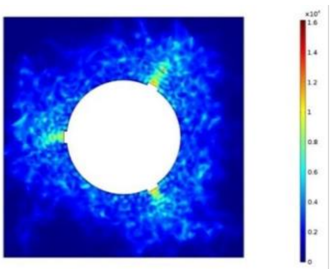


Figure 7 Tangent plane of the temperature field at the feed center 3600s

(2) Different feed length analysis

Fig 8 to Fig 10 show the electric field profile between the feed center and the reservoir center when the feed length is 10, 30, and 50mm, respectively. It can be observed from the figure that the electric field intensity around the feed is significantly higher than that in the center of the reservoir. This shows that the strong electromagnetic field generated by microwave has a significant heating effect on the near-well area near the feed. In the center of the reservoir, the electric field strength is weak and the heating effect is relatively weak.



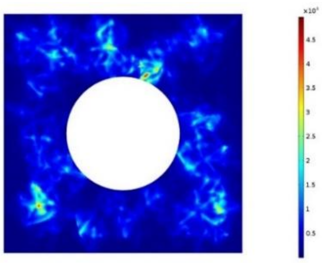


Figure 8 The length of the feeder is 10mm. The electric field die cutting plane at the center of the feeder and the center of the reservoir under working conditions

Figure 9 The length of the feeder is 30mm. The electric field die cutting plane at the center of the feeder and the center of the reservoir under working conditions

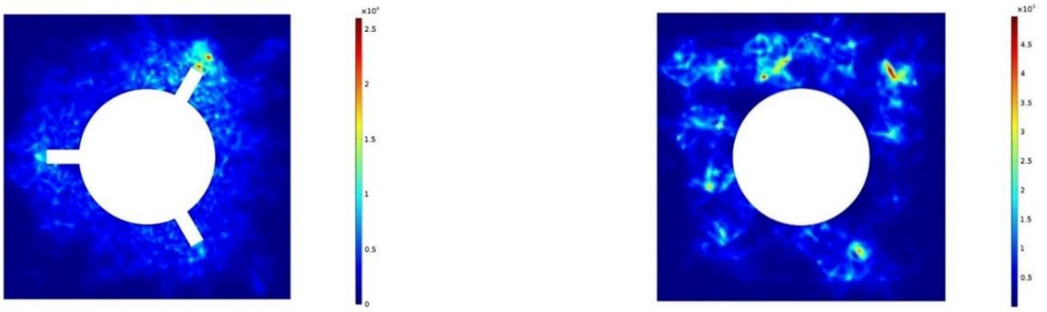


Figure 10 The length of the feeder is 50mm. The electric field die cutting plane at the center of the feeder and the center of the reservoir under working conditions

3. Summary

In this chapter, the mass and energy conservation equations for hydrate decomposition are comprehensively examined. The mathematical model of hydrate decomposition is established by considering the complexity of the process, including three phases (gas phase, water phase, solid phase) and three components (gas phase, water phase, hydrate), under idealized constraint conditions. The following conclusions are drawn:

(1) The mass conservation equation and energy conservation equation of hydrate are thoroughly analyzed, leading to the establishment of a mathematical model for hydrate decomposition. Furthermore, the basic analytical process for solving the model is provided, offering a solid theoretical basis for hydrate modeling and decomposing pressure.

(2) The constructed microwave heating hydrate model enables multi-field bidirectional direct coupling analysis. Under preset working conditions, the microwave heating system gradually heats up due to heat conduction influence during long-term reservoir center heating. After 1 hour, the highest temperature near the well wall reaches 294K, while temperatures around the feedways exceed 310K. This indicates that microwaves can transfer energy from the feeder to the near-well area, with the position closest to the feeder experiencing the largest temperature change rate. Additionally, microwaves generate a strong electromagnetic field at the feeder area, significantly impacting heating in the near-well area. A comparison between two feeders and three feeders in same layer suggests that designing an appropriate number of feeders should consider sweep and coverage range.

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