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Research on Natural Gas Hydrate Extraction Technology Based on Numerical Simulation

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ABSTRACT

A mathematical model is established based on the equation of conservation of mass, energy and momentum to study the spatial distribution law of reservoir properties such as permeability and water saturation. The effects of different pressure reduction amplitude, initial absolute permeability and water saturation on mining efficiency are analyzed to determine the parameter sensitivity. The simulation results show that the appropriate pressure drop amplitude and lower water saturation can help to improve the gas release efficiency. Meanwhile, the spatial distribution of reservoir physical properties is demonstrated by three-dimensional visualization technology, which provides an important reference for optimizing the extraction strategy. The results of natural gas hydrate extraction technology based on numerical simulation provide a scientific basis for the efficient extraction of natural gas hydrate and promote the development of related technology.

KEYWORDS

Natural Gas Hydrate; Numerical Modeling; Extraction Technology; Reservoir Physical Properties.

1. INTRODUCTION

Natural gas hydrate is a solid material formed by water and natural gas molecules under specific conditions, with high energy density and wide distribution potential. According to estimates, global reserves of natural gas hydrate resources may reach more than twice the amount of conventional natural gas resources, making natural gas an important candidate for future energy development[1] . Although natural gas hydrates are stable in a high-pressure, low-temperature environment, once conditions change, the hydrates rapidly decompose into water and gas, making the extraction process extremely unstable. Complex physical and chemical changes, such as phase transitions, seepage and diffusion, occur during the extraction process, making it difficult to achieve good extraction results without accurate modeling and prediction[2] .

Numerical simulation, as a powerful analytical tool, can predict and optimize the natural gas hydrate extraction process under different conditions. Through simulation, researchers can explore the effects of multiple extraction strategies and analyze the impact of different parameters on the extraction efficiency, thus providing a scientific basis for actual extraction. Especially when determining key parameters such as pressure drop, initial permeability and water saturation, numerical simulation can help identify the optimal extraction plan and enhance the efficiency of resource utilization. Therefore, based on numerical simulation technology, this paper discusses the extraction process of natural gas hydrate in depth.

2. MATHEMATICAL MODELING IN GAS HYDRATE EXTRACTION

The mathematical model is mainly based on the conservation equations of mass, energy and momentum, which provides a mathematical basis for natural gas hydrate extraction. Combined with the phase transition model, the flow, heat change and phase transition of gas in the extraction process can be effectively analyzed through numerical simulation. It lays an important theoretical foundation for further optimizing the extraction scheme and improving the resource utilization efficiency.

2.1. Mass conservation equations

The conservation of mass equation describes the conservation of matter in a system. In natural gas hydrate extraction, it is expressed by the following equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = S \tag{1}$$

where ρ is the density of the fluid, $\mathbf{v}$ is the velocity field, and S is a source term representing a possible mass gain or loss, e.g., gas production or consumption.

2.2. Equation of conservation of momentum

The conservation of momentum equation describes the motion of a fluid under an acting force. The conservation of momentum for gas hydrate extraction is expressed as:

$$\rho \frac{\partial \mathbf{v}}{\partial t} + \rho(\mathbf{v} \cdot \nabla)\mathbf{v} = -\nabla p + \mu \nabla^2 \mathbf{v} + \mathbf{f} \tag{2}$$

where p is the pressure, μ is the viscosity of the fluid, and $\mathbf{f}$ is the external force (e.g., gravity) term. The flow of the gas and its interaction with the hydrate is modeled through the conservation of momentum equation.

2.3. Energy Conservation Equation

The conservation of energy equation takes into account the change in heat during the mining process and is expressed in the following equation:

$$\frac{\partial}{\partial t}(\rho e) + \nabla \cdot (\rho e \mathbf{v}) = -\nabla \cdot \mathbf{q} + Q \tag{3}$$

where e is the internal energy per unit mass, $\mathbf{q}$ is the heat flow density, and Q is the heat source term. The change in heat due to phase change and fluid flow during the mining process is analyzed through the energy conservation equation.

2.4. Phase transition modeling

The phase transition of hydrates is a key process in mining. In this paper, a phase transition model is used to describe the kinetics of hydrate decomposition. The kinetic equations for the phase transition are as follows:

$$\frac{d\theta}{dt} = k\left(\theta_s - \theta\right) \tag{4}$$

where θ is the hydrate content, θ_s is the content at equilibrium, and k is the phase transition rate constant. The kinetic equations for the phase transition were used to predict the rate of hydrate decomposition under specific conditions.

2.5. Numerical Solution Methods

Numerical solution using finite element method or finite difference method to deal with complex boundary conditions and nonlinear problems, applicable to the simulation of hydrate mining under different geological conditions[3] .

3. SENSITIVITY ANALYSIS OF GAS HYDRATE EXTRACTION PARAMETERS

3.1. Different magnitudes of blood pressure reduction

In the extraction process of natural gas hydrate, pressure drop is a key factor to promote hydrate decomposition and gas release. Changes in buckling amplitude directly affect the extraction efficiency, so it is particularly important to conduct sensitivity analysis of buckling amplitude.

3.1.1. Impact of pressure drop on mining efficiency

The depressurization process changes the phase state of hydrates from solid to gas or liquid. The greater the depressurization, the sooner the hydrate begins to decompose and the sooner the permeability begins to increase, as shown in Figure 1 below:

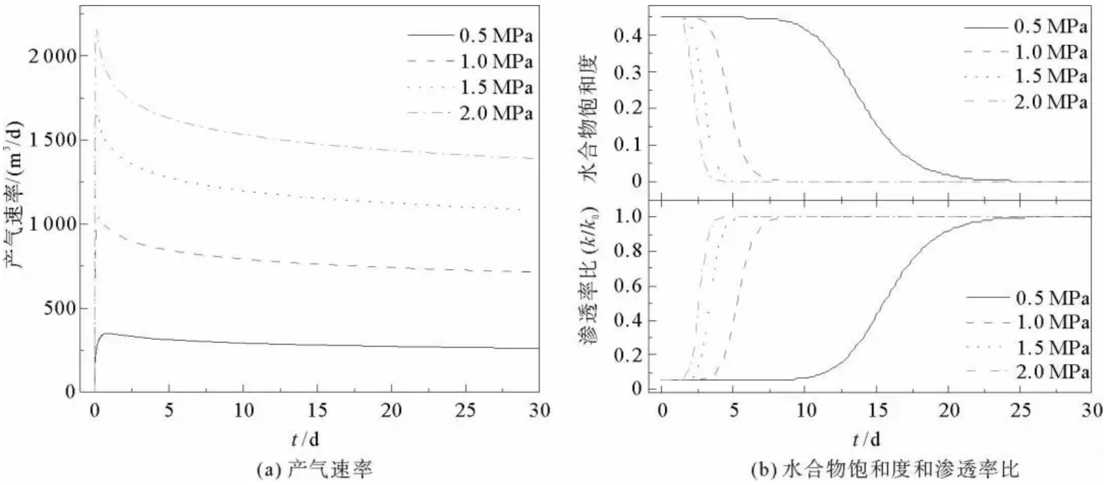

Fig. 1 Variation of each parameter of hydrate under different buckling amplitude

According to Fig. 1, it can be seen that appropriate pressure reduction can make hydrate decompose rapidly and release a large amount of natural gas. It is very important to grasp the magnitude of pressure drop, too small a drop may lead to incomplete hydrate decomposition, thus reducing the extraction efficiency; while too large a drop may lead to a rapid drop in the local temperature and the formation of secondary hydrates, thus affecting the output of gas.

The bucking process is shown in equation (5):

$$\Delta P = P_{\text{initial}} - P_{\text{final}} \tag{5}$$

Where ΔP is the pressure drop amplitude, P_{initial} is the initial pressure before extraction, and P_{final} is the final pressure after extraction. The effect of pressure drop magnitude on extraction efficiency is usually analyzed by the relationship between gas production and pressure drop magnitude[4] .

3.1.2. Comparison and analysis of simulation results

Numerical simulation is used to study the mining process under different buckling amplitudes. In this paper, various bucking amplitudes, such as 10%, 20%, 30% and 50% bucking experiments, are set up to analyze their effects on gas production.

During the simulation, the gas production with time was recorded for each pressure drop amplitude, and the results showed that the gas production reached the highest value at 30% pressure drop amplitude, while the gas production decreased significantly at 10% pressure drop amplitude. The simulation results are shown in Table 1 below:

Table 1 Simulation results of different blood pressure lowering amplitudes

Blood pressure reduction (%)	Gas production (m^3)	Gas production rate (m^3/h)
10	50	5
20	120	12
30	200	20
50	150	15

From the table, it can be seen that the gas production and gas production rate are at the highest level when the pressure drop amplitude is 30%. It can be seen that the decomposition rate of hydrate is the highest at moderate buckling amplitude, and the gas release efficiency is also increased. However, at 50% buckling amplitude, although the initial gas production was high, the temperature decreased due to excessive buckling, and secondary hydrates were formed in some areas, which limited the gas release in the later stage. This result suggests that excessive depressurization during the extraction process does not necessarily improve the overall extraction efficiency, but may instead result in a waste of resources. Future research should continue to explore more refined pressure-relief strategies to optimize the extraction efficiency and achieve sustainable development of gas hydrate resources.

3.2. Different initial absolute permeability

In the extraction of natural gas hydrates, the initial absolute permeability is a key parameter that affects gas flow and yield, and permeability determines the ability of a fluid to flow in a porous medium.

3.2.1. Influence of permeability on gas production

Permeability is a physical parameter that describes the ability of fluids to flow in a formation and is expressed in units of Darcy. The higher the permeability, the lower the resistance to fluid flow in the pore medium and the faster the gas is released. For hydrate extraction, an appropriate permeability can significantly increase gas production.

According to Darcy's law, the relationship between fluid flow rate and permeability is expressed as:

$$z = -u \cdot \nabla P \tag{6}$$

where z is the flow rate, u is the permeability, and ∇P is the pressure gradient. When the permeability increases, the flow rate of the gas increases for the same pressure gradient. Therefore, increasing the initial permeability helps to accelerate the rate of gas release from the hydrate, which in turn enhances the gas yield[5] .

3.2.2. Simulation results for parameter variations

In order to study the effect of different initial absolute permeability on gas production, this paper sets different permeability conditions for numerical simulation, with initial absolute permeability of 100 mD, 500 mD, 1000 mD and 1500 mD, mining time of 48 hours, and pressure drop of 30%. The simulation results are shown in Table 2 below:

Table 2 Simulation results for parameter variations

Permeability (mD)	Gas production (m^3)	Gas production rate (m^3/h)
100	80	1.67
500	150	3.21
1000	250	5.21
1500	300	6.55

As can be seen from the table, both gas production and gas production rate are significantly increased with the increase of initial absolute permeability. The highest gas production was achieved at a permeability of 1500 mD, showing a significant flow advantage.

The simulation results show that at lower initial permeability (e.g., 100 mD), the release of gas is more restricted, resulting in lower gas production and gas yield, as the fluid encounters greater resistance and slows down the flow in the porous medium, which in turn affects the gas release rate. At high permeabilities (e.g. 1500 mD), there is less resistance to fluid flow and gas can be released from the hydrate more quickly.

3.3. Different initial water saturation levels

3.3.1. Effect of water saturation on the mining process

Water saturation is the ratio of water to pore volume in a formation expressed as a percentage. In natural gas hydrate extraction, variations in water saturation affect gas migration and release. Under high water saturation conditions, hydrate decomposition is limited because the presence of water may inhibit gas flow. At the same time, the decomposition of hydrates can lead to interactions between the produced gas and water, affecting the rate of gas release.

In theory, the effect of water saturation is described by the following relation:

$$S_w + S_g + S_h = 1 \tag{7}$$

Among them, S_w , S_g and S_h are the saturation of water, gas and hydrate phases, respectively. As the initial water saturation increases, the saturation of the gas phase S_g decreases and the barrier to gas release increases, thus affecting the mining efficiency.

3.3.2. Simulation analysis and discussion of results

In order to study the influence of different initial water saturation on the mining process, this paper sets the following water saturation conditions for numerical simulation: initial water saturation of 20%, 40%, 60%, 80%, mining time of 48 hours, and pressure reduction of 30%. The simulation results are shown in the following table:

Table 3 Initial water saturation simulation results

Water saturation (%)	Gas production (m^3)	Gas production rate (m^3/h)
20	300	6.25
40	220	4.58
60	150	3.12
80	70	1.46

From the table, it can be seen that the gas production and gas production rate decreased gradually with the increase of initial water saturation. The gas production reaches its maximum at 20% water saturation, while at 80% water saturation, the gas production decreases significantly. This phenomenon can be attributed to the obstruction of gas migration by the presence of water, which increases the difficulty of gas release and thus reduces the overall extraction efficiency. Under high water saturation conditions, water occupies more space in the pore space, limiting gas flow. Further analysis revealed that with the increase of water saturation, the interaction between gas and water becomes more complicated, resulting in the inability of gas to be released smoothly. This not only affected the gas migration rate, but also led to a significant reduction in the gas production efficiency during the mining process.

4. NATURAL GAS HYDRATE EXTRACTION PROCESS BASED ON NUMERICAL SIMULATION

4.1. Analysis of the temporal distribution pattern of gas production

According to the results of numerical simulation, the change of gas production with time can be divided into three stages, which are initial rapid growth stage, stabilization stage and decay stage. The initial rapid growth stage refers to the early stage of mining, due to the significant effect of pressure reduction, the rapid decomposition of hydrates, and the rapid increase in gas release. This phase usually lasts for several hours to tens of hours, and the gas production increases exponentially to reach the initial peak. As mining progresses, the gas production gradually stabilizes. In this stage, the gas release rate gradually slows down, forming a relatively stable gas production platform. At this time, the decomposition rate of hydrate and gas flow rate reach a certain balance. Eventually, as the hydrate is gradually depleted, gas production begins to decline. This phase usually occurs in the later stages of extraction, when the driving force for gas release is weakened and extraction efficiency is significantly reduced.

By counting the gas production in different time periods, the simulation results show that the gas release accounts for more than 50% of the total production in the early stage of mining (0-12 hours), while it accounts for 30% of the total production in the stabilization stage (12-36 hours). The sharp decrease in gas production during the decay phase (after 36 hours) indicates that the mining strategy needs to take appropriate measures for different phases in order to optimize the production.

It can be found through the analysis of the trend of gas production over time that a reasonable extraction strategy needs to consider the characteristics of gas production at different stages and optimize it according to the main factors affecting gas production. Adjustments for factors such as pressure reduction amplitude, initial permeability, water saturation, temperature and pressure changes, etc., are made to improve the extraction efficiency of natural gas hydrates and maximize the sustainable use of resources.

4.2. Spatial distribution pattern of reservoir physical properties

The physical characteristics of the reservoir, including permeability, porosity and water saturation, show uneven spatial distribution due to geological factors (e.g., depositional environment, tectonic movement, etc.). The spatial distribution characteristics of permeability in the reservoir are observed through numerical simulation. Areas of higher permeability are often associated with the development of fractures or pore structures in the formation. In the simulation, the permeability can range from a few millidarcies (mD) to several thousand mD. Typically, permeabilities in the range of 10-100 mD are common in mining areas, while high quality reservoirs may reach hundreds of mD. The distribution of water saturation in the reservoir also exhibits heterogeneity. The saturation in different areas may vary depending on the distribution of water flow and hydrates. Zones of high water saturation usually imply suppressed gas release, which is essential for optimizing the recovery strategy. In some zones, water saturation can reach more than 80%, while in other zones it may be below 20%.

Numerical simulations were performed to create a three-dimensional stereogram of the permeability, as shown in Figure 2 below:

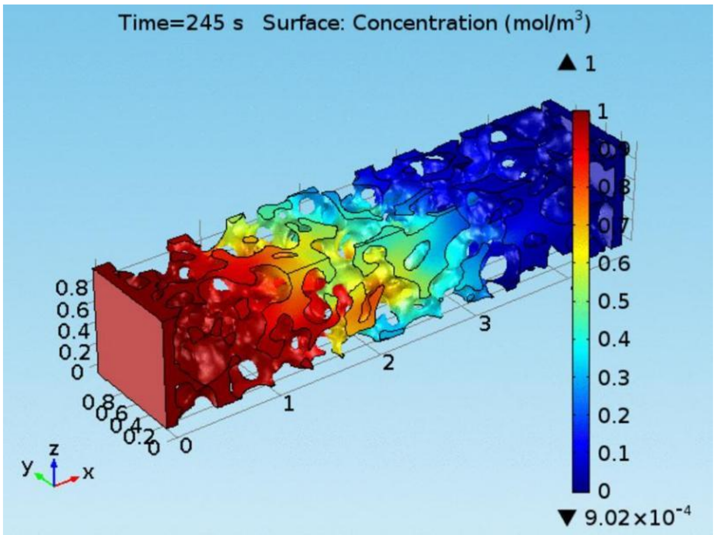

Fig. 2 Three-dimensional stereogram of permeability

Different colors in the graph represent different permeability values, e.g., red areas indicate high permeability (>500 mD), while blue areas indicate low permeability (<100 mD). This intuitive graphical representation allows the researcher to easily identify areas with high extraction potential. The spatial distribution of water saturation was also demonstrated by visualization techniques. The use of different colors to indicate different levels of water saturation helps researchers to quickly understand which areas have a higher potential for hydrate extraction and which areas may be challenged by flow restrictions.

The combination of the visualization results of permeability and water saturation can be analyzed at a deeper level. In the actual mining process, combining the physical distribution of the reservoir and formulating a targeted mining strategy will help to maximize the recovery rate of resources and improve the mining efficiency.

5. CONCLUDING REMARKS

In this paper, the extraction technology of natural gas hydrate and the influence of its key parameters are discussed in depth through the method based on numerical simulation. The results show that factors such as pressure reduction magnitude, initial permeability and water saturation during the extraction process have a significant impact on the gas release efficiency. Appropriate pressure-relief strategies can not only promote the decomposition of hydrates, but also effectively enhance the gas production and thus optimize the utilization of resources. The impact of the non-uniformity of the reservoir on the extraction efficiency is found through the analysis of the spatial distribution of reservoir physical properties. The application of visualization technology provides researchers with an intuitive data display, which helps them to quickly identify key mining areas and supports the development of more accurate mining strategies.

Future research can further deepen the exploration of dynamic monitoring and real-time adjustment mechanism in the process of natural gas hydrate extraction. By continuously improving the theoretical model and empirical research, we can provide more scientific guidance for the efficient exploitation of natural gas hydrate and promote its application in sustainable energy development.

REFERENCES

[1] HUI Cheng-Yu, ZHANG Yiqun, ZHANG Pan-Pan, et al. Numerical simulation of natural gas hydrate production capacity based on radial well fracturing composite pressure reduction method[J]. Natural Gas Industry, 2022, 42(12):152-164.

[2] Xing Lanchang, Wang Shuo, Zhang Huanhuan, et al. Numerical simulation study on evaluating the permeability of hydrate-bearing sediments based on the excitation method[J]. New Energy Progress, 2023, 11(4):320-332.

[3] LI Xiaoyang, ZHANG Xin, TIAN Yingying, et al. Feasibility study of new technology to increase production of marine gas hydrate[J]. Drilling process, 2023(5):87-92.

[4] XIA Xingfan, GAO Fei, ZHAO Bo, et al. Flow deposition study of hydrate slurry based on OpenFoam[J]. Chemical Engineering, 2022, 50(10):47-52.

[5] ZHAI Cheng, WU Di, QIN Dongdong. Orthogonal numerical simulation study of reservoir deformation damage induced by thermal decomposition of natural gas hydrate injection[J]. Special oil and gas reservoir, 2024, 31(2):112-119.