Numerical Simulation of Natural Gas Hydrate Production with Multiple Fracturing Horizontal Wells

Bijun Tan¹, Tiankui Guo¹*, Jia Wang², Tianxi Yu²

¹School of Petroleum Engineering, China University of Petroleum (East China), Qingdao, Shandong, 266580, China
²Engineering Technology Research Institute of Xinjiang Oilfield Company, Karamay, Xinjiang, 834000, China

*Corresponding author’s e-mail: guotiankui@upc.edu.cn

Abstract. Natural gas hydrate (NGH) has great development prospects as alternative energy source. However, the commercial extraction of hydrate never become reality by conventional depressurization. Hydraulic fracturing assisted depressurization has been proposed to promote gas production. In this work, we presented a 3D multiple fracturing horizontal wells model. Firstly, we compared it with conventional horizontal wells. Then, taking gas production rate and cumulative gas production as performance indexes, the sensitivity analysis of fracturing parameters was conducted. The best fracture parameters for multiple fracturing horizontal wells in this specific hydrate reservoir are the fracture number of 5, the fracture length of 100 m, and the fracture conductivity of 50 μm²•cm, respectively.

1. Introduction

Natural gas hydrate (NGH) is a crystal compound formed by natural gas and water under low temperature and high pressure conditions [1], which is considered the main alternative energy in the future. It is speculated that the reserves of hydrate are twice the total amount of traditional fossil fuels that have been proven [2]. The China Geological Survey conducted the second production test with horizontal wells in Shenhu area in 2020, with gas production of 8.61×10⁵ m³ in total and 2.87×10⁴ m³ per day, which are two world records with the maximal total and average daily gas yield. This successful test brings a significant breakthrough on NGH production with horizontal wells.

At present, depressurization, thermal stimulation, CO₂ exchange and inhibitor injection are the main methods of hydrate exploitation, among which depressurization is the most widely used, mature and efficient [3-5]. However, this method has the disadvantages of limited range of bottom-hole pressure drop and rapid decrease of porosity with the increase of hydrate saturation [6]. So some scholars began to make a preliminary study on hydrate reservoir stimulation. Morids et.al. [7] compared the productivity of horizontal wells and vertical wells in different types of reservoirs, and proved that horizontal wells can effectively improve productivity. Konno et al. [8] conducted fracturing experiments on sandstone sediments with a hydrate saturation of 72%, and observed the extension of fractures along the direction of the minimum principal stress. The experiments by Too et al [9] also showed artificial fractures can be formed in sandy reservoirs with gas hydrate saturation of 50% - 75%. Yu et al. [10] increased the permeability from 40 mD to 800 mD, which led to the increase of average daily natural gas production by about 2.1 times. Furthermore, Feng et al. [11] and Sun et al. [12] have found that increasing the permeability and size of fractures is the main way to enhance the effect of hydraulic fracturing, but the...
The effect of hydraulic fractures is obvious only in the early stage of production. Numerical simulation on hydrate stimulation is mostly focused on single vertical well hydraulic fracturing or horizontal wells, and there is no systematic research on multistage fracturing in horizontal wells. Thus, we proposed a 3D model to study the gas extraction of multiple fractures along horizontal well using the simulator HydrateResSim. We do not discuss the reconstruction methods and fracturing fluid system because of the lack of field-scale hydraulic fracturing of NGH reservoir.

2. Simulation Preparation

2.1. Mathematical Model

HydrateResSim developed by the Lawrence Berkeley National Laboratory successfully implements the simulation of gas hydrate formation and decomposition by using the methods of depressurization, thermal stimulation, and injection inhibition [13] and makes it possible to simulate cases considering four phases (liquid, gas, hydrate, and ice), and four components (water, methane, hydrate, and water-soluble inhibitors) [14].

To simplify the analysis, this paper makes the following assumptions:

(1) Fracture zone is a single porous medium;
(2) The hydraulic fractures are simple rectangular zone where the permeability is higher than that of surrounding reservoir;
(3) Fracture characteristics remain stable in mining process;
(4) Flows of aqueous and gaseous phases follow Darcy's law.

2.2. Geological Model

The model is 500 m × 500 m × 80 m in x, y and z, respectively. The z direction includes the overburden layer, the hydrate-bearing layer (HBL) and the underburden layer, with a thickness of 30 m, 20 m and 30 m, respectively. The formation is assumed to be homogeneous, and the key reservoir property parameters are shown in Table 1. Besides, the horizontal well was set as 400 m along the x direction. The upper and lower boundary is the supply boundary, and the outer boundary is the closed boundary. As is shown in Figure 1, the fracture number is 4, fracture height is 12 m, the fracture length is 100 m, and fracture conductivity is 50 μm²•cm. The production time of the horizontal production well is set to be 3000 days and the bottom hole pressure is maintained at 4.5 MPa.

It is assumed that there is only heat transfer and no material exchange among the overburden layer, underburden layer and HBL. Both the overburden and underburden layer are evenly meshed into 3 grids, while the HBL consists of 12 grids unevenly with four grids of 2 m, 4 grids of 1 m and 4 grids of 2 m to observe the temperature and pressure distribution. The grid of X-Y planes is 10 m × 10 m and the grid of wellbore and fracture zone is refined, each of which is 1 m × 1 m. Taking 4 fractures as an example, 52488 grids are divided, including 34992 active grids. Figure 2 shows schematically the mesh generation of HBL.

Table 1. Basic parameters

| Parameter                        | Value  |
|----------------------------------|--------|
| Initial temperature T₀ at the center of the HBL, °C | 13.26  |
| Initial pressure P₀ at the center of the HBL, MPa | 13.83  |
| Intrinsic permeability k of the HBL, μm² | 0.075  |
| Porosity of the HBL, φ           | 0.38   |
| Initial gas hydrate saturation of the HBL S₀h | 0.42   |
| Initial water saturation of the HBL S₀w | 0.58   |
| Thermal conductivity of formation, W/m•°C | 3.92   |
| Temperature gradient, °C/100 m   | 4.32   |
| Specific heat of hydrate, J/kg•°C | 1000   |
3. Result Analysis

In order to evaluate the hydrate productivity of multiple fracturing horizontal well system, we compared it with conventional horizontal well.

Figure 3-4 shows the comparison of CH₄ production under no fracture and four fractures. It is apparent that the production rate of multiple fracturing horizontal well and conventional well increase first and then decrease, with the former is significantly greater than the latter. The reason is that the permeability of fracture zone is higher than that of no fractured layer and fractures enlarge the diameter of the fluid migration channels in the initial of stage. As exploitations progress, the hydrate saturation of fractured reservoir decreases, which makes the gas production rate decrease rapidly, so the gas production rate is lower than that of no fracture in the later stage. With figure 4, the cumulative gas production under 4 fractures is higher than that of no fracture, which indicates that multiple fracturing horizontal well play an important role in improving hydrate productivity. At 3000 days, the cumulative gas production with 4 fractures is 5.3 × 10⁷ m³, which increase gas production by 72.08%.
Figure 5 shows the distribution of pressure, temperature and hydrate saturation in the x-z plane (-50m ~ -30m) under the condition of no fracture and four fractures after 500 days. Fig. 5 (a) and (c) show that the pressure drop range is effectively increased under multi-stage fracturing, and the corresponding hydrate decomposition range is also significantly increased. For hydrate decomposition is an endothermic reaction, it can be clearly found that the low-temperature zone propagates along the fractures and the fractures are the main channels for pressure drop and fluid flow. However, when the temperature is too low, it will induce the formation of ice which will inhibit the decomposition of hydrate, so it is necessary to select the appropriate depressurization rate and amplitude.

4. Sensitivity Analysis of Fracture Parameters

The hydraulic fracture parameters of multiple fracturing horizontal wells influence greatly on oil and gas production [15]-[17]. Multistage fracturing fracture parameter optimization mainly involves fracture spacing, fracture conductivity, and fracture length. Hence, the determination of the optimal combination of fracture parameters becomes extremely critical.

4.1. Fracture number

Different cases with fracture numbers (3 to 8) were carried out to study the influence on fracture numbers on hydrate exploitation. There are many fractures evenly extending along horizontal wells, with fracture spacing of 100-44 m, fracture length of 100 m and fracture conductivity of 50 $\mu m^2 \cdot cm$.

Figure 6. The gas production rate curves with different fractures numbers

Figure 7. The cumulative gas production curves with different fractures numbers
Fig. 6–7 show the change of cumulative gas production and gas production rate with different fracture numbers. In the early stage of production, a fracture zone with high conductivity is formed near the wellbore and high permeability is always maintained, in which case, the gas production rate grows faster with the increasing of fracture number. When the number of fractures exceeds 5, the increase of gas production rate will slow down. In this work, considering the optimal input-output ratio, fracture number with a value of 5 corresponding to a fracture spacing of 66 m shows the best performance on yield with $5.7 \times 10^7 \text{ m}^3$.

4.2. Fracture length

The fracture length refers to the distance from the fracture tip to the intersection of the fracture root with the wellbore [15]. Taking 5 fractures with a fracture conductivity of $50 \mu\text{m}^2\cdot\text{cm}$ as the basic model parameters, the gas production under different fracture lengths (25, 50, 100, 150, 200m) was compared.

It can been seen that the gas production rate of fracture length, 100 m, is greater than those of the case of 25 m and 50 m and the cumulative gas production increases linearly at the same time. This also revealed that the fractures appear longer and their role in hydrate decomposition is more obvious. However, when the length exceeds 100 m, both two curves have a little disparity. It is unnecessary to pursue an excessively high fracture length and the optimal fracture length is 100 m.
4.3. Fracture conductivity

The fracture conductivity refers to fracture permeability multiplied by fracture width. The practice shows fracture conductivity is closely related to production of multiple fracturing horizontal well [16]. The fracture number and length in the basic model were set to 5, 100 m and the simulation under different fracture conductivity of 10, 20, 30, 40, 50, 60, 70 $\mu$m$^2$cm was conducted.

Fig.12-13 illustrate that the gas production rate and cumulative gas production are positively correlated with conductivity. Specifically, the cumulative gas production increases logarithmically with conductivity and reaches the inflection point when the fracture conductivity is 30 $\mu$m$^2$cm. After that, the cumulative gas production rate slows down with the increase of fracture conductivity. Considering the economic cost, the optimal fracture conductivity in NGH reservoir is 30 $\mu$m$^2$cm.

In summary, considering the actual construction conditions, the fracturing technology cost and stimulation effect comprehensively, multiple fracturing parameters should be optimized to obtain the highest production value via the most economical and effective measures.

However, there are many shortcomings in the model: (1) Without changes in formation stress. The structure in NGH reservoir is relatively complex, in which case, changes of pressure and ice generated during production can easily lead to formation sand production or plugging, leakage and seepage of well structure. Therefore, the simulation conclusion should be used in conjunction with the field without heterogeneity.
5. Conclusions
In this work, we proposed a 3D multiple fracturing horizontal wells model and analyzed the temperature, pressure, hydrate saturation as well as gas production compared with conventional horizontal wells. Moreover, the sensitivity analysis of fracturing parameters was carried out. The main conclusions are as follows:

(1) Multiple fracturing horizontal wells can increase stimulated reservoir volume and bottom-hole pressure drop significantly and increase gas production by 72.08%, which is proved an efficient way for exploitation of NGH reservoir.

(2) In this paper, the best combination of fracturing parameter is found to be fracture number of 5, fracture length of 100 m, and fracture conductivity of 50 $\mu$m$^2$·cm, which gives optimal gas production.

Acknowledgments
This work is supported by the National Natural Science Foundation of China (Grant No. 52074332).

References
[1] Chong Z R , Yang S H B , Babu P , et al. Review of natural gas hydrates as an energy resource: Prospects and challenges[J]. Applied Energy, 2016:1633-1652.
[2] Lee S Y , Holder G D . Methane hydrates potential as a future energy source[J]. Fuel Processing Technology, 2001, 71(1):181-186.
[3] E Zhao, J Hou, Q Du, et al. Numerical modeling of gas production from methane hydrate deposits using low-frequency electrical heating assisted depressurization method[J]. Fuel, 2021, 290.
[4] Li X S , Xu C G , Zhang Y , et al. Investigation into gas production from natural gas hydrate: A review[J]. Applied Energy, 2016, 172(Jun.15):286-322.
[5] Zheng R , Li S , Li X . Sensitivity analysis of hydrate dissociation front conditioned to depressurization and wellbore heating[J]. Marine and Petroleum Geology, 2018, 91.
[6] Liu X , Zhang W , Qu Z , et al. Feasibility evaluation of hydraulic fracturing in hydrate-bearing sediments based on analytic hierarchy process-entropy method (AHP-EM)[J]. Journal of Natural Gas Science and Engineering, 2020, 81:103434.
[7] MORIDIS G, REAGAN M, ZHANG Keni, et al. The use of horizontal wells in gas production from hydrate accumulations[C]/Proceedings of the 6 International Conference on Gas Hydrates, 6-10July 2008, Vancouver, British Columbia, Canada.
[8] Konno Y, Jin Y, Yoneda J, et al. Fracturing Behavior of Methane-Hydrate-Bearing Sediment[C]// AGU Fall Meeting. AGU Fall Meeting Abstracts, 2016.
[9] Too, Lin J, Cheng, et al. Hydraulic fracturing in a penny-shaped crack. Part II: Testing the frackability of methane hydrate-bearing sand[J]. Journal of natural gas science and engineering, 2018.
[10] Yu T , Guan G , Abudula A , et al. Gas recovery enhancement from methane hydrate reservoir in
the Nankai Trough using vertical wells[J]. Energy, 2019, 166:834-844.
[11] Feng Y, Chen L, Suzuki A, et al. Enhancement of gas production from methane hydrate reservoirs by the combination of hydraulic fracturing and depressurization method[J]. Energy Conversion and Management, 2019, 184:194-204.
[12] Sun J, Ning F, Liu T, et al. Gas production from a silty hydrate reservoir in the South China Sea using hydraulic fracturing: A numerical simulation[J]. Energy Science & Engineering, 2019, 7(1).
[13] Moridis G J. HYDRATERESSIM User's Manual: A Numerical Simulator for Modeling the Behavior of Hydrates in Geologic Media. 2005
[14] Moridis G J. Numerical Studies of Gas Production From Class 2 and Class 3 Hydrate Accumulations at the Mallik Site, Mackenzie Delta, Canada[J]. SPE Reservoir Evaluation & Engineering, 2004, 7(3):175-183.
[15] Guo T, Zhang S, Ge H, et al. A new method for evaluation of fracture network formation capacity of rock[J]. Fuel, 2015, 140:778-787.
[16] Guo T, Tang S, Liu S, et al. Physical Simulation of Hydraulic Fracturing of Large-Sized Tight Sandstone Outcrops[J]. SPE Journal, 2020.
[17] Guo, T, Zhang, et al. Experimental study of hydraulic fracturing for shale by stimulated reservoir volume[J]. Fuel Guildford, 2014.