Experimental study on sand production characteristics in natural gas hydrate deposits

Tianbo Yu*, Yu Liu and Yongchen Song

Key Laboratory of Ocean Energy Utilization and Energy Conservation of Ministry of Education, Dalian University of Technology, Dalian, Liaoning province, 116024, China

*Corresponding author’s e-mail: yutianbo@mail.dlut.edu.cn

Abstract. During the process of natural gas hydrate exploitation, the cementation state of the stratum changes due to the decomposition of skeleton hydrate. Fine sand in the reservoir will migrate to the wellbore with the fluid, which is the so-called sand production phenomenon. Sand production will bring great harm to hydrate exploitation. In this paper, a set of visualized sand production simulator was designed to obtain the factors influencing the sand production characteristics in different working conditions. It is found that fine sand will invade and block the gravel layer and it is accompanied by the subsidence of the sand layer. Fluid flow rate and initial hydrate saturation are important factors affecting the characteristics of sand production. In addition, it is of certain guiding significance to select the appropriate median diameter ratio of gravel to sand for sand control in the actual exploitation process.

1. Introduction

Natural gas hydrate, also known as combustible ice, is a cage-shaped crystalline substance[1]. It is mainly found in marine sediments and land permafrost in nature. Compared with other fossil fuels, natural gas hydrate has the characteristics of abundant reserves, high energy density and clean energy source[2]. It also indicates that natural gas hydrate has become the most promising strategic energy in the 21st century[3].

However, during hydrate exploitation by the depressurization method, due to the large differential pressure of production and the decomposition of skeleton hydrate into methane gas and water, the mechanical strength of the reservoir is reduced and the cementation is weakened. Fine particles in the reservoir will migrate with the fluid and move out of the wellbore[4]. Sand production in hydrate exploitation process will lead to the collapse and blockage of the production layer, which will affect the exploitation efficiency. Therefore, the study of sand production characteristics is of great significance for the economic, safe and efficient exploitation of hydrate.

Due to the characteristics of long production cycle and high cost in the field test of natural gas hydrate sand production, some experiments and numerical simulation on the sand production characteristics of natural gas hydrate have been carried out in recent years to obtain a large number of sand production data and effectively obtain the characteristics of sand production[5,6]. In order to explore the influence of fine sand particles in the reservoir on hydrate decomposition, Jung et al. carried out a sand production experiment on a large submarine simulation equipment and mixed fine kaolinite clay in the sand sample[7]. It was found in the experiment that, with the progress of gas generation from hydrate decomposition, the fine sand grains deposited on the bubbles would move to the pore throat along with the gas-water interface, thus causing the pore throat to be blocked, and the further growth of the bubbles would promote the migration of skeleton particles. Based on the experimental results, it was proposed
that even small sand grains can greatly reduce the permeability of sediments, thus reducing the efficiency of gas production. Uchida et al. by further development and coupling thermo-hydro-mechanical model (THMC) [8-10], put forward the analysis model of sand movement in gas hydrate sediment and numerically studied the effect of the operation method on the reduction of sand production during hydrate decomposition. It was found that reducing the pressure reduction rate was the most effective to reduce the sand production, and the shear deformation of the reservoir largely depended on the inhomogeneity of the stress distribution. Lu et al. studied the sand production characteristics of natural gas hydrate by the depressurization method, and found that the hydrate decomposition can be divided into three stages. Sand production in the first two periods: fine sand in the first period and sand grains in the second. In addition, the unique spatter effects produced by hydrate decomposition may provide the driving force for sand transport, and the bubbles or gaseous water droplets produced by hydrate decomposition may enhance the sand carrying capacity. The subsidence of hydrate deposits was affected by the amount of sand production, and the maintenance of crustal stress may affect the rate and range of subsidence [11].

At present, most of the researches focus on the sand production mechanism in hydrate reservoir, and there are few quantitative studies on the sand production characteristics of large-volume sand production device. In addition, the migration and plugging rules of fine sand in hydrate reservoir have not been revealed systematically. In this study, a large-volume visualized sand production device was designed to measure the amount and the particle size distribution of sand production in real time at different driving fluid flow rates, median particle size ratios of gravel to sand layer and initial hydrate saturation. In addition, in order to obtain the characteristics of sand production in hydrate sediments, the migration and blockage rules of fine sand were also observed.

2. Experimental section

2.1. Experimental Apparatus

Figure 1 represents the experimental system diagram of sand production in hydrate bearing sediment. Its main part is a visualized vessel made of white steel, with an internal size of 420* 250* 200mm and a volume of 21L. The container is mainly divided into left and right parts. The sand filling chamber on the left was used to fill the sand layer, and the overburden pressure was applied through the pressure loading system to compact the sand layer. The gravel pack chamber on the right was used to fill the gravel layer. A visual plexiglass window was installed in the container, and the migration and blockage of fine sand in the container was observed by the camera. The left inlet of the container was connected to a large water reservoir with a capacity of 1000L, and the liquid was injected into the container through a fully automatic booster pump. The turbine flowmeter was used to measure the liquid flow rate in the experiment. Sand particle size was obtained by a laser particle size analyzer.

![Figure 1. Hydrate sand production simulator.](image-url)
2.2. Experimental materials
The gravel packing chamber adopted glass sand with particle size distribution of 1-2.5mm to simulate gravel, which played a role of proper sand control. The sand filling chamber adopted the method of multi-layer sand filling to observe the migration of fine particles and the process of sand production. The specific method of multi-layer sand filling was to layer the selected silt with the median diameter of 0.082mm and the selected ISO standard beach sand with the median diameter of 0.253mm into sand filling chamber. Since ice and hydrate have similar bonding properties, ice powder was used to simulate the hydrate in the sediment.

2.3. Experimental steps
The mass of sand and ice powder was calculated from the set porosity and initial hydrate saturation. The required amount of ISO standard beach sand and silt were weighed and mixed with ice powder separately. Afterwards, they were stratified to fill the sand chamber. A certain amount of glass sand was then filled into the gravel packing chamber. Next, the sand production simulator was sealed. These operations were carried out in an air bath at -2°C. The overburden pressure loading system applied a specified amount of pressure to compress the sand layer and the gravel layer. Vacuum pump was used to remove air from the sand production simulator. Then the air bath temperature was adjusted to 1°C. At this time, the water flowed into the hydrate sand production simulator at a specified flow rate, and the sand production experiment began. CMOS cameras recorded the migration and blockage characteristics of fine particles in the sand container in real time. At regular intervals, the sand in the liquid-sand separator was dried and weighed to obtain the sand output. When the volume of injected fluid reached 1000L, the experiment was stopped. The collected sand was put into the laser particle size analyzer to measure the sand particle size.

3. Result and discussion
In order to obtain the characteristics of sand production in hydrate deposits, the experiments focused on the amount, instantaneous rate and particle size of sand production at different driving fluid flow rates, median diameter ratios of gravel to sand and initial hydrate saturation. The experimental conditions and some results are shown in Table 1.

| No. | Flow rate (L/min) | Median diameter ratio of gravel to sand | Initial hydrate saturation(%) | Cumulative sand production(kg) | Median particle size of sand production (μm) |
|-----|-------------------|----------------------------------------|------------------------------|------------------------------|-------------------------------------------|
| 1   | 3                 | 7.2                                    | 40                           | 0.213                        | 75.28                                     |
| 2   | 10                | 7.2                                    | 40                           | 0.705                        | 124.11                                    |
| 3   | 5                 | 7.2                                    | 40                           | 0.366                        | 84.22                                     |
| 4   | 5                 | 4.6                                    | 40                           | 0.185                        | 70.58                                     |
| 5   | 5                 | 10.5                                   | 40                           | 0.597                        | 105.74                                    |
| 6   | 5                 | 7.2                                    | 0                            | 0.382                        | 86.31                                     |
| 7   | 5                 | 7.2                                    | 80                           | 0.335                        | 83.49                                     |

3.1. Influence of fluid flow rate on sand production
Fluid flow rate is one of the important factors affecting sand production characteristics, which has been written in previous literature. In this group of experiments, fluid flow rates of 3L/min, 5L/min and 10L/min were used to observe the sand production phenomenon under the condition that other variables were the same, corresponding to No.1, No.3 and No.2, respectively. Figure 2 represents the cumulative sand production, sand production instantaneous rate and sand particle size distribution curve at different fluid flow rates.
As can be seen from Figure 2(b), sand production can be roughly divided into three processes. At the beginning of the experiment, the sand production rate increases rapidly, which is due to the rapid movement and vast production of free fine sand under the carrying of fluid. Subsequently, the sand production rate shows a trend of constant fluctuation. Because part of the skeleton sand is exfoliated to form free sand under the fluid drag and hydrate decomposition. As the sand moves to the gravel layer to block the pores, the sand production rate at the end of the experiment is continuously reduced until it is stable. In addition, it can be seen from the figure that, with the increase of the driving fluid flow rate, the time to reach the stable sand production stage becomes longer, the cumulative sand production increases significantly, and the sand production rate fluctuates more violently, which is because skeleton sand is more likely to be free sand at a high fluid flow rate. From the analysis of sand particle size in the right graph, it can be found that with the increase of the driving fluid flow rate, the median particle size and the maximum particle size increase obviously. It also indicates that the larger the fluid flow rate is, the stronger the driving capacity and carrying capacity will be provided. The fluid flow rate is the primary factor affecting the sand production characteristics.

3.2. Influence of median diameter ratio of gravel to sand on sand production
Since the hydrate reservoir of the south China sea belongs to the unconsolidated ultra-fine silt reservoir, the filling type technology is usually adopted in the actual exploitation process to enhance the sand control effect. In this study, large particle glass sand was used to simulate gravel layer. Although the larger gravel size can improve the permeability of hydrate reservoir, it will reduce the additional skin of sand control and cause a large amount of sand output at the same time. Although the smaller gravel size has a good sand control effect, it is easy to block the pores and seriously affect the exploitation efficiency.

We usually apply the principle of proper sand control to unconsolidated ultra-fine silt reservoir. Therefore, it is important to select the appropriate median particle size ratio of gravel to sand to make the reservoir conform to the principle of proper sand production. The principle is that it not only ensure the fine grain output to dredge the internal flow channel, but also the skeleton sand is prevented from being produced in large quantities to cause voids in sediment.

Figure 3. Sand production characteristics of different median diameter ratios of gravel to sand.

(a)

(b)

(c)
In this group of experiments, median diameter ratios of gravel to sand of 4.6, 7.2 and 10.5 were used in No.4, No.3 and No.5, respectively, to obtain the influence of this factor on sand production. Figure 3 shows the cumulative sand production, sand production instantaneous rate and sand particle size distribution curve at different median diameter ratios of gravel to sand. It is found that with the increase of the median diameter ratio of gravel to sand, the cumulative sand production and the maximum sand production rate increase significantly, which is due to the enlargement of the pore throat and the improvement of the permeability of the reservoir. It can be seen from Figure 3(c) that with the increase of the median size ratio of gravel to sand, the median size and the maximum size increase. It's worth noting that when the median diameter ratio of sand to gravel is 7.2 which means $D_{50}/d_{50}$ is between 5 and 8, the median particle size of sand production is very close to that of silt layer, which accords with the principle of proper sand production.

3.3. Influence of initial hydrate saturation on sand production
Hydrate saturation usually refers to the volume percentage of hydrate in the pores of natural hydrate reservoirs and is an important factor affecting the sand production characteristics in the process of exploitation. To a certain extent, hydrate saturation determines the mechanical properties and bonding state of sediments. In this group of experiments, the influence of hydrate saturation on sand production characteristics was obtained under three different initial hydrate saturation. No.6, No.3 and No.7 correspond to the hydrate sediment layers with initial hydrate saturation of 0%, 40% and 80% respectively. Figure 4 describes the sand production results of this group of experiments.

![Figure 4. Sand production characteristics of different initial hydrate saturation.](image)

As can be seen from the Figure 4(a) and Figure 4(b), with the increase of initial hydrate saturation in the sedimentary layer, the cumulative sand production and the maximum sand production rate decrease. This is because the high content of hydrate acts as a cohesive support, which enhances the mechanical strength and internal friction of the hydrate reservoir, thus reducing the possibility of sand production to some extent. In addition, it can be found from the analysis of the sand production rate in the whole experiment process that the higher the initial hydrate saturation is, the greater the fluctuation of the sand production rate will be, and the longer the time to reach the stable sand production stage will be. This can be explained as follows: it takes a long time for the hydrate reservoir with high hydrate content to fully decompose, which brings longer instability to the reservoir and higher randomness of sand production. Therefore, it should be noted that although the increase of hydrate saturation can reduce the total amount of sand production, the decomposition of hydrate increases the risk and uncertainty of sand production to some extent. The right curve shows the particle size distribution of sand production in this group of experiments. It can be found that the median particle size of sand production under three working conditions is very close, which also indicates that initial hydrate saturation has a small impact on the particle size of sand production.

3.4. The phenomenon of sand migration and blockage
The observation of the sand migration process has a very important guiding significance in deepening the understanding of sand production characteristics. Therefore, in this experiment, the process of migration and intrusion into the gravel layer of fine silt in the hydrate deposit under No.3 was recorded.
by the camera. Figure 5 represents the sand production phenomenon at different time throughout the experimental period.

![Images of sand production phenomenon](image1)

Figure 5. The phenomenon of sand migration and blockage.

The white sand layer in the figure is silt layer used to observe the migration process, while the yellow sand layer is ISO standard beach sand layer. The light green sand layer is glass sand layer used to simulate gravel packing. Figure 5(a) represents the sand layer at time 0, when the fluid has not been injected. Figure 5(b) and Figure 5(c) show the moment when water flow into the sand layer and gravel layer respectively. In Figure 5(d), water has completely filled the container and the migration of white silt can be observed. With the continuous injection of water, as shown in Figure 5(e) and Figure 5(f), a large amount of silt intrude into the gravel layer. Due to the gradual increase of sand production, the subsidence of sand layer can also be observed at this time. As more sand is carried to the gravel layer, the phenomenon of plugging the gravel pores begins to appear and the rate of sand production decreases and gradually stabilizes.

4. Conclusion

In this paper, the characteristics of sand production in the process of hydrate decomposition in a multilayer sand filled sediment with gravel pack were investigated. It mainly included the amount, instantaneous rate and particle size of sand production at different driving fluid flow rates, median diameter ratios of gravel to sand and initial hydrate saturation. In addition, the migration process of fine silt was also captured. According to the experimental results, the following conclusions are drawn:

(1) Sand production can be roughly divided into three processes. At the beginning of the experiment, the sand production rate increases rapidly, then the sand production rate shows a trend of constant fluctuation, and finally the sand production rate gradually decreases until it becomes stable.

(2) Fluid flow rate is an important factor affecting sand production characteristics. The larger the flow rate is, the stronger the driving capacity and carrying capacity will be provided.

(3) Proper selection of the median diameter ratio of gravel to sand can effectively improve the sand control effect. when the median diameter ratio of gravel to sand is between 5 and 8, the median particle size of produced sand is very close to that of silt layer, which accords with the principle of proper sand production.

(4) The increase of initial hydrate saturation reduces the amount of sand production to some extent. However, it takes a long time for the hydrate reservoir with high hydrate saturation to fully decompose, which increases the risk and uncertainty of sand production.
(5) With the injection of the fluid, a large amount of silt intruded into the gravel layer and produced from the simulated wellbore outlet. The increase of sand production is accompanied by the subsidence of the sand layer.

References
[1] Sloan, E.D., Koh, C.A. (2008) Clathrate hydrates of natural gases. CRC Press, Boca Raton.
[2] Kvenvolden, K.A. (1998) A primer on the geological occurrence of gas hydrate. Geological Society, 137(1): 9-30.
[3] Lee, J. (2010) Experimental study on the dissociation behavior and productivity of gas hydrate by brine injection scheme in porous rock. Energy Fuels, 24(1): 456–63.
[4] Collett, T., Bahk, J.J., Baker, R. (2015) Methane Hydrates in Nature—Current Knowledge and Challenges. Journal of Chemical & Engineering Data, 60(2): 319-329.
[5] Suzuki, S., Kuwano, R. (2016) Evaluation on stability of sand control in mining methane hydrate. Production research, 68(4): 311-314.
[6] Lee, J., Ahn, T., Lee, J.Y. (2013) Laboratory test to evaluate the performance of sand control screens during hydrate dissociation process by depressurization. In: International Society of Offshore and Polar Engineers. Szczecin. 13-035.
[7] Jung, J.W., Jang, J., Santamarina, J.C. (2012) Gas Production from Hydrate-Bearing Sediments: The Role of Fine Particles. Energy & Fuels, 26(1): 480–487.
[8] Uchida, S., Klar, A., Charas, Z. (2013) Thermo-hydro-mechanical sand production model in hydrate-bearing sediments. In: Proceedings of the International EAGE Workshop on Geomechanics and Energy. Lausanne. 01-11.
[9] Uchida, S., Klar, A., Yamamoto, K. (2016) Sand production model in gas hydrate-bearing sediments. International Journal of Rock Mechanics & Mining Sciences, 86: 303-316.
[10] Uchida, S., Lin, J. S., Myshakin, E. (2017) Numerical simulations of sand production in interbedded hydrate-bearing sediments during depressurization. In: The 9th International Conference on Gas Hydrates. Denver. pp. 25-30.
[11] Lu, J., Xiong, Y., Li, D., Shen, X., Wu, Q. (2018) Experimental investigation of characteristics of sand production in wellbore during hydrate exploitation by the depressurization method. Energies, 11(7): 1673.