Multiphase Non-Equilibrium Pipe Flow Behaviors in the Solid Fluidization Exploitation of Marine Natural Gas Hydrate Reservoir

Na Wei[1,*], Jinzhou Zhao[1], Wantong Sun[1], Shouwei Zhou[1], Liehui Zhang[1], Qingping Li[2], Haitao Li[1], Qiang Fu[1,2], Xin Lv[2] and Lijun Zheng[2]

[1]State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu, China.

[2]CNOOC Research Institutes Limited Liability Company, Beijing, China.

[*]Corresponding Author: Na Wei. Email: weina8081@163.com.

Currently, marine natural gas hydrate has attracted people's attention due to its huge amount of resources. As a creative way to securely and efficiently exploit metastable hydrate reservoir which is in shallow subsurface of sea floor and with weak cementing, the method of solid fluidization exploitation is to excavate and crush the marine natural gas hydrate reservoir, transport the hydrate to the sea surface platform through the airtight pipeline, and finally the methane gas is obtained after post-processing.

In the process that the hydrate solid particles are transported up, as the temperature rises and the pressure drops, the hydrate rises to a certain critical position and will decompose and produce a large amount of gas, causing that the liquid-solid two-phase flow in wellbore changes into complicated gas-liquid-solid multiphase non-equilibrium flow, which will further affect the hydrate dynamic decomposition, and the security risks such as well control and solid phase transportation are increased at the same time. Based on the law of conservation of energy and basic equations of heat transfer, considering the process of solid fluidization exploitation of marine gas hydrate, the temperature distribution model of mixed fluid in wellbore is established. The wellbore pressure distribution model is established based on the process of multiphase mixed fluid flow in wellbore in solid fluidization exploitation of marine natural gas hydrate. Based on the process of solid fluidization exploitation of marine gas hydrate, a hydrate phase equilibrium model is required to be established in order to determine whether the hydrate solid particle decomposes in a certain temperature and pressure condition during the rising process. In the riser pipe flow, according to the equilibrium model of hydrate, the hydrate solid particles will not decompose before rising to the critical decomposition position, and the decomposition rate is zero in this process. The hydrate solid particles will decompose after arriving to the critical decomposition position. In order to calculate the decomposition of hydrate, the dynamic decomposition model of hydrate in multiphase riser pipe flow is established, in which the gas hydrate is assumed to be methane hydrate. Then the mathematical model of wellbore multiphase flow coupled hydrate dynamic decomposition are established, and numerical calculation method is proposed and verified. In order to simplify the model, it is assumed that the solid phase particles of hydrate can be transported safely in the horizontal section, and the migration velocity is equal to the liquid phase velocity. The temperature of the mixed fluid in wellbore in the subsea horizontal well section remains the same as the seawater temperature at the outside seafloor. The pressure at the wellhead is equal to the wellhead back pressure.

In the process of finite difference numerical calculation, the spatial domain is the wellbore, the time domain is the hydrate solid particles transported from the bottom hole to the wellhead, and the calculation sequence is from the wellhead to the bottom hole. The numerical calculation process is illustrated with the multi-

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phase non-equilibrium pipe flow process. In order to verify the accuracy of the numerical calculation method established in this paper, the large physical simulation experimental results of marine natural gas hydrate solid fluidization exploitation by Zhou et al. is chosen to be compared. The error between the numerical results obtained in this paper and the experimental results in Zhou's paper is small, and the variation trend is consistent. The accuracy of the numerical model and the calculation method established in this paper has been verified, which lays the foundation for the application of the numerical model.

Then, in order to obtain the multiphase non-equilibrium pipe flow behaviors in the process of transporting the hydrate solid particles to the sea surface platform with seawater in the airtight pipeline, the established mathematical model and numerical calculation method are used to carry out the numerical model application analysis of different liquid delivery capacities, solid throughputs (daily gas production), liquid densities and wellhead back pressures. In addition, we put forward the field construction guidance measures based on multiphase non-equilibrium pipe flow characteristics as follows. The liquid delivery capacity should be increased appropriately in order to prevent well control problems and improve the transportation capacity for solid particles in the field construction of solid fluidization exploitation of marine natural gas hydrate reservoir. Increasing the solid throughput can increase the amount of hydrate transported to the sea surface platform in per time unit, and further increase the natural gas production in the field construction of solid fluidization exploitation of marine natural gas hydrate reservoir. However, the safety problem caused by well control will be more serious. Therefore, the solid throughput can only be improved under the premise of well control safety. Increasing the wellhead back pressure can significantly improve the wellbore pressure and reduce the risk of well control safety caused by gas expansion at wellhead. Therefore, it is necessary to increase the wellhead back pressure appropriately in the field construction of the solid fluidization exploitation of marine natural gas hydrate reservoir.

Through the research and analysis above, we come to conclusions as follows:

(1) The increase of liquid delivery capacity can significantly reduce the wellbore temperature and phase equilibrium pressure of the hydrate, so that the critical decomposition position of hydrate moves up. It can also significantly improve the velocities of gas, liquid and solid phase, and can reduce the gas holdup and solid phase content.

(2) With the increase of solid throughput, the wellbore temperature and hydrate phase equilibrium pressure do not change, the wellbore pressure increases in the lower well section and does not change obviously in the upper well section, the critical decomposition position of hydrate stays constant, the solid content and gas holdup at wellhead increase significantly, the liquid holdup decreases significantly, and the velocities of gas, liquid and solid phases all increase.

(3) The increase of wellhead back pressure can significantly increase the wellbore pressure, so that the hydrate critical decomposition position moves up. It can also significantly reduce the gas holdup after the hydrate decomposes, reduce the solid velocity and liquid velocity, increase the solid velocity, reduce the solid content, and increase the liquid holdup.

(4) The appropriate increase of solid throughput can increase the production of natural gas in the field construction of the solid fluidization exploitation of marine natural gas hydrate reservoir. However, problems such as well control risks will intensify. In order to prevent wellbore flow safety problems such as well control risk, and improve the transportation capacity for hydrate solid particles, the liquid delivery capacity, liquid density and wellhead back pressure should be increased appropriately.

This study provides a theoretical basis for the prediction of multiphase non-equilibrium pipe flow in the solid fluidization exploitation. Meanwhile, it also provides the technical support for the field construction parameter optimization and well control safety.

Keywords: Natural gas hydrate; solid fluidization exploitation; non-equilibrium multiphase wellbore flow; decomposition; well control risks; construction parameter