Contribution ID: **604** Type: **Oral Presentation**

Simulation of boundaries and parameters variations of natural gas hydrate in thermofluidic dissolution based on multi-field coupling under pore-scale modeling

Monday, 13 May 2024 13:55 (15 minutes)

When natural gas hydrates are heated and dissolved, the boundaries of fluid-solid will apparently be changed, and average permeability and equivalent thermal conductivity change in coupling. We designed two different microstructures, grain-coating type and pore-filling type, based on two common storage modes. The model size is 50 μm × 22 μm, and the solid particles are 2.0 μm × 2.0 μm. Then we use the Dual Distribution Function model (DDF) of Lattice Boltzmann method to simulate the processes of hydrate dissolution and heat convection based on coupling thermal-flowing-mechanic-chemical (TFMC).

To reduce the impact of nonlinear conditions on calculation results, it is necessary to partition the simulation area along the flowing direction and calculate the data of each partition. The grain-coating type has an initial hydrate saturation of 43.6% and its permeability, as determined by Darcy's law, increases from 0.43D to 2.91D. Similarly, the pore-filling type model has an initial hydrate saturation of 36.6% and its permeability increases from 0.43D to 2.64D. The relationship between permeability K and hydrate saturation Sh is linear, as the simulation area was divided into four equal parts. However, the relationship between thermal conductivity (λ) and hydrate saturation (Sh) in both models is non-linear, which calculated by the convective heat transfer formulation. As the hydrate saturation decreases, the equivalent thermal conductivity firstly increases exponentially and then linearly. The initial thermal conductivity λ of the two models is about 1.47, and the final λ of the grain-coating type is about 8.47, and the final λ of the pore-filling type is about 11.63. Both models split at around 2/3 of initial saturation. The thermal conductivity equivalent, λ, is exponential with saturation from the starting point to the cut-off point, but becomes linear when saturation is less than the cut-off point. The exponential approximation is due to the high proportion of hydrates and the gradual weakening of the thermal diffusion rate compared to the convective heat transfer rate.

To investigate the multi-field coupling effect of TFMC, we analysed the flow rate (seepage field), the initial hydrate saturation Sh (solid field) and the activation energy ΔE or phase change potential ΔH (chemical field). Changes in velocity will not affect the linear relationship of permeability, but will significantly increase thermal conductivity and shorten the nonlinear section. The changes of initial hydrate saturation Sh will not affect the linear law of permeability, but it is necessary to increase the number of calculated partitions to make the results more linear. The demarcation point of equivalent thermal conductivity is kept on about 2/3, only the final results are changed. The activation energy change (ΔE) and phase change potential (ΔH) indicate different types of hydrates. The permeability or equivalent thermal conductivity do not change significantly.

In summary, the DDF-LBM can be used to simulate the unsteady convective heat transfer process of hydrate dissolution. According the above analysis, more accurate parameters can be provided for thermal flow mining natural gas hydrate under seafloor, which considering the multi-field coupling conditions of TFMC.

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Primary authors: LI, Zhengyi (China University of Petroleum (East China); University of Science and Technology Beijing); Prof. WANG, Zhiyuan (China University of Petroleum (East China))

Co-authors: Prof. XIE, Chiyu (University of Science and Technology Beijing（USTB）); Prof. SONG, Hongqing (University of Science and Technology Beijing （USTB）); Prof. ZHANG, Jianbo (China University of Petroleum (East China))

Presenter: LI, Zhengyi (China University of Petroleum (East China); University of Science and Technology Beijing)

Session Classification: MS09

Track Classification: (MS09) Pore-scale modelling