

Review

Modeling and Numerical Investigations of Gas Production from Natural Gas Hydrates

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Abstract: As ice-like crystals and non-stoichiometric compounds comprising gas and water, natural gas hydrates have drawn significant attention as a potential alternative energy source. This work focuses on holistically reviewing theoretical modeling and numerical studies conducted on the production of gas from natural gas hydrates. Firstly, fundamental models for the dissociation of a hydrate in a porous sediment are summarized in terms of the phase equilibrium and dissociation kinetics. The main features of different models and improvements for them are identified by clarifying crucial driving mechanisms and kinetic parameters. Subsequently, various numerical works addressing the dissociation of a hydrate in a porous sediment and the flow characteristics in a wellbore are reviewed, including aspects such as the theoretical background, computational scheme, and the physics involved. In general, profiting from a significant capacity to solve nonlinear differential equations, numerical simulations have contributed to great progress in fundamentally understanding the mechanism driving gas production and in developing effective exploitation methods. Owing to the substantial fundamental physics involved in the exploitation of natural gas hydrates, existing challenges, alternative strategies, and future directions are provided correspondingly from a practical application perspective.

Keywords: natural gas hydrates; hydrate exploitation; theoretical model; numerical simulation; multiphase flow; heat and mass transfer



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1. Introduction

Known as combustible ice, natural gas hydrates are ice-like crystals and non-stoichiometric compounds comprising gas and water [1]. Gas molecules (such as ethane, methane, and carbon dioxide) are enclosed by hydrogen-bonded water molecules. Because of their need for high-pressure and low-temperature environments, natural gas hydrates are commonly found and distributed in subsea sediments and permafrost zones [2,3]. Compared with fossil fuels, natural gas hydrates present a series of advantages, such as rich reserves, low levels of pollution, and high energy densities and have consequently drawn significant attention as a potential alternative energy source [4]. Since the first report by Davy [5], several countries have achieved great progress in exploring trial production techniques [6–9]. In particular, the China Geological Survey recently carried out a secondary trial production in the Shenhu Sea Area of the South China Sea, and continuous production for 30 days was successfully achieved with a total gas output of 861,400 m³ and the daily production of 28,700 m³ of gas [9]. The production feasibility of natural gas hydrates was further confirmed for commercial development in the future.

It has been determined that more than 95% of the total hydrate reserves are focused in deep subsea areas [10]. As a complex compound, the formation of a natural gas hydrate at the microscopic scale is a time-dependent kinetic, time-independent thermodynamic, and statistically random process and is strongly related to the specific environment it occurs in [11,12]. Once crystal embryos are formed, intrinsic kinetics, as well as heat and mass transfer in a separate or coupled manner, drive the hydrates' growth. With continuous efforts in the last two centuries, the underlying basic physics of the nucleation and growth kinetics of gas hydrates has been comprehensively and systemically elucidated with great progress, guiding significant advances in engineering exploitation and utilization with the controllable formation and growth of hydrates [12].

Currently, various methods of exploitation, such as depressurization, solid fluidized mining, thermal stimulation, and the injection of chemical additives, are being proposed to exploit natural gas hydrates [7–9,13,14]. By continuously supplying artificial heat to the hydrate reservoir, thermal stimulation is utilized to modify the reservoir's thermodynamic conditions and consequently provoke the dissociation of hydrates [8]. The method of injecting chemical additives aims to shift the hydrate's phase equilibrium and achieve hydrate dissociation under local pressure–temperature conditions [13,14]. Among these methods, the depressurization method presents great development potential due to its economical and effective advantages and has been successfully used in record production tests conducted by the China Geological Survey [9], as illustrated in Figure 1. In this method, a downhole electric submersible pump in the production well is utilized to reduce the pressure of the hydrate reservoir close to the wellbore. The pressure variation causes the dissociation of the solid hydrate, resulting in the production of gas [15–17]. On the one hand, a controllable pressure difference is crucial to maintaining stable and efficient production. Real production commonly involves fluctuating production rates of gas and water [18]. On the other hand, in real production systems, a multiphase, multicomponent flow composed of soil particles, hydrate particles, gas, and water can remarkably influence the reservoir and wellbore pressure [15,19]. During production, the flow system is simultaneously accompanied by the growth, fragmentation, and aggregation of hydrate particles [20,21]. Therefore, an understanding of gas–liquid–solid multiphase flow characteristics coupled with the nucleation and growth kinetics of hydrate particles is crucial for developing a controllable technique of exploiting natural gas hydrates.

In general, the exploitation of natural gas hydrates involves extensive basic issues, such as dissociation kinetics, thermodynamics, multi-scale characterization, heat and mass transfer, and multiphase–multicomponent flows [12,15,21,22]. These issues are strongly coupled with each other and simultaneously define production factors and efficiency. Because of a lack of complex geologic parameters and real production data, modeling and numerical investigations play crucial roles in the exploitation of natural gas hydrates and facilitate exciting progress in understanding the physical mechanism from the system scale to the laboratory scale [22,23]. However, due to the extreme complexity of this theme, existing modeling and numerical investigations are commonly implemented with excessive assumptions and simplifications which significantly deviate from realistic exploitation conditions. Hence, from the perspective of realistic exploitation, this review focuses on holistically summarizing theoretical modeling and numerical studies conducted on the production of gas from natural gas hydrates, including fundamental models of natural gas hydrates (such as phase equilibrium and dissociation kinetics models) and a numerical model of the dissociation of a hydrate in a porous sediment and the flow characteristics in a wellbore. The mechanistic understanding, model development, and a numerical scheme with key issues and a knowledge of gas are reviewed and discussed for their application in realistic exploitation. Finally, existing challenges, alternative strategies, and future directions are correspondingly provided to promote efficient production strategies.

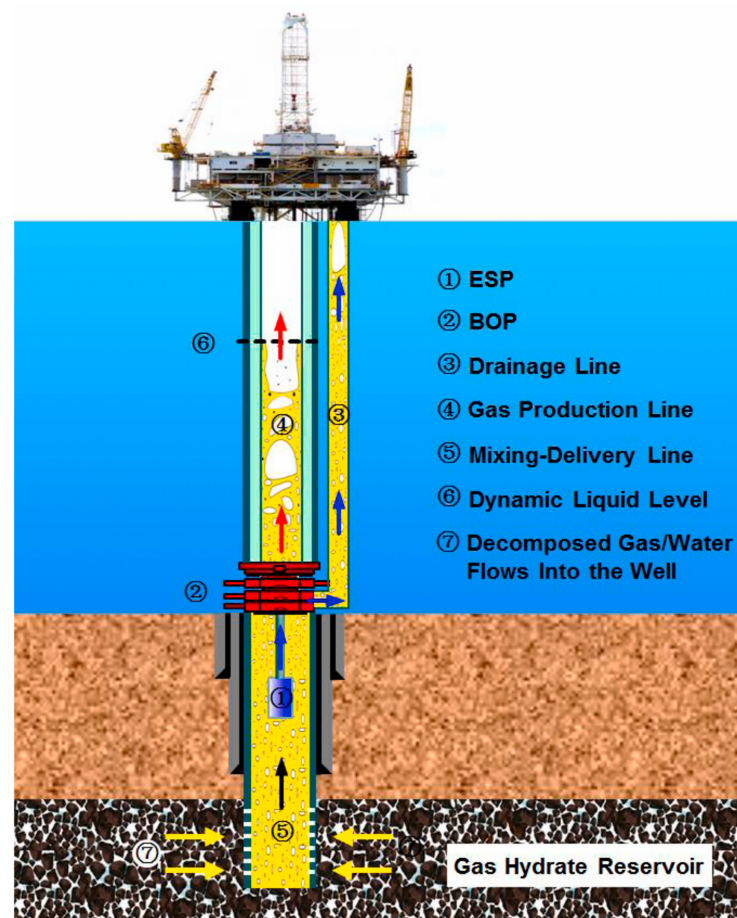


Figure 1. An illustration of a marine production system using the depressurization method for natural gas hydrates [15]. ESP: electric submersible pump; BOP: blowout preventer.

2. Fundamental Models for Natural Gas Hydrates

2.1. The Equilibrium of Natural Gas Hydrates

High-pressure and low-temperature environments are crucial for the stable existence of natural gas hydrates. The thermodynamic equilibrium characteristics of natural gas hydrates could dictate critical pressure and temperature information for the formation and dissociation of hydrates and dissociation and can be consequently seen as the most fundamental and primary issue for hydrate exploitation. Modeling efforts from the perspective of thermodynamic dynamics have been continuously devoted to exploring the equilibrium characteristics of natural gas hydrates [22,24]. Significantly, Van der Waals and Platteeuw [25] first developed a classical chemical potential model for a hydrate–water system and predicted the equilibrium pressures for various gases. Subsequently, various equilibrium models were proposed on the basis of the van der Waals–Platteeuw model [26,27]. Subsequently, with the consideration of hard-sphere repulsion, hard-chain formation, dispersion, and association, Li et al. [28] utilized an equation of state based on the statistically associating fluid theory to consider the thermodynamically inhibiting effects of various gases on the formation of gas hydrates. The predicted equilibrium conditions were found to have excellent agreement with the measured results. Chen and Guo [29] first proposed a two-step formation mechanism with a quasi-chemical reaction process for a basic hydrate as a first step and the process of the absorption of gas molecules in the linked cavities as a second step. Based on this novel mechanism, they proposed a simple equilibrium model by combining the chemical reaction and physical absorption equilibrium. The model’s accuracy was verified by obtaining substantial measurements for different pure gases and mixtures. Generally, various equilibrium models have been

developed successfully and provide accurate predictions for the equilibrium characteristics of bulk hydrates [30].

It should be noted that the environment of the porous media in a real hydrate deposit is a crucial issue for the equilibrium conditions of hydrates. Hence, considerable efforts have been made to develop thermodynamic models for the equilibrium of hydrates in porous media. Based on the van der Waals–Platteeuw model, Clarke et al. [31] introduced the Kelvin equation to consider the capillary effect and realized a prediction of hydrate equilibrium conditions in porous media. Following the same approach, the Gibbs–Thomson equation was used to define the capillary effect [32]. Notably, based on equal fugacities and equal activities, Li et al. [33] proposed two thermodynamic methods for predicting hydrate equilibrium conditions in porous media. The Trebble–Bishnoi equation and the Soave–Redlich–Kwong equation were employed in the fugacity and activity approaches for the non-hydrate phase, respectively. The hydrate phase was considered by combining the van der Waals–Platteeuw model and the capillary model in these two approaches. Furthermore, substantial improvements, such as a realistic distribution of pore size [34] and the introduction of a contact angle model [35], were carried out to provide an accurate prediction.

In conclusion, modeling progress makes it practicable to fundamentally reveal the underlying equilibrium characteristics of natural gas hydrate deposits and define hydrate dissociation conditions when designing an exploitation strategy. However, investigations of hydrate equilibrium are still far from completed because of the complex geological conditions of the hydrate reservoir and the variable coexistence of hydrates. High-accuracy thermodynamic models which consider the realistic effect of the porous media are highly desirable for the accurate determination of hydrate equilibrium conditions.

2.2. Dissociation Kinetics of Natural Gas Hydrates

The nucleation, growth, and dissociation of natural gas hydrates commonly occur in porous media and depend not only on the temperature and pressure but also the characteristics of the porous media [1,3]. Multiple physics processes, i.e., heat and mass transfer, multi-component, multi-phase fluid flow, and intrinsic kinetics, strongly interact with the porous media during the nucleation, growth, and dissociation of the hydrate [22,24,36]. It is equally important to establish systematic understanding in the form of a complete circle, i.e., nucleation–growth–dissociation. It should be noted that the current work aims to summarize modeling and numerical investigations for the exploitation of natural gas hydrates. Hence, the production of gas from natural gas hydrates, namely the dissociation of the hydrates, is specially focused on. Understanding the dissociation kinetics of natural gas hydrates is essentially important to progressing the production of natural gas hydrates. On the small/experimental scale, early studies mainly focused on exploring the dissociation kinetics of natural gas hydrates in a bulk system [37]. A stirred semi-batch tank reactor was used to sustain isothermal and isobaric conditions. It was experimentally demonstrated that the kinetics of a hydrate are remarkably affected by the bulk temperature, pressure, supercooling, and gas–water contact area [38]. The available kinetic models were developed on the basis of the two-film theory and crystallization [39]. Further modeling investigations demonstrated that the intrinsic dissociation kinetics governed by pressure, temperature, the interfacial area, and the intrinsic rate constant significantly dominate gas production [40,41].

In comparison with the case of the bulk system, dissociation kinetics in porous media are more practical and complicated. Substantial efforts have been continuously devoted to developing a comprehensive model by coupling all the primary physics through the porous media, including the heat and mass transfer, multi-component, multi-phase fluid flow, and intrinsic dissociation kinetics [42,43]. Different models which consider several of or either of these physics under different conditions were developed, achieving great progress in understanding the dissociation kinetics of natural gas hydrates in porous media, as summarized in Table 1. In 1987, Kim et al. [40] carried out an experimental

investigation to determine the dissociation kinetics of a methane hydrate with the help of a semi-batch stirred-tank reactor. Hydrate dissociation was achieved by reducing the pressure of the hydrate slurry in a pure water system under an isothermal condition. The Kim–Bishnoi intrinsic kinetic model was correspondingly proposed, considering the intrinsic dissociation kinetics for the first time [40]. Neglecting the heat and mass transfer, the hydrate dissociation was simplified into two steps, namely the destruction of the clathrate lattice and the desorption of gas on the particle's surface, as illustrated in Figure 2. Accordingly, the difference in fugacity between the gas and the hydrate's solid phases at equilibrium was solely defined as the driving force for the dissociation. The Kim–Bishnoi model correspondingly constructed a proportional relationship between the dissociation rate and the interfacial area and the intrinsic rate constant. As the most fundamental and classical model for understanding the kinetics of hydrate dissociation, the Kim–Bishnoi model is continuously improved and extended to consider the effects of particle size [44] and mixed gases [45,46].

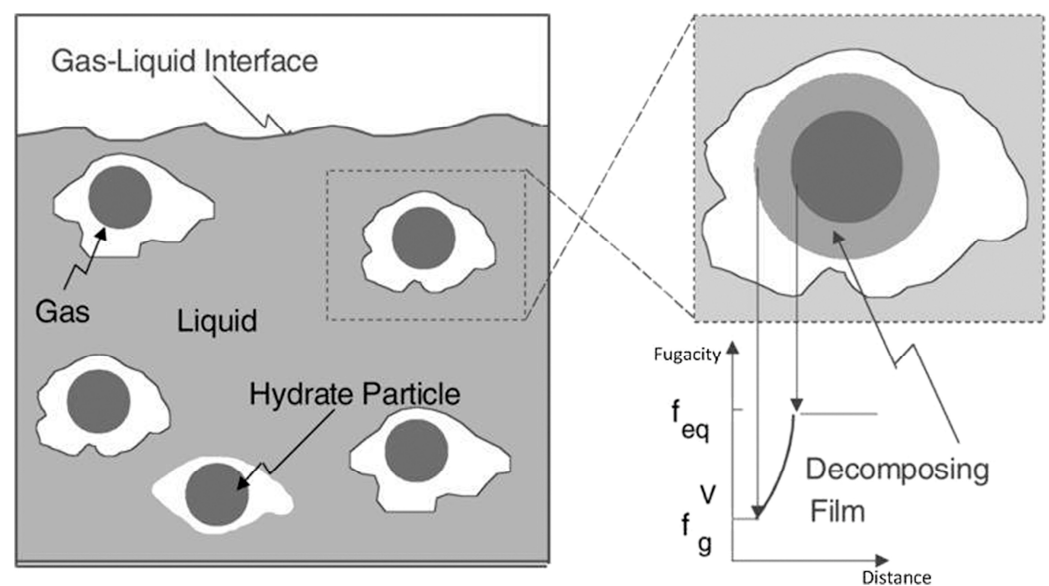


Figure 2. An illustration of the mechanism of the dissociation of a hydrate in a bulk system [42,43]. The driving force of the dissociation is defined as the difference, $f_{eq} - f_{eq}^v$, between the fugacity of the gas at the equilibrium (f_{eq}) and the fugacity of the gas at the solid surface (f_{eq}^v).

Another classical dissociation model considering thermal stimulation was proposed by Selim and Sloan [36]. The distribution of the hydrate in the porous media is seen as a one-dimensional and planar, semi-infinite system with constant physical properties, as illustrated in Figure 3. Initially, a constant heat flux is imposed on the hydrate's surface to increase its temperature to the equilibrium temperature. Subsequently, dissociation happens with a moving front along the positive x direction, and the moving surface is constantly maintained at the equilibrium temperature. With an assumption that the formed water phase is fully removed during dissociation due to gas purging, the dissociation of the hydrate is simplified into a problem of moving-boundary ablation at a constant heat flux, and heat transfer with constant physical properties is considered for the hydrate bulk. The system is consequently divided into two regions, namely the dissociated region containing the water and gas phases as well as the undissociated region containing the solid hydrate. Based on the measurements, the reliability of the Selim–Sloan model has been validated [47]. Although the intrinsic dissociation kinetics and mass transfer are neglected, the Selim–Sloan model provides a feasible method for studying heat transfer within the porous media and dissociation front.

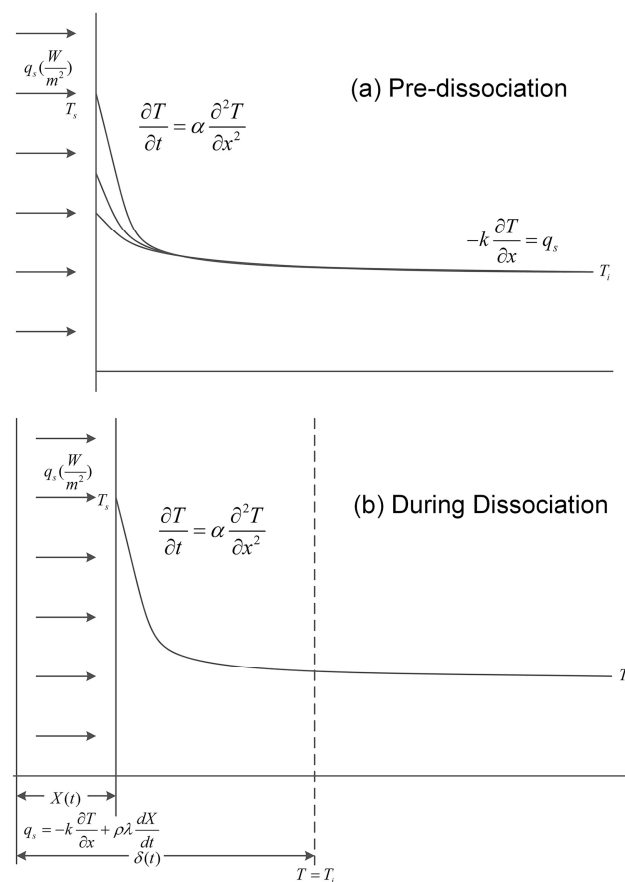


Figure 3. An illustration of the dissociation of a hydrate treated as a moving-boundary ablation problem [36,42]. The bulk of the hydrate is assumed to be in the semi-infinite zone with $0 < x < \infty$ along the x -axis. In the pre-dissociation stage, a fixed heat flux q_s is imposed on the hydrate's surface $x = 0$. During the dissociation, on the y -axis, the hydrate's temperature T_i will be gradually raised to the equilibrium temperature at the hydrate's surface T_s .

Table 1. Summary of dissociation kinetics models of gas hydrates.

Authors	Heat Transfer	Intrinsic Kinetics	Fluid Flow	Porous Media	Model Approach
Kim et al. [40]	—	✓	—	—	Analytical
Selim and Sloan [36]	✓	—	✓	✓	Analytical
Jamaluddin et al. [48]	✓	✓	—	—	Numerical
Yousif et al. [49]	—	✓	✓	✓	Numerical
Hong et al. [50,51]	✓	✓	✓	✓	Analytical
Li and Zhang [52]	✓	—	—	✓	Analytical

Subsequently, various dissociation kinetic models were developed considering dissociation mechanisms [42]. By coupling the Kim-Bishnoi model and the Selim–Sloan model, Jamaluddin et al. [48] developed a kinetic model which considers both heat transfer and the intrinsic kinetics. Following the Kim–Bishnoi model, the dissociation rate of the hydrates was defined in the form of the intrinsic kinetic rate, which was coupled with the heat transfer solution, following the Selim–Sloan model. This model guided the coupling of different dissociation regimes. For the first time, Yousif et al. [49] developed a one-dimensional, three-phase model for the production of gas using a depressurization approach which significantly considers the flow of the fluid in porous media by embedding Darcy's equation into the mass and energy equations. Linearization and iterative solutions were carried out for these nonlinear conservation equations. Significantly, Hong et al. [50,51] proposed a simple analytical model for the dissociation of a hydrate in porous media using the

depressurization method. Referring to the real conditions of a hydrate reservoir, three primary regimes, including heat transfer, fluid flow within the porous media, and intrinsic dissociation kinetics, were comprehensively considered in this model [50]. Heat transfer in the hydrate region was treated as a melting boundary problem. The intrinsic dissociation kinetic was solved following the Kim–Bishnoi model. The gas–water two-phase flow within the porous media was incorporated using Darcy’s law. At the dissociation interface, a mass balance was employed to implement the coupled solution. Recently, considering the self-similarity characteristics of the porous sediment, Li and Zhang [52] used a fractional number to define the irregular geometry of the hydrate particles and proposed a fractional shrinking-core model which referred to a shrinking-core dissociation process of the hydrate in the porous media, as illustrated in Figure 4a,b. One significant feature of this model is the introduction of a fractal analysis which can eliminate mathematic iteration and self-replication.

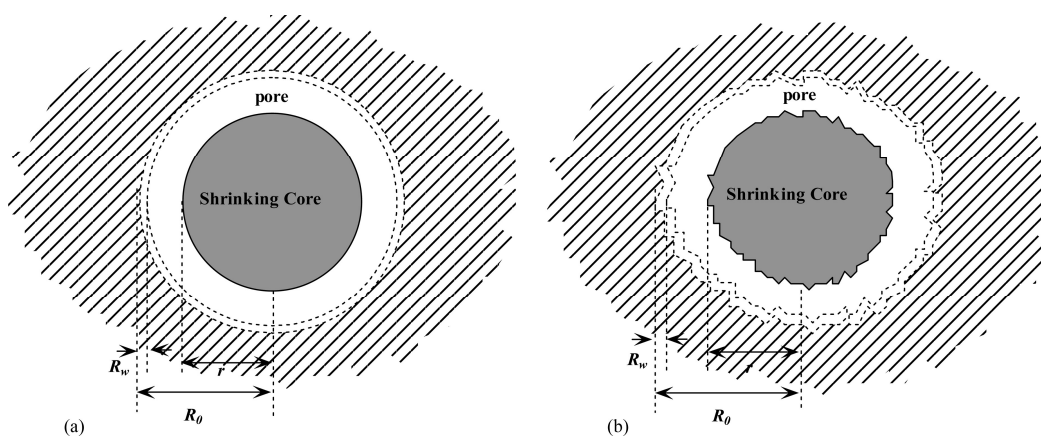


Figure 4. An illustration of the fractal-dimension shrinking-core model with the radius of unreacted core r , the averaged core radius of the porous media R_0 , and the thickness of the bound water layer R_w [52].

Apart from macroscopic modeling studies, molecular dynamic (MD) simulations have been widely utilized as effective tools for studying the dissociation kinetics of natural gas hydrates at the microscopic molecular level [42]. MD simulations can depict the dissociation kinetics of natural gas hydrates occurring at the nanometer and nanosecond scales, which is greatly challenging to achieve via the experimental methods. Substantial MD studies have been carried out to simulate hydrate dissociation, including the successive dissociation mechanisms, coupled heat and mass transfer during dissociation, and the formation dynamics of nanobubbles. Using the MD method, Ding et al. [53] numerically studied hydrate dissociation at the microscopic molecular level. It was found that hydrate dissociation occurs in two successive stages. The first stage refers to the diffusion process of the host molecules which is responsible for the fracture of the lattice structure. The second stage corresponds to the escape of methane molecules from the cavities and aggregate. This two-step dissociation mechanism remains consistent with previous work by Kim et al. [40]. Bagherzadeh and his coworkers [54,55] carried out an MD simulation to quantify the dissociation rate of a hydrate under non-equilibrium conditions and the dissociation rate of a hydrate in contact with a silica surface. Via MD simulations, Bai et al. [56] demonstrated that during dissociation, the coupling of heat and mass transfer resistance in the solid-like layer of water on the hydrate’s surface plays a dominant role in the self-preservation effect. Recently, Bagherzadeh et al. [57] carried out MD simulations, aiming to study the formation conditions of methane nanobubbles and to clarify the influence of nanobubbles on the dissociation rate.

Although various kinetic models and MD studies with different aspects have greatly progressed our fundamental understanding of dissociation kinetics of hydrates, there are

still some limitations on achieving a comprehensive consideration of the driving mechanisms due to excessive assumption and simplification. The main reason is that the dissociation of a hydrate strongly depends on the special porous characteristics of the sediments and the complex reservoir environments involved. First, in defining the intrinsic rate constant and the heat transfer within the porous media, the permeability and porosity of the porous media are commonly assumed to be constant. However, these characteristic parameters undergo time-dependent variations during the dissociation of the hydrate. It is crucial to comprehensively understand the effects of the varying porous characteristics on the intrinsic kinetics and heat transfer. In addition, for simplification, Darcy's law was used to couple the two-phase gas–water flow during the dissociation of a hydrate. The underlying assumption is that the porous media are isotropic and homogeneous, with a slow and viscous fluid flow. As a crucial driving mechanism, the effects of the particle size and the deformation of the porous media on the fluid flow are neglected. The effect of the fluid flow in the field-scale process becomes more important in comparison with the laboratory and reservoir scales. Meanwhile, when solving nonlinear conservation equations, those kinetic models are limited in terms of accuracy due to the linearization approach. In general, a more comprehensive and accurate modeling method covering all the key driving mechanisms and approaching reality is highly desirable and remains a great challenge.

3. Numerical Simulations for Hydrate Exploitation

3.1. Numerical Simulations for the Dissociation of Hydrates in Sediments

With great developments in scientific computing, a numerical method which uses the discretization method to solve a series of differential equations has been developed as an excellent tool for complex multi-physics coupling problems and has been successfully used in the natural gas hydrate research community [22,24,42]. Compared with theoretical and analytical methods, the numerical method can provide a more comprehensive consideration of the driving mechanism and accurate predictions for the dissociation of hydrates at various scales and under various boundary conditions. For example, the fluid flow through the porous media in the dissociation of a hydrate is defined using Darcy's law for simplification in the theoretical and analytical approaches. However, using the numerical method, the complete forms of the Navier–Stokes equations for the fluid flow can be solved directly with consideration for the effect of the hydrate particles. Profiting from its significant advantages, the numerical method has made great progress in the hydrate dissociation and the production process, involving multiple physics and their coupling effects, e.g., heat and mass transfer, intrinsic kinetics, and multiphase flow in porous media.

Substantial numerical efforts have been devoted to simulating the dissociation kinetics in the hydrate-bearing sediments using the computational fluid dynamics (CFD) method [16,58–70]. Nazridoust and Ahmadi [58] carried out the first attempt to numerically model the dissociation of a hydrate in a porous sandstone core. Considering the hydrate dispersed in the pores, an axisymmetric core model was constructed including three phases (hydrate, gas, and water). The continuity equations of different phases and the energy equations for the effective medium were solved for the multiphase flow and thermal characteristics, and Darcy's law was used to consider the fluid flow within the porous media. Using a Users' Defined Code, the source/sink terms were incorporated into the governing equations to consider the dissociation rate, the absorbed heat, and the generation of gas and water [40,59]. In addition, the time-dependent variations in the relative permeability and effective porosity of the core during dissociation were included using Corey's model [60]. With this two-dimensional model, the temporal and spatial evolutions of the pressure, flow, and temperature profiles in the sandstone core were numerically evaluated, considering different temperatures, outlet pressure, and permeability conditions. Corresponding to the experimental investigation of the dissociation of a hydrate, Sean et al. [61,62] further performed a CFD simulation. Significantly, the kinetic model considered the Gibbs free energy difference between the hydrate's phase and the surrounding aqueous phase as the driving

force. The dissociation of the hydrate under the water flow conditions was numerically studied using the developed kinetic model. The dissociation rate constant was defined by combining the measured overall dissociation rate with the computed concentration distribution of methane. It found that the dissociation rate constant is independent of the water flow rate and the pressure, indicating the intrinsic nature of the rate constant.

Similar to the model developed by Nazridoust and Ahmadi [58], Liang et al. [63] developed a two-dimensional axisymmetric model to carry out a CFD simulation for the dissociation of a hydrate in a cylindrical, porous core sample using the depressurization method at the laboratory scale. Governing equations considering the mass transfer, energy conservation, and intrinsic kinetics were numerically solved using the finite difference method. Several crucial parameters, including the outlet pressure, initial gas saturation, surrounding temperature, and core permeability, were studied for the rate of gas generation. Subsequently, this model was further extended to study the hydrate's dissociation characteristics, considering thermal injection, microwave stimulation, a combined production method, and soil compressibility [16,64–66]. Recently, Chen et al. [67] developed a two-dimensional, core-scale numerical model which considers the multiphase dissociation flows of hydrates within porous media. They especially focused on the thermal boundary effects and depressurization process, as well as the corresponding parametric influence on the core-scale internal flow. It should be noted that a solid hydrate can be seen as a part of the solid frame of the sediments. The dissociation of the hydrate will alter the porous structure, resulting in a variation in the reservoir's permeability and porosity. The multiphase flow in the porous media is consequently affected during dissociation. Therefore, understanding the complex thermal–hydrodynamic–mechanical–chemical coupled characteristics is essential and has been widely explored [22,68–73]. Based on the hybrid finite volume and finite element method, Wan et al. [71] developed a thermal–hydrodynamic–mechanical–chemical coupled model to evaluate the fluid flow in the hydrate-bearing sediment and its geomechanical characteristics. Recently, based on a formation experiment on a methane hydrate via the excess water technique in a small reactor with sandy porous media [72], Yin et al. [73] developed an inverse modeling approach using the TOUGH (Transport of Unsaturated Groundwater and Heat) + HYDRATE code and studied the spatially heterogeneous dissociation characteristics via depressurization, as shown in Figure 5. So far, various numerical models for the dissociation of a hydrate have been developed with great success to consider the driving mechanisms via different methods [24,67].

3.2. Numerical Simulations for the Flow Characteristics of Hydrates in a Wellbore

Well drilling in hydrate-bearing sediments is of great importance for the development and exploitation of gas hydrates [22,24]. Similar to the dissociation of hydrates in sediments, the drilling process also involves complex multiphysics coupling [74], as illustrated in Figure 6. Different phases, including sediment particles, hydrate particles, gas, and water, form a multiphase flow in the wellbore. Due to the specific environmental conditions, the hydrate particles in the flow system present complex dynamics, including growth, dissociation, aggregation, and fragmentation. The transport of heat, mass, and momentum between phases commonly occurs during the drilling process. Therefore, the multiphase flow in the wellbore is coupled with the complex dynamics of the hydrate particles as well as heat, mass, and momentum transport. Understanding such a complex multiphysics coupling problem plays a crucial role in achieving the controllable exploitation of gas hydrates through drilling.

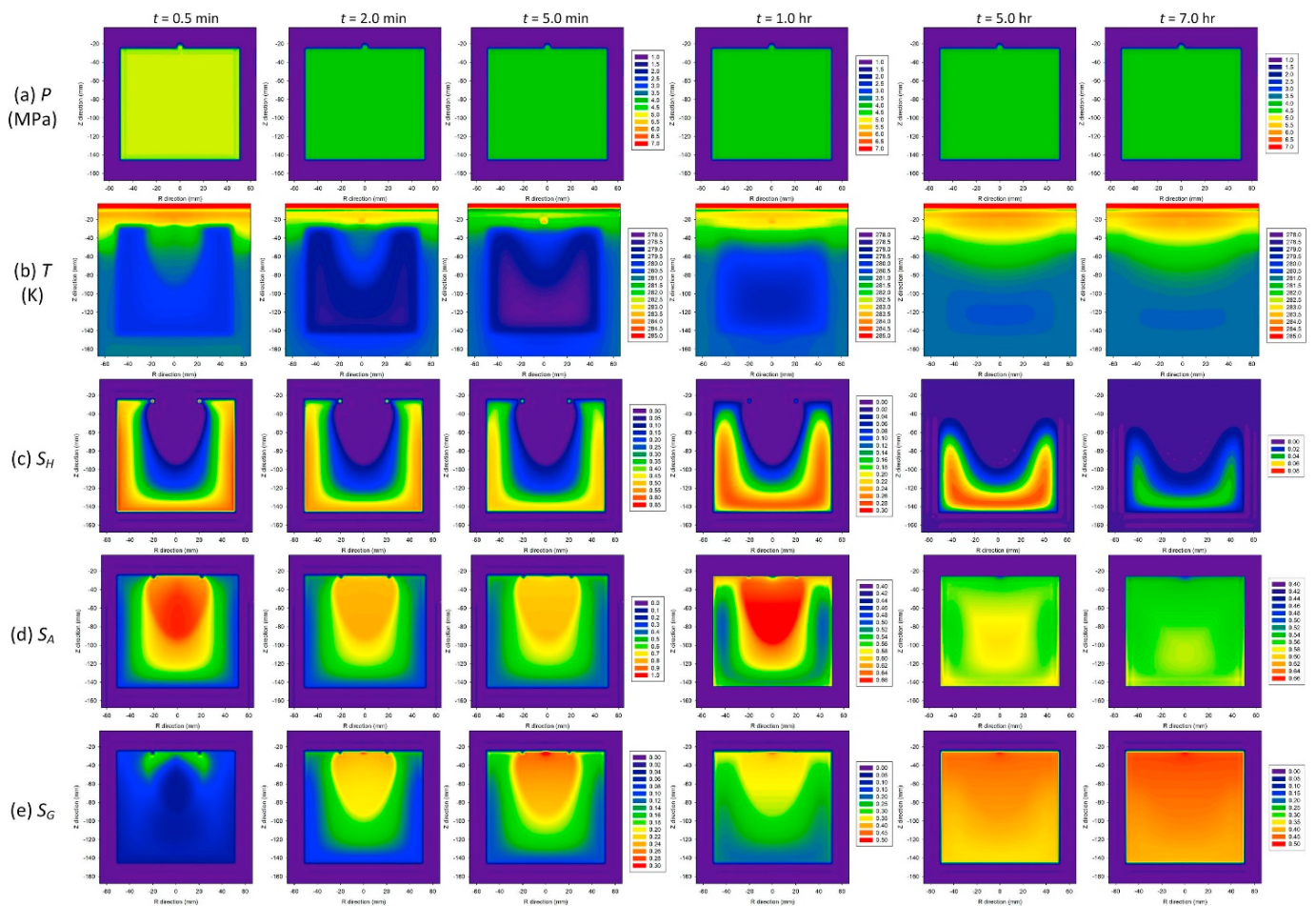


Figure 5. The spatial distributions of the pressure P , temperature T , and phase saturation (S_H for the hydrate phase, S_A for the aqueous phase, and S_G for the gas phase) over time [73].

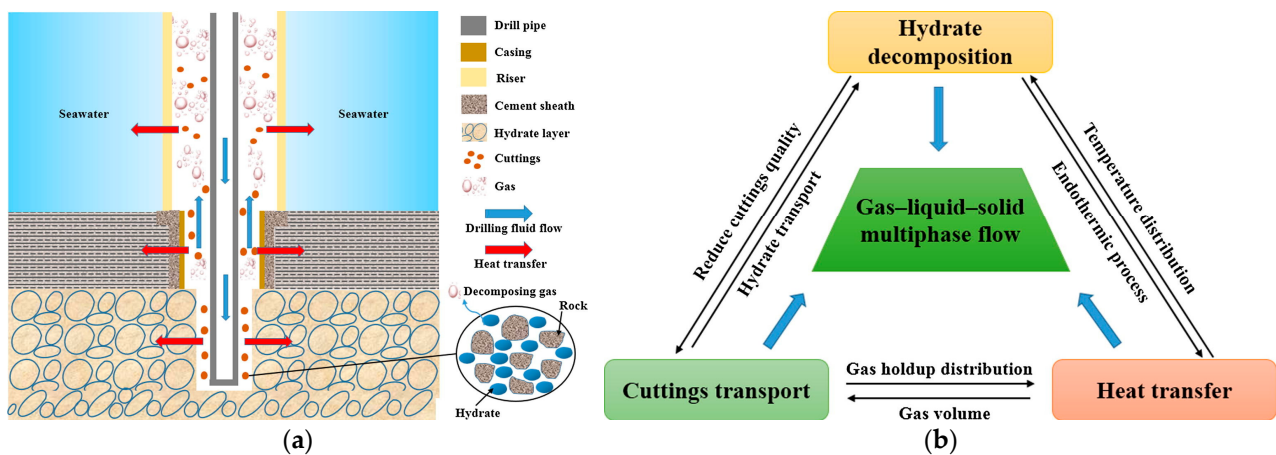


Figure 6. Well drilling in a hydrate-bearing sediment [74]: (a) mechanisms of multiphysics coupling; (b) inter-coupling of hydrate decomposition, cuttings transport and heat transfer.

Due to harsh environmental conditions and the complexity of the drilling process, experimental investigations are remarkably limited. By coupling the successfully developed dissociation model discussed in Section 2 with a multiphase flow, the flow characteristics in the wellbore or the production tube were numerically studied with great success [15,21,22,24,75]. Balakin et al. [76,77] developed an Eulerian–Eulerian CFD model to simulate the multiphase flow and deposition characteristics of hydrate particles in a

laboratory-scale low-pressure flow loop. Based on the Eulerian–Eulerian two-fluid model, Xu et al. [78] further introduced the population balance theory (PBM) for considering the particle dynamics of hydrates, as shown in Figure 7. Based on the multiphase flow model, the pressure-drop characteristics [21,79–81], the flow regimes [79,80], and the critical factors for the safe flow of hydrate slurry [82,83], have been explored widely. Furthermore, extensive efforts have been devoted to developing a multiphysics coupling model. Wei et al. [84] developed a coupled model including the temperature and pressure models in the wellbore, a dynamic dissociation model, and a multiphase flow model. The developed numerical model was used to study the interrelationships of the varying pressure, temperature, dissociation rate, hydrate dissociation, phase contents, and velocities in the wellbore. Based on a gas–liquid–solid three-phase model, Li et al. [85] further considered the kinetic dissociation of hydrate particles by introducing source terms into the conservation equations to describe the interphase heat, mass, and momentum exchange. The interaction of the multiphase flow and the dissociation of the hydrate were analyzed. Coupling the multiphase flow model with the transfer of heat between the wellbore and reservoir, Gao et al. [86,87] studied the effects of the temperature and pressure at the bottom of the wellbore on a hydrate with a riser and without a riser. Considering the interactions between the hydrate’s dynamic dissociation, the transport of cuttings, and heat transfer in the multiphase flow system, Liao et al. [74] developed a coupled transient gas–liquid–solid flow model. The effects of the wellhead pressure, the density of the drilling fluid, and the injection temperature on the multiphase flow characteristics were studied comprehensively. Recently, Kang et al. [88] combined the developed annulus hydrate slurry multiphase flow model with the hydrate dissociation kinetic model and the thermal model and numerically simulated the multiphase upward flow of a hydrate slurry in a vertical, concentric annulus. A series of influence factors were discussed in terms of the flow pattern, the dissociation of the hydrate, and the production of gas.

Due to their great capacity to solve nonlinear differential equations, numerical models have greatly contributed to progress in fundamentally understanding the complex multiphysics process of the dissociation of a hydrate in the sediment and flow system during drilling. Table 2 provides a summary of numerical simulations of the dissociation of a hydrate in a sediment and flow system during drilling. However, owing to the complexity and vastly different driving factors for each specific case, more comprehensive and precise numerical models considering all factors and with a clearer and more accurate picture for each driving mechanism are highly desired. Furthermore, the indications and the relationship between the core-scale model and real, field-scale production should be provided more attention from the perspectives of both understanding the mechanism and real production.

Table 2. Summary of numerical simulations of hydrate dissociation in a sediment and wellbore.

Authors	Multiphysics Process	Numerical Approach	Research Object
Nazridoust and Ahmadi [58]	Heat and mass transfer, fluid flow, intrinsic kinetics, and porous media	Two-dimensional CFD	Porous sandstone cores
Sean et al. [61,62]	Heat and mass transfer, fluid flow, and intrinsic kinetics	Three-dimensional CFD	Hydrate balls at the laboratory scale
Liang et al. [63]	Heat and mass transfer, fluid flow, intrinsic kinetics, and porous media	Two-dimensional CFD	Porous media at the laboratory scale
Chen et al. [67]	Heat and mass transfer, fluid flow, intrinsic kinetics, porous media, and three-phase gas–liquid–solid flow	Two-dimensional CFD	Porous sandstone cores
Wan et al. [71]	Heat and mass transfer, intrinsic kinetics, porous media, multi-phase flow, and geomechanical solid deformation	The volume finite element method coupled with the finite element method	Porous sandstone cores

Table 2. Cont.

Authors	Multiphysics Process	Numerical Approach	Research Object
Balakin et al. [76,77]	Two-phase liquid–solid flow	Three-dimensional Eulerian–Eulerian CFD	Slurry flow in pipelines
Xu et al. [78]	Heat and mass transfer, intrinsic kinetics, two-phase liquid–solid flow, and the dynamic evolution of the hydrate particles	Three-dimensional Eulerian–Eulerian CFD coupled with PBM	slurry flow in the horizontal pipe
Wei et al. [84]	Heat and mass transfer, intrinsic kinetics, and two-phase gas–liquid flow	Two-dimensional self-developed code	Wellbore flow during drilling
Kang et al. [88]	Heat and mass transfer, intrinsic kinetics, and multi-phase flow	Two-dimensional self-developed code	Slurry flow in the annulus

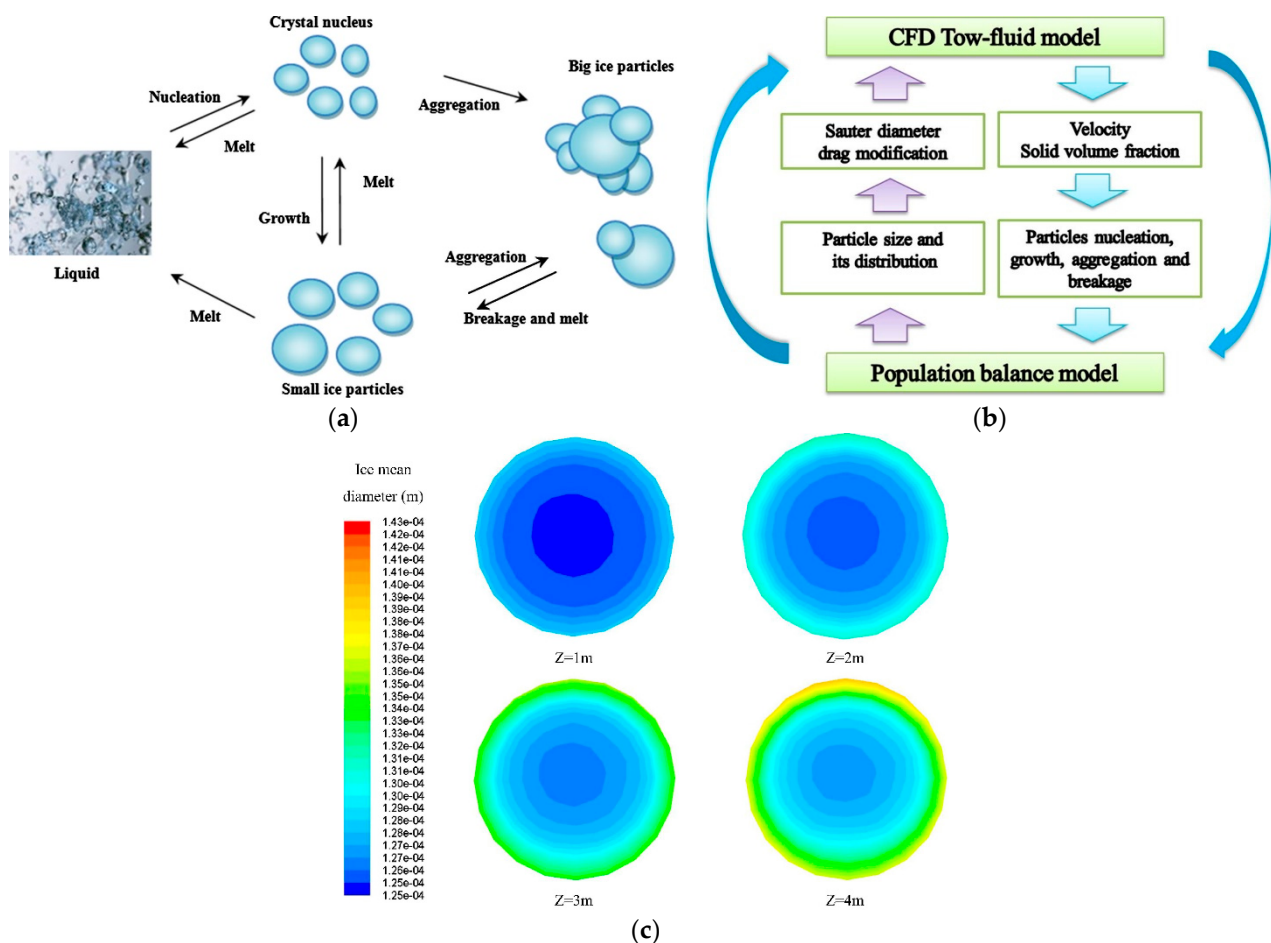


Figure 7. The CFD-PBM approach for the flow of ice slurry in horizontal pipes: (a) a schematic of the particle dynamics of hydrates; (b) the coupled framework of the CFD-PBM model; (c) the mean size contours of ice on distinct cross-sections along the flow direction (z is the axial distance) [78].

4. Conclusions

In this work, the research progress in the modeling and numerical investigation of the production of gas from natural gas hydrates was revised and outlined comprehensively. Firstly, fundamental models for the dissociation of a hydrate in porous sediment (including the phase equilibrium and dissociation kinetics) were reviewed and summarized. Subsequently, numerical simulations for the hydrate's dissociation in a porous sediment and the flow characteristics in the wellbore were presented and reviewed. Meanwhile, comments and further improvements were provided properly. In general, more efforts should be devoted to elaborately considering the effect of the porous characteristics of sediments

when studying the dissociation kinetics. On the one hand, the permeability and porosity of the porous sediments undergo time-dependent variations during dissociation and have considerable influences on defining the intrinsic rate constant and heat transfer. On the other hand, Darcy's law with isotropic and homogeneous assumptions overlooked the effects of the particle size and the deformation of the porous media on the fluid flow. Compared to the laboratory and reservoir scales, the effect of the fluid flow becomes increasingly important in the field-scale process and should be considered more. In the future, a more comprehensive and accurate kinetic model which covers all key driving mechanisms and approaches reality remains highly desirable. Numerical simulations with great capacity for solving nonlinear differential equations have offered great progress in understanding the complex multiphysics process of the dissociation of a hydrate in a sediment and the flow system during drilling. However, to be a typical multiphysics coupling problem, the production of gas from natural gas hydrates flexibly depends on different driving factors with variations in the reservoir characteristics. Therefore, we highlight that considerable efforts are still required to develop more comprehensive and precise numerical models which consider all factors and produce a clear and accurate picture of each driving mechanism for production. Furthermore, there is an urgent need to clarify the indication and relationship between the core-scale model and real, field-scale production. With the fast growth of computational power, a multiscale numerical scheme from the laboratory-scale core to field-scale production is highly desirable for both understanding the mechanism and developing efficient production strategies for natural gas hydrates.

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Nomenclature

f_{eq}	the fugacity of the gas at the equilibrium, pa
f_{eq}^v	the fugacity of the gas at the solid surface, pa
P	pressure, pa
q_s	the specified heat flux on the hydrate surface, $W\ m^{-2}$
r	the radius of the unreacted core, m
R_0	the averaged core radius of the porous media, m
R_w	the thickness of the bound water layer, m
SH	the phase saturation of the hydrate phase, -
SA	the phase saturation of the aqueous phase, -
SG	the phase saturation of the gas phase, -
T	temperature, k
T_i	the initial temperature of the hydrate, k
T_s	the equilibrium temperature at the hydrate's surface, k
x, y, z	components in the Cartesian coordinate system, m

Superscripts

A	aqueous
eq	equilibrium
G	gas
H	hydrate
s	the hydrate's surface

Abbreviations

BOP	blowout preventer
CFD	computational fluid dynamics
ESP	electric submersible pump
MD	molecular dynamic
PBM	population balance theory
TOUGH	transport of unsaturated groundwater and heat

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