

NUMERICAL SIMULATION OF GAS PRODUCTION FROM METHANE HYDRATE RESERVOIRS

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ABSTRACT

We present results of numerical simulation of gas production from methane hydrate reservoirs. A numerical simulator capable of simulating hydrate reservoirs was developed, based on the FEHM (Finite Element Heat and Mass) Computer Code, the Los Alamos National Laboratory (LANL)'s in-house porous flow simulator. The simulator was used to model gas production from a hypothetical hydrate reservoir under hot water injection and depressurization production schemes. A number of simulation runs were performed to determine the sensitivity of results to variation in values of different operational and reservoir parameters. The results show that the gas production predictions are sensitive to operational parameters such as injection temperature, injection rate and pumping well pressure. It was also observed that numerical grid size has significant impact on simulation results. Further work is needed to help understand the effect of variability in different parameters on numerical simulation results.

Keywords: Gas hydrates, numerical simulation, dissociation, kinetics, porous media

NOMENCLATURE

A_{HS} Hydrate surface area per unit volume [μm^{-1}]
 ΔE Activation energy [J/mol]
 f_e Equilibrium hydrate fugacity [MPa]
 f_g Gas fugacity [MPa]
 g Acceleration due to gravity [m^2/sec]
 h Enthalpy [MJ]
 k Intrinsic permeability [m^2]
 k_{eff} Effective permeability [m^2]
 k_l Relative permeability of phase 'l'
 k_d^0 Intrinsic dissociation constant [$\text{mol m}^{-2} \text{MPa}^{-1} \text{sec}^{-1}$]
 K Thermal conductivity [w/mK]
 \dot{m}_g Gas production rate due to dissociation [$\text{kg}/\text{m}^3\text{s}$]
 M_g Molecular weight of methane
 P Pressure [MPa]
 q_m Mass source/sink [kg/sec]
 q'_m Mass source/sink due to hydrate dissociation/formation [kg/sec]

q_e Energy source/sink [MJ/sec]
 q'_e Energy source/sink due to hydrate dissociation/formation [MJ/sec]
 R Universal gas constant [J mol/K]
 S_l Saturation of phase 'l'
 T Temperature [$^{\circ}\text{C}$]
 u Internal energy [MJ]
 u_r Internal energy of porous media [MJ]
 μ Viscosity [cP]
 ϕ Porosity
 ρ Density [kg/m^3]
 ρ_r Density of rock [kg/m^3]

INTRODUCTION

Hydrates of methane gas represent a substantial energy resource that is believed to exceed the total energy content of known fossil fuel reserves [1, 2]. Despite the vastness of this resource, it is not yet significantly exploited for energy. One of the reasons for this is the limitation in our understanding of how the hydrate reservoirs behave. A large amount of literature exists on the fundamental behavior of pure gas hydrates. On the other hand, hydrate behavior in porous media is

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not yet completely understood. Progress needs to be made to understand the reservoir scale behavior of hydrates, in order to determine how this energy resource can be efficiently and economically produced. Experiments to understand hydrate behavior in field are currently in progress, including, the Mallik project [3]. A number of papers have reported results of laboratory experiments on hydrate behavior in porous media [4, 5, 6, 7, 8, 9, 10, 11]. These studies have focused on understanding fundamental processes taking place in hydrate-bearing porous media under different production scenarios and on developing fundamental relationships to model these processes. In addition to the experimental work, numerical modeling studies on methane hydrate in porous media have also been reported. Currently, very few numerical simulators have the capability to model the flow and heat/mass transfer processes taking place in hydrate reservoirs [7, 12, 13, 14]. Very few numerical studies report on sensitivity studies focused on impact of model parameter variability and assumptions on simulation results. It is important to understand these effects, as large uncertainty exists in values used for field properties. Sensitivity studies not only identify impact of variability in parameter values on results but they can also be used to help identify areas where further research could be useful. In this paper we present results of a numerical modeling study on field scale simulations of production from a hypothetical hydrate reservoir. The numerical simulations were performed using a modified version of an existing code at the Los Alamos National Laboratory (LANL). The simulator was used to analyze data from laboratory experiments on hydrate dissociation, performed at the National Institute of Advanced Industrial Science and Technology (AIST), Japan. Results of that work have been reported in Pawar et al. [15]. The laboratory scale simulation study was extended to field scale.

DEVELOPMENT OF NUMERICAL SIMULATOR

The hydrate reservoir simulator was developed by modifying LANL's in-house porous flow simulator, FEHM (Finite Element Heat and Mass). FEHM is extensively used to simulate non-isothermal, multiphase flow and transport through both unsaturated and saturated porous media. It simulates flow of water/air and transport of heat and contaminants in 1-, 2- and 3-D heterogeneous

porous media. It can also be used to simulate fractured media using an equivalent continuum, discrete fracture, dual porosity or dual permeability approach. Information on the basic conservation equations, constitutive relationships and numerical methods in FEHM is given in [16, 17].

The basic FEHM code was modified to add the capability to simulate subsurface methane hydrate behavior. A kinetic rate based formulation was used to develop the equations for hydrate simulation. This was done because our work was initially focused on simulating laboratory experiments at which scale the kinetic effects are important. The formulation represented hydrate formation and dissociation behavior based on a kinetic rate law. The basic governing equations are mass and heat balance equations, written for individual components, hydrate (H), methane gas (M) and water (W). The mass balance equations are written to take into account mass transfer through advection by incorporating Darcy's law for flow in porous media. The balance equations also include terms for addition or loss of mass due to hydrate dissociation or formation. The balance equations for individual component (i) are as follows:

Mass Balance:

$$-\bar{\nabla} \cdot \frac{kk_i \rho_l}{\mu_i} \bar{\nabla} P_i + q_{mi} + q'_{mi} + \frac{\partial}{\partial z} \left(g \frac{kk_i \rho_l}{\mu_i} \cdot \rho_i \right) + \frac{\partial}{\partial t} (\phi S_i \rho_i) = 0 \quad (1)$$

Energy Balance:

$$-\bar{\nabla} \cdot \frac{kk_i \rho_l}{\mu_i} h_i \bar{\nabla} P_i - \bar{\nabla} \cdot (K \bar{\nabla} T) + q_{ei} + q'_{ei} + \frac{\partial}{\partial z} \left(g \frac{kk_i \rho_l}{\mu_i} \cdot \rho_i h_i \right) + \frac{\partial}{\partial t} [\phi S_i \rho_i u_i + (1 - \phi) \rho_r u_r] = 0 \quad (2)$$

The balance equations are written for each component, forming six equations. The six equations are further reduced by combining the energy equations into a single energy balance equation. The resulting four equations (3 mass and 1 energy) are solved for four variables, pressure, temperature, and saturations of water and hydrate. It should be noted here that an equilibrium

formulation would yield three balance equations and the associated three independent variables. This would normally produce a large computational advantage for the equilibrium approach over the kinetic formulation with four equations and four independent variables. However, the fact that the hydrate phase is immobile allows the algebraic reduction of the degrees of freedom from four to three during solution of algebraic equations in the kinetic formulation. This reduction technique is described in [18]. Thus the flexibility of the kinetic approach is available at no significant additional computational expense. The Control Volume Finite Element Method is used to transform the partial differential equations into an algebraic system of equations. This system of equations is solved with multi-degrees of freedom preconditioned conjugate gradient methods, using GMRES or BCGS acceleration techniques.

Thermodynamic properties of methane, water, and hydrate (and their respective derivatives) are provided as rational function approximations of temperature (T) and pressure (P). In addition to the thermodynamic properties, saturation dependent properties such as relative permeabilities and capillary pressures are also required during simulation of multi-phase flow. FEHM offers several well-known relative permeability and capillary pressure functions (e.g., Brooks-Corey, van Genuchten) to the user. In addition to these commonly used relationships, methane hydrate specific relationships which were derived based on laboratory experiments performed at the AIST are also available to simulate fluid flow through hydrates. Hydrate specific processes such as mass/heat transfer due to hydrate dissociation, change in intrinsic permeability of the medium and thermodynamic equilibrium for hydrate were modeled using following formulations.

Kinetics of Hydrate Dissociation

The terms q'_{m1} and q'_{e1} in equations (1) & (2) represent rate of mass and heat generation due to hydrate formation or dissociation. A number of expressions have been proposed for hydrate dissociation. FEHM uses the Kim et al. [19] model as well as a rate law derived from the AIST experimental data to model hydrate dissociation. Values of parameters in these models can be varied

through input data in order to study the sensitivity of simulation results on parameter variability.

Effect of hydrate on permeability

The intrinsic permeability of porous media can change due to presence of hydrates. Masuda et al. [7] have proposed an empirical expression to take into account change in the intrinsic permeability.

$$k_{eff} = k(1 - S_H)^n \quad (3)$$

Equation (3) says that the effective permeability is inversely proportional to the hydrate saturation and the medium is impermeable when it contains only hydrate. The exponent 'n' can be determined through laboratory experiments.

Hydrate Phase Equilibrium

van der Waals and Platteeuw [20] have proposed a model to calculate the hydrate phase equilibrium. In addition, a large number of experimental data have also been reported on the methane hydrate phase equilibrium [21]. In FEHM, the hydrate Pressure-Temperature equilibrium can be calculated based on van der Waals and Platteeuw model as well as a relationship calculated from the experimental data. In addition, user specified phase equilibrium relationships can also be used.

NUMERICAL SIMULATION OF HYDRATE RESERVOIR

The simulator described above was used to simulate production from a hypothetical hydrate reservoir. Figure 1 shows a schematic of the hydrate reservoir used in this study.

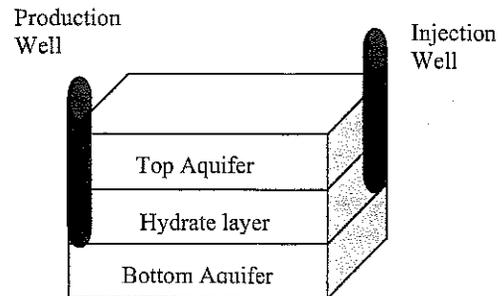


Figure 1. A schematic of the hydrate reservoir.

The reservoir had three layers, a hydrate layer sandwiched between two aquifer layers. The properties of the reservoir are listed in Table 1.

Parameter	Top Aquifer	Hydrate Layer	Bottom Aquifer
Thickness	10 m	10 m	10m
Porosity	0.4	0.4	0.4
Permeability	10^{-12} m^2	10^{-12} m^2	10^{-12} m^2
Hydrate Saturation	0.0	0.6	0.0
Water Saturation	1.0	0.4	1.0
Rock Thermal Conductivity	2.7 w/mK	2.7 w/mK	2.7 w/mK

Table 1 Values of parameters used for hydrate reservoir simulation.

Initially the reservoir was at 5 MPa and 5 °C. The areal extent of the reservoir was 100 m x 100 m. A 5 x 5 x 3 numerical grid in the x, y and z direction was used for the simulations. Each of the grid block was 20 m long in the x and y direction and 10 m thick in the z direction. A simple linear relative permeability relationship, with zero residual water and gas saturations, was used to represent multi-phase flow. A number of different simulation runs were performed with this model as described below.

Effectiveness of production methods

We studied the gas production behavior using two different production methods, injection of hot water and depressurization. For the hot water injection method, a five-spot pattern was used. As shown in Figure 1, a production well and an injection well were situated in the opposite corners of the reservoir. Water at 30 °C was injected at a constant rate of 4 kg/s, while the production well was pumped at 2 MPa. For the depressurization method, the reservoir was produced through the production well (shown in Figure 1). The injection well was not active during these sets of simulations. The production well was pumped at 2 MPa. Figure 2 shows a comparison between the cumulative gas production after 500 days of production for the two production methods. The inflections in the cumulative gas production predictions for hot water injection method are due to the kinetic formulation used in the numerical simulator. As can be seen from the figure, depressurization by itself produces significantly less gas compared to hot water injection method. During depressurization, the rate of gas production goes down significantly as the pressure in the

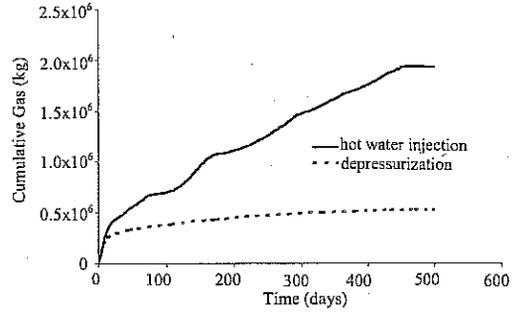


Figure 2. Comparison of cumulative gas production (kg) for the hot water injection and depressurization production methods.

reservoir approaches 2 MPa. As continued pumping does not reduce the pressure further, no additional gas is liberated in the reservoir due to hydrate dissociation. Figure 3 shows pressure distribution in the hydrate layer after 10 days of production during simulation of depressurization method.

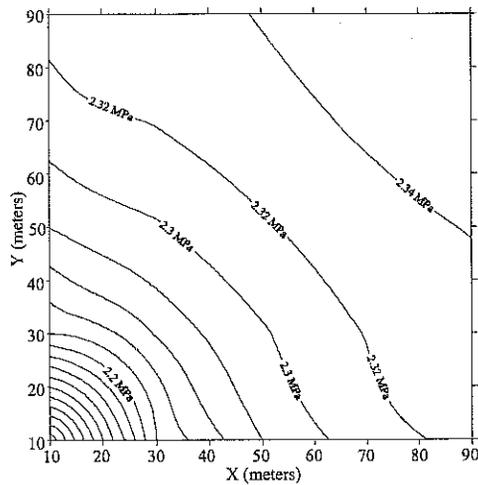


Figure 3. Pressure distribution in the hydrate layer after 10 days of production through depressurization method.

As can be seen from the figure, even only after 10 days of production the pressure in the reservoir is already close to 2 MPa. Figure 4 shows the hydrate saturation in the reservoir after 500 days of production. Since there is no significant dissociation, a large fraction of the initial hydrate is still present after 500 days.

As can be seen from the figure, increasing the water temperature significantly increases the total amount of gas produced from the reservoir. The rate of injected water was varied between 2 kg/s and 8 kg/s. The resulting cumulative gas production predictions for the 4 injection rates are shown in Figure 8.

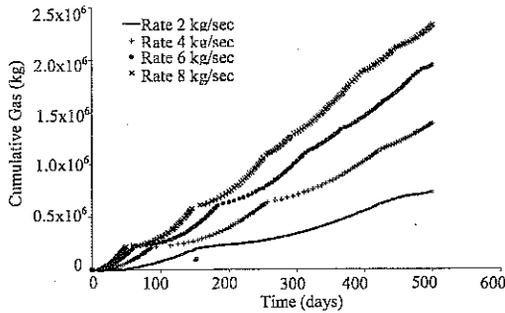


Figure 8. Comparison of cumulative gas production (kg) for different hot water injection rates.

These are expected results as in both cases higher amount of hydrate is dissociated due to increased energy supplied through either the higher temperature or higher mass of hotter injected fluid.

Effect of production well pumping pressure

The pumping pressure of the production well can influence the production behavior for both the hot water injection and depressurization method. The production well pressure was varied between 2 MPa to 4 MPa for both cases. Figures 9 and 10 show the results for hot water injection and depressurization case respectively.

For both cases, the initial pressure in the reservoir was 5 MPa. As can be seen from both figures, increasing the pressure differential increases the amount of gas produced. The effect is extremely pronounced for depressurization method. The figure shows results only for 2 MPa and 3 MPa cases, as no significant amount of gas was produced for the 4 MPa case. This is because, the equilibrium temperature for 4 MPa is very close to the initial temperature in the reservoir. Reducing the pressure to 4 MPa, does not result in any significant amount of hydrate dissociation. Similar response is seen in the 3 MPa case. This behavior is also exhibited in the hot water injection method.

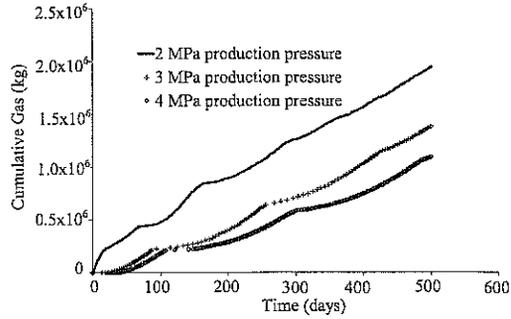


Figure 9. Comparison of cumulative gas production (kg) for different production well pressures for hot water injection method.

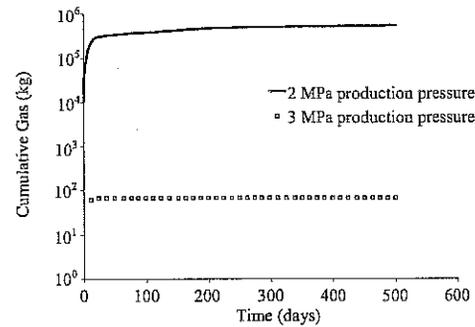


Figure 10. Comparison of cumulative gas production (kg) for different production well pressures for hot water injection method.

For this case, significantly high incremental recovery is achieved by reducing the production well pressure from 3 MPa to 2 MPa.

Effect of hydrate dependent fluid flow parameters on production during hot water injection method

In addition to variability in operational parameters, effect of variability in hydrate dependent reservoir properties was also studied. Presence of hydrate can impact fluid flow behavior of the porous media. Masuda et al. [7] postulated that presence of hydrate reduces the intrinsic permeability. Similarly, hydrates can have an effect on relative permeability of gas and water. Jaiswal et al. [11] report experimental results on hydrate-gas-water relative permeability behavior. We studied the impact of variability in both these properties. First the effect of change in exponent in the

permeability reduction relationship (equation 3) was studied. The value of the exponent was varied between 0 and 9. Note that changing the exponent changes the effective permeability of the hydrate layer only and does not have any effect on the aquifer layer permeability. The results comparing the cumulative gas production are shown in Figure 11.

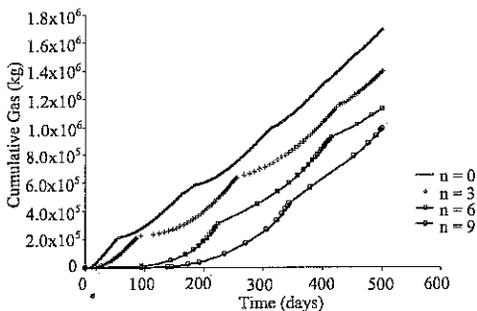


Figure 11. Comparison of cumulative gas production (kg) for different values of exponent in equation 3.

The amount of total gas produced reduces as the effective permeability of hydrate layer reduces. For the higher exponent values, a delay is observed in gas production response. As the effective permeability of the hydrate layer decreases, less amount of hot water flows through it resulting in decreased gas production. The effect of variability in relative permeability was studied by varying the residual water saturation between 0.0 and 0.2. Results of the simulation runs are shown in Figure 12.

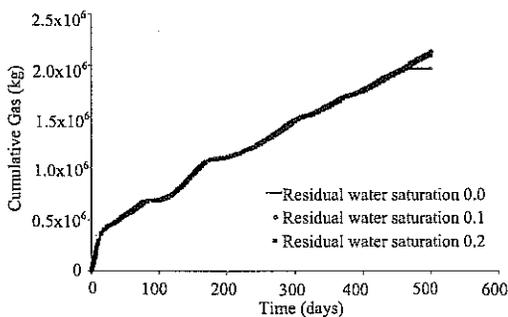


Figure 12. Comparison of cumulative gas production (kg) for different values of residual gas water saturation.

Changing the value of residual water saturation does not have any significant impact on cumulative gas production, for the range of values studied. Results shown here assume a linear relative permeability relationship. Similar investigations for other relationships are currently in progress.

Effect of hydrate re-formation

During the simulations of AIST laboratory experiments it was observed that in order to better match the experimental data, the numerical model had to take into account hydrate dissociation as well as re-formation of hydrate from dissociated gas and water [15]. We explored the effect of hydrate re-formation on the hydrate reservoir simulations for both production methods. Kinetics of hydrate re-formation were modeled with the same rate law as the one used for simulations of laboratory experiment [15]. The results are shown in Figures 13 and 14.

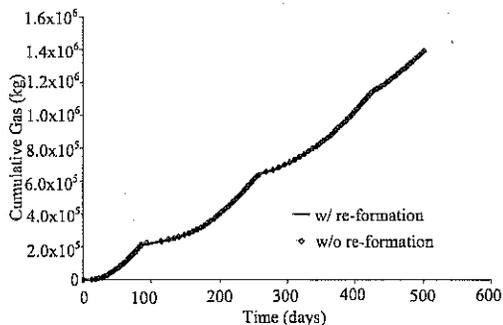


Figure 13. Effect of hydrate re-formation on cumulative gas production (kg) for hot water injection production scenario.

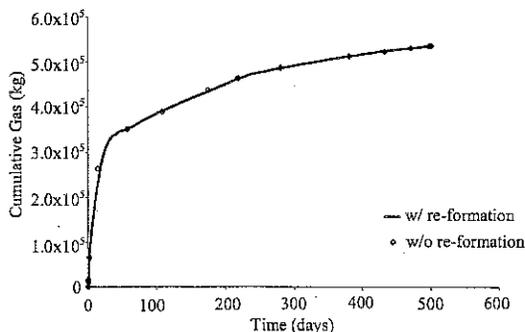


Figure 14. Effect of hydrate re-formation on cumulative gas production (kg) for depressurization production scenario.

As can be seen from the figures, hydrate reformation does not seem to have a significant impact on total gas production. This observation is significantly different than the laboratory experiment simulation results. Further work is currently being done to help understand this scale effect.

Effect of grid block size in the numerical simulation grid

As mentioned earlier, a uniform grid with block size of 20 meter in both x and y direction was used for the simulations. The effect of numerical grid resolution on simulation results was studied. The block size was changed to 10 meter in the x and y direction, while it was not changed in the z direction. This resulted in a 10 x 10 x 3 numerical grid. Figure 15 shows the comparison of cumulative gas production results for the two grid resolutions for hot water injection scenario.

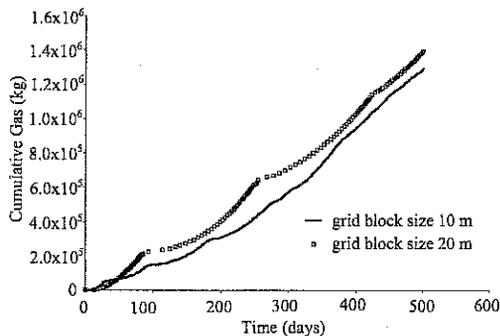


Figure 15. Effect of grid resolution on cumulative gas production (kg) for hot water injection scenario.

As can be seen from the figure, changing the grid size changed the cumulative gas production prediction. We explored this issue further to understand whether the production difference was resulting due to the kinetic formulation used in the numerical model. To explore the effect of grid resolution and its relationship with hydrate dissociation, a new model containing only the hydrate layer was developed. This was done because we wanted to isolate the hydrate layer so as to minimize the impact of the surrounding aquifer and movement of fluids in the aquifer. The properties of hydrate layer were same as those given in Table 1, except the initial saturations were changed to 0.5 for water and hydrate. The grid

block size was varied between 5 meters to 50 meters. These simulations took into account only hydrate dissociation and not its re-formation. Results of the grid block size effect on cumulative gas production are shown in Figure 16.

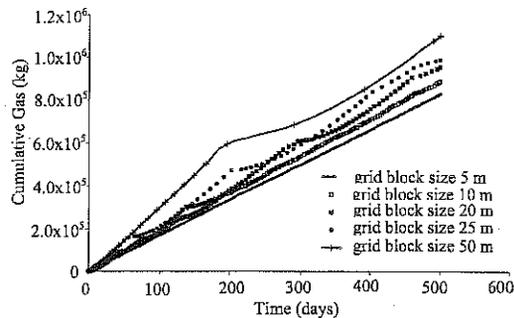


Figure 16. Effect of block size of the numerical grid on the cumulative gas production (kg) for hydrate layer only model.

As evident in the figure, numerical grid block size has significant impact on total gas production. The gas production varies by as much as two times when the grid resolution is changed by an order of magnitude. As mentioned earlier, the numerical simulator used the Kim et al. [19] model for hydrate dissociation. This model is a volume based model, in that the gas production rate is a volume property. As the grid resolution changes, the gas production could be changing because of change in volume in the kinetic rate expression. In order to understand this further, we varied the rate of gas dissociation by changing parameters in the kinetic expression. The Kim et al. equation for volumetric gas mass production rate is as follows;

$$\dot{m}_g = k_d^0 \exp\left(\frac{\Delta E}{RT}\right) M_g A_{HS} \phi S_H (f_e - f_g) \quad (4)$$

The original value proposed for intrinsic dissociation constant, k_d^0 , is 1.24×10^{11} . In order to understand effect of variation in the rate law, the value of intrinsic dissociation constant was varied from 1.24×10^{10} to 1.24×10^{12} for model with 20 m size grid blocks. The results are shown in Figure 17.

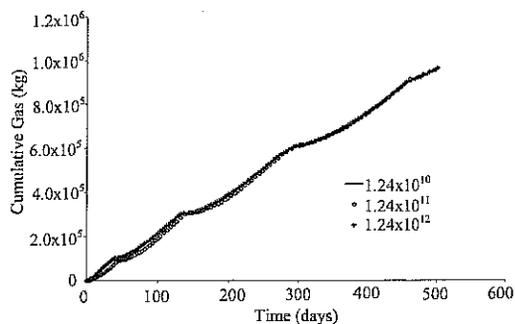


Figure 17. Effect of variation in intrinsic dissociation constant on cumulative gas production (kg).

As can be seen from the figure, changing the rate over two orders of magnitudes by changing the hydrate dissociation constant does not significantly change the cumulative gas production behavior. Further work is currently being done to understand effect of grid resolution and to identify whether it is an observation specific to the kinetic formulation.

CONCLUSIONS

A numerical simulator capable of simulating hydrate reservoirs is developed. The simulator can be used to perform non-isothermal, multi-phase, multi-dimensional fluid flow calculations in hydrate reservoir. The simulator was used to simulate production behavior of a hypothetical hydrate reservoir. The effectiveness of two different hydrate production schemes, hot water injection and de-pressurization, was explored. The hot water injection method provides significantly better production performance compared to de-pressurization method. Effect of variability in different operational and hydrate specific reservoir properties on simulation predictions was explored. It was observed that injected water temperature, injection rate and production well pressure have an impact on cumulative gas production for hot water injection method. For de-pressurization method, the production well pumping pressure has an impact on gas production behavior. Effect of variability in hydrate specific fluid flow properties was also studied. The exponent used to define the effective permeability of a hydrate-containing medium has an inverse effect on the gas production. Changing the relative permeability relationship, through changing the residual water

saturation did not have a significant impact on gas production behavior for the range of residual saturation values studied. It was also observed that even-though hydrate re-formation could be an important process taking place in the laboratory experiments, it has relatively low impact on gas production at reservoir scale. Finally, it was observed that grid size used in the numerical models has a pronounced effect on gas production behavior. This effect could be due to the kinetic formulation used to define the hydrate dissociation behavior. Changing the value of intrinsic dissociation constant used in the dissociation rate law did not have any impact on cumulative gas production, for the range of values studied. Further work is currently being done to understand the numerical grid effects as well as the issue of scale related to hydrate re-formation. Results of this study show that it is important to understand the impact of variability in parameters used in the numerical simulations on the simulation results. Further field-work such as the Mallik project as well as laboratory work is needed to help identify range of parameter values and processes taking place in hydrate reservoirs to effectively perform hydrate reservoir simulations.

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