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Development and Application of Gas Hydrate Reservoir Simulator Based on Depressurizing Mechanism

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Abstract–Natural gas hydrates are known to occur in vast quantities at the ocean floor or in permafrost regions. In-situ hydrate contains great volumes of methane gas, which indicates a potential future energy resource. In this study, we have developed a three-dimensional, multi-phase (gas, water, and hydrate) flow finite-difference model by using implicit pressure explicit saturation technique in order to investigate simultaneous flow through ice-liked hydrate reservoir. The developed model is based on the depressurizing method as producing mechanism. The model evaluates local gas generation dissociated from the hydrate with the aid of kinetic dissociation theory proposed by Kim-Bishnoi. The computation of kinetic dissociation uses the empirical dissociation rate as a function of specific surface area between phases and pressure difference. With the developed model, a one-dimensional system has been simulated for analyzing the production performance of a hydrate reservoir and for investigating the effect of hydrate saturation on absolute permeability and relative permeability characteristics. Also, for the three-dimensional field-scaled reservoir system, a number of numerical exercises have been conducted to understand the effect of mass transfer and to characterize the flowing mechanism under the conditions of increased permeability resulting from the dissociation hydrate.

Key words: Natural Gas Hydrate, Multi-phase Flow, Gas Hydrate Reservoir FDM Model, Kinetic Dissociation, Production Performance

INTRODUCTION

Gas hydrates are members of substances known as clathrates, because they consist of a host-molecule forming a hydrogen bonded lattice structure and a guest-molecule entrapped in a lattice. Hydrate-forming gases are low molecular hydrocarbons such as methane, ethane, propane and butane, or nitrogen, carbon dioxide, hydrogen sulfide, etc. Hydrates are bonded by physical interaction between encaged gas and water rather than by chemical interaction, and hence, hydrates can be broken down easily at dissociating conditions. The breakdown of one unit volume of hydrate at an atmosphere yields about 170 unit produced volumes of gas.

Several development schemes of a hydrate gas reservoir have been proposed: a thermal injection technique in which an external source of energy is used; a depressurization method by which gases are generated with decrease in reservoir pressure below the hydrate dissociating condition; and the injection of inhibitor such as methanol changing the dissociation condition. Thermal injection method has been suggested in several studies [McGuire et al., 1982; Bayles et al., 1987; Kamath et al., 1987; Selim et al., 1990]. However, this technique has the disadvantage of energy loss to the surroundings. On the other hand, the depressurization mechanism has been applied to only one example for gas production from the Messoyakha hydrate gas reservoir in Russia. Vergin et al. [1980] proposed an isothermal depressurizing numerical model. In this model the heat required for hydrate dissociation is supplied from the surroundings. Yousif et al. [1990] developed the moving boundary model of the dissociating front, and it was considered that there is a temperature gradient in the hydrate zone. However, their model assumed that only gas flows through porous media while water is immobile. Yousif et al. [1991] also developed a one-dimensional three-phase model for a core-scaled system.

In this study, a three-dimensional, multi-phase field-scaled model has been developed for investigating the production performances of a hydrate gas reservoir. The proposed model implements a gas-water-hydrate kinetic model proposed by Kim-Bishnoi [1987] for calculating the mass generation rate during hydrate dissociation.

With the aid of a developed numerical simulator in this study, the flowing mechanism accompanying mass transfer during the dissociation has been analyzed. A parametric study of the model has also been conducted for the parameters of permeability, condition of producing well, and hydrate saturation to understand the effects of reservoir properties on gas production performance.

DEVELOPMENT OF HYDRATE RESERVOIR SIMULATOR

The most general diffusivity equation for a multi-phase flow,

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multi-dimensional hydrate gas reservoir has been derived by combining the continuity equation, equation of motion, and equation of state for multi-phase (gas, water, and hydrate). These equations are based on the following assumptions:

1. The flow of gas and water obeys Darcy's law, and hydrate is stagnant in porous media.
2. The generated gas and water by dissociation have not reformed hydrate again.
3. Although hydrate dissociation is an endothermic process, the temperature is assumed to be constant throughout the reservoir. This assumption is valid because the heat of the reservoir itself has been supplied by dissociated heat, instantly and the boundary pressure is not far enough below the dissociation pressure to ensure slow dissociation.

The derived governing equations for each phase flow through porous media are given as follows [Aziz et al., 1979]:

Gas phase:

$$\frac{\partial}{\partial t}\left(\frac{\phi S_g}{B_g}+\frac{\phi R_{sw} S_w}{B_w}\right)=\nabla\cdot\left(\frac{kk_{rg}}{\mu_g B_g}\nabla\Phi_g\right)+\nabla\cdot\left(\frac{kk_{rw}R_{sw}}{\mu_w B_w}\nabla\Phi_w\right)+Q_g+R_{sw}Q_w \quad (1)$$

where, $\nabla\Phi=\nabla P+\rho g\nabla D$

Water phase:

$$\frac{\partial}{\partial t}\left(\frac{\phi S_w}{B_w}\right)=\nabla\cdot\left(\frac{kk_{rw}}{\mu_w B_w}\nabla\Phi_w\right)+Q_w \quad (2)$$

Hydrate phase:

$$\frac{\partial}{\partial t}\left(\frac{\phi S_H}{B_H}\right)=-Q_H \quad (3)$$

where, B is formation volume factor which means the volume ratio of standard and reservoir conditions, and S_l is saturation, expressed as a fraction of occupied volume of phase l in pore volume. The source or sink terms of Q in Eqns. (1) through (3) are composed of production rate at well and local mass transfer rate from hydrate:

$$Q_g=q_{g(well)}-\frac{\dot{m}_g}{\rho_g} \quad (4)$$

$$Q_w=q_{w(well)}-\frac{\dot{m}_w}{\rho_w} \quad (5)$$

$$Q_H=\frac{\dot{m}_H}{\rho_H} \quad (6)$$

where $q_{g(well)}$ and $q_{w(well)}$ are production rates of gas and water at the well. Local mass transfer rate of phase is defined as follows:

$$\dot{m}_H=\dot{m}_g+\dot{m}_w \quad (7)$$

$$\dot{m}_g=\dot{m}_H\frac{M_g}{M_g+N_H M_w} \quad (8)$$

Hydrate number of N_H is a number of moles of water per one mole of gas in hydrate phase, and its value of typical methane hydrate is 6.3.

In this study, the local gas generation rate is estimated by using Kim-Bishnoi model:

$$\dot{m}_g=K_d A_s(P_e-P) \quad (9)$$

Again in Eqs. (1) and (2), k represents absolute permeability, and it has different characteristics from conventional natural gas reservoirs, that is, the absolute permeability is a rock property and it is determined by pore size, pore structure, and its connectivity. The absolute permeability is generally assumed to be a constant regardless of saturation change in a conventional gas reservoir. However, in a hydrate gas reservoir system, it can vary as hydrate is dissociated. In reality, gas and water are almost immobile at the hydrate saturation of 20-30%. Fig. 1 illustrates the change of absolute permeability with hydrate saturation.

Now, relative permeability of k_r as a function of saturation in

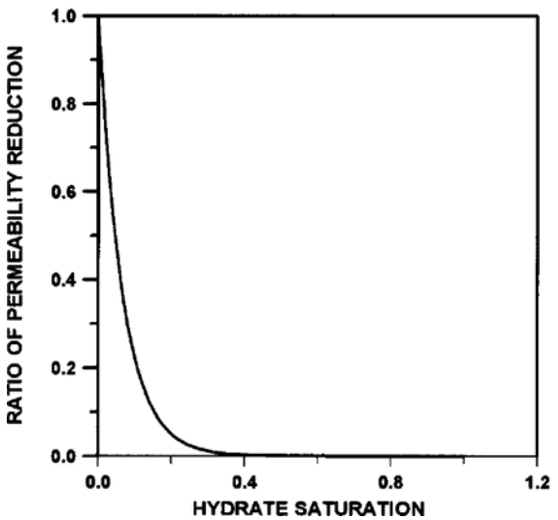

Fig. 1. The change of absolute permeability with hydrate dissociated.

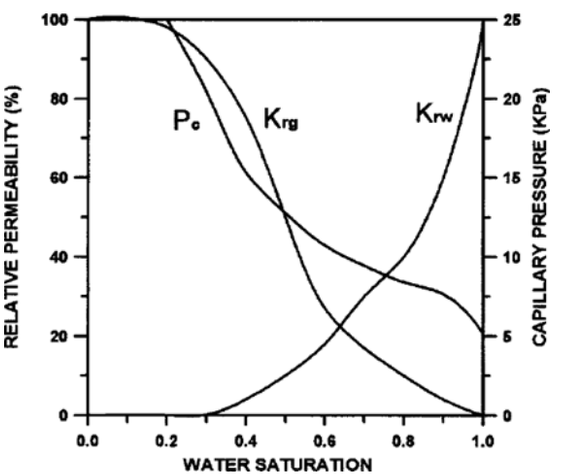

Fig. 2. Relative permeability and capillary pressure curves of Berea sandstone.

Eqs. (1) and (2) is a measure of the ability of two or more fluids rather than a single fluid to flow through porous media, and it is the most important and uncertain factor. The typical relative permeability curve for Berea sandstone is shown in Fig. 2. Berea sandstone is a commonly used homogeneous rock as a standard for measurement of petrophysical properties. In addition to Eqs. (1) through (3), the saturation and capillary pressure relationships are adopted for the complete mathematical form. The typical capillary pressure with water saturation for Berea sandstone is shown in Fig. 2. In order to solve the aforementioned equations, the finite difference method has been utilized, and Eqs. (1)-(3) are combined as one equation as function of pressure. From this equation, it is solved for pressure with aid of a fully implicit Newton-Raphson iteration method, and then explicitly solved for saturation with the resulting pressure (Implicit Pressure Explicit Saturation, IMPES Technique). Finally, production rate is then solved, explicitly.

RESULTS AND DISCUSSION

In order to check the sensitivity of the proposed numerical model, a parametric study has been conducted for a one-dimensional hydrate reservoir system. The parameters such as in-situ rock permeability, dissociation reaction rate constant, and hydrate saturation were investigated for this parametric study by examining the dissociation front between hydrate and gas-water. The employed data of the base system are listed in Table 1. In this one-dimensional system, the single producing well is placed at the right edge of the reservoir with constant wellbore pressure of 2.48 MPa. The dissociating pressure at 274 °K was estimated as 2.84 MPa by using statistical thermodynamic hydrate model [Sung et al., 1988].

As a first investigation, the model has been simulated to examine the effect of well condition on the production performance. In the base case, in-situ rock permeability is specified as 100 milidarcy (md; 1 md=9.869×10^{-12} cm^2) without well stimulation. In the meantime, for other cases, wells are simulated to in-situ rock permeabilities of 50, 100 and 150 md, and non-well blocks of the reservoir have the same initial permeabilities of 100 md. From the results shown in Fig. 3, since the well in base case was not simulated, moving time of dissociation front was delayed at the beginning until the well block pressure reached the dissociation pressure. The delay time for the well block dissociation was 440 days in this system. However, it was seen that the magnitude of well simulation had almost no effect on hydrate dissociation. This is because the flow in porous media is mostly depending on in-situ rock permeability throughout the reservoir, rather than well block itself. This phenomenon can be also seen by investigating the various in-situ rock permeabilities of the whole reservoir. These were simulated for reservoir permeabilities of 50, 100 and 150 md with well simulation. The results in Fig. 4 show that as flowing mobility is

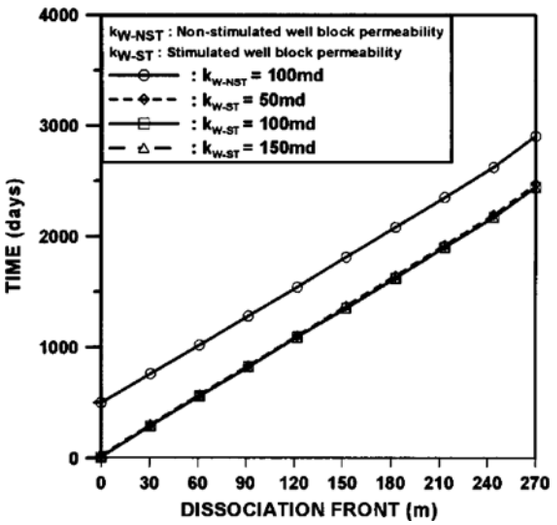

Fig. 3. The effect of well condition on hydrate dissociation.

Table 1. Input data for hydrate gas reservoir simulator

Input Data	One-dimensional System	Three-dimensional System
System volume [m^3]	28316846.6	137053537.5
Initial horizontal permeability [md]	100	100
Initial vertical permeability [md]	–	10
Temperature [°K]	274	280.15
Initial pressure [MPa]	3.17	6.89
Porosity	0.188	0.2
Initial water saturation	0.17	0.2
Initial hydrate saturation	0.43	0.3
Hydrate dissociation pressure [MPa]	2.84	4.14
Wellbore pressure [MPa]	2.50	3.45
Hydrate reaction rate constant [kmol/(m^{2}Pas)]	4.4×10^{-16}	4.4×10^{-16}
Viscosity of water [cp]	1	1

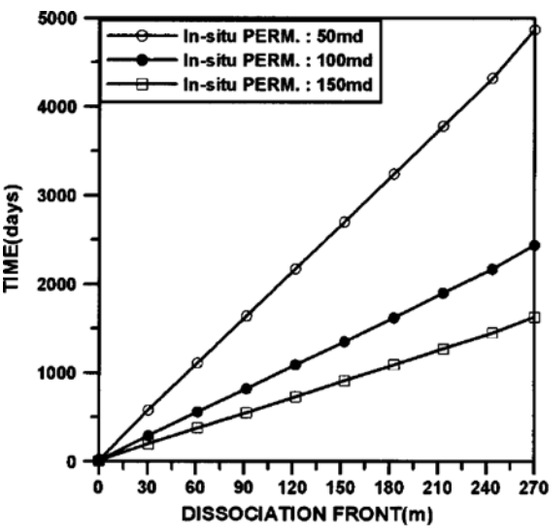

Fig. 4. The effect of in-situ permeability on hydrate dissociation.

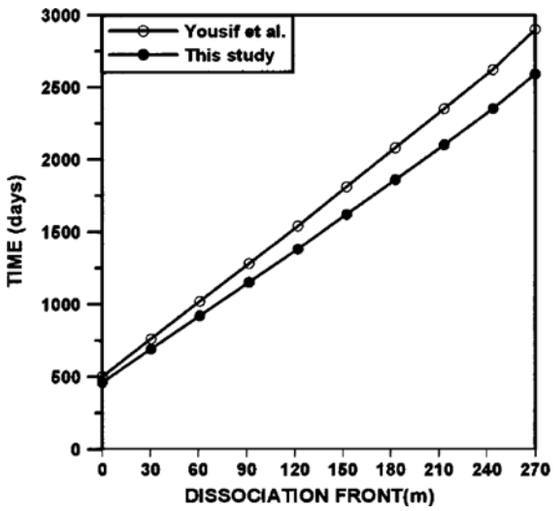

Fig. 5. The effect of dissociation reaction rate constant on hydrate dissociation.

becoming lower, the time until the whole formation is dissociated takes longer, that is, 4,870, 2,440, and 1,630 days for 50, 100 and 150 md, respectively.

This time, the hydrate dissociation model proposed by Yousif et al. was compared against this study implemented by Kim-Bishnoi model in terms of dissociation reaction rate constant. The major difference between the two models is the consideration of mass transfer resistance which is contained in the Yousif et al. model. From the results illustrated in Fig. 5, the starting times of dissociation near the well were the same in both cases; however, the front was propagated faster in this model. From this figure, it was also noted that the discrepancy in front moving velocity is gradually greater as more and more is produced at the well.

For the analysis of various values of hydrate saturation on the dissociation, three different cases were run and the results are presented at Fig. 6. In this figure, it is noted that the dissociation front is moving faster as hydrate saturation is lowered as expected, because the dissociated gas and water are able to flow more easily toward the well. In the system studied, when hydrate saturation increases to 0.42 and 0.5 from 0.3, the dissociating times up to 213 m in the system were taken as 1,640 and 8,580 days, respectively.

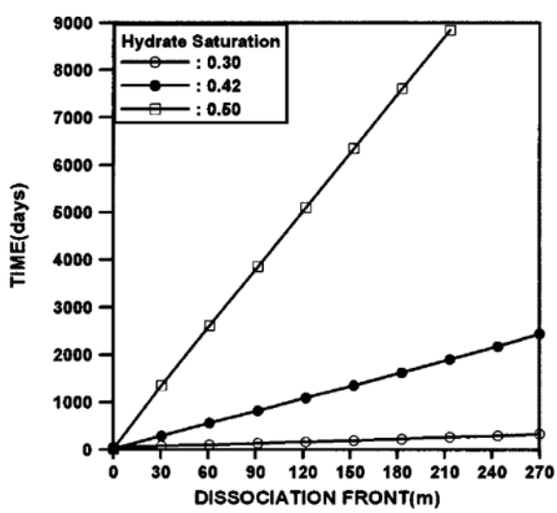

Fig. 6. The effect of hydrate saturation on hydrate dissociation.

The developed model was used to investigate the production behavior for a one-dimensional gas hydrate reservoir as a simple system. The reservoir and physical fluid properties are listed in Table 1.

The resulting pressure distributions versus distance at various times of 500, 1,000, 1,500, 2,000, 2,500, and 2,892 days are presented in Fig. 7. From this figure, a sharp front was observed, that is, the left side of the front represents a totally dissociated zone, and the other side is a non-dissociated zone, whereas the pressure behavior of a conventional natural gas reservoir monotonically increases with distance in most cases. The sharp front

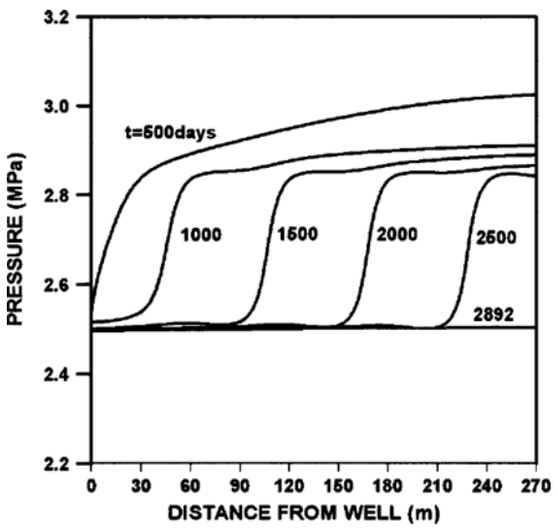

Fig. 7. Pressure distribution along the distance at various times in one-dimensional system.

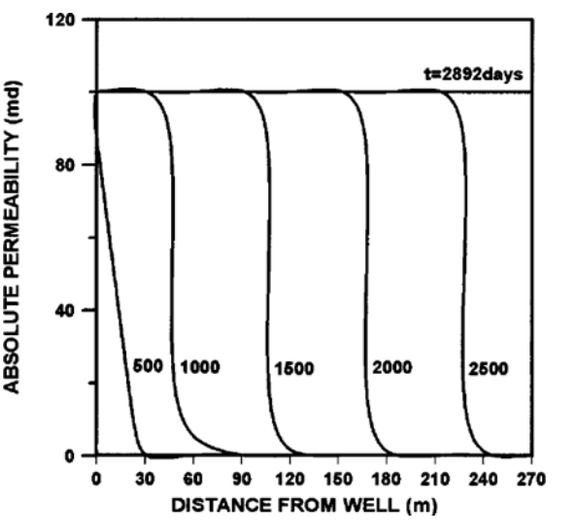

Fig. 8. Absolute permeability variation due to hydrate dissociation in one-dimensional system.

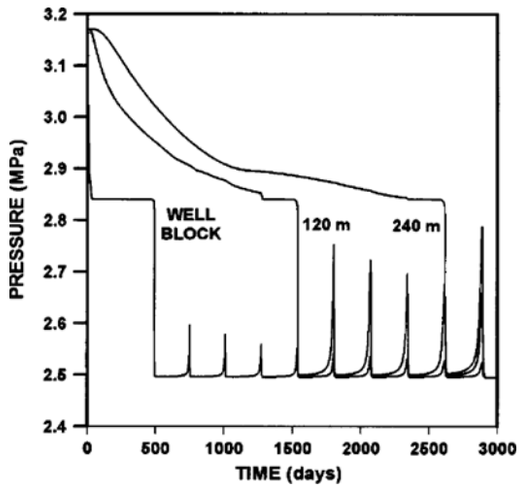

Fig. 9. Pressure behavior with time at various locations.

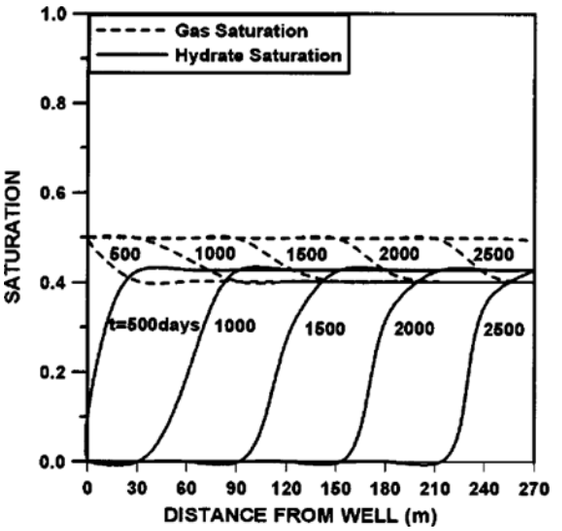

Fig. 11. Gas production performance in one-dimensional system.

is formed because the absolute permeability was changed from 0.16 md at the beginning to 100 md due to the dissociation as shown in Fig. 8, and hence the liberated gas and water can be expanded more easily. The pressure versus time at the locations of well block, and 120 m and 240 m from the well are presented in Fig. 9. This figure shows that the well block pressure steeply falls to wellbore pressure when it reaches the dissociation pressure. Since then, the pressure behavior shows sharp peaks repeatedly with uniform propagation of the dissociation front due to the influx of the liberated gas and water from the other blocks. Similar results to the pressure behavior were observed in saturation distributions as presented in Fig. 10.

The effect of hydrate dissociation can be also seen in the production behavior (refer to Fig. 11). In conventional gas reservoirs, the calculated production behaviors are in general continuously declining. Meanwhile, pulse type production performance was observed, and overall it declines as shown in Fig. 11. The estimated delayed time between the pulses is considered to be yielded by the size of grid block; therefore, as size of the block approaches to zero, continuous declining behavior is expected. However, this kind of phenomenon will be seen in an actual field, anyway. In the one-dimensional system studied, initial free gas is 7.12×10^5 m^3 and hydrate contains 4.13×10^6 m^3. From the numerical simulation, gas was produced 4.08×10^6 m^3 (recovery of 84%) after about 8 years of production.

Finally, in order to test the applicability of the model for the field, a numerical simulation has been performed for the three-dimensional hydrate reservoir system. The reservoir is composed of three layers with uniform thickness, and a single producing well is placed at the center of the reservoir and is completed throughout all layers with constant well operating pressure of 3.45 MPa at the top layer. The reservoir and physical fluid properties are listed in Table 1. In the process of the

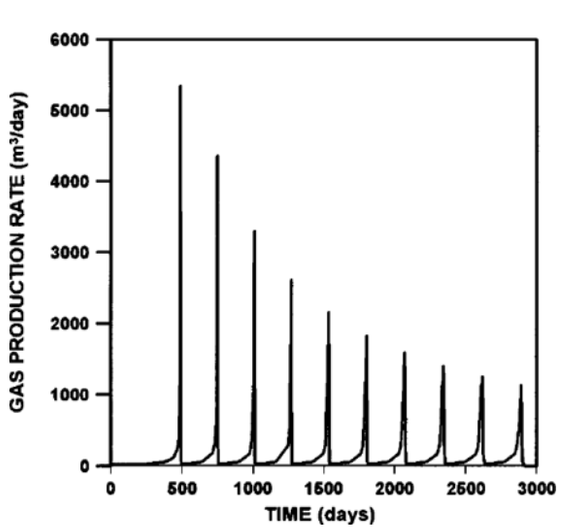

Fig. 10. Distributions of gas and hydrate saturations with time in one-dimensional system.

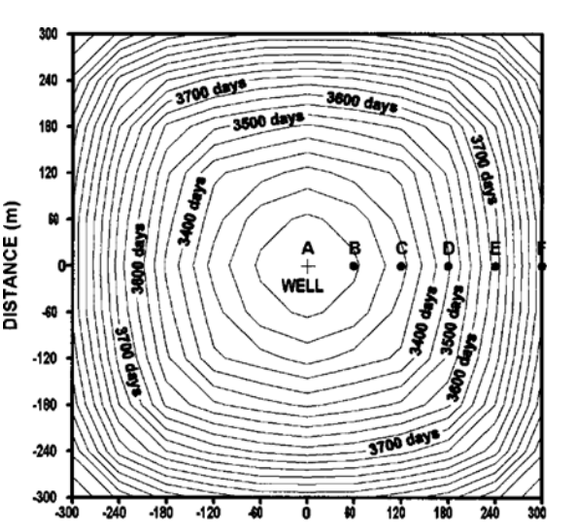

Fig. 12. The hydrate dissociation front at top layer in three-dimensional system.

numerical study, with many numbers of trials, we found that the calculated pressure oscillated at the dissociating blocks, and therefore a time step size of 0.001 day was used.

As a result, Fig. 12 shows the contour of the location of dissociation front at every 50 days for the top layer. As shown in this figure, while the dissociation front of the one-dimensional system was advanced uniformly, in a three-dimensional system it is slowly moving far from the well by observing the density of the contour line. It can be explained that due to the greater expansion of the dissociated area far from the well compared to the one-dimensional system, the amount of liberated gas and water is larger; hence, the pressure is increased and dissociation is delayed. This phenomenon can also be seen in pressure behavior (Fig. 13). In this figure, each line is corresponding to locations of A, B, C, D, E, and F with equal distance in Fig. 12. The results in Fig. 13 show that the dissociating front at each node is delayed as location is far from the well point although intervals between the locations are equal. Again, through the investigation of pressure behavior in Fig. 13, it is seen that the pressure during the dissociation falls instantaneously as in the one-dimensional system, and then it is increased and fluctuating due to the influx of gas and water from the dissociated neighboring blocks. Fig. 14 presents gas and water production rates at the production well completed for all three layers. As illustrated in Fig. 14, gas and water start producing at 3,080 days due to the hydrate dissociation; however, the marked pulse of production observed in one-dimensional system does not appear, since the amount of dissociation is greatly increased as the dissociated area expands to the boundary. In the three-dimensional system studied, initial free gas is 1.99×10^8 m^3 and hydrate contains 4.44×10^8 m^3 of methane gas initially. From the simulations, gas was produced 4.95×10^8 m^3 (recovery of 77%) after 13 years of production.

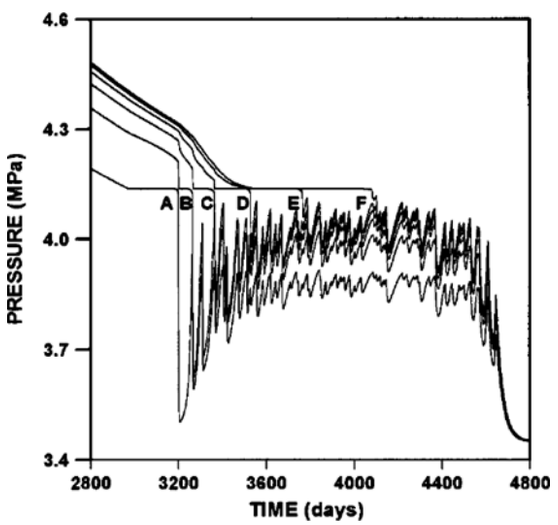

Fig. 13. Pressure behavior with time at various locations in the system.

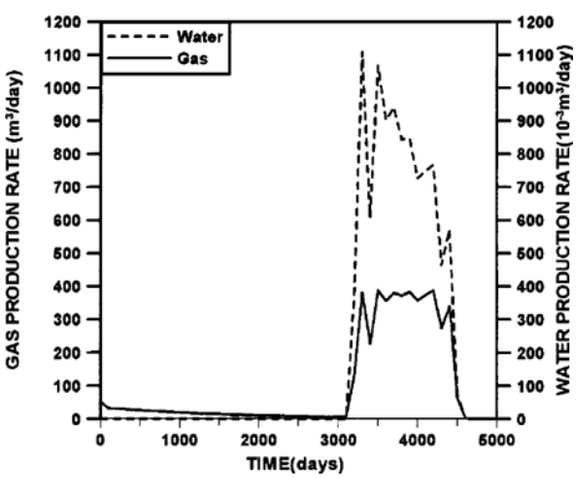

Fig. 14. Gas and water production behaviors in three-dimensional system.

CONCLUSIONS

This study presents a three-dimensional, multi-phase finite-difference gas hydrate reservoir simulator employing the kinetics model for hydrate dissociation under depressurizing mechanism. A parametric study has been performed to investigate sensitivity of the developed model. Also, the model has been applied to one-dimensional as well as three-dimensional hydrate systems. From the analysis of results, the following conclusions have been drawn:

1. From the parametric studies, it was found that the dissociation front is moving faster when well block is stimulated, however, magnitude of stimulation does not affect much on the hydrate dissociation. It was also cleared that the dissociation front is quickly propagated because the flowing mobility is becoming higher as in-situ rock permeability or the fraction of free gas is increased.
2. In the case of simulation of one-dimensional gas hydrate reservoir, the sharp decrease in pressure was observed at the dissociated block because of increase in absolute permeability which brings about higher flowing transmissibility of the liberated gas and water. We also found the marked pulse on the production performance with continuous decline overall.
3. In the numerical exercise for the field-scaled three-dimensional gas hydrate system, it was noted that the dissociation front is slowly propagated far from the well, not like in the one-dimensional system which was uniformly moved. On the producing behavior, the marked pulse did not appear in the three-dimensional system due to the greater increases in the amount of dissociation as the dissociated area expanded.

ACKNOWLEDGMENT

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NOMENCLATURE

A_s : specific area [m^{-1}]

B : formation volume factor
D : depth [m]
g : acceleration of gravity [m/sec^2]
k : permeability [md]
K_d : dissociation reaction rate constant
k_r : relative permeability
M : molecular weight [kg/kmol]
$\dot{m}$: mass transfer rate per unit volume [kg/(m^3·sec)]
N_H : hydrate number
P : pressure [Pa]
P_c : capillary pressure [Pa]
P_e : dissociation pressure [Pa]
Q : source or sink term [m^3/day]
R_{sw} : solubility of gas in water
S : saturation

Greek Letters

Φ : potential [Pa]
ϕ : porosity
μ : viscosity [cp]
ρ : density [kg/m^3]

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