

Gas production from layered methane hydrate reservoirs

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ABSTRACT

Reservoir simulations are used to find the production strategies for methane gas hydrate reservoirs. Most of these simulation models assume homogeneous reservoirs in absence of substantial well data. Many natural gas hydrate reservoirs are heterogeneous. Majority of the heterogeneity comes from the depositional layering at different geological time scales. Examples are Mount Elbert, block 818 in Gulf of Mexico, Walker Ridge 313 Site. The effect of cross-flow or no cross-flow between the layers is still unknown. In the present work, layered gas hydrate reservoir, underlain by a confined aquifer, with cross-flow between the layers is studied. A 3-dimensional, multi-component, multiphase, thermal, compositional simulator developed by Sun and Mohanty (2005) is used. Earlier work showed that for a confined, homogeneous reservoir underlain by an aquifer layer, depressurization method gives the highest recovery. So, in the present work, only depressurization of the reservoir is considered. In layered reservoirs recovery is found to be dependent on the total volume of the hydrate present in the reservoir, depressurization potential of the reservoir and the enthalpy available for dissociation irrespective of the layering. The layering suggests the positions and progress of the dissociation fronts.

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1. Introduction

Gas hydrates are ice like structures formed from gas and water molecules at high pressure and low temperature. The hydrate formation and dissociation for methane gas molecules can be represented as follows:



where, n is the hydration number. The hydration number of methane is approximately 6 [1]. In recent years, the gas production from methane hydrate reservoirs has become hot topic of research [2–5] because of increasing energy demand and hydrates can be next new source of energy. In addition, these reservoirs can be used for long term geological sequestration of CO_2 in the form of CO_2 hydrate. Naturally occurring methane hydrate reservoirs have been found in arctic regions and along the coastlines of many countries in marine sediments where the temperature and pressure conditions are suitable for gas hydrate reservoirs [6]. Fig. 1 shows the equilibrium diagram of methane hydrates.

Above the equilibrium line, at high pressure hydrates are stable, while at the conditions below the equilibrium line methane exists

in gaseous form. The solid vertical line shows the freezing point of water at 273.15 K. In geological settings the pressure and temperature both increase with depth by hydrostatic pressure and geothermal gradient. Therefore, in a small region we encounter conditions conducive for methane hydrate formation. The amount of gas stored in these hydrate reservoirs is huge due in part to the storage capacity of hydrate as they have about 164 times the amount of gas as compared to gas present at STP in the same volume [7]. The total amount of gas stored in the naturally occurring methane hydrate reservoirs estimated by Kvenvolden [8] is $21 \times 10^{15} \text{ m}^3$ at STP. This amount is twice the amount of carbon present in other fossil fuels around the world. Milkove [9] also predicted the amount of gas present in hydrate to about $3\text{--}5 \times 10^{15} \text{ m}^3$ methane at STP (standard temperature and pressure), which is less than Kvenvolden estimates but still is quite large. To extract this energy a technology suitable for gas hydrate reservoirs is needed for which we need to understand the behavior of these reservoirs under different production conditions.

Four types of hydrate reservoirs have been classified named as Class 1, Class 2, Class 3 and Class 4 [10]. Class 1 hydrate reservoirs are underlain by a free gas layer e.g. Messoyakha Field in Russia. Class 2 hydrate reservoirs have an aquifer below the hydrate bearing zone, for example Mallik site and Eastern Nankai trough. Class 3 hydrate reservoirs are bound by shale layers at the overburden and under-burden as in Qilian Mountain permafrost in

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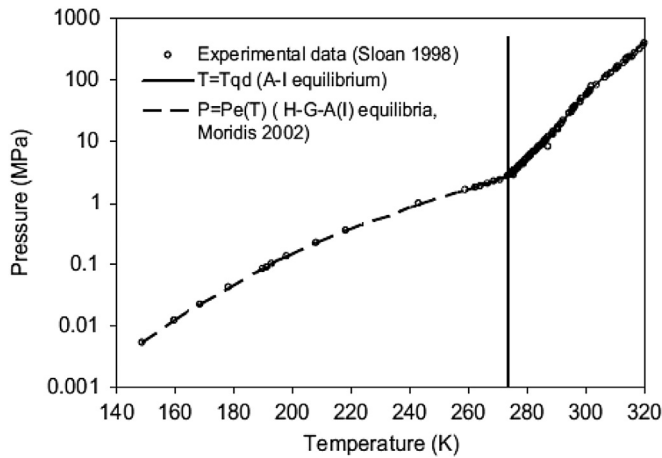


Fig. 1. Equilibrium pressure vs temperature curve for methane hydrates.

China. Class 4 hydrate reservoirs are related specifically to oceanic accumulations and involve the low saturation hydrate deposits (<10%) in disperse form that lack confining geological strata as in Krishna Godavari basin in India or Gulf of Mexico in the USA [11]. In the present study Class 2 hydrate reservoirs are considered.

For dissociation of hydrates and gas production three methods and their combinations have been suggested [12–19]. For confined reservoirs depressurization is suggested as the best method [20]. If the depressurization pressure is too low then the dissociation of hydrate is fast. Hydrate dissociation is an endothermic process and enthalpy of dissociation is taken from the reservoir in depressurization method. Therefore, fast hydrate dissociation at low pressure decreases the reservoir temperature below water freezing point. Ice formation is seen in the case, which is undesired as it decreases the effective porosity and hence permeability [20]. In the present work, a higher depressurization pressure is used to eliminate the undesired event of ice formation. For unconfined reservoirs, thermal stimulation is necessary as depressurization is difficult. Phirani et al. [21] used warm water injection for thermal stimulation in unconfined reservoirs. Inhibitor injection is another suggested method for gas hydrate reservoirs. CO₂ can act as an inhibitor while forming CO₂-hydrate and hence simultaneous CO₂ sequestration and methane production can be achieved [22,23]. In the present work, a confined, Class 2 reservoir is considered, so depressurization method is used for gas production.

For heterogeneous hydrate reservoirs Reagan et al. [24] have worked on Mount Elbert unit D reservoir and considered layer cake model of reservoir in absence of substantial well data across the field. In the study it is seen that hydrate dissociate at the interface of two layers and increase the gas production. In the present work we have tried to find out the reasons and conditions when such phenomena happens and if the dissociation at the interface of two hydrate bearing layers impacts the gas recovery. An in house simulator from UT-Austin is used for our work. The numerical model is 3-dimensional, compositional, thermal which considers heat transfer, multiphase fluid flow and equilibrium thermodynamics of hydrates [25]. Energy and mass balance equations are solved in space and time domain. Two components (methane, water) and four phases (hydrate, gas, aqueous-phase and ice) are considered in the simulator. The primary variable switch method is used to track ice melting, freezing and hydrate formation and dissociation. The kinetics of hydrate formation and dissociation are relatively fast as compared to flow in the field

scale so all the phases in a grid block are assumed to be in equilibrium at the pressure and temperature of the grid-block. The simulator is explained in Section 2 below. This simulator has been validated against several other simulators for problems in the code comparison study conducted by US DOE [26] as the substantial well production data is not available and against core scale experimental results Phirani et al. [27].

2. Model description

2.1. Reservoir domain, initial and boundary conditions

A three layered reservoir with a thickness of 10 m is considered as shown in Fig. 2. The bottom most layer is a 2 m thick aquifer. The top 8 m is hydrate bearing zone with 2 layers.

The porosity across the layers vary which changes the permeability according to Civan's law [28]. The change in porosity also changes the total amount of hydrate present in the layer even if the hydrate saturation is same. The permeability also changes with hydrate formation and dissociation. Initial pressure in the reservoir is 9 MPa at the bottom which varies with hydrostatic gradient. Initial temperature is 280.7 K at the bottom of the reservoir which varies with a geothermal gradient of 0.03 K/m. In this work three porosities are considered, 0.3, 0.21, and 0.14; so that Civan's law gives at least one degree of magnitude variation in permeability. The rock with porosity of 0.3 will have a permeability of 158 md, 0.21 porosity will have 16 md permeability and 0.14 porosity will have 1.5 md permeability when hydrates are not present in the rock. With hydrate saturation of 0.6 the permeability changes to 0.64 md for 0.3 porosity, 0.09 md for 0.21 porosity and 0.01 md for 0.14 porosity. The reservoir is depressurized at a constant pressure of 4 MPa at the production well shown in Fig. 2. The enthalpy of dissociation comes from the porous medium, over-burden and under-burden. A quarter pattern of Fig. 2 is considered for simulation because of symmetry. The lateral boundaries have no mass flow and heat flow condition due to symmetry. The overburden and under-burden have no mass flow boundary condition. The heat transfer can happen by a specified heat transfer coefficient at over-burden and under-burden. For the base case an average heat transfer coefficient of 0.2 W/m²/K is calculated assuming over-burden and under-burden as infinite conducting medium. The reservoir model is discretized in time by backward Euler method and in space by finite volume method to give a fully implicit scheme of solution. The discretization in space is 15 × 15 × 10 grid blocks. Different reservoir properties used in the simulator are described below.

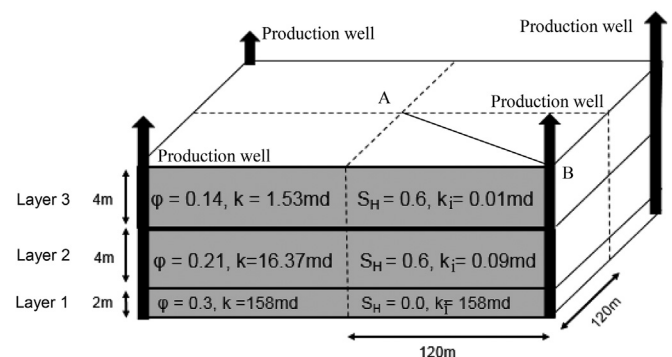


Fig. 2. Class-2 layered hydrate reservoir schematic considered for gas production.

2.2. Transport properties

Civan's power law model is used for permeability calculations in presence of gas hydrate:

$$\frac{K^e}{K_o} = \frac{\varphi}{\varphi_o} \left(\frac{\varphi^e (1 - \varphi_o)}{\varphi_o (1 - \varphi^e)} \right)^{2\beta} \quad (2)$$

where K^e is the effective permeability, K_o is reference permeability, φ_o is reference porosity, β is the rock parameter, φ^e is the effective porosity of gas and aqueous phase which can be related to absolute porosity as:

$$\varphi^e = \varphi(S_G + S_A) \quad (3)$$

For relative permeability modified Brooks-Corey model is used:

$$k_{rG} = k_{rG}^o (S_{G,e}^*)^{n_G} \quad (4)$$

$$k_{rA} = k_{rA}^o (S_{A,e}^*)^{n_A} \quad (5)$$

where n_j is exponential parameter and k_{rj}^o is end point relative permeability for phase j .

The capillary pressure is given by:

$$p_c = p_{ce} (S_{A,e}^*)^{-n_c} \quad (6)$$

$$p_{ce} = p_{ce0} \sqrt{\frac{\varphi^e k_o}{\varphi_o k}} \quad (7)$$

In equation (6), n_c is the parameter for pore structure and p_{ce} is the entry capillary pressure. The entry pressure is correlated to effective porosity φ^e as in equation (7). p_{ce0} is entry pressure under reference porosity φ_o and absolute permeability k_o . The normalised saturation for phase j ($S_{j,e}^*$) used in equations (4)–(6) are described by:

$$S_{j,e}^* = \frac{S_{j,e} - S_{jr,e}}{1 - S_{Gr,e} - S_{Ar,e}} \quad (8)$$

Here $S_{jr,e}$ is residual saturation based on effective pore volume and $S_{j,e}$ is saturation of gas and aqueous phase based on effective pore volume which can be given by:

$$S_{j,e} = \frac{S_j}{\sum_{j=G,A} S_j} \quad (9)$$

where S_j is saturation of gas and aqueous phase based on total pore volume.

2.3. Thermal properties

Fourier's law of heat conduction is used for conductive heat transport in addition to convection by Darcy's flow. The thermal conductivity of a grid-block is volume weighted average of conductivities of all the phases and rock. Formation and dissociation of gas hydrate is considered to be in equilibrium at grid scale as the process is much faster than the flow in the reservoir. Peng Robinson equation is used to calculate the thermodynamic properties of methane like enthalpy. Specific enthalpy of other phases is calculated by correlations from literature. Solubility of methane in aqueous phase and water in gas phase are also taken from literature.

The important parameters are given in Table 1. Appendix A shows the mass and energy balance equations used in the simulator.

3. Analysis methodology

Many layered reservoir systems were simulated using the above model, of which a few important cases are used below for explaining the important parameters in heterogeneous gas hydrate reservoirs that impact gas recovery. Apart from gas recovery, the information of dissociation fronts is also important as gas hydrate are solid and they can be a part of the porous structure so their dissociation may cause instability of structure leading to collapse. If the time and position of dissociation front is known prior to the production operation then it can help us design the production methodology to avoid the structure collapse. In the following sections we first compare the layered reservoir with homogeneous reservoir to establish the parameter in the layered reservoir that affect gas recovery. Then we discuss different layering systems to find the position of dissociation fronts. Enthalpy from over-burden and under-burden plays an important role in hydrate dissociation during depressurization i.e. not only the thermal parameters of the reservoir but over-burden and under-burden are also important which translate to heat transfer coefficient in the simulator. Next, the sensitivity of initial hydrate saturation is studied as more hydrates lead to less initial permeability and dissociation would require more energy leading to slow gas recovery. After that the sensitivity to intrinsic permeability of reservoir is shown to affects gas production. Finally, an example of gas production strategy is discussed which is based on the results of the present work.

4. Results and discussion

4.1. Effect of reservoir heterogeneity

The gas recovery from the layered reservoir shown in Fig. 2 is compared with the homogeneous reservoir to see the impact of heterogeneity on the gas recovery.

4.1.1. Results

Fig. 3(a) shows the comparison of cumulative gas recovery in terms of percentage of IGIP (initial gas in place) of a layered reservoir with a homogeneous reservoirs.

The schematic of layered reservoir is shown in Fig. 2(base case), where layer 1 is an aquifer layer with porosity 0.3, layer 2 is hydrate layer with porosity 0.21 and layer 3 is hydrate layer with porosity 0.14. The porosity of homogeneous reservoir is 0.28 (Phirani and Mohnaty, 2009). The intrinsic permeability at these porosities are: porosity 0.3, permeability 158 md; porosity 0.28, permeability 100 md; porosity 0.21, permeability 16 md; porosity 0.14,

Table 1
Reservoir parameters.

Hydrate density	910 kg/m ³	Reference permeability (k_o)	100 md
Hydrate heat conductivity	0.49 W/m/K	Reference porosity (Φ_o)	0.28
Hydrate heat capacity	1.62 kJ/kg/K	Permeability rock constant (β)	2
Ice density	917.1 kg/m ³	Gas rel. permeability constant (n_G)	2
Sand density	2670 kg/m ³	Water rel. permeability constant (n_w)	4
Sand heat conductivity	5.57 W/m/K	Pore structure parameter (n_c)	5
Sand heat capacity	0.83 kJ/kg/K	Residual water, gas saturation	0.2, 0.0

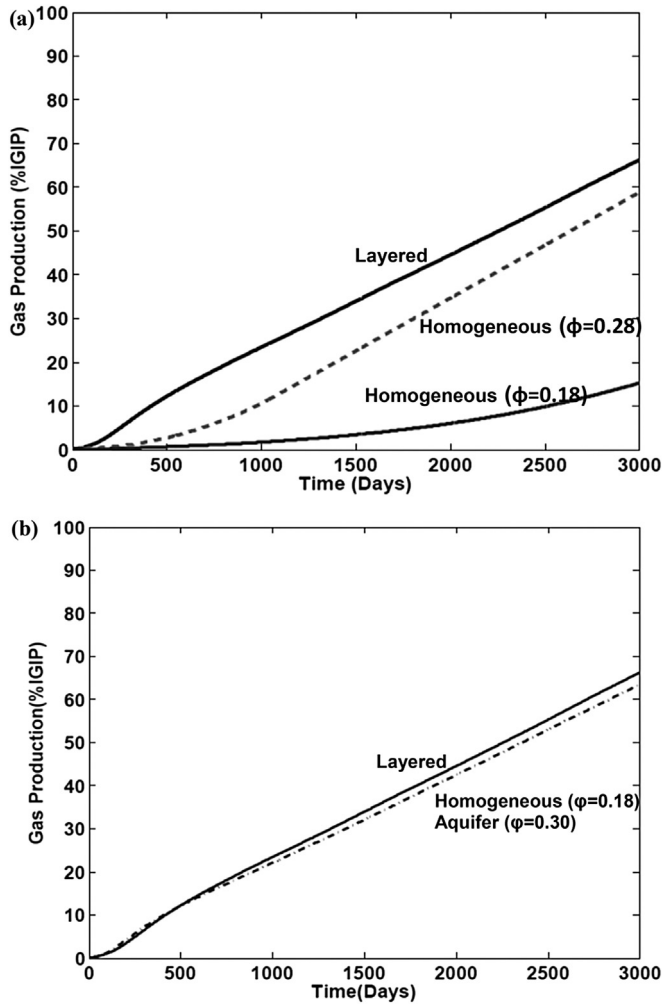


Fig. 3. (a). Gas production comparison for layered reservoir and homogeneous reservoirs. (b). Gas production comparison for layered reservoir and homogeneous reservoir.

permeability 1.5 md. But, with initial hydrate saturation of 0.6, considered in all the cases the permeability changes to: porosity 0.3, permeability 158 md (aquifer layer so no hydrate present); porosity 0.28, permeability 0.44 md; porosity 0.21, permeability 0.09 md; porosity 0.14, permeability 0.01 md. Heterogeneous case shows more gas recovery than homogeneous case even when average porosity and hence permeability of the hydrate bearing zone are low in the heterogeneous reservoir.

Fig. 4(a) shows the hydrate saturation profiles for the heterogeneous case along the diagonal surface, AB in Fig. 2, with producer on right side, after 367 days of production. There are two dissociation fronts in the case, one near the aquifer at 2 m height from the bottom and another at the interface of two different porosity layers in hydrate bearing zone at 6 m height from the bottom. The aquifer acts as a heat source and helps in depressurization at the hydrate water contact due to high permeability in aquifer, which leads to more hydrate dissociation at hydrate water contact. So aquifer dissociation front is similar to homogeneous reservoirs as shown by Phirani and Mohanty [15]. The other dissociation front appears at the interface of two hydrate bearing layers. This is due to two factors: different permeability and different amount of hydrate present (due to different porosity) at the interface. As hydrate start dissociating, initially less hydrates are available in the upper most

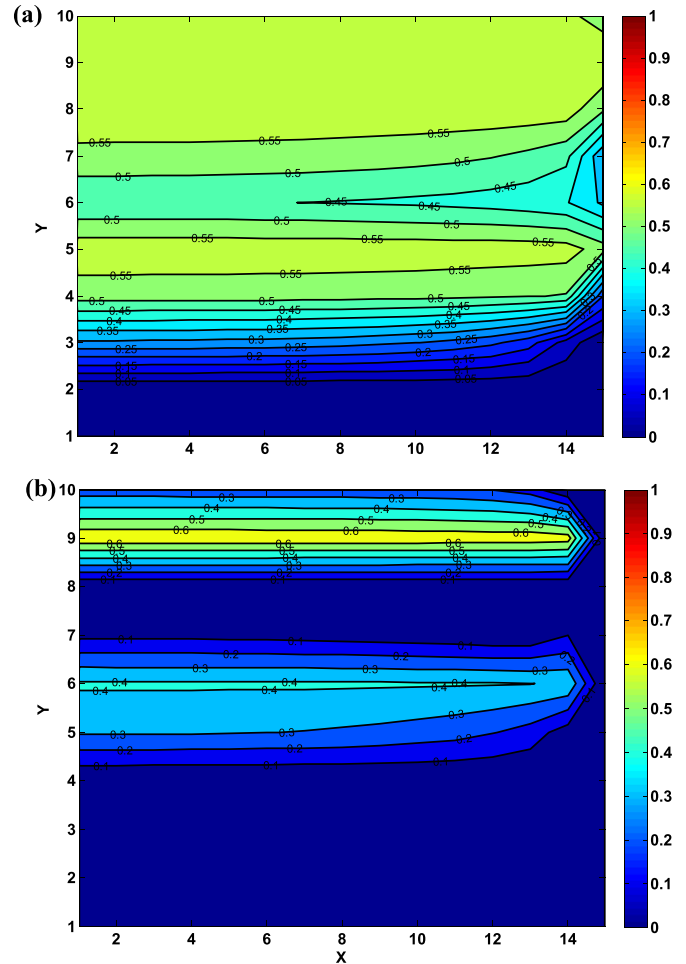


Fig. 4. (a) Hydrate saturation profile at 367 days for 4 MPa production pressure in Fig. 2. X-Axis is grid block number on the diagonal AB crossing producer on right. Y-axis is height of the reservoir. (b) Hydrate saturation profile at 2204 days for 4 MPa production pressure in Fig. 2.

layer and a higher temperature is seen in the upper layer, but pressure is high due to less depressurization as permeability is low. So high permeability layer at the interface, at 6 m height from reservoir bottom, is in contact with high temperature layer having high enthalpy in comparison to the high permeability regions away from the interface. In the middle layer, layer 2 in Fig. 2, the depressurization is more due to high permeability than upper most layer. So at the interface of two hydrate bearing layers at 6 m height from the bottom, we have high temperature and low pressure which leads to a hydrate dissociation front. As more hydrate dissociate at the interface, permeability increases, which perpetuates the phenomena. Fig 4(b) shows the hydrate saturation after 2204 days of production. At this time the gas produced in the reservoir moves up due to gravity and hydrates reform near overburden where porosity and permeability are low. The energy released due to hydrate reformation helps hydrate dissociation in lower grids. So hydrate dissociation is dependent on the enthalpy available for dissociation in a particular layer and depressurization potential of the layer and the reservoir as a whole.

The above results give the inference that the dissociation front at the interface of two hydrate bearing layers leads to faster gas recovery. To exclude other parameters that may lead to faster gas recovery, another homogeneous case is considered where average porosity is equal to the average porosity of the hydrate bearing

layers of heterogeneous case (average porosity 0.18) so that amount of hydrates in the reservoir are same to compare the gas recovery. This leads to even less gas recovery as shown in Fig 3(a). But in this case the aquifer depressurization is less, due less porosity and permeability in the aquifer, 0.18 porosity for homogeneous case and 0.3 porosity for heterogeneous case. To eliminate the depressurization factor another case is considered where porosity in the hydrate bearing zone is 0.18, same as layered case and in the aquifer is 0.3. Now the gas recovery is similar to the heterogeneous case as shown in Fig. 3(b).

4.1.2. Discussion

The above results show that the gas recovery depends on the amount of hydrate present, heat content and depressurization potential of the reservoir and only minor variation in recovery is caused by the layering in the rocks. This is further confirmed when the porosity of hydrate bearing layers is changed keeping the average porosity same as discussed in Section 4.2.

4.2. Effect of permeability variation

The permeability of different layers in hydrate bearing zone is varied to see its effect on gas recovery and dissociation fronts. Different porosities are considered which translate in different permeability according to Civan's Model [15]. In Fig. 5(a), 'case a' shows the base case that was considered to see the effect of layers in a hydrate reservoirs in Section 4.1. Next, the permeability of the

hydrate bearing layers are varied as shown in 'case b'. The 'case c' in Fig. 5(a) has a smaller and less permeable aquifer with porosity 0.21 and high porosity (porosity 0.3) hydrate layer is in contact with aquifer and low porosity (porosity 0.14) is near the overburden, similar to 'case a'. In 'case d', the aquifer size is same as 'case c' and high porosity layer is near overburden and low porosity layer is in contact with aquifer, similar to 'case b'.

4.2.1. Results

In 'case b', the high porosity hydrate layer is near the overburden and low porosity layer is near the aquifer. The gas recovery with time for this case is similar to gas recovery from 'case a' as shown in Fig. 5(b). The recovery and recovery rate depend on the heat available for hydrate dissociation, amount of hydrates present and depressurization potential as discussed in the Section 4.1, and 'case a' and 'case b' are similar in these respects, therefore have similar gas recovery rates. The 'case c' and 'case d' in Fig. 5(a) also have similar amount of heat available in the reservoir, same amount of gas hydrate, and same depressurization potential of aquifer so have similar gas recovery rates as shown in Fig. 5(b). But the gas hydrate dissociation fronts appear at different positions and times for these reservoirs as discussed below.

Fig. 6 shows the hydrate saturation profiles at 367 days and 2204 days for 'case b' in Fig. 5(a), which is similar to 'case a' in aquifer

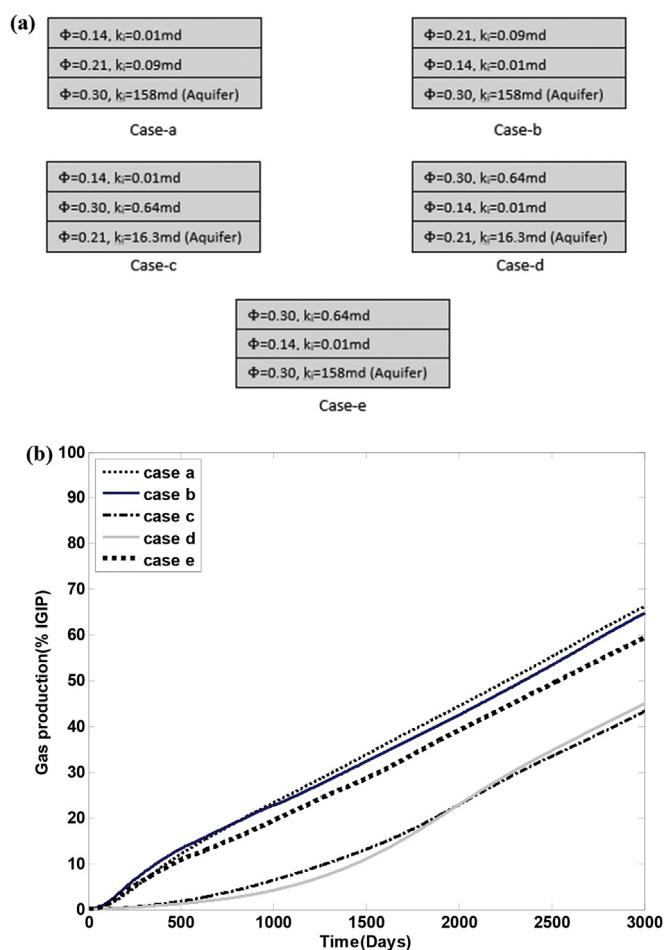


Fig. 5. (a) Reservoir models for different layering. (b) Gas recovery for cases in Fig. 5(a).

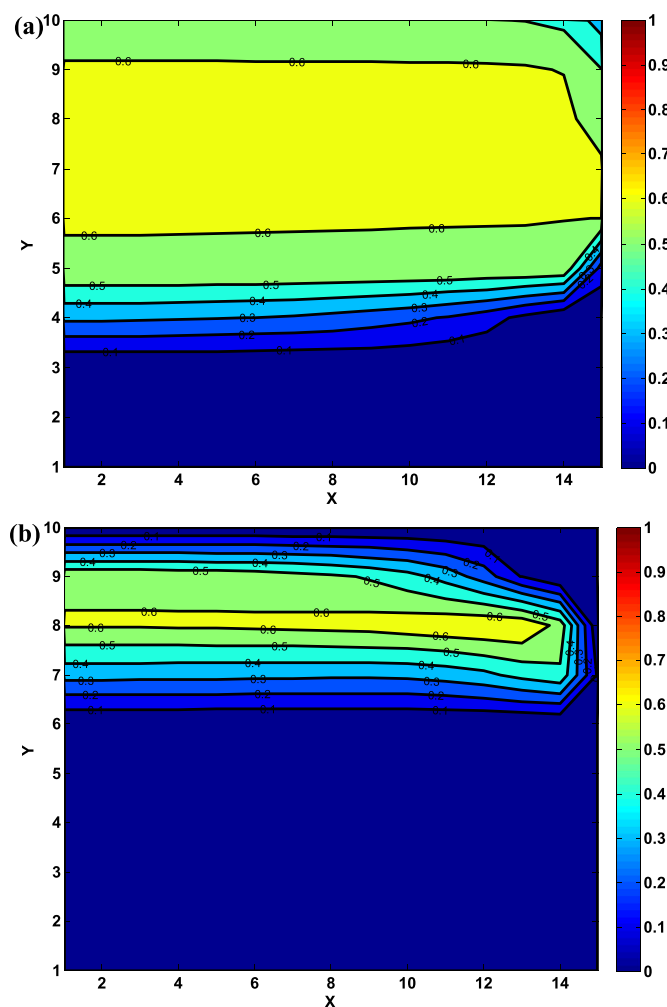


Fig. 6. (a) Hydrate saturation profile at 367 days and 4 MPa production pressure for 'case b'. (b) Hydrate saturation profile at 2204 days and 4 MPa production pressure for 'case b'.

size, amount of gas hydrate and average porosity of hydrate bearing zone. In contrast to Fig. 4(a) which shows hydrate saturation profile of 'case a' at 367 days, hydrate dissociation fronts in 'case b' are limited to overburden and near aquifer. There is no hydrate dissociation front at the interface of two hydrate bearing layers. This is due to large amount of dissociation at the hydrate water contact as shown in Fig. 6(a), where '0' hydrate saturation contour is at more than 3 m height (y-axis) from the bottom of the reservoir as compared to about 2 m height in Fig. 4(a). Hydrate saturation at 2204 days is shown in Fig. 6(b) which show dissociation fronts progressing from the overburden and hydrate water contact unlike in 'case a' where dissociation front progresses at the interface also (Fig. 4(b)).

Fig. 7 shows the hydrate saturation profile for cases c and d, in Fig. 5(a), at 367 days and 2204 days. When lower porosity hydrate bearing layer is near overburden ('case c') then initial dissociation fronts are at the interface of the two hydrate bearing layers, at 6 m height and at the aquifer hydrate contact at 2 m height from the bottom as shown in Fig. 7(a). This is similar to 'case a'. While, at 2204 days (Fig. 7(b)) dissociation near overburden also starts. But when the low porosity hydrate layer is near aquifer ('case d', similar to 'case b'), then dissociation starts at hydrate water contact and overburden as shown in Fig. 7(c) which shows hydrate saturation profile of 'case d' at 367 days. In this case, a dissociation front has started developing at the interface of the two hydrate bearing layers also, 6 m above the bottom of reservoir, and the dissociation

front progresses also as shown in hydrate saturation profile at 2204 days shown in Fig. 7(d). Hydrate start reforming also in the low porosity layer near the aquifer as shown in Fig. 7(d).

4.2.2. Discussion

In 'case b' no dissociation front appears at the interface of two hydrate bearing layers (Fig. 6(a, b)) unlike in 'case a' (Fig. 4(a, b)). In 'case b', less hydrates are present at hydrate water contact because of low porosity that require less enthalpy for dissociation, therefore, a large dissociation front is seen in Fig. 6(b). Also, high permeability aquifer has a large contact area with low permeability hydrate layer which leads to significant depressurization near hydrate water contact. The large amount of dissociation at the hydrate water contact reduces the temperature of the low porosity hydrate bearing layer in 'case b' and enthalpy transfers towards the hydrate water contact from above. In addition, the pressure in the high porosity hydrate layer at the top does not decrease significantly being away from the aquifer. Therefore, at the interface of two hydrate layers we have higher pressure and less enthalpy as compared to 'case a' and the dissociation front is not seen in the 'case b'. This is also evident in 'case c' and 'case d' in Fig. 5(a) as discussed below, where aquifer porosity is 0.21 and hydrate layers have porosity of 0.3 and 0.14.

Cases c and d in Fig. 5(a) have a less porous aquifer which leads to less depressurization as compared to cases a and b. The gas recovery is also slower in cases c and d as shown in Fig. 5(b). The

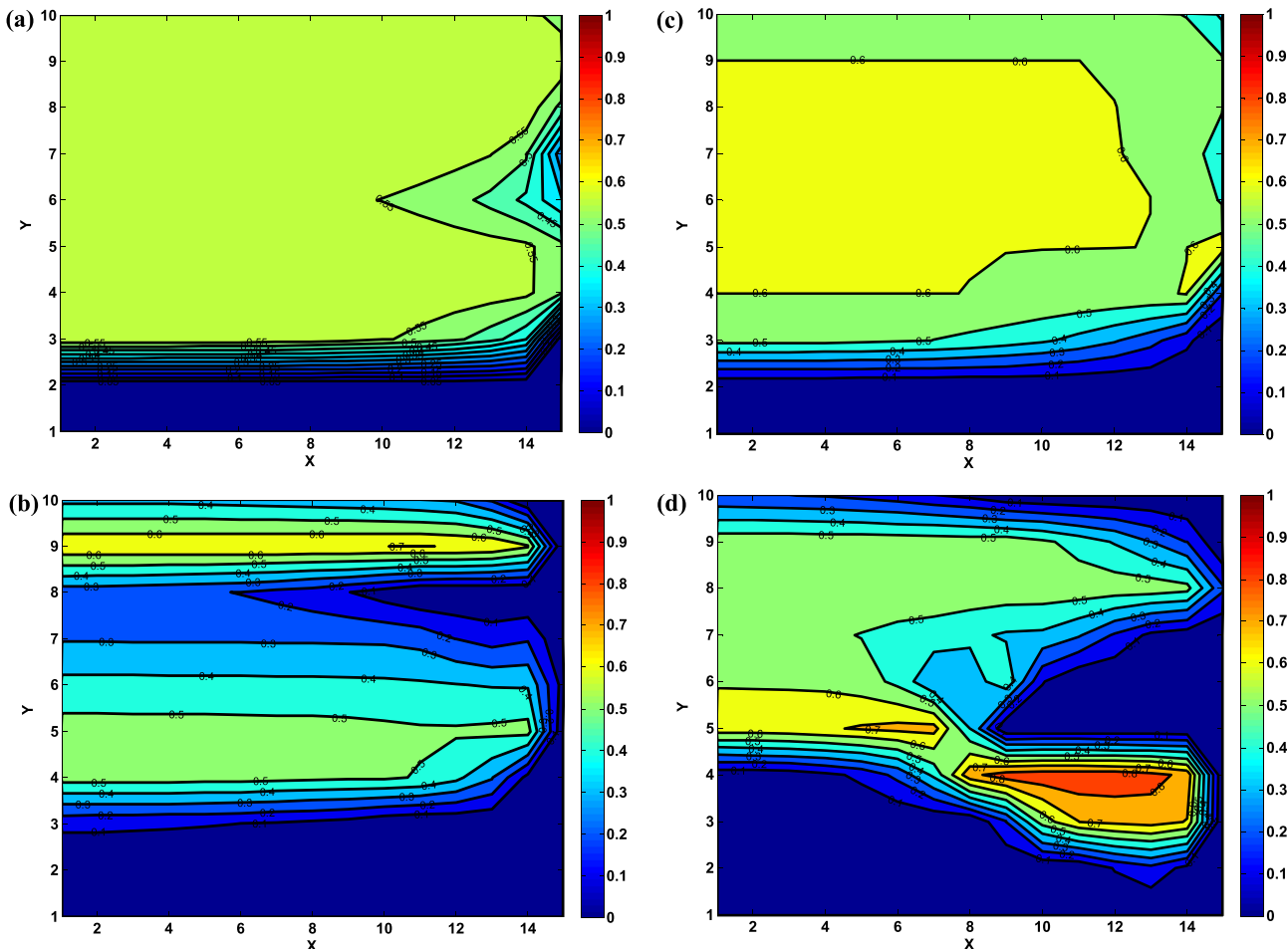


Fig. 7. (a) Hydrate saturation profile at 367 days and 4 MPa production pressure for 'case c'. (b) Hydrate saturation profile at 2204 days and 4 MPa production pressure for 'case c'. (c) Hydrate saturation profile at 367 days and 4 MPa production pressure for 'case d'. (d) Hydrate saturation profile at 2204 days and 4 MPa production pressure for 'case d'.

dissociation fronts for 'case c' appear at similar positions as in 'case a', at the hydrate water contact, interface of two hydrate bearing layers and near over-burden as shown in Fig. 7(a). These dissociation fronts are less prominent than 'case a' (Fig. 4(a)). The front near the aquifer is slow moving due to less porosity and permeability of aquifer which leads to a lower depressurization in aquifer. The low porosity layer at the top has high energy due to no hydrate dissociation and high porosity hydrate bearing layer near the aquifer has low pressure due to high permeability which leads to a dissociation front at the interface of the two hydrate bearing layers. At the interface the amount of hydrate to be dissociated is more in 'case c', in comparison to 'case a', due to high porosity of middle hydrate layers in 'case c' which leads to a less prominent dissociation front at the interface of two hydrate layers. In 'case d', similar to 'case b', a prominent dissociation front appears at the hydrate water contact and near the overburden (Fig. 7(c)), but a dissociation front starts appearing at the interface of two hydrate bearing layers at 6 m height from the bottom and progresses with time as shown in Fig. 7(d). This dissociation front is not seen in 'case b'. This front appears due to the low depressurization potential of aquifer in 'case d' which leads to less dissociation at hydrate water contact in comparison to 'case b' (Fig. 6(b)). Less enthalpy is used in hydrate dissociation which can be transferred to the high porosity layer near the over-burden where the pressure has decreased leading to a dissociation front at the interface of two hydrate layers. To confirm the above hypothesis, 'case e' shown in Fig. 5(a) is considered, where aquifer porosity is considered to be 0.3 in comparison to 0.21 aquifer porosity in 'case d', and this should not have a dissociation front at the interface of two hydrate bearing layers and the dissociation front at the hydrate water contact should be fast moving. Fig. 8(a, b) show the hydrate saturation profiles for 'case e' in Fig. 5(a) (at 367 days and 2204 days) and no dissociation front appears at the interface of two hydrate bearing layers as anticipated.

In all the above cases the dissociation front at the interface of hydrate bearing layers always move towards the low porosity hydrate bearing layer. This is due to less amount of hydrate present which require less enthalpy of dissociation.

4.3. Sensitivity analysis

4.3.1. Sensitivity to heat transfer coefficient at over-burden and under-burden

The heat transfer coefficient at the over-burden and under-burden impacts enthalpy drawn to the reservoir from the adjacent rocks and hence the gas production from layered hydrate reservoirs. The heat transfer coefficient for the above cases is $0.2 \text{ W/m}^2\text{K}$. This is calculated for an infinite rock at over-burden and under-burden using sand heat conductivity and maintaining a constant temperature at initial value at over-burden and under-burden. If the conductivities of the rock layers above and below are different, a different heat transfer coefficient would be needed in the model. Fig. 9 shows the effect of heat transfer coefficient at under-burden and over-burden on gas recovery for 'case a' in Fig. 5(a).

Fig. 10(a, b, c) show hydrate saturation profiles when heat transfer coefficient is 0.02 W/K/m^2 , 0.2 W/K/m^2 and 2 W/K/m^2 , respectively, at 1010 days. The heat transfer from over-burden and under-burden and hence the hydrate dissociation is slower for heat transfer coefficient of 0.02 W/K/m^2 because the hydrate dissociation progress is slow as shown in Fig. 10(a). The hydrate dissociation slows down at 500 days as shown in Fig. 9, as till that time the enthalpy inside the reservoir domain is being used. After 500 days the enthalpy transfer from the over-burden and under-burden is needed, which is very slow and hence dissociation slows down. In

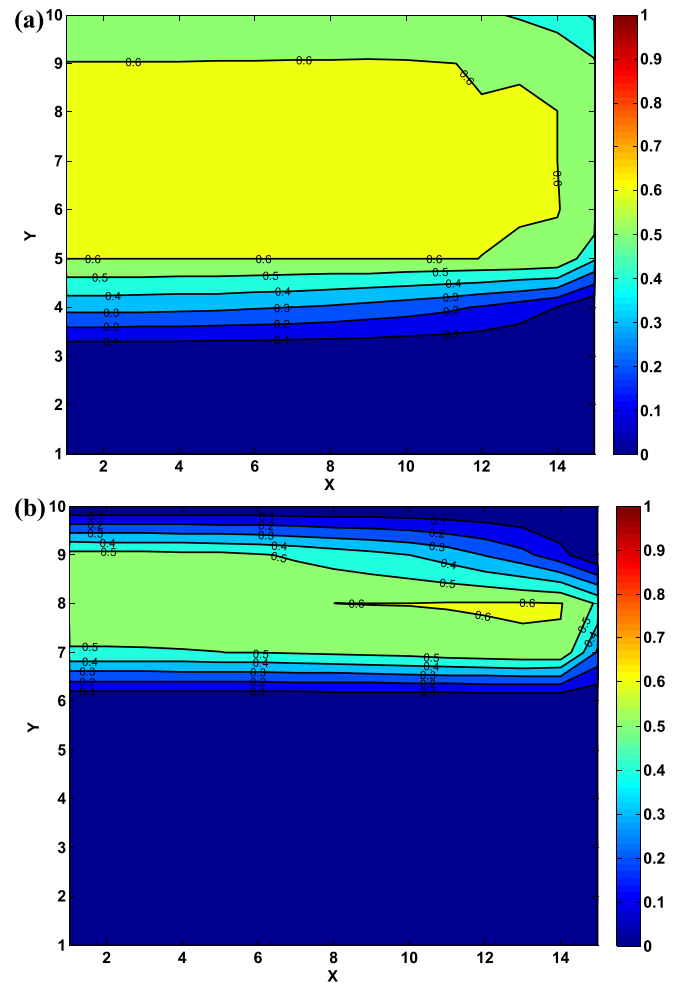


Fig. 8. (a) Hydrate saturation profile at 367 days and 4 MPa production pressure for 'case e'. (b) Hydrate saturation profile at 2204 days and 4 MPa production pressure for 'case e'.

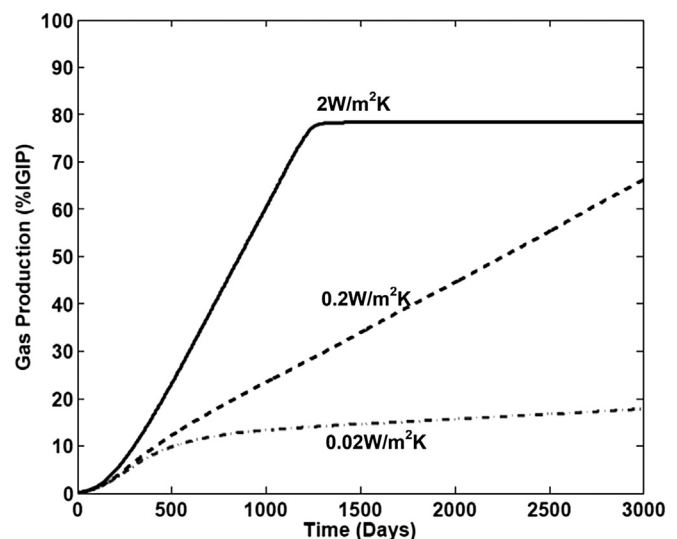


Fig. 9. Effect of heat transfer coefficient at under-burden and over-burden on gas production for 'case a'.

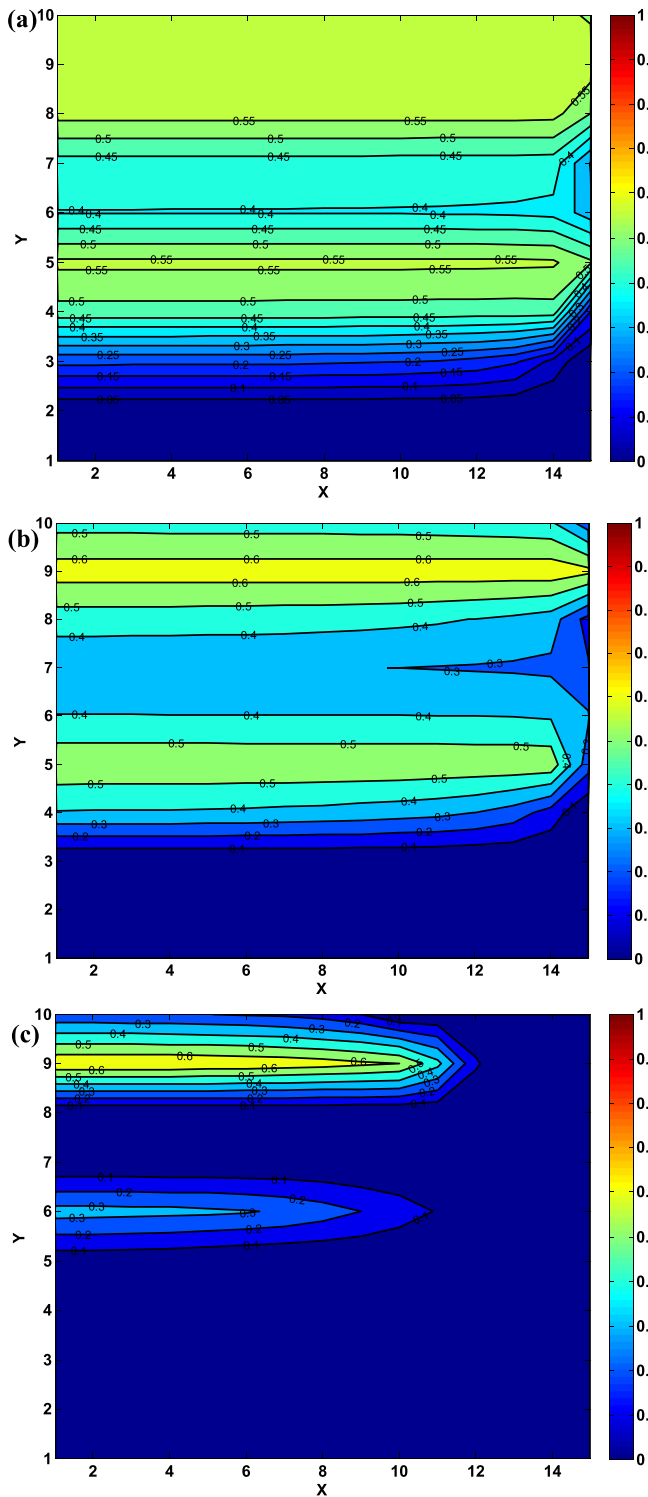


Fig. 10. (a) Hydrate saturation profile at 1010 days and 4 MPa production pressure for 0.02 W/m²K heat transfer coefficient at under-burden and over-burden. (b) Hydrate saturation profile at 1010 days and 4 MPa production pressure for 0.2 W/m²K heat transfer coefficient at under-burden and over-burden. (c) Hydrate saturation profile at 1010 days and 4 MPa production pressure for 2 W/m²K heat transfer coefficient at under-burden and over-burden.

the case of high heat transfer coefficient, i.e. very conductive over-burden and under-burden, the depressurization and conductivity inside the reservoir are the rate determining processes as the enthalpy transfer from over-burden and under-burden are very fast.

4.3.2. Effect of initial hydrate saturation

Fig. 11 shows the gas production for layered reservoir 'case a' for different initial hydrate saturations.

As hydrates are solid the effective porosity and hence permeability decreases with increasing hydrate saturation. The permeability of rock with porosity 0.3 (aquifer), 0.21 and 0.14 is 158.03 md, 16.37 md and 1.53 md respectively when no hydrates are present. But the permeability decreases to 158.03 md, 0.02 md and 0.002 md if $S_H = 0.7$. For $S_H = 0.4$, the permeability is 158.03 md, 0.84 md and 0.09 md. Aquifer layer permeability does not change because hydrates are not present. The permeability across hydrate bearing layers are comparatively larger for $S_H = 0.4$ than for $S_H = 0.7$. The rate of pressure decrease is higher because of the high permeability in $S_H = 0.4$ case leading to faster rate of gas recovery. But the gas recovery during initial days for $S_H = 0.7$ is higher than the gas recovery for $S_H = 0.4$, as shown in Fig. 11, because the initial production is from the near well and aquifer area, which depends on the amount of hydrate present in the area and permeability does not affect the production. Ultimate gas recovery increases as the initial hydrate saturation increases.

4.3.3. Effect of intrinsic permeability

Fig. 12 compares the simulation results for gas production for layered reservoir of 'case a' with different intrinsic permeability for same porosity.

At the permeability of 1580 md at porosity of 30%, gas recovery is higher (about 73% OGIP). If the permeability is 158 md at 30% porosity hydrate dissociation slows down, because of less permeability pressure in the reservoir decreases slowly and consequently the gas production decreases. For permeability of 15.8 md at 30% porosity the hydrate dissociation further slows down due to slow decrease in pressure across the reservoir. Depressurization becomes the rate determining process with decreasing permeability.

Table 2 summarizes the above results.

4.4. Example gas production strategy based on above results

4.4.1. Strategy for well completion

From above results one of the features of class 2 confined hydrate reservoirs is dissociation at hydrate water contact for

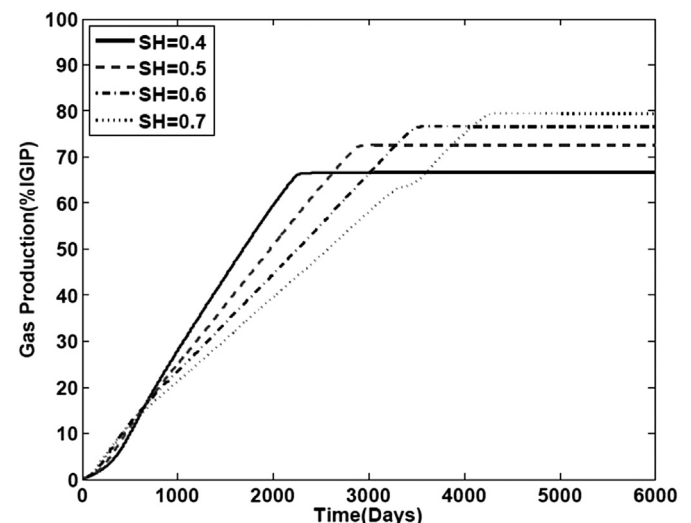


Fig. 11. Effect of hydrate saturation on gas recovery.

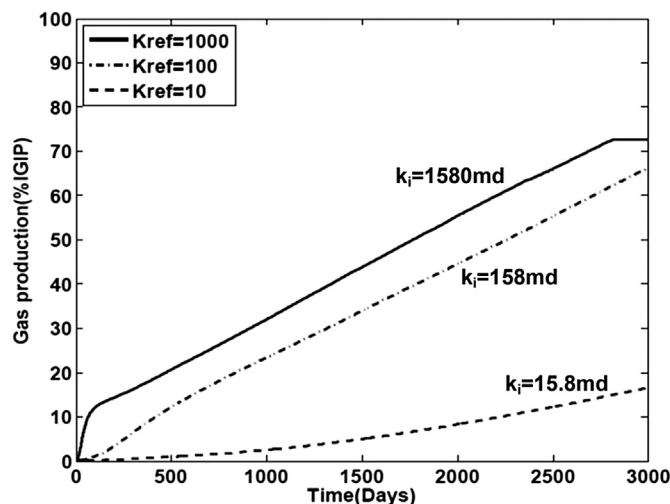


Fig. 12. Effect of intrinsic permeability on gas production for 'case a'.

which depressurization in the aquifer i.e. well completion in the aquifer is important. To confirm this hypothesis two models of well completions are simulated. In one the well is completed only in hydrate layer and another well is completed only in aquifer layer for 'case a' in Fig. 5(a). In Fig. 13, the gas recovery is compared to the base case when well is completed in both hydrate and aquifer zone.

Gas recovery is not affected much when well is completed only in the aquifer zone but slows down when well is completed only in the hydrate zone as the depressurization of hydrate bearing layer is difficult through the well due low effective permeability. For low permeability aquifer as in 'case c', the depressurization in both, hydrate bearing zone and aquifer zone are important. Fig. 13 shows the gas recovery rate for 'case c' for three well completions. When well is completed in the aquifer and the hydrate zone we get the maximum recovery and recovery rate. The recovery rate decreases when well is completed only in the aquifer or in the hydrate zone. In 'case c', the aquifer permeability is less so aquifer depressurization is not as significant so we get a higher recovery when the well is completed only in the hydrate zone compared to well completed only in the aquifer zone.

Table 2

Review table summarizing studies done and results.

Study	Result
Comparison of layered and homogeneous reservoir	Gas recovery depends on amount of hydrate, enthalpy available and depressurization potential
Different layering scenarios	Dissociation front appears at interface of two hydrate bearing layers and expands in low porosity layer. The appearance of the dissociation front depends on the enthalpy available.
Heat transfer coefficient at over-burden and under-burden	More the heat transfer coefficient, more enthalpy available from the surrounding which leads to high gas recovery rate
Initial hydrate saturation	High initial hydrate saturation decreases the initial effective permeability decreasing the gas recovery rate
Intrinsic permeability	High intrinsic permeability assists in gas flow and depressurization leading to high gas recovery rate

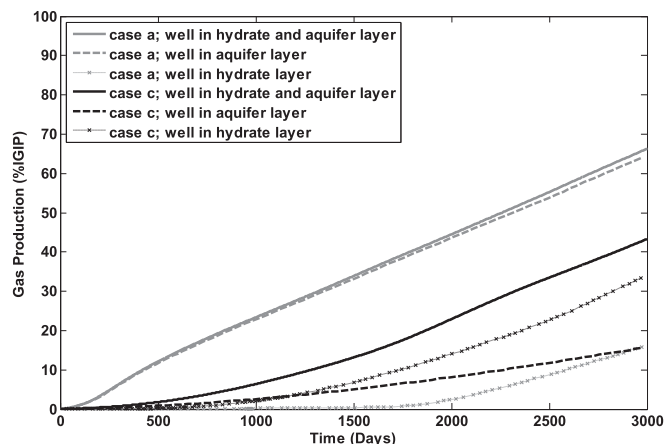


Fig. 13. Effect of well completion on gas recovery.

5. Conclusions

In this work we investigated heterogeneous class 2 gas hydrate deposit using numerical simulations. On the basis of the results of this study we draw following conclusion.

1. The cumulative gas recovery and gas recovery rate for a confined, class 2, layered hydrate reservoir is dependent on the total volume of hydrates in the reservoir which governs the enthalpy requirement for the hydrate dissociation, depressurization potential and enthalpy available from surroundings irrespective of the layering.
2. For heterogeneous class 2 hydrate reservoirs, we are first to find that hydrate dissociate at the interface of two hydrate bearing layers. This dissociation front expands in the low permeability layer and helps in hydrate dissociation. But there may be some scenarios in layered reservoirs where the dissociation front at the interface of two hydrate bearing layers may not appear or is not dominant. Permeability contrast between the hydrate bearing layers affects the time and position of these dissociations fronts.
3. Heat transfer coefficient at the over-burden and under-burden plays an important role in gas recovery from hydrate deposits as hydrate dissociation is an endothermic process. The larger the heat transfer coefficient the greater enthalpy is transferred from the surrounding increasing the gas recovery rate.
4. Sensitivity to initial hydrate saturation indicate that the gas recovery is slower for high hydrate saturation contrary to intuitive understanding. But initial production rate is well in line with intuitive belief that higher the hydrate saturation more the gas recovery rate as in initial days the travel distance for gas is less. With time the travel distance increases and less effective permeability decreases the depressurization effect and increases the travel time decreasing the gas recovery rate.
5. Sensitivity to intrinsic permeability shows that gas recovery rate increases for high intrinsic permeability as it provides favorable conditions for gas flow.
6. For class 2 hydrate reservoirs the well should be completed in aquifer and hydrate zone to get benefit from the depressurization of aquifer which increases gas recovery rate.

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Nomenclature

ϕ	porosity
ϕ^e	effective porosity
ϕ^0	reference porosity
K^0	reference permeability (md)
K^e	effective permeability (md)
K	intrinsic permeability (md)
K_i	initial permeability (md)
S_j	saturation of phase j based on total volume.
S_{jr}	residual saturation of phase j based on total volume.
k_{rj}	relative permeability of phase j
k_{rj}^0	end point relative permeability of phase j
$S_{j,e}^*$	effective normalized saturation of phase j for relative permeability curve
n_j	Corey's exponent for phase j
P_c	capillary pressure (MPa)
P_{ce}	entry capillary pressure (MPa)
nc	pore structure parameter for capillary pressure curve
ρ_j	density of phase j . (kg/m ³)
ρ_R	density of rock j . (kg/m ³)
w_j^i	weight fraction of component i in phase j .
F^i	mass flux of component i .
q^i	source term of component i .
U_j	total internal energy per unit volume of phase j . (J/m ³)
U_R	internal energy of sand phase. (J/Kg)
H_j	specific heat of phase j . (J/Kg)
λ	effective thermal conductivity W/m/K
J_j^i	molecular diffusion of component
i	due to dispersion in j phase.

Superscript

i (methane) m , (water) w , (energy) e

Subscript

j (aqueous phase) A , (gas phase) G

Appendix A

The governing mass balance equations for methane and water used in simulator are:

$$\frac{\partial}{\partial t} \left(\phi \sum_{j=H,I,A,G} \rho_j S_j w_j^m \right) + \nabla \cdot F^m = q^m \quad (A1)$$

$$\frac{\partial}{\partial t} \left(\phi \sum_{j=H,I,A,G} \rho_j S_j w_j^w \right) + \nabla \cdot F^w = q^w \quad (A2)$$

The energy balance equation is:

$$\frac{\partial}{\partial t} \left(\phi \sum_{j=H,I,A,G} (\rho_j S_j U_j) + (1 - \phi)(\rho_R U_R) \right) + \nabla \cdot F^e = q^e \quad (A3)$$

The flux in mass transport equation that account convection and dispersion in equation (A1) and (A2) are given as:

$$F^i = \rho_G v_G w_G^i + \rho_A v_A w_A^i + J_G^i + J_A^i \quad (A4)$$

Here v_G and v_A are velocities of gas phase and aqueous phase according to Darcy's law.

The energy flux in equation (A3) through convection and conduction is:

$$F^e = \rho_G v_G H_G + \rho_A v_A H_A - \lambda \nabla T \quad (A5)$$

Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.energy.2015.01.077>.

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