

Effect of geological layers on hydrate dissociation in natural gas hydrate reservoirs



Piyush Bhade, Jyoti Phirani*

Department of Chemical Engineering, Indian Institute of Technology Delhi, Hauz Khas, New Delhi 110016, India

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ABSTRACT

Naturally occurring reservoirs of methane gas hydrate have been found in arctic and marine environments around the world. They are an attractive source of energy as natural gas can be produced from these hydrate deposits by depressurization or thermal stimulation. Reservoir simulations are used to find the optimum production strategies for methane gas hydrate reservoirs. Most of these simulation are carried out for homogeneous hydrate reservoirs in absence of substantial well data. These gas hydrate reservoirs are inherently heterogeneous because of the geological settings of the hydrate bearing sediments. 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 effects of geological layering on gas production and hydrate dissociation fronts in the reservoir are still unknown. In the present work, a 3-dimensional, multiphase, multi-component, thermal simulator is used to study layered gas hydrate reservoir, underlain by an aquifer, with cross-flow between the layers. Gas production from the reservoir and gas hydrate dissociation fronts in the reservoir are found for different aquifer permeability, different layering and well completions. In layered confined reservoirs, recovery is found to be dependent on (a) the total volume of the hydrate present in the reservoir which governs the enthalpy requirement for dissociation, (b) depressurization potential of the reservoir which depends on the effective permeability and (c) the enthalpy available for dissociation which depends on the reservoir enthalpy and heat transfer from over and under-burden. The layering suggests the positions and progress of the dissociation fronts and affects the gas recovery depending on the aquifer permeability. This effect is seen because of the pressure variation in different layers and enthalpy available for hydrate dissociation. In unconfined reservoirs the effect of layering on dissociation front positions is found to be insignificant as the pressure variation in the layers is insignificant because of the unconfined aquifer. A weakly un-confined aquifer also renders the depressurization ineffective.

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1. Introduction

Gas hydrates are crystalline solid compounds where gas molecules, called 'guests', are bounded by ice like crystal lattices of water molecules, called hosts, at high pressure and low temperature (Sloan and Koh, 2007). The gas hydrate forming molecules are generally small like methane, ethane, propane and carbon dioxide. Natural gas hydrate deposits generally occur in the permafrost or in oceanic sediments where the conditions of high pressure and low temperature are favourable for the hydrate formation and stability.

These gas hydrates are considered to be a new source of fossil energy (Makogon and Omelchenko, 2013; Riedel et al., 2006; Milkov, 2003). The hydrate formation and dissociation is described by the reaction:



where, n is the hydration number. The hydration number of methane is approximately 6 for the hydrates found in the natural hydrate deposits (Sloan and Koh, 2007). Fig. 1 shows the p_e - T curve for methane hydrate in salt free system, where, p_e is the equilibrium pressure of three phase equilibria H (hydrate) + G (gas) + A (aqueous) and $\text{H} + \text{G} + \text{I}$ (ice) at temperature T (Sloan and Koh, 2007). The curve is represented by a regression formula obtained by Moridis (2003) through fitting experimental data

* Corresponding author.

E-mail addresses: jphirani@chemical.iitd.ac.in, jyotiphirani@gmail.com (J. Phirani).

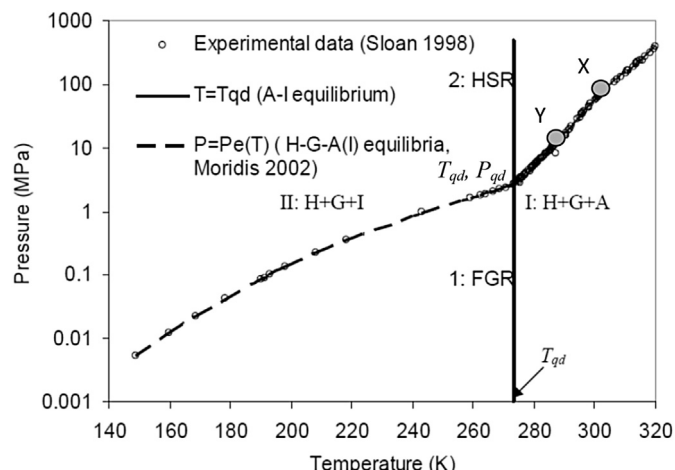


Fig. 1. p_c - T phase diagram for methane hydrate.

reported by Sloan and Koh (2007). T_{qd} is the quadruple point temperature for methane hydrate which intersects the methane hydrate equilibrium curve at P_{qd} where four phases (hydrate, gas, ice and water) can coexist. p_c - T diagram is divided into two regions (region I and region II) by the solid vertical line. Region I ($T > T_{qd}$), is H + G + A region where water exists in liquid or aqueous phase (A). Region II ($T < T_{qd}$) is H + G + I region where water exists in solid or ice phase (I). p_c - T diagram is divided in two regions (region 1 and region 2) by the dashed phase boundary $p_c = p_e(T)$. Region 1 is the hydrate stable region (HSR) however region 2 is the free gas region.

In the most recent review of this subject, the present estimate of total quantity of methane present in the form of gas hydrates is of the order of 10^6 trillion cubic meter (Boswell and Collett, 2011). This new found source of fossil energy is huge and methane present in these hydrate deposits is very concentrated as hydrates contain 164 times the amount of gas present in the same volume at STP (Sun et al., 2005). To meet the increasing energy demand, while the conventional energy resources are depleting, the gas recovery from these hydrate reservoirs is important. Finding a safe and efficient method to recover natural gas from hydrate deposit is important to make the recovery commercial.

At present, four types of hydrate deposits have been identified which are classified as: Class 1 – hydrate deposits underlain by a free gas layer, Class 2 – hydrate deposits underlain by an aquifer, Class 3 – single hydrate zone confined by shale layers, Class 4 – hydrate reservoirs in oceanic accumulations and low saturation hydrate deposit in dispersed form (Moridis and Sloan, 2007). The economic and effective methods of hydrate dissociation from these reservoirs are needed for gas production. The widely proposed methods for gas production due to hydrates dissociation from these deposits are: 1) Depressurisation (Cheng et al., 2013; Li et al., 2012a, 2012c; Zatsepina et al., 2011; Uddin et al., 2014), in which the pressure inside the hydrate deposit is dropped below the hydrate dissociation pressure, below the equilibrium line in Fig. 1, by maintaining a low pressure at production well. 2) Thermal stimulation (Castaldi et al., 2007; Kamath, 1987; Li et al., 2008; Phirani et al., 2009a; Sun et al., 2014) in which heat is provided to the reservoir by injecting steam or hot water to raise the reservoir temperature above equilibrium temperature. 3) Inhibitor injection (Dong et al., 2009; Li et al., 2007; Sira et al., 1990), in which the chemicals like salt and alcohol are used to shift the hydrate pressure vs temperature equilibrium conditions. 4) CO_2 injection (Mohebbi and Behbahani, 2014; White and Mcgrail, 2008), in which methane gas is replaced by CO_2 in clathrate cages. Combination of

above methods can also be used to recover gas from hydrate deposits (Li et al., 2011, 2012b; Yang et al., 2010). In the present study Class 2 hydrate reservoirs are considered for our investigation. A previous study for confined, Class-2 reservoirs showed that the depressurisation method is the most effective and economical method for gas recovery (Phirani and Mohanty, 2009). But, the depressurisation pressure lower than the quadruple point pressure causes the ice formation in the reservoir (Moridis et al., 2009). Ice formation decreases the effective porosity and consequently the permeability also decreases which slows down the gas recovery (Phirani and Mohanty, 2009). To avoid ice formation, the depressurisation should be carried out at a higher pressure than the quadruple point pressure (Moridis et al., 2009).

Most of the literature on gas production from hydrate reservoirs focuses on homogeneous reservoirs (Moridis, 2003; Li et al., 2007; Moridis and Sloan, 2007; Li et al., 2008; Moridis et al., 2009; Li et al., 2011; Phirani and Mohanty, 2009; Li et al., 2012(b)). The effect of geological layers on hydrate dissociation in a natural gas hydrate reservoirs during depressurisation has not been studied thoroughly. Reagan et al. (2010) used reservoir simulations of Mount Elbert unit C and D (Class 3 hydrate reservoirs) to study the effect of heterogeneity in intrinsic properties such as permeability, initial hydrate saturation and porosity of hydrate bearing formation in a layer cake model and observed that the heterogeneity in the real reservoirs causes the complex flow behaviour inside the reservoir and near the well. This complex behaviour, if not identified before the production will affect the flow of fluids towards the well compelling revisions in the production strategies for efficient recovery. Bhade and Phirani (2015) showed that for two layered hydrate reservoir the gas recovery and recovery rate for hydrate reservoirs depend on the total volume of hydrate present in the reservoir, depressurisation potential and enthalpy available from surroundings irrespective of the layering. In the present work we have studied a multi-layered hydrate reservoir with cross-flow between the layers. The geological layering as well as aquifer permeability are found to have a significant effect on the gas production and fluid flow behaviour in the multi-layered reservoirs. An in-house simulator from UT–Austin is used for this study. In the absence of real world well data from hydrate reservoirs, for validation purpose the reservoir simulators available are validated against each other in the US DOE code comparison study. The simulator used in this study has been validated against several other simulators for the problems in the US DOE code comparison study (Wilder et al., 2008) and also against core scale experimental results (Phirani et al., 2009b).

2. Methodology

Reservoir simulations are used to find the behaviour of the layered gas hydrate reservoir under depressurization conditions. Appendix A describes the mass and energy balance equations used in the simulator. In this section, the reservoir domain used, initial and boundary conditions and discretization used for the simulations are elaborated first. Then, the thermal and transport properties of the fluids and the sediments used are delineated. The numerical scheme used to solve the mass and energy balance equations described in Appendix A is outlined next.

2.1. Reservoir description

This study considers a horizontal confined reservoir of thickness 10 m as shown in Fig. 2. The bottom 2 m of the reservoir is considered to be an aquifer ($S_A = 1$). The top 8 m of reservoir is considered to be hydrate layer with hydrate saturation of 0.6 ($S_H = 0.6$, $S_A = 0.4$). The reservoir is assumed to be developed

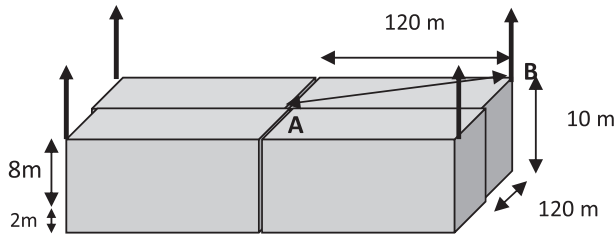


Fig. 2. Class-2 hydrate reservoir schematic considered for gas production.

symmetrically with four production wells and a quarter of the pattern, shown in Fig. 2, of area $120\text{ m} \times 120\text{ m}$ is simulated. The production wells are completed in the hydrate as well as in the aquifer zone. The simulated domain is discretized in $15 \times 15 \times 10$ grid blocks. The initial pressure of the reservoir is considered to be 9 MPa at the bottom which decreases with height according to a hydrostatic gradient. Initial temperature at the bottom of the reservoir is 280.7 K which decreases with a geothermal gradient of 0.03 K/m moving upwards. For depressurization of the reservoir a constant pressure of 4 MPa is considered at the producing well. At this depressurization pressure, which is above the quadruple point pressure, the event of ice formation is avoided in the reservoir (Moridis et al., 2009).

2.2. Thermal properties model

The equilibrium curve shown in Fig. 1 is used for the hydrate formation and dissociation thermodynamics in the simulator used in this study. The hydrate formation and dissociation are considered to be in equilibrium at the grid scale. The thermodynamic properties of gaseous methane are calculated by Peng Robinson equation of state (Talaghat, 2014). The solubility of methane in the aqueous phase, the water vapour fraction in the gas phase, specific internal energy, and specific enthalpy of non-gaseous phases are taken from the literature and are stated by Sun et al. (2005). Some of the important parameters are stated in Table 1.

2.3. Transport properties model

To calculate the permeability, power law model proposed by Civan (2001) is used as stated below

$$\frac{K_e}{K_0} = \frac{\phi^e}{\phi_0} \left(\frac{\phi^e(1-\phi_0)}{\phi_0(1-\phi^e)} \right)^{2\beta} \quad (2)$$

where, K_e is the effective and K_0 is the intrinsic permeability. ϕ^e is effective porosity and ϕ_o is the reference porosity. The effective porosity for the fluid phases can be related to the absolute porosity as

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

Brooks Corey relation is used to calculate the relative

permeability of the gas and aqueous phases as

$$k_{rG} = k_{rG}^0 \left(S_G^{e*} \right)^{n_G} \quad (4)$$

$$k_{rA} = k_{rA}^0 (S_A^{e*})^{nA} \quad (5)$$

where, k_{ij}^0 and η_j are the end point relative permeability and exponential parameter for phase j . The normalised saturation for phase j (S_A^{e*}) is given by

$$S_j^{e*} = \frac{S_j^e - S_{jr}^e}{1 - S_{Gr}^e - S_{Ar}^e} \quad (6)$$

where, saturation of the gas and aqueous phases based on the effective pore volume are

$$S_j^e = \frac{S_j}{\sum_{j=G,A} S_j} \quad (7)$$

The capillary pressure is related to the effective aqueous saturation by following equation:

$$P_c = P_{ce} \left(S_A^{e*} \right)^{-nc} \quad (8)$$

where, p_{ce} is the entry pressure which is correlated to the effective porosity as

$$P_{ce} = P_{ce0} \sqrt{\frac{\phi^e K_0}{\phi_0 K}} \quad (9)$$

The transport parameters used in the simulator are stated in [Table 2](#).

2.4. Numerical model

An in-house 3D, finite volume simulator developed by [Sun and Mohanty \(2006\)](#) is used that takes into account heat transfer, multiphase flow of fluids and equilibrium thermodynamics of methane hydrates as described above. Three components (methane, water and hydrate) and four phases (hydrate, gas, aqueous and ice phase) are considered in the simulator. The energy and mass balance equations as mentioned in [Appendix A](#) are solved in space and time domain. $120\text{ m} \times 120\text{ m} \times 10\text{ m}$ reservoir volume simulated is divided in to $15 \times 15 \times 10$ grid blocks. The simulator uses fully implicit scheme to solve the discretized equations in time. The Newton–Raphson method is used to solve the nonlinear equations. As the kinetics of the hydrate formation and dissociation are very fast as compared to the flow in field scale, all the phases are assumed to be in equilibrium at a particular pressure and temperature at grid scale ([Kim et al., 1987](#)). Primary variable switch method (PVSM) which has been proven to be a robust technique in dealing with the phase transitions ([Falta et al., 1992](#); [Forsyth and](#)

Table 1
Thermal parameters used in the simulator.

Hydrate density	910 kg/m ³
Ice density	917.1 kg/m ³
Sand density	2670 kg/m ³
Hydrate heat conductivity	0.49 W/m/K
Sand heat conductivity	5.57 W/m/K
Sand heat capacity	0.83 kJ/kg/K
Hydrate heat capacity	1.62 kJ/kg/K

Table 2
Transport parameters used in the simulator.

Reference permeability(k_o)	100 md
Reference porosity (Φ_o)	0.28
Gas rel. permeability constant (n_G)	2
Water rel. permeability constant (n_w)	4
Permeability rock constant (β)	2
Pore structure parameter (nc)	5
Residual water, gas saturation	0.2,0.0

Simpson, 1991) is used to track the phase status of each grid block. This simulator uses the continuum scale modelling so the coupling between thermodynamics, kinetics and transport processes at the microscopic level is neglected.

3. Simulation cases of layered gas hydrate reservoirs

A systematic study of the layered reservoirs is needed to understand the effects of the heterogeneity on gas production and hydrate dissociation, which are necessary for designing a production strategy for layered hydrate reservoirs. Therefore, four layered reservoir systems are simulated, using the model described in Section 2, as shown in Fig. 3. To mimic the reservoir heterogeneity, varying combinations of layers of porosity 0.21 and 0.14 are considered in hydrate bearing zone. The intrinsic permeability of the rock with 0.21 porosity is 16 md and at 0.14 porosity is 1.5md using Civan's correlation. When the rock is saturated with the hydrates the effective permeability decreases. At hydrate saturation of 0.6 the effective permeability of 0.21 porosity layer is 0.09 md and for 0.14 porosity layer, the permeability is 0.01 md as mentioned in Fig. 3.

In Fig. 3, 'case a', 2 m thick 0.21 porosity hydrate layers (high porosity hydrate layer, referred to as 'HPHL') are at the extremities of the hydrate zone. In 'case b' 2 m thick 0.14 porosity layer (low porosity hydrate layer, referred as LPHL) are near the over-burden and aquifer. In 'case c' and 'case d' four 2 m thick HPHL and LPHL are considered in the hydrate zone. Three aquifers with different permeability are considered for all the four cases shown in Fig. 3. The aquifer permeability is varied by varying the porosity of the aquifer layer. The three permeability values considered are porosity

0.3 with an intrinsic permeability of 158md, porosity 0.21 with an intrinsic permeability of 16md and porosity 0.14 with an intrinsic permeability 1.5md. In all the above cases the total amount of gas hydrates in the reservoirs considered are equal i.e. the enthalpy requirement for complete hydrate dissociation and Initial Gas in Place (IGIP) are same. In the next section we discuss the effects of aquifer permeability, reservoir layering in hydrate zone and un-confinement of the attached aquifer on hydrate dissociation, dissociation fronts and gas production. The hydrate layers for all the cases considered are named as L1, L2, L3 or L4 as shown in Fig. 3.

4. Results and discussion

The design of a production method for a gas hydrate reservoir is dependent on the dissociation fronts in the reservoir as the dissociation front may be a point of collapse for the hydrate reservoirs. Gas hydrate are solid, so their dissociation creates a void in the rock structure and if the hydrates are an integral part of the sediment structure, which is another area of investigation, the dissociation may lead to the failure of the structure. Therefore, knowledge of the dissociation fronts prior to the production is necessary for designing a production strategy. The gas production rate from these reservoirs is another design parameter for the production strategy. In the sub-sections below we delineate the effects of different reservoir parameters that influence the gas production rate and dissociation fronts in the reservoirs. These parameters are (a) the aquifer permeability (b) heterogeneity or layering in the hydrate zone (c) well completions and (d) un-confinement of the aquifer.

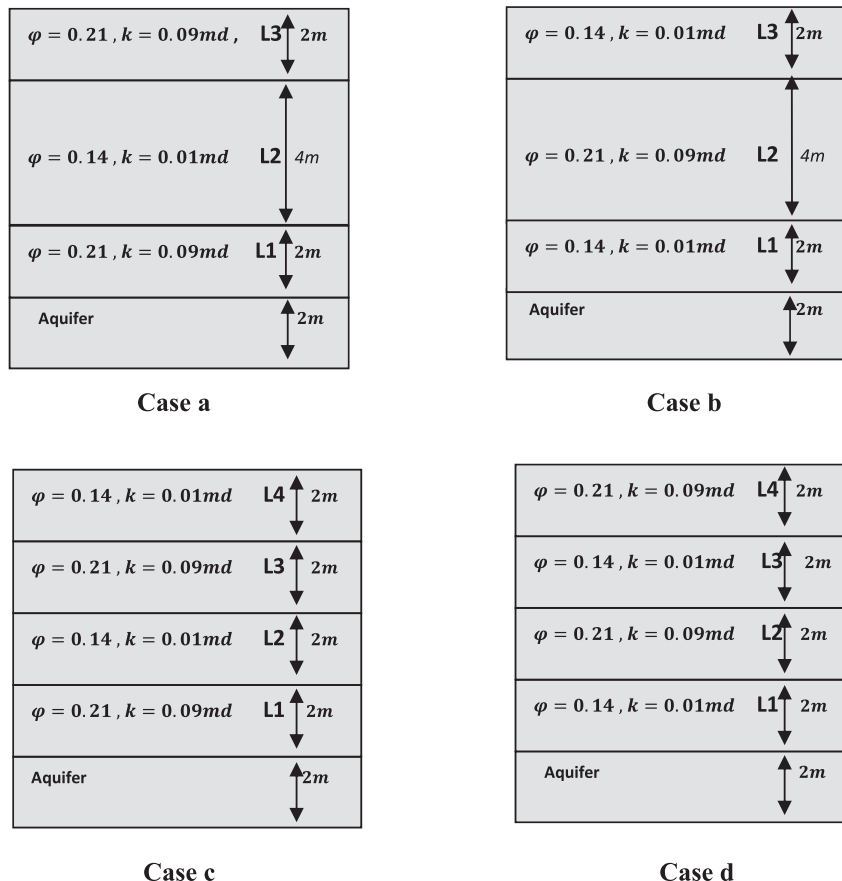


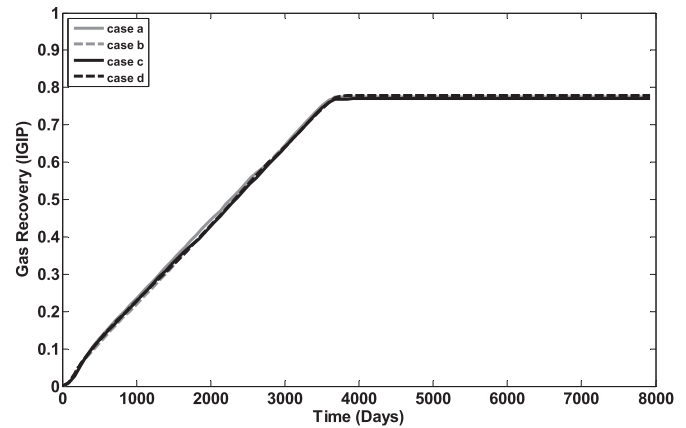
Fig. 3. Reservoir model for different layering.

4.1. Effect of aquifer permeability

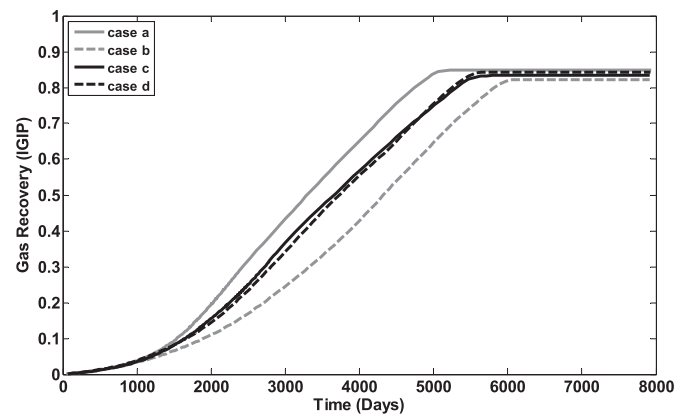
Multi-layered reservoirs with aquifer of different permeability are considered as shown in Fig. 3. The average porosity of the hydrate bearing zone is set to 17.5%, where hydrate saturation is 0.6 for all the cases. The porosity of the aquifer layer is varied as shown in Table 3. The maximum aquifer permeability considered is 158md and minimum aquifer permeability considered is 1.5md. Fig. 4 shows the percentage of initial gas in place (IGIP) recovered with time from the multi layered reservoirs shown in Fig. 3. Fig. 4(a) shows the gas recovery for the cases when aquifer permeability is 158md. The gas recovery rate does not vary significantly with the layering in the hydrate bearing zone even though the dissociation fronts in these cases appear at different positions as discussed in Section 4.2. Fig. 4(b) shows the gas recovery when aquifer permeability is 16md. In this case, the gas production rate varies with heterogeneity of the reservoir, while the final gas recoveries for all the cases are in a very short range. The gas production with time is highest for 'case a' and least for 'case b'. Fig. 4(c) shows the gas production for all the cases when aquifer permeability is 1.5md. 'Case a' has the maximum gas production with time, however 'case b' has the least. This scenario is same as 16md permeability aquifer. The ultimate gas recovery, among the three aquifers considered, is highest when aquifer permeability is 1.5md. Comparing the gas recovery for different aquifer permeability for 'case a', reservoir with aquifer permeability of 158md has recovered 80% of the gas at 4000 days, reservoir with aquifer permeability of 16md has recovered 70% of the initial gas in place and reservoir with aquifer permeability of 1.5md has recovered 50% of the gas. In the sections below we discuss the effect of aquifer permeability on gas recovery rate and the ultimate gas recovered in view of different parameters causing the variation.

4.1.1. Effect of aquifer permeability on gas recovery rate

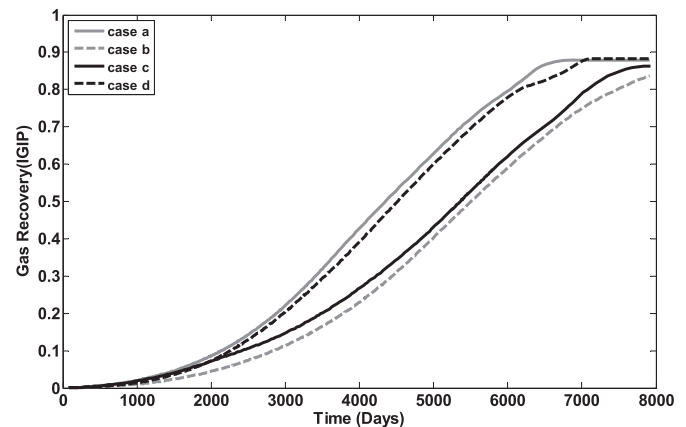
The gas recovery depends on the amount of hydrate dissociated, which in turn depends on the depressurization and enthalpy available that promote hydrate dissociation. In the case of high permeable aquifer depressurization is dominant, as water in the high permeability aquifer can be easily drawn out from the reservoir, which leads to decreased reservoir pressure. Now, Fig. 1 shows points 'X' and 'Y' as two conditions at which the hydrate start dissociating to gas and water. 'X' point is at a higher pressure and hydrate dissociation starts at a temperature T_x . If temperature is below T_x hydrates are stable. For point 'Y' hydrate start dissociating at a lower temperature than T_x . We can deduce that if we have lower pressure in the reservoir the hydrate dissociation starts at a lower temperature. Therefore, the enthalpy requirement (to heat the hydrate and surrounding rock to hydrate dissociation temperature) is low at low reservoir pressure. For the reservoirs considered in this work, the enthalpy requirement is the lowest when aquifer permeability is 158 md in all the cases in Fig. 3 and depressurization is dominant phenomena for hydrate dissociation. In this case, the heterogeneity in the hydrate zone does not impact gas production rate significantly as seen in Fig. 4(a). Enthalpy requirement is the most when the reservoir pressure is the highest for aquifer permeability of 1.5 md. Enthalpy requirement is



(a)



(b)



(c)

Fig. 4. (a): Gas Recovery from layered reservoirs with aquifer permeability of 158md. (b): Gas recovery from layered reservoirs with aquifer permeability of 16md. (c): Gas recovery from layered reservoirs with aquifer permeability of 1.5md.

intermediate for hydrate reservoir attached to aquifer with a permeability of 16 md. In both the above cases enthalpy plays an important role in hydrate dissociation and the gas production rate is impacted by heterogeneity in the hydrate zone as seen from Fig. 4(b, c).

Fig. 5 shows the pressure and temperature profiles of 'case a', for the three aquifers considered, at 490 days which help in explaining the difference in gas recovery rates. Fig. 5(a) shows the pressure

Table 3

Different size aquifer considered for study.

Aquifer porosity	Aquifer permeability
0.30	158 md
0.21	16 md
0.14	1.5md

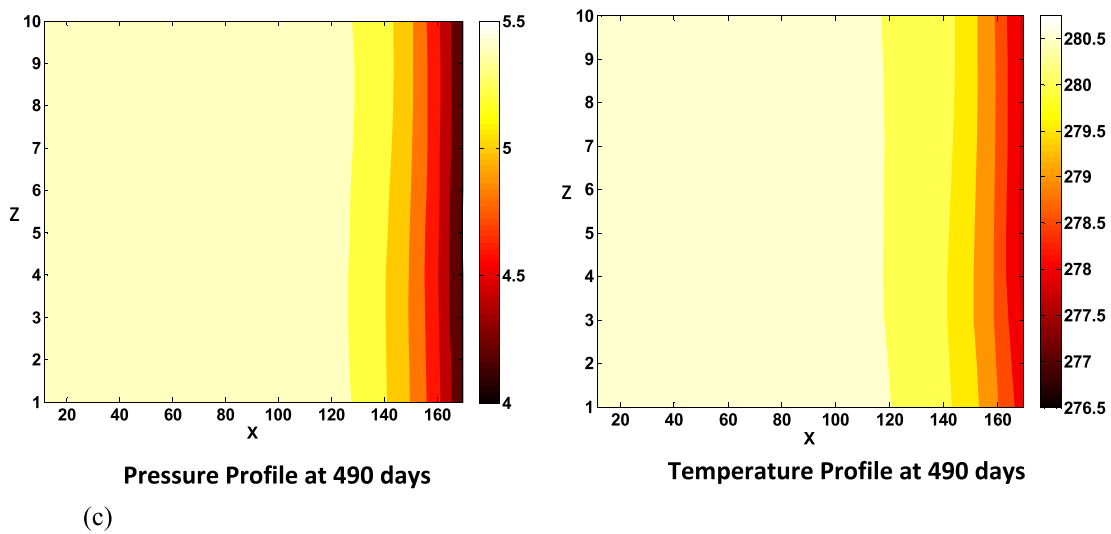
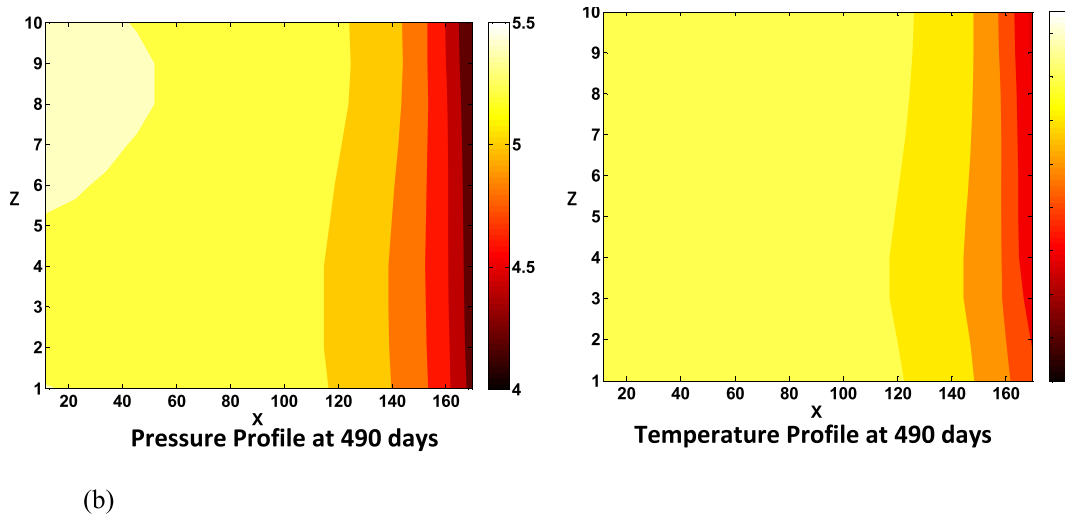
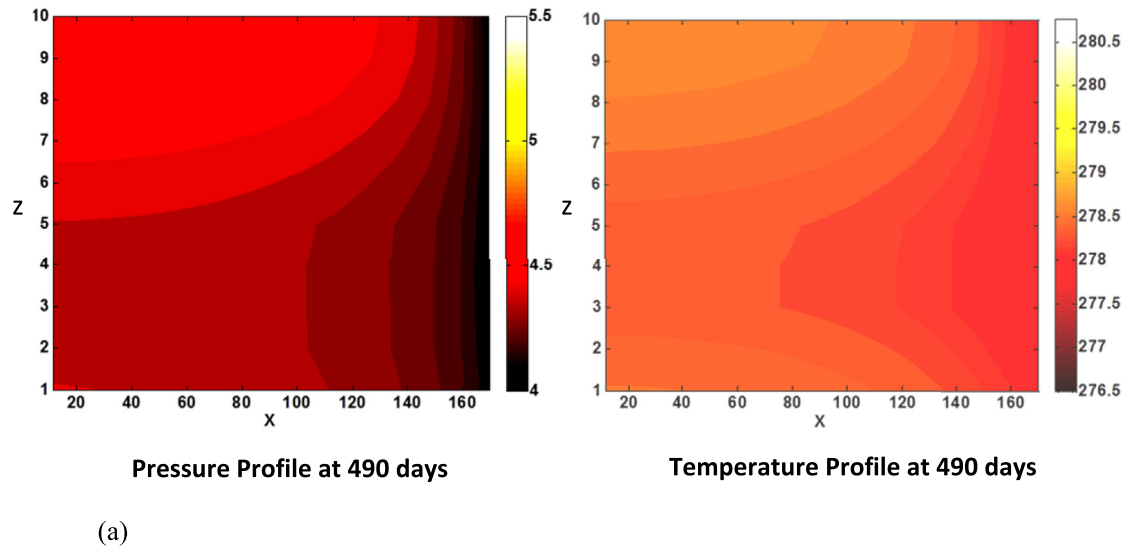


Fig. 5. (a): Pressure and temperature profiles for 'case a' with aquifer permeability of 158 md at 490. (b): Pressure and Temperature profile for 'case a' with aquifer permeability of 16 md at 490 days. (c): Pressure and temperature profile for 'case a' with aquifer permeability of 1.5 md at 490 days.

and temperature profiles of 'case a' with an aquifer permeability of 158 md at 490 days. The profiles are of a vertical plane of the diagonal AB as shown in Fig. 2. At 490 days, in the reservoir with aquifer permeability of 158md, we see that the maximum reservoir pressure is 4.5 MPa and due to hydrate dissociation the temperature has decreased from initial temperature of ~280 K. Temperature near over-burden and under-burden are high due to heat transfer from the sediments above and below the reservoir. For the reservoir with aquifer permeability of 16md, the maximum temperature at 490 days is 280 K (initial temperature) from Fig. 5(b) and maximum pressure is 5.4 MPa in a small region and varies to 5.2 MPa near the well. The depressurization in this reservoir is slower than the reservoir with 158md permeability aquifer which hinders the hydrate dissociation and hence the gas production. Due to higher temperature in the reservoir the temperature difference from over-burden and under-burden is smaller so the enthalpy transfer is also slower. At high reservoir pressure the hydrate dissociation temperature is also higher. Therefore to reach the dissociation temperature the enthalpy requirement for heating the sediments and water is also high. If the enthalpy requirement is high then the layering starts impacting the gas production rate as seen in Fig. 4(b).

For the reservoir with aquifer of permeability 1.5md, the decrease in the reservoir pressure is even less as shown in Fig. 5(c) and the temperature does not vary significantly from the initial conditions at 490 days. Thus, the depressurization potential in the reservoir depends on the aquifer permeability which governs the hydrate dissociation and gas recovery rate from the reservoir.

Fig. 6 shows the fraction of initial water produced with time. The water production does not vary significantly for the different cases but varies for different aquifer permeability considered. The water produced is shown for 'case a' in Fig. 6. 30% of the initial water (free water and water in the hydrate form combined) is removed when aquifer permeability is 158md. For the 16md permeability aquifer and 1.5md permeability aquifer the water removed are 18% and 13% respectively. More the amount of water produced in the initial days, more is the pressure drop, leading to a high gas recovery rate.

4.1.2. Effect of aquifer permeability on ultimate gas recovery

Comparing the ultimate gas recovery for 'case a', 80% of the gas is recovered from the hydrate reservoir when the aquifer permeability is 158md. When the aquifer permeability is 16 md ultimate gas recovery is 85% and for the aquifer permeability of 1.5 md the

recovery is 89% as shown in Fig. 4(a, b, c). So the reservoir with high permeability aquifer has less ultimate gas recovery than the low permeability aquifer because the amount of water removed from 0.3 porosity aquifer with permeability of 158md is high as compared to 16md and 1.5md permeability aquifers. Around 30% of water is produced from 158md permeability aquifer however the final water production for 16md and 1.5md permeability aquifers are 18% and 13%. So more the amount of water removed, more the pore volume is released in reservoir which the dissociated gas occupies to maintain the reservoir pressure which leads to less ultimate gas recovery for a high permeability aquifer.

4.2. Effect of layering

Fig. 4(a) shows that when the aquifer is highly permeable, depressurization is fast and the layering does not have an effect on the gas recovery rate. However, the dissociation fronts for all the cases appear at different positions as shown by hydrate saturation profiles in Fig. 7(a). The absolute amount of hydrate (area $\times$ height $\times$ porosity $\times$ saturation) is low in LPHL. At 490 days, for 'case a', the dissociation is significant in layer L1 (refer Fig. 3) near the aquifer as shown in Fig. 7(a). In 'case b' the permeability in the layer L1 is low, so depressurization effect is less and the dissociation front in layer L1 near the aquifer is not as significant as in 'case a', shown in Fig. 7(a). There is another dissociation front at the interface of layer L2 (HPHL) and layer L3 (LPHL) in 'case b'. This front develops because depressurization in L2 is more due to high porosity and in the top layer L3 there is no significant hydrate dissociation due to low porosity. Therefore, temperature is high in L3 and pressure is low in L2 and the combined effect leads to a dissociation front at the interface of L2 and L3. In 'case c' the major dissociation front is near the aquifer which is in contact with, layer L1 (HPHL), leading to more depressurization. There is another dissociation front in this case at the interface of layer L3 (HPHL) and layer L4 (LPHL) same way as in 'case b'. But the dissociation front is not sharp because the depressurization in L3 is slower due to less thickness of the HPHL in comparison to 'case b'. However, in 'case d' the hydrate dissociation phenomenon in the top two layers L3 and L4 is same as top 4 m in 'case a' but there appears a sharp dissociation front at the interface of L2 and L3. Because it is difficult to depressurize layer L3 (LPHL) and no external heat source (over-burden, under-burden) is near, so the temperature remains higher in L3 than the surrounding layers. Layer L2 has more depressurization due high porosity and large area in contact with L1, which has high hydrate dissociation. Due to the depressurization the hydrates dissociate in L2 and temperature lowers. Due to the temperature gradient in L2 and L3 enthalpy is directed towards L2 from L3 and a dissociation front appears at the interface of L2 and L3 as seen in Fig. 7(a).

Despite of the different dissociation fronts during initial days the gas recovery rate does not vary for different cases if aquifer permeability is high, i.e. 158md. The position of the dissociation front is important as methane hydrates are solid and can be supporting the grain structure. If the dissociation front position is known apriori then the production strategy can be planned such that the structural integrity of the reservoir is not compromised. But when the aquifer permeability is small as in case of aquifer porosity of 0.21 and 0.14 with permeability's 16md and 1.5md respectively, the gas recovery rate varies with layering as explained below.

4.2.1. Layering impact on the gas recovery

For the low aquifer permeability of 16md or 1.5md the layering in the hydrate zone affects the gas recovery from the hydrate reservoirs. Fig. 4(b, c) show the gas recovery for the four cases of layering for the aquifer permeability of 16md and 1.5md. The difference in recovery arises due to the combined effect of

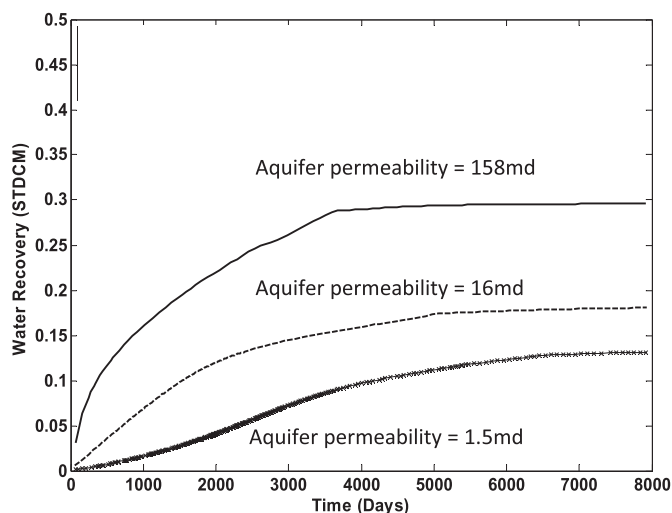


Fig. 6. Water recovery from layered reservoir 'case a' for different aquifer permeability.

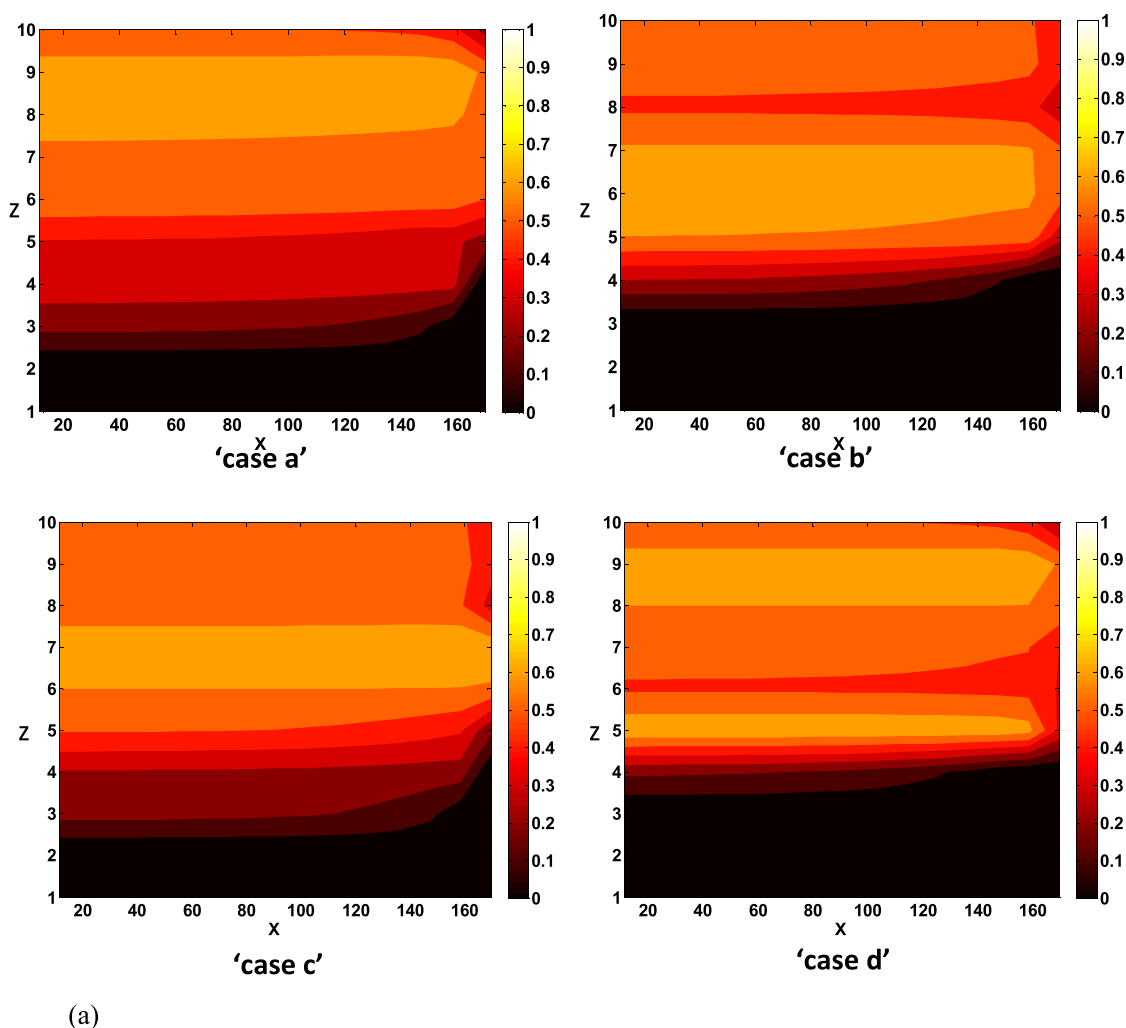


Fig. 7. (a): Hydrate saturation profile for all cases with aquifer permeability of 158 md at 490 days. (b): Hydrate saturation profile for all the cases with aquifer permeability of 16 md at 2040 days. (c): Hydrate saturation profile for all the cases with aquifer permeability of 1.5 md at 3350 days.

depressurization and enthalpy available for the hydrate dissociation. Enthalpy plays an important role when aquifer permeability is low unlike the case of a high permeable aquifer with 158md permeability for which the depressurization is the dominating factor for hydrate dissociation. For the cases discussed in the present work (aquifer permeability of 16md and 1.5md) the highest recovery rate is for 'case a' and the least recovery is for 'case b' as shown in Fig. 4(b, c). In 'case a' the high porosity hydrate bearing layers, with large amount of hydrates, are near the boundary and so can easily get the required enthalpy from overburden and underburden in comparison to 'case b', where low porosity layers are near the boundary of the hydrate bearing zone.

The hydrate saturation profiles for the cases with aquifer permeability of 16md after 2040 days of depressurization are shown in Fig. 7(b). Referring Fig. 4(b), at 2040 days there appears a significant difference in gas production for 'case a' and 'case b'. Fig. 7(b) shows that after 2040 days in 'case a', the hydrates have dissociated near the overburden in large quantity. The high porosity layer attached to the aquifer depressurises to a larger extent because of large surface area in contact with high permeability aquifer. Fig. 7(b) shows that hydrates have dissociated till 3 m of height from the bottom completely and a large amount have dissociated beyond 3 m of height. So due to the combined effect of enthalpy gain and depressurisation, the gas recovery rate is high for

'case a'. But 'case b' has two low porosity layers at the boundary of hydrate bearing zone. The low porosity layer at the top has less amount of hydrate and it resists the depressurisation so requires a higher temperature for dissociation and we see less dissociation near the overburden in Fig. 7(b) for 'case b'. Layer L2 (refer Fig. 3) is depressurized more and L3 has high temperature and we see a dissociation front appearing at the interface of L2 and L3. The layer L1, attached to the aquifer, also has less amount of hydrate dissociated compared to 'case a' because the depressurization is less due to low permeability of L1. Layer L2 has high porosity and can depressurize but the enthalpy available from the surroundings is low. Since the depressurisation has less effect in 'case b' and 'case a' has combined effect of depressurisation and enthalpy, less gas recovery for 'case b' at 2040 days is seen in Fig. 4(b). As the reservoir heterogeneity increases in 'case c' and 'case d' the gas production rate remains in between 'case a' and 'case b' as in Fig. 4(b). In both the cases, the high porosity layer is either near the aquifer or near the overburden. For 'case c' the high porosity layer is attached to the aquifer, so amount of hydrate dissociated in this layer is high and low porosity layer is attached to the overburden so less dissociation is seen as shown in Fig. 7(b). For 'case d' the high porosity layer is attached to the overburden so enthalpy effect for hydrate dissociation dominates in this layer but the low porosity layer is attached to the aquifer which resists the depressurisation and less hydrates

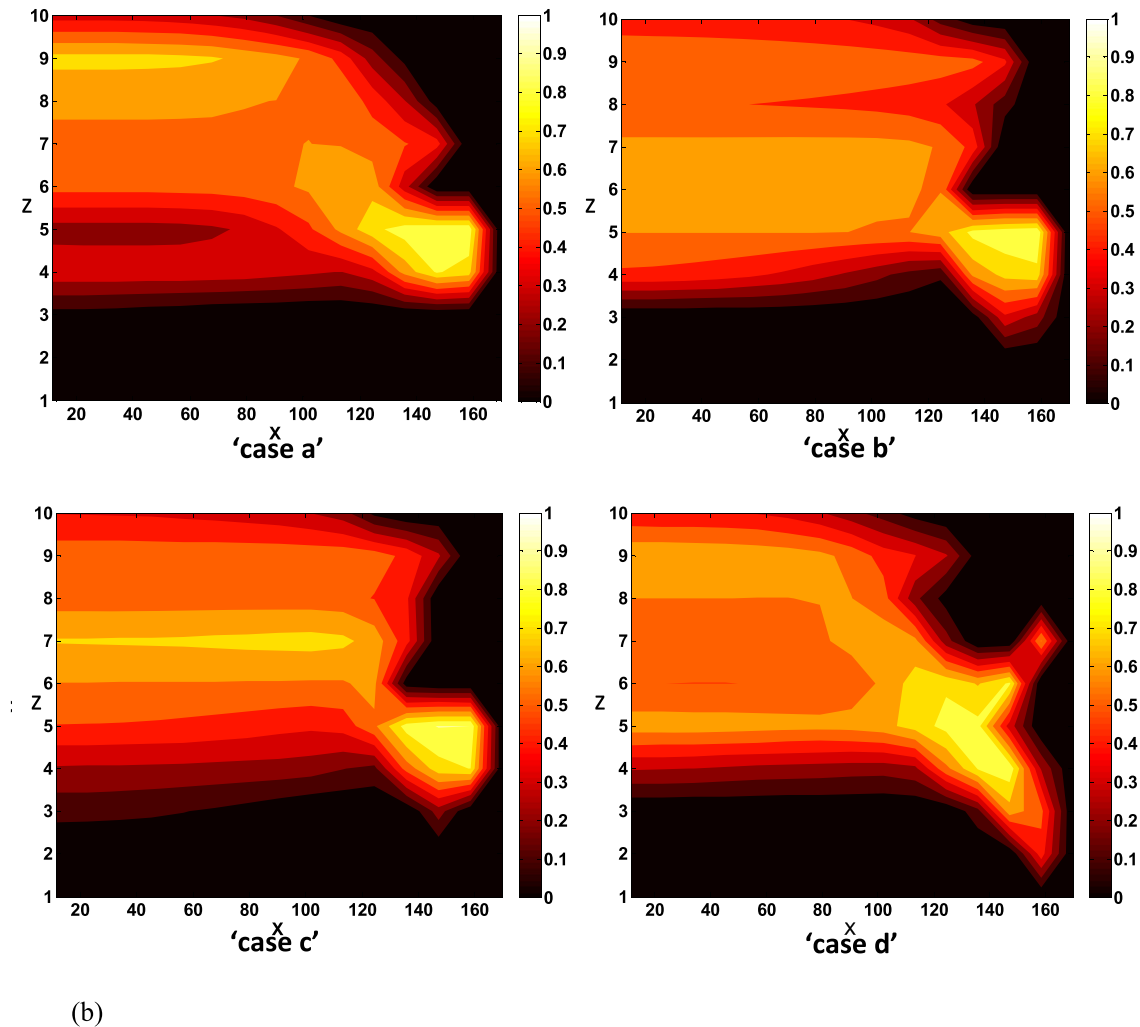


Fig. 7. (continued).

dissociate in this layer as shown in Fig. 7(b). In all the above cases, the hydrates re-form near the well. As methane is produced, it moves towards the well and upwards due to gravity. It flows slowly in the low permeability layers and when the temperature is low it reacts with water to re-form methane hydrate.

For an aquifer of permeability 1.5md, the gas recovery is slowest and the difference in gas recovery for different cases are seen at 3350 days from Fig. 4(c). The hydrate saturation profiles for all the cases for the aquifer of permeability 1.5md are shown in Fig. 7(c) after 3350 days of depressurization. The gas recovery is significantly high for 'case a' than 'case b' at 3350 days as in Fig. 4(c). In 'case a' the hydrates starts dissociating in high porosity hydrate layers at the overburden and underburden at faster rate than 'case b' as shown in Fig. 7(c). In 'case a' the dissociation is more near the overburden as compared to the layer attached to the aquifer as depressurization is very low due to low permeability of the aquifer and enthalpy requirement for dissociation is met at the overburden. 'Case c' shows a little higher recovery than 'case b' as enthalpy requirement dominate which is met at the overburden but the layer near the aquifer has less hydrate and depressurize less leading to less hydrate dissociation in 'case b' in comparison to 'case c'. 'Case d' shows a little lower recovery than 'case a'. Dissociation near the over-burden is same but near the aquifer is less due to less depressurization in 'case d' in comparison to 'case a'. Fig. 7(c) shows the hydrate reformation majorly for 'case a' and 'case c' as more gas

is produced near the aquifer which moves up due to gravity and high pressure is encountered in low porosity layers leading to hydrates reformation. Fig. 7 shows that the heterogeneity governs the location of the dissociation front and aquifer permeability governs the extent of dissociation.

4.3. Effect of well completions

In all the cases discussed above the well is completed in hydrate zone and aquifer zone. Fig. 8 shows the gas production for 'case a' for the aquifer permeability of 158md, 16md and 1.5md with porosity 0.3, 0.21 and 0.14 respectively for different well completions. As discussed above, for highly permeable aquifer depressurization is dominant, so well completion in aquifer is important for depressurization. Fig. 8 shows that if the well is completed only in the aquifer for the reservoir attached to aquifer with permeability of 158md, the gas production decreases only marginally. But, if the well is completed only in the hydrate zone, the depressurization is difficult due to very low permeability of hydrate zones and the gas production rate slows down. For 'case a' and aquifer permeability 16 md, the depressurization and enthalpy transfer both play equally important role. Therefore, if the well is completed in the hydrate zone or the aquifer zone the gas production rate decreases significantly for both. For well completion only in the hydrate zone, the dissociation due to depressurization and enthalpy transfer in the

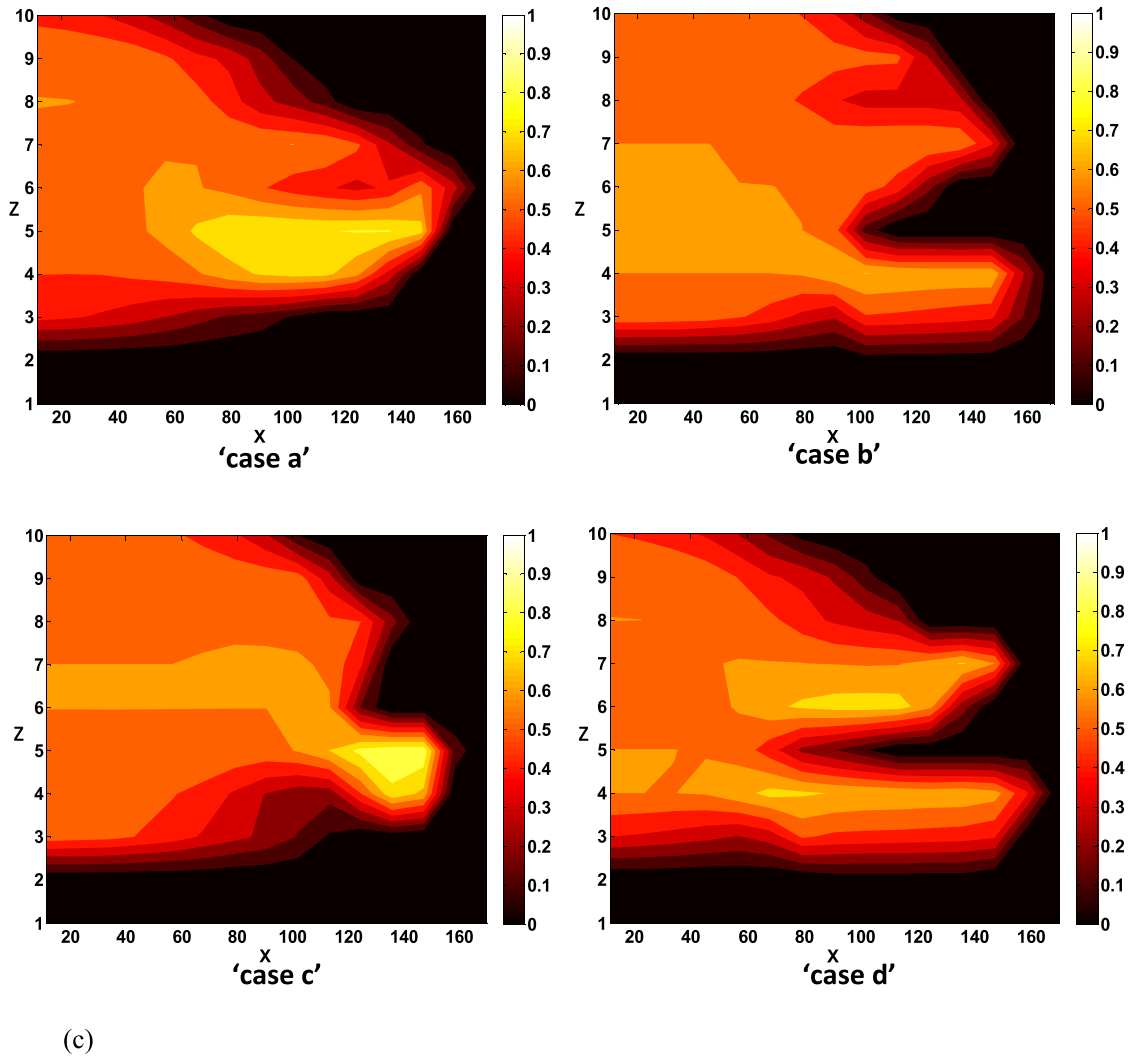


Fig. 7. (continued).

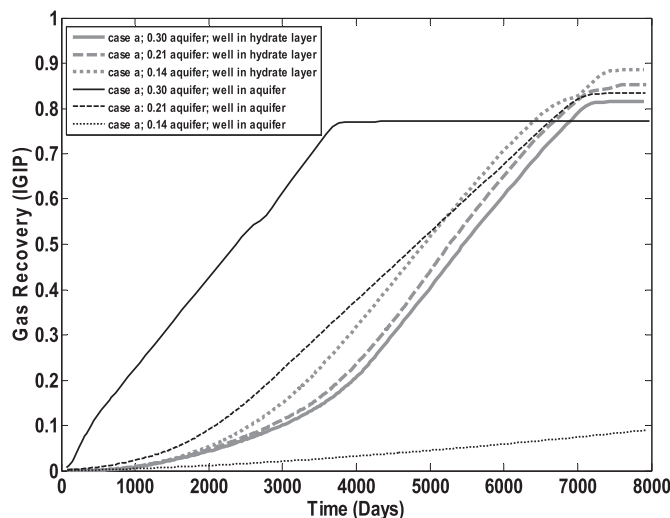


Fig. 8. Gas production for different well completions.

hydrate zone is seen, but the dissociation due to depressurization in the aquifer is not seen, decreasing the gas production rate. If the well is completed only in the aquifer, no significant depressurization is seen in the reservoir away from the aquifer and benefit from the enthalpy transfer from the overburden is not seen. Fig. 8 shows that the gas production decreases for both the well completions discussed above. When the aquifer permeability is 1.5 md, then the well completion in the aquifer does not help significantly in depressurization of the reservoir due to less permeability. Fig. 8 shows only 10% of the gas is recovered when the well is completed only in the aquifer. The gas production rate decreases a little when the well is completed only in the hydrate zone.

4.4. Effect of degree of un-confinement of the attached aquifer

Fig. 9 shows the comparison of gas recovery from confined reservoirs with the unconfined reservoirs. To simulate an unconfined reservoir, 3 m of aquifer thickness is considered making the total thickness of the reservoir 11 m. This 120 m × 120 m × 11 m reservoir is discretized in 15 × 15 × 11 grids. A constant pressure boundary of 9 MPa (initial pressure) is considered at the underburden. The pressure drop between the bottom-most grid layer of the aquifer and the boundary is the driving force for the water inflow or fluid

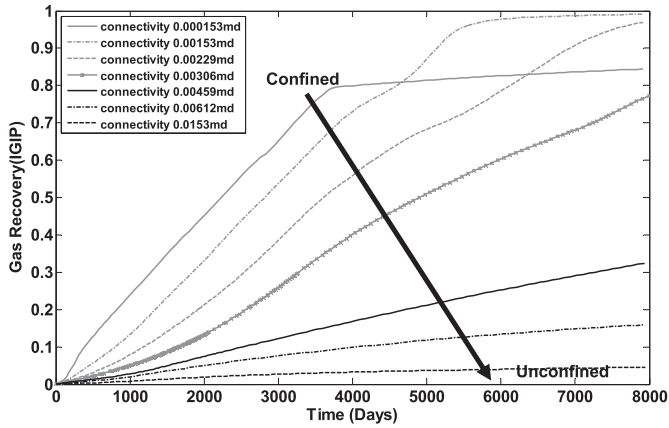


Fig. 9. Gas production comparison for confined and unconfined reservoirs.

outflow from the bottom boundary. The degree of un-confinement in the aquifer is mimicked by changing the permeability of the bottom 1 m of the aquifer layer. Fig. 9 shows the results of 'case a' for different degrees of un-confinement of the aquifer attached. The results indicate that if the degree of un-confinement (permeability of last 1 m aquifer layer) is 0.000153md, the reservoir behaves almost like a confined reservoir and the gas recovery is same as that of the gas recovery in 'case a' of Fig. 4(a). However, as the un-confinement increases the gas production decreases. Increasing the degree of un-confinement starts the communication of the aquifer with the hydrate reservoir and the water influx from the aquifer decreases the depressurization and hence the hydrate dissociation. The permeability as low as 2 microdarcy of the last layer in the aquifer decreases the depressurization potential in the reservoir as can be seen in Fig. 9. So the depressurization is not an effective method of hydrate dissociation for the unconfined reservoirs because of the constant influx of water from the aquifer attached. Extensive investigation is needed to study the flow behaviour in the unconfined, layered, Class 2 hydrate reservoirs and to find the efficient methods of gas production.

5. Conclusions

We have investigated depressurisation of layered methane hydrate reservoirs underlain by an aquifer. We draw the following conclusions on the basis of this study.

1. For Class 2, confined hydrate reservoirs attached to a high permeability aquifer, the depressurization is dominant phenomenon for methane hydrate dissociation. Layering in the hydrate zone does not have a significant impact on the gas recovery, but the dissociation fronts vary with heterogeneity.
2. In Class 2, confined hydrate reservoirs attached to a low permeability aquifer, the hydrate dissociate due to combined effect of depressurization and enthalpy available from the overburden and underburden. The gas production and dissociation fronts are affected by the heterogeneity in the reservoir.
3. The well completion in the aquifer is necessary for efficient production of the gas when depressurization has an effect on the hydrate dissociation i.e. for high permeable aquifer.
4. But when the aquifer is attached to an unconfined reservoirs, even a small degree of un-confinement makes the depressurization ineffective due to the continuous encroachment of water from the aquifer. The water from the aquifer keeps producing and depressurization is not felt in the hydrate zone.

5. In Class 2 hydrate reservoirs the characterization of aquifer is very important for predicting the gas recovery and location of dissociation fronts during depressurization

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Notations

K^e	is the effective permeability
K_o	is reference absolute permeability
ϕ_o	is reference porosity
ϕ^e	is the effective porosity of gas and aqueous phase
n_j	exponential parameter for phase j
k_{rj}^o	end point relative permeability for phase j
nc	parameter for pore structure
p_{ce}	entry capillary pressure
p_{ceo}	entry pressure under reference porosity ϕ_o and absolute permeability K_o
$S_{jr,e}$	residual saturation based on effective pore volume
$S_{j,e}$	saturation of gas and aqueous phase based on effective pore volume
S_j	saturation of gas and aqueous phase based on total pore volume
ρ_j	density of phase j
ρ_R	density of rock j
S_j^i	saturation of phase j based on total volume
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
U_R	internal energy of sand phase
H_j	specific heat of phase j
λ	effective thermal conductivity
J_j^i	mass flux of component i due to dispersion in j phase.
p_G	gas pressure
p_e	equilibrium gas pressure

Superscript

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

Subscript

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

Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.jngse.2015.05.016>.

Appendix A

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

$$\frac{\partial}{\partial t}(\phi C^m) + \nabla \cdot \bar{F}^m = q^m \quad (A1)$$

$$\frac{\partial}{\partial t}(\phi C^w) + \nabla \cdot \bar{F}^w = q^w \quad (A2)$$

$$\frac{\partial}{\partial t}(\phi U) + \nabla \cdot \bar{F}^e = -q^e \quad (A3)$$

where, C^m , C^w and U are given by following equations

$$C^m = \sum_{j=H,I,A,G} \rho_j S_j w_j^m \quad (A4)$$

$$C^w = \sum_{j=H,I,A,G} \rho_j S_j w_j^w \quad (A5)$$

$$U = \sum_{j=H,I,A,G} (\rho_j S_j U_j) + (1 - \phi)(\rho_R U_R) \quad (A6)$$

Mass is transferred through convection and dispersion. The mass flux is evaluated with

$$F^i = \rho_G v_G w_G^i + \rho_A v_A w_A^i + J_G^i + J_A^i \quad (A7)$$

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

Heat is transferred through conduction and convection. The heat flux is evaluated with

$$F^e = \rho_G v_G H_G + \rho_A v_A H_A - \lambda \nabla T \quad (A8)$$

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