Gas production from methane hydrates upon thermal stimulation; an analytical study employing radial coordinates

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Abstract

In this study, a radial analytical model for methane hydrate dissociation upon thermal stimulation in porous media considering the effect of wellbore structure has been developed. The analytical approach is based on a similarity solution employing a moving boundary separating the dissociated and undissociated zones. Two different heat sources are considered: i) line heat source; and ii) wellbore heat source with specific thickness consisting of casing, gravel, and cement. The temperature and pressure distributions, dissociation rate, and energy efficiency considering various initial and boundary conditions, and reservoir properties are investigated. Direct heat transfer from the heat source to the reservoir without considering the heat conduction in the wellbore thickness causes higher the dissociation rate and gas production in the line heat source model compared to the wellbore heating model. Increasing the heat source temperature or decreasing its pressure increases gas production. However, employing them simultaneously results in greater gas production but reduces energy efficiency. The dissociation rate has direct relation with porosity, thermal diffusivities, and thermal conductivities of the reservoir, but is not dependent on the reservoir’s permeability.
Introduction

Gas hydrates are ice-like components known as clathrates [1]. These consist of gas molecules, such as methane, trapped inside crystalline water molecules which can be formed wherever a sufficient amount of gas and water in combination with high pressure and low temperature conditions exist. Such conditions can be found in deep permafrost regions and submarine zones [1-3]. One volume of methane hydrate (MH) can produce approximately 164.6 volumes of methane and 0.87 volumes of water at standard pressure and temperature conditions [4]. The estimate of the total volume of MH available worldwide reveals that MH can make a significant contribution to future sources of energy, as it exceeds the total volume of conventional gas resources worldwide [5, 6]. However, before considering MH as a reliable and alternative source of energy, more investigation is required to thoroughly understand the behavior of this complicated material and to make gas production from MH economically possible.

Considering that the entrapped gas and water are bonded through physical interaction in MH, which is weaker than the chemical interactions, any change in MH equilibrium temperature or pressure would easily induce MH instability and dissociation. Main methods of MH dissociation that have been reported so far are as follows [1, 7]: i) thermal stimulation by increasing the temperature of the reservoir above the equilibrium temperature [8, 9]; ii) depressurization by decreasing the pressure inside the MH reservoir below the equilibrium pressure of the hydrate [10, 11]; iii) depressurization in conjunction with thermal stimulation that is reported to have a better efficiency compared to the two previous methods [12]; iv) inhibitor injection by injecting fluids, such as methanol, that will induce instability of the MH formation [13, 14]; and v) replacement of methane by CO$_2$ in MH reservoirs, which also helps global warming and climate change mitigations [15-19]. Despite several findings regarding the hydrate dissociation methods, further investigation is required to shed more light on the potential of different methods and their aspects.

There have been many mathematical studies of hydrate dissociation employing both analytical and numerical methods. Analytical solutions provide fast answers with a better mechanistic understanding of the phenomena. However, numerical methods are more comprehensive and complicated, requiring fewer assumptions. In 1982, a 3D numerical model consisting of an MH layer with a free gas zone was developed to study MH dissociation upon depressurization by considering the effect of conduction heat transfer and gas flow [20]. In 1986, this work was
extended by considering the effect of the water flow produced during the dissociation [21]. In 1991, a numerical model investigated MH dissociation by depressurization in porous media with gas-water flow considering three phases of water, gas, and MH without the effect of heat transfer [22]. Then, the previous work was extended by taking into account the water-gas flow and convective-conductive heat transfer [23, 24]. MH dissociation upon thermal stimulation was simulated by assuming an impermeable moving dissociation boundary, which separates the dissociated and undissociated zones, and considering different media permeabilities [25]. Another numerical work by employing finite difference method and considering the effect of heat transfer in depressurization method showed that the process is a function of well pressure [26]. In the same year, TOUGH2 simulator, which is capable of simulation of different dissociation methods considering four components and up to nine phases in either kinetic or equilibrium models, was employed to show the possibility of gas production from MH using both depressurization and thermal stimulation [27]. Results retrieved from TOUGH2 showed the feasibility of gas production from MH reservoirs in in the Mackenzie Delta, Northwest Territories, Canada, upon depressurization and thermal stimulation with higher efficiencies achieved by using both methods together [28]. Another numerical work reported that the kinetic reaction models should be taken into account in order to avoid under-prediction of recoverable MH, while, requiring more computational effort compared to the equilibrium reaction models [29]. A numerical work using TOUGH-Fx/HYDRATE simulator showed low gas production upon depressurization with high amount of water production from disperse oceanic MH reservoirs with low hydrate saturation [30].

In 1990, Selim and Sloan [31] investigated MH dissociation upon thermal stimulation by using an analytical 1D model by assuming a moving dissociation boundary. They also studied the effect of gas convection heat transfer and its flow, while assuming the produced water to remain motionless in the pores. In 1982, a study on hydrate dissociation upon both thermal stimulation using hot water injection and depressurization by employing two models (the frontal-sweep model, and the fracture-flow model) was performed [32]. The results showed that the depressurization is more feasible compared to thermal stimulation. Makogon [33] provided analytical expressions for the temperature and pressure distributions during MH dissociation upon depressurization including the effect of the throttling process in the energy equation and assuming a moving dissociation boundary. This work was extended by considering the water and gas movement and similarity solutions for temperature and pressure [34]. In 2001, another model was generated based on
Makogon’s model [11] including the heat conduction. An analytical work using depressurization reported that the effect of the gas-water two-phase flow on MH dissociation is smaller than the effect of heat transfer and the intrinsic kinetics of MH decomposition [35]. Recently, an analytical work was designed based on experimental conditions (i.e., the reservoir was assumed to be finite, and there was heat transfer from outside of the reservoir into the hydrate zone) to study the MH dissociation by depressurization, thermal stimulation, and the combination of both methods [36].

In the experimental investigations on MH dissociation upon different methods, the size of the setup significantly affects the outcome of tests and is reported as one of the major challenges in experimental works [37]. For instance, the scale of the experiment’s setup determines the main involving mechanism in the hydrate dissociation in porous media [37], which is one of the followings: i) heat transfer in the decomposing zone; ii) the intrinsic kinetics of hydrate decomposition; or iii) the multiphase flow (i.e., gas-water flow) during gas production [35]. Tang et al. [38] showed that the determining factor in the core-scale experiments is the intrinsic kinetics of hydrate decomposition; while, in larger scale experiments or field works, the controlling mechanism is heat transfer in the decomposing zone. An experimental work showed that MH dissociation using thermal stimulation is a moving boundary ablation process in a 3D cubic hydrate simulator (CHS) [39]. Li et al. [40] employed two hydrate simulators with different scales to experimentally investigate the MH dissociation upon depressurization. They reported that the gas production period is longer for the larger scale simulator. Conduction heat transfer was shown to be the main mechanism for heat transfer to the dissociating zone in an experimental work on MH dissociation [41]. Wang et al. [37] by employing a 3D Pilot-Scale Hydrate Simulator (PHS) reported that ice formation in pores during MH dissociation below the quadruple point in the sandy sediment increases the dissociation rate. Another experimental work studied the dissociation of water-saturated hydrate samples using a pilot-scale hydrate simulator via different methods and reported that depressurization in conjunction with thermal stimulation is the optimum method [42]. Nowadays, this field of investigation has attracted the researchers’ interest to perform more mathematical studies as well as real field or experimental works or employing parameters from real reservoirs [43-48].

Studies over the past decades have provided substantial information about MH dissociation and the associated consequences in the reservoirs. However, it should be noted that the wellbore
structure can affect the process, such as the heat transfer mechanism during thermal stimulation method. The analytical works conducted about the hydrate dissociation to present [47, 49-51] have not considered the impact of wellbore geometry and the associated structure (i.e., wellbore radius and the associated outer layers) on MH dissociation upon thermal stimulation by wellbore heating, which might induce unreliability while comparing to experiments or field works. Recently, Roostaie and Leonenko [52] mathematically overcame this gap of knowledge and showed that the wellbore structure, consisting of layers: casing, gravel, and cement, can also affect the interactions in the reservoir and the efficiency of the process upon thermal stimulation. They designed an analytical semi-infinite 1D model and verified it against previous numerical and experimental works. This study aims to expand the previous work by considering an infinite 2D radial geometry and cylindrical wellbore along with another model with a line heat source. This is critical to recognize the role played by the wellbore structure in hydrate dissociation via wellbore heating. It should also be noted that employing radial coordinates in the previous analytical studies of thermal stimulation have not been treated in much detail. These assumptions make the outcomes closer to the real operational conditions.

The present work develops 2D analytical models assuming an infinite hydrate reservoir in radial coordinates and two different heat sources: i) line heat source (no thickness); and ii) wellbore heat source consists of three main completion layers of casing, cement, and gravel. The energy efficiency, gas production, and temperature and pressure distributions are calculated and verified against the previous experimental and mathematical studies. The results of this work shed more light on assessing the gas production from MH reservoirs upon thermal stimulation. Therefore, this study makes a major contribution to research on MH dissociation upon wellbore heating by analytically demonstrating, for the first time, the effect of wellbore geometry and structure on the MH dissociation in radial coordinates. The outcomes obtained using such conditions are closer to the real-condition tests making them more valuable and reliable.
• **Modeling**

A schematic of the hydrate dissociation in the proposed 2D radial geometry is shown in Figure 1. The dashed circle shows the moving dissociation boundary, and the grey region denotes the wellbore thickness consisting of a cement, gravel, and two layers of casing (Figure 1). It should be noted that there are many different wellbore structures and geometries in the literature [53-55], and the proposed wellbore structure in this study is taken as the general wellbore model as understood to the best of our knowledge [56-59].

It should be mentioned that the geometry of the other case using a line heat source is exactly the same as Figure 1, but it uses a line heat source without thickness in the center of the reservoir instead of a wellbore with a specified thickness. The following steps are considered as the basics of MH dissociation in this work: i) before dissociation begins, the reservoir with a porosity of $\phi$ is assumed to be filled with MH with temperature $T_0$ in equilibrium; ii) at time $t = 0$, the heat source warms up by increasing its temperature (at the inner surface for the case with wellbore thickness) to a new temperature $T_i$, which is higher than the hydrate equilibrium temperature, and is kept constant afterward; iii) MH dissociation begins with a sharp moving boundary surface showing the rate of hydrate dissociation and separating the water and gas produced in the dissociated zone (Zone I) from the undissociated zone (Zone II).
During dissociation, the dissociated zone temperature is higher than the hydrate zone’s inducing heat transfer from the Zone I to Zone II. Principally, the input heat from the heat source is consumed in two different ways: i) increasing the temperature of the matrix sediments in the Zone I and the produced water and gas from the dissociation; and ii) hydrate dissociation and the temperature increase of the matrix materials in Zone II. Over time, Zone I becomes larger and absorbs higher amount of input heat (the first way mentioned above), which reduces the rate of hydrate dissociation and the speed of the moving interface.
Figure 2 shows the temperature and pressure distributions in the system after dissociation begins. The temperature and pressure distributions in Zone I \((T_I \text{ and } P)\) are respectively \(T_s < T_i < T_i\) and \(P_i < P < P_s\), and the temperature distribution in the Zone II \((T_{II})\) is \(T_0 < T_{II} < T_s\) by assuming a constant hydrate pressure equal to the equilibrium pressure. It should be noted that \(T_I\) at the outer surface of the well changes over time, but it is always lower than \(T_i\).

The produced gas will be streaming towards the heat source according to Darcy’s Law and inducing a sudden change in density at the dissociation front due to gas production. Other assumptions made in the models of this study, which are consistent with the previous analytical works [31, 60, 61], are: i) pores of the media are filled by hydrates; ii) thermodynamic equilibrium at the dissociation interface for temperature and pressure; iii) the water produced from the dissociation process remains motionless in the pores of dissociated zone; iv) constant thermophysical properties of the phases; v) gas shows an ideal behavior; vi) the produced gas
instantaneously reaches thermal equilibrium with the local sediments; vii) no viscous dissipation or inertial effects.

Two types of heat source are considered in this part: line heat source and well heat source. Basic equations are the same for both types of heat sources, but the boundary conditions are different. The basic equations are presented in the following formulas.

The continuity equation of gas in Zone I is:

$$\phi \frac{\partial \rho_g}{\partial t} + \left( \frac{\partial \rho_g v_g}{\partial r} \right) = 0, \quad t > 0$$  \hspace{1cm} (1)

where $\phi$ is reservoir (matrix) porosity, $\rho_g$ is gas density (kg/m$^3$), $v_g$ is gas velocity (m/s), and $r$ is the radial distance (m). The gas velocity in Zone I is calculated by using Darcy’s Law:

$$v_g = -\left( \frac{k}{\mu} \right) \left( \frac{\partial p}{\partial r} \right), \quad t > 0$$ \hspace{1cm} (2)

where $k$ is gas permeability (m$^2$), $\mu$ is gas viscosity (mPa.s), and $P$ is pressure (Pa).

Equations 3 and 4 show the energy balance in Zones I and II, respectively:

$$\rho_i C_{pi} \frac{\partial T_I}{\partial t} + \frac{\partial \rho_g C_{pg} v_g T_I}{\partial r} = k_I \frac{\partial}{\partial r} r \frac{\partial T_I}{\partial r}, \quad t > 0, \quad \text{in Zone I}$$ \hspace{1cm} (3)

$$\frac{\partial T_{II}}{\partial t} = \frac{\alpha_{II}}{r} \frac{\partial}{\partial r} r \frac{\partial T_{II}}{\partial r}, \quad t > 0, \quad \text{in Zone II}$$ \hspace{1cm} (4)

where $\rho_i$ is density (kg/m$^3$) of the matrix in Zone I, $\rho_g$ is gas density (kg/m$^3$), $C_{pi}$ is specific heat capacity (J/(kg.K)) of the matrix in Zone I, $C_{pg}$ is specific heat capacity of gas (J/(kg.K)), $T_I$ is the temperature (K) of the matrix in Zone I, $T_{II}$ is the temperature (K) of the matrix in Zone II, $\alpha_{II}$ is thermal diffusivity (m$^2$/s) of the matrix in Zone II, and $k_I$ is the thermal conductivity (W/(m.K)) of the matrix in Zone I.

The gas density in Zone I can be evaluated by the following equation using Ideal Gas Law:

$$\rho_g = \frac{mP}{RT_I}, \quad R_{out} < r < S, \quad t > 0$$ \hspace{1cm} (5)
where \( m \) is gas molecular mass (kg/mol), and \( R \) is the universal gas constant (J/(mol.K)). The above equations represent the fundamental concept of the process. The initial and boundary conditions in both models are: i) temperature of the heat source is constant and equal to \( T_i \); and ii) the pressure of the heat source is constant and equal to \( P_i \). These conditions are stated in equations 6 and 7:

\[
T_i = T_i, \begin{cases} 
\text{Line heat source: } r = 0, t > 0 \\
\text{Wellbore heat source: } r = R_{in}, t > 0 
\end{cases} \tag{6}
\]

\[
P = P_i, \begin{cases} 
\text{Line heat source: } r = 0, t > 0 \\
\text{Wellbore heat source: } r = R_{out}, t > 0 
\end{cases} \tag{7}
\]

Heat transfer equation through the wellbore thickness is stated by equation 8:

\[
-k_w A_w \frac{\partial T_i}{\partial r} = \frac{(T_i - T_{i-1})}{R_w}, r = R_{out}, t > 0 \tag{8}
\]

\[
R_w = \frac{\ln(r_i / r_1) + \ln(r_i / r_2) + \ln(r_i / r_3) + \ln(r_i / r_4)}{2\pi k_s} \tag{9}
\]

where \( A_w \) is the wellbore area (m\(^2\)), \( R_w \) is thermal resistivity of the wellbore (W/K), \( k_s \) is the thermal conductivity (J/(s.m.K)), \( r \) is radius (m), the \( s, c, \) and \( g \) subscripts respectively stands for steel (casing), cement, and gravel, and the subscripts 1-5 are schematically shown on Figure 1.

The Antoine Equation (equation 10) is employed to calculate the dissociation interface pressure, which is a thermodynamic relationship between the temperature and pressure of the moving dissociation interface:

\[
P_s = \exp(A_a - B_a / T_s), r = S, t > 0 \tag{10}
\]

where \( P_s \) is the pressure (Pa) and temperature (K) at the moving interface, and \( A_a \) and \( B_a \) are constants. The mass and energy balances at the dissociation interface are represented in equations 11 and 12. The heat of MH dissociation represented and the associated boundary conditions are represented in equations 13-16 [31]:

\[
F_{sH} \rho_H \frac{dS}{dt} + \rho_g \mathbf{v}_g = 0, r = S, t > 0 \tag{11}
\]
\[
k_{II} \frac{\partial T_{II}}{\partial r} - k_{I} \frac{\partial T_{I}}{\partial r} = \phi \rho_{H} Q_{Hd} \frac{dS}{dt}, \ r = S, t > 0
\] 
(12)

\[Q_{hyd} = c + dT_s \] 
(13)

\[T_{I} = T_{II} = T_s (t), \ r = S, t > 0 \] 
(14)

\[T_{II} = T_0, \ r \to \infty, t > 0 \] 
(15)

\[T_{II} = T_0, 0 < r < \infty, t = 0 \] 
(16)

where \(\rho_{H}\) is the hydrate density (kg/m\(^3\)), \(k_{II}\) is the thermal conductivity (W/(m.K)) of Zone II, \(Q_{Hd}\) is heat of MH dissociation (J/kg), and \(c\) and \(d\) are constants. In equation 11, \(F_{gH}\) is a constant that represents the ratio of mass of the methane gas trapped inside the hydrate to the total mass of hydrate (0.1265 kg CH\(_4\)/kg hydrate) [31].

The following equations 17-19 are obtained respectively from equations 1, 3, and 11 by employing equations 2 and 5 in order to eliminate the gas velocity and density.

\[
\phi \frac{\partial}{\partial t} \left( \frac{P}{T_I} \right) - k \frac{\partial}{\partial r} \left( \frac{P}{T_I} \frac{\partial P}{\partial r} \right) = 0 
\] 
(17)

\[
\rho_{I} C_{pl} \frac{\partial T_I}{\partial t} + \frac{km}{\mu R} \frac{\partial}{\partial r} \left( \frac{P}{r} \frac{\partial P}{\partial r} \right) = k_{I} \frac{\partial}{\partial r} r \frac{\partial T_I}{\partial r}, \ t > 0, \text{in Zone I} 
\] 
(18)

\[
F_{gH} \phi \sigma_{H} \left( \frac{dS}{dt} \right) - \frac{kmP}{\mu RT_I} \frac{\partial P}{\partial r} = 0, \ r = S, t > 0 
\] 
(19)

The similarity solution using a dimensionless parameter (equation 20) is employed for transformation, simplification, and solution of the equations mentioned above. This method, which was first introduced by Neumann [62, 63], satisfies the initial and boundary conditions and assumes the movement of the dissociation interface to be inversely proportional with the square root of time \((t^{1/2})\) as follows:

\[
\lambda = \frac{r}{\sqrt{4\alpha_{H}t}} 
\] 
(20)

On the moving dissociation interface, equation 20 becomes:
\[ \beta = -\frac{S}{\sqrt{4\alpha_\mu t}}, \ r = S, t > 0 \]  

(21)

And, on the outer surface of the wellbore:

\[ \lambda_{os} = \frac{R_{out}}{\sqrt{4\alpha_\mu t}}, \ r = R_{out}, t > 0 \]  

(22)

The abovementioned equations transformed by employing equations 20-22 and presented in the supplementary information.

By considering the procedure recommended by previous works [62, 63], the following solutions for the temperature distributions considering different heat sources are assumed by implementing the exponential integral (Ei) function:

Line heat source:

\[
\begin{align*}
T_I (\lambda) &= T_i - A Ei \left((-a\lambda + b)^2\right) + A Ei \left(-b^2\right) \\
T_{II} (\lambda) &= T_0 + B Ei \left(-\lambda^2\right)
\end{align*}
\]  

(23)

Wellbore heat source:

\[
\begin{align*}
T_I (\lambda) &= -A_1 Ei \left((-a\lambda + b)^2\right) + A_1 Ei \left(-b^2\right) + C \\
T_{II} (\lambda) &= T_0 + B_1 Ei \left(-\lambda^2\right)
\end{align*}
\]  

(24)

A, B, C, A_1, B_1, a, and b constants are defined in the supplementary information.

The pressure distribution in Zone 1 for both heat sources can be calculated from the equation S7 as follows:

\[
P(\lambda) = \left(P_0^2 + \frac{4F_{phi}}{\phi H \mu R \beta} \int [T_I d \lambda] \right)^{1/2}
\]  

(25)

Then, by replacing and integrating \(T_I\) from equations 23 and 24, the pressure distributions for both heat sources will be achieved as shown in equations 26 and 27:

Line heat source:

\[
P = \left(P_0^2 + L(\beta)M (\beta)\lambda + AL(\beta)(N(0) - N(\lambda))\right)^{1/2}
\]  

(26)

Well heat source:

\[
P = \left(P_0^2 + L(\beta)(K(\beta)\lambda - A_1 N(\lambda) - (K(\beta)\lambda_{os} - A_1 N(\lambda_{os}))\right)^{1/2}
\]  

(27)
where $L(\beta)$, $M(\beta)$, $N(\lambda)$, and $K(\beta)$ are defined in the supplementary information. The obtained solutions for temperature and pressure distributions satisfy the basic equations and boundary conditions (equations 1-19) by direct substitution.

Heat flux from the wellbore (J/(s.m$^2$)) as a function of time can be calculated from the following formula:

$$ u_r = -k_I \frac{\partial T_I}{\partial r}, \ r = R_{out} \tag{28} $$

Equation 28 can be transformed to an equal equation according to equation 20 (provided in the supplementary information).

Total heat input into the reservoir from the heat source (J/m$^2$) up to time $t$ can be calculated by integrating equation 28 as follows:

$$ Q_n = -k_I \int_0^t \frac{\partial T_I}{\partial r} dt, \ r = R_{out} \tag{29} $$

The total volume of produced gas at standard temperature and pressure (STP) of dry gas can be calculated as follows:

$$ V_{rp} = \frac{n_n RT_{STP}}{P_{STP}} \tag{30} $$

where $V_{rp}$ and $n_n$ respectively are the total volume (m$^3$/m$^2$) and total moles (mole/m$^2$) of produced gas per average surface area of the moving interface up to time $t$ at $T_{STP}$ and $P_{STP}$ as temperature and pressure of at STP conditions, respectively. Further details are provided in the supplementary information.

The energy efficiency ratio is introduced as the amount of energy that could be produced from combustion of the produced gas to the amount of input energy to the system during hydrate dissociation. To evaluate the efficiency of gas production during the dissociation process using thermal stimulation method, the following calculation is used [64]:

$$ \eta_r = \frac{V_{rp} Q_g}{Q_{st}} \tag{31} $$
where $\eta_f$ is the energy efficiency ratio, and $Q_g$ is the heating value of the gas at STP conditions (J/m³).

- **Results and discussion**

  As equation 20 indicates, $\beta$ is representative of both the dimensionless position and velocity ($v_s / (4\alpha_{II}t)^{1/2}$) of the dissociation interface. The value of $\beta$ is only dependent on $P_s$ and $T_s$ (equation S28), which are dependent on the pressure and temperature of the heat source (outer surface of the heat source in the wellbore heat source case) according to their associated equations in the previous section. The temperature at the outer surface of wellbore is time-dependent, inducing $P_s$ and $T_s$ at the dissociation front to change over time; however, the temperature of the line heat source in the other case remains constant. Therefore, $P_s$ and $T_s$ should change during dissociation in the wellbore heat source case, but they remain constant in the line heat source case. The proposed properties and parameters are presented in Table 1, which are obtained from the previous studies [31, 65-67]. As shown in Figure 3, $\beta$ increases at the beginning in the wellbore heating case because the temperature at the wellbore surface increases as the process continues, but tends to converge to the associated value of $\beta$ in the line heat source case as the temperature at the outer surface of the wellbore converges to temperature $T_i$ of the inside of the well.

| Table 1. Parameters used in the modeling. |
|--------------------------------------------|
| Radius of inner surface of wellbore, $R_{in}$ ($r_I$), m | 0.07 |
| $r_2$, m | 0.077 |
| $r_3$, m | 0.092 |
| $r_4$, m | 0.099 |
| Radius of outer surface of wellbore, $R_{out}$ ($r_5$), m | 0.124 |
| Thermal conductivity of cement, $k_c$, W/(m.K) | 0.933 |
| Thermal conductivity of gravel, $k_{gr}$, W/(m.K) | 0.4 |
| Thermal conductivity of casing (steel), $k_s$, W/(m.K) | 43.3 |
| Porosity, $\phi$ | 0.3 |
| Permeability, $k$, $\mu$m² | 1 |
| Thermal diffusivity of Zone I, $\alpha_I$, $\mu$m²/s | 2.89×10⁶ |
| Thermal conductivity of Zone I, $k_I$, W/(m.K) | 5.57 |
| Thermal diffusivity of Zone II, $\alpha_{II}$, $\mu$m²/s | 6.97×10⁵ |
| Thermal conductivity of Zone II, $k_{II}$, W/(m.K) | 2.73 |
| Hydrate density, $\rho_H$, kg/m³ | 913 |
Heat of dissociation of hydrate, $Q_{Hd}$, J/kg

Gas heat capacity, $C_{pg}$, J/(kg.K)

Gas viscosity, $\mu$, Pa.s

Heating value of the gas at STP conditions, $Q_g$, MJ/m³

Molecular mass of methane, $m$, g/mol

Mass ratio of the methane gas trapped inside the hydrate to the total mass of hydrate, $F_{gH}$

Universal gas constant, $R$, J/(mol.K)

| Parameter                                      | Value                  |
|-----------------------------------------------|------------------------|
| $Q_{Hd}$                                      | $446.12 \times 10^3 - 132.638T$ |
| $C_{pg}$                                      | 8766                   |
| $\mu$                                         | $10^4$                 |
| $Q_g$                                         | 37.6                   |
| $m$                                           | 16.04                  |
| $F_{gH}$                                      | 0.1265                 |
| $R$                                           | 8.314                  |

Figure 3. Dimensionless position of interface at $T_0=280$ K and various $T_i$ and $P_i$ values.

Figure 4 represent the effect of boundary conditions on the interface movement 100 days after the beginning of the process considering both heat sources. The value of $\beta$ decreases by increasing the pressure and decreasing the temperature of the heat source. The initial temperature of MH also has a direct effect on $\beta$. Selim et al. [31]. have reported the same trend, but the value of $\beta$ in the present model is slightly lower (about 6%) compared to their work [31]. That could be due to two reasons: i) the conduction heat transfer in the wellbore structure in the present work that decreases the amount of transferred heat to the reservoir; ii) in the previous work [31], only flat heat source with constant temperature without wellbore thickness was considered. Another numerical work on MH dissociation upon depressurization showed that decreasing the pressure of wellbore and
increasing the reservoir temperature would increase the rate of dissociation [68]. This work was also validated with experiments performed by Masuda [23].
Furthermore, the associated temperature and pressure at the locus on which the dissociation temperature is equal to 280 K is shown on Figure 4 by the dashed lines. On the loci left (lower $P_i$) and right (higher $P_i$) of this locus, the dissociation temperature decreases and increases, respectively. The dissociation temperature could be considered to be mainly dependent on heat source pressure, while it is almost independent from the temperature of the heat source and MH. This is in agreement with the previous work by Selim et al. [31], where it was also reported that for lower heat source pressures of 6 MPa, $T_s$ may reduce to the freezing temperature of water and ice generation, which can induce the stoppage of the dissociation. For the situations in which $T_s$ is higher than the MH temperature, some part of input heat from the heat source will be consumed to increase the temperature of MH close to the dissociation front to the $T_s$ value. If $T_s$ approaches $T_0$ all heat from the heat source is consumed for dissociation. On the other hand, if $T_s$ falls below $T_0$, some part of the required heat for dissociation will be provided from the hydrate zone, resulting in the temperature reduction of the hydrate zone near the dissociation interface.

Temperature and pressure distributions for the two heat sources are calculated and presented in Figures S1 and S2 considering three different time frames and the following boundary conditions (BCs): BC 1) $T_i = 450 \, K$, $P_i = 10 \, MPa$, and $T_0 = 280 \, K$, and BC 2) $T_i = 563.5 \, K$, $P_i = 7.6 \, MPa$, and $T_0 = 275 \, K$. The dashed lines in the temperature distribution diagrams (Figure S1) represent the temperature at the dissociation interface separating Zone I from Zone II. The effect of temperature increments of the outer surface of the wellbore on the interface temperature is small because this temperature increment decreases over time (as shown in the Figure S1), also the dissociated zone absorbs larger part of the heat transferred from the wellbore. The positions of the interface in the case with the wellbore heat source in the different time frames (Figures S1a and S1b) are smaller compared to the case with the line heat source (Figures S1c and S1d) due to the effect of heat conduction in the wellbore structure. Pressure values at the interface (Figures S2a and S2b) are not constant and increase due to the temperature increment at the wellbore surface, but, tend to converge to the associated values of the line heat source case (Figures S2c and S2d) as the temperature at the well surface gets closer to that of inside the well. Tsimpanogiannis et al. [60]
built up a semi-analytical model and reported that increasing the temperature of the well would increase the pressure at the interface. The results of temperature distribution are also consistent with an experimental work performed by Li et al. [39] on MH dissociation upon thermal stimulation. They reported that the decomposition progresses by a moving boundary separating the dissociated and undissoicated zones.

The results of temperature distribution also illustrate that the distance between the dissociation interface and the heat source is longer in the line heat source model compared to that of the wellbore heating model. This is due to the direct heat transfer from the line heat source to the reservoir, while there is heat conduction in the wellbore thickness in the other model. This difference decreases over time as the dissociation interface moves further and Zone I thickens, absorbing larger amount of input heat and reducing the negative effect of heat source thickness.

Figure 5 shows the volume of produced gas (m$^3$) in STP conditions in both models with different heat sources, as well as amount of input heat (MJ/m$^2$), and energy efficiency for the model with wellbore heating considering two BCs during 100 days. The volume of produced gas is higher for the line heat source case compared to the wellbore case due to the interface location mentioned earlier. The produced gas volume and the input heat are higher by applying BC 2 compared to that of BC 1. However, the energy efficiency is higher in the BC 1 case compared to that of BC 2. The reason is that the difference between the amounts of input heat for the two BCs is higher than the difference between the amounts of produced gas for the BCs (Figure 5). Thus, increasing the heat source temperature and decreasing its pressure would increase the rate of dissociation but will not increase the total efficiency of the process. As the dissociation progresses, Zone I becomes bigger, and the matrix sediments and the dissociation products absorb a larger part of the input heat decreasing the slope of produced gas and energy efficiency. Song et al. [64] experimentally achieved a similar trend for the energy efficiency of gas production from MH upon thermal stimulation by hot water injection. They reported the energy efficiency between 18 and 40, which is in a good agreement with the present results. In another experimental work by Wang et al. [12] on the gas production from MH using thermal stimulation by hot water injection, the same trend for the energy efficiency and gas production was reported. Selim et al. [31] reported a constant energy efficiency between 6.4-11.2. The difference between their results of energy efficiency and the ones of the present study could be due to the heat transfer in the wellbore structure, which
induced variable values, and the radial geometry of the present study, which caused more gas production as the moving interface becomes larger. Li et al. [69, 70] conducted experimental works on MH dissociation upon thermal stimulation in a 5.8 L cubic reactor. They observed that the energy efficiency of the process is approximately 20.6. Wang et al. [71] also reported an energy efficiency between 6 and 20 during experimental studies on MH dissociation upon thermal stimulation. Tang et al. [72] through experiments reported that increasing temperature and decreasing the pressure improve the energy ratio (the same as the energy efficiency) of MH dissociation upon thermal stimulation. Bayles et al. [73], who analytically studied MH dissociation upon cyclic steam injection, reported the same trend for the energy efficiency, which converged between 4 to 9.6, and gas production for one year dissociation. The slight difference between their results and the present ones could be due to the direct steam injection into the reservoir and the cyclic pattern of the process in their work.

![Graph](attachment:graph.png)
Additionally, the effect of various parameters, stated in Table 2, on the dissociation process is investigated through a parametric study. Figures 6 and 7 respectively shows the rate of dissociation and gas production resulted from the parametric study. These results indicate the following points: i) higher thermal diffusivities and conductivities of Zone I cause higher dissociation rate and higher gas production; ii) lower thermal diffusivities and conductivities of Zone II cause higher dissociation rate, while higher thermal diffusivities and lower thermal conductivities increase the gas production; iii) the dissociation rate and gas production remains almost constant by changing the permeability and gas viscosity; and iv) dissociation rate and gas production have respectively an inverse and direct relation with the porosity of the media.

Figure S3 in the supplementary file, which displays the input heat from the wellbore to reservoir during the parametric study in the case with wellbore heating. Actually, increasing the thermal conductivity of Zone I significantly increases the amount of input heat from the reservoir (Figure S1a). Higher thermal diffusivity (lower heat capacity while the density is constant) makes the media to store less heat, which in turn, increases the transferred heat to the dissociation front. Eventually, higher thermal diffusivity and higher thermal conductivity increase the dissociation rate (Figure 6a) and gas production (Figure 7a). Lower thermal diffusivity of Zone II increases the
storage of the transferred heat to this zone form the dissociation interface. At the end, this stored heat is released and consumed for dissociation increasing the dissociation rate (Figure 6b). Higher thermal conductivity of Zone II reduces the dissociation rate and gas production due to faster heat transfer to this zone from the moving interface instead of being consumed by dissociation. Higher thermal diffusivity of Zone II increases the gas production (Figure 7b) due to the reduction of heat storage in this zone inducing more heat consumption on dissociation and more gas production. Lower thermal diffusivity and higher thermal conductivity of Zone II increase the input heat (Figure S3b) due to the same reason stated for input heat increment induced by the same change of the same characteristics of Zone I (Figure S3a). But, the input heat increment for the case of Zone II is much lower than that of Zone I due to the direct contact of Zone I with the wellbore. Higher porosity reduces the conduction heat transfer and the input heat from wellbore (Figure S3c), and ultimately, reduces the dissociation rate (Figures 6c and 6d). Furthermore, higher porosity increases the amount of MH trapped in the pores eventually increasing the amount of produced gas (Figures 7c and 7d).

Figure S4 represents that the energy efficiency in the case with wellbore heating has direct relation with the thermal diffusivity of Zones I and II (Figures S4a and S4b) due to the higher gas production and lower input heat by increasing thermal diffusivities. On the other hand, energy efficiency decreases by increasing the thermal conductivity of Zones I and II. This is due to: i) the increment of input heat induced by higher thermal conductivities, which is more pronounced for Zone I (Figure S3a); and ii) the lower gas production caused by increasing the thermal conductivity of Zone II.

Selim et al. [31] reported the similar results for the rate of dissociation, as shown in Figure 6, during the same parametric study. Zhao et al. [74] mathematically investigated the gas production from MH using thermal stimulation and showed that increasing the thermal conductivity had a direct positive effect on the dissociation process. They also reported that the relative permeability of water and gas has almost no impact on the dissociation because the convective heat transfer of water and gas has negligible effect on the process. In another numerical work, They showed that increasing sediments’ thermal conductivity increased the gas generation rate at the beginning of dissociation upon depressurization [75]. It should be mentioned that both of their works were verified against Masuda’s experimental work [23]. Tsimpanogiannis et al. [60] performed a
parametric study of effects of different physical parameters on the MH dissociation upon thermal stimulation. They showed that increasing the thermal conductivity of the porous media induced more MH dissociation. Moridis et al. [28] conducted numerical analyses of various gas production scenarios from five methane hydrate-bearing zones at the Mallik site and showed that the higher initial formation temperature, well temperature, and formation thermal conductivity increased the amount of produced gas; while, it is not affected by the permeability of the formation and the specific heat of the rock and MH. It is in accord to the results shown in Figures 6 and 7, because the amount of produced gas has a direct relation to the rate of dissociation ($\beta$). It should be noted that the difference between the results of experimental works and the present work, which is not significant, is due to some of different working conditions, such as direct hot water injection into the reservoir, time period of experiments, and model parameters (i.e. hydrate saturation).

| Table 2. Range of parameters employed in the parametric study. |
|---------------------------------------------------------------|
| Porosity, $\phi$                                             | 0.1 to 0.5 |
| Permeability, $k$, $\mu$m$^2$                                | 0.1 to 5   |
| Thermal diffusivity of Zone I, $\alpha_I$, $\mu$m$^2$/s      | 1×10$^6$ to 5×10$^6$ |
| Thermal conductivity of Zone I, $k_I$, W/(m.K)               | 3 to 7     |
| Thermal diffusivity of Zone II, $\alpha_{II}$, $\mu$m$^2$/s | 4×10$^5$ to 8×10$^5$ |
| Thermal conductivity of Zone II, $k_{II}$, W/(m.K)           | 1 to 5     |
| Gas viscosity, $\mu$, Pa.s                                   | 10$^{-4}$ to 10$^{-6}$ |
Figure 6. The effect of various parameters on the interface movement after 100 days dissociation considering both types of heat sources: a) thermal diffusivity and thermal conductivity of Zone I, b) thermal diffusivity and thermal conductivity of Zone II, c) porosity with various permeabilities, and d) porosity with various gas viscosities.

Dashed lines and solid lines are respectively representative of the model with wellbore heat source and the model with line heat source.
Produced gas (m$^3$)

\[ K_I = 10^{-6} \]
\[ K_I = 2(10^{-6}) \]
\[ K_I = 3(10^{-6}) \]
\[ K_I = 4(10^{-6}) \]
\[ K_I = 5(10^{-6}) \]

\[ K_{II} = 4(10^{-7}) \]
\[ K_{II} = 5(10^{-7}) \]
\[ K_{II} = 6(10^{-7}) \]
\[ K_{II} = 7(10^{-7}) \]
\[ K_{II} = 8(10^{-7}) \]
Figure 7. Produced gas after 100 days dissociation considering both heat sources and various parameters: a) thermal diffusivity and thermal conductivity of Zone I, b) thermal diffusivity and thermal conductivity of Zone II, c) porosity with various permeabilities, and d) porosity with various gas viscosities.

Dashed lines and solid lines are respectively representative of the model with wellbore heat source and the model with line heat source.

- **Conclusions**

In the present study, for the first time, 2D radial analytical models are developed to investigate MH dissociation upon thermal stimulation by wellbore heating. Two types of heat sources are considered: i) line heat source; and ii) wellbore heat source with layers of casing, cement, and gravel. The effects of various reservoir parameters and boundary conditions on dissociation are also evaluated. Two main factors are evaluated to assess the process: i) moving dissociation boundary position/velocity ($\beta$), and ii) energy efficiency of the process ($\eta$). Taken together, the results suggest the following conclusions:

- The rate of dissociation and overall efficiency of the process are dependent on both wellbore structure, which is a design parameter. Using a wellbore heat source causes a reduction in the dissociation rate and the produced gas compared to the other case with line heat source.
- Temperature at the wellbore surface changes due to the heat conduction in the wellbore, which depends on the wellbore structure.
- Both pressure and temperature at the dissociation front depend on the temperature at the wellbore surface.
- Increasing the well temperature while decreasing its pressure increases the dissociation rate and produced gas while reduces the energy efficiency. Thus, more information on the initial and boundary conditions including wellbore structure (number of layers, thicknesses, and thermal properties) would be helpful to establish a greater degree of accuracy on this matter and to improve the energy efficiency of the process.
- Only conductive heat transfer was considered during the dissociation process in the proposed parametric study.
- Gas production, input heat, and energy efficiency of the process is significantly dependent on the thermal diffusivity, porosity, and thermal conductivity of the reservoir. While, different reservoir’s permeabilities and viscosities do not affect the outcome of dissociation.
- There is a good agreement between the results of the present study and previous experimental and numerical studies validating the assumptions made in the model development.

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| Nomenclature                | Symbol      | Description                                                                 |
|-----------------------------|-------------|------------------------------------------------------------------------------|
| Dimensionless variable in equation S9 | \( A \) | Dimensionless variable in equation S9                                       |
| Pressure in Zone I          | \( P \)    | Pressure in Zone I                                                           |
| Dimensionless variable in equation S10 | \( A_1 \) | Dimensionless variable in equation S10                                       |
| Pressure at the interface   | \( P_s \)  | Pressure at the interface                                                    |
| Dimensionless constant in equation 10 | \( A_a \) | Dimensionless constant in equation 10                                        |
| Pressure of the heat source | \( P_i \)  | Pressure of the heat source                                                  |
| Average area of the dissociation front | \( A_v \) | Average area of the dissociation front                                       |
| Pressure of gas at STP conditions | \( P_{STP} \) | Pressure of gas at STP conditions                                             |
| Wellbore area               | \( A_w \)  | Wellbore area                                                                |
| Heat of MH dissociation     | \( Q_{Hd} \) | Heat of MH dissociation                                                      |
| Dimensionless constant in equation S13 | \( a \) | Dimensionless constant in equation S13                                       |
| Heating value of the gas at STP conditions | \( Q_g \) | Heating value of the gas at STP conditions                                    |
| Dimensionless variable in equation S11 | \( B \) | Dimensionless variable in equation S11                                       |
| Total input heat to the reservoir from the heat source | \( Q_n \) | Total input heat to the reservoir from the heat source                      |
| Inside radius of the wellbore | \( R_{in} \) | Inside radius of the wellbore                                                 |
| Outside radius of the wellbore | \( R_{out} \) | Outside radius of the wellbore                                               |
| Thermal resistivity of the wellbore | \( R_w \) | Thermal resistivity of the wellbore                                           |
| Dimensionless constant in equation S14 | \( b \) | Dimensionless constant in equation S14                                       |
| Radial distance             | \( r \)    | Radial distance                                                              |
| Dimensionless variable in equation S12 | \( C \) | Dimensionless variable in equation S12                                       |
| Inside radius of wellbore \( (R_{in})/\) | \( r_1 \) | Inside radius of wellbore \( (R_{in})/\)                                    |
| Inside radius of casing 1   | \( r_2 \)  | Inside radius of casing 1/                                                   |
| Inside radius of gravel part | \( r_3 \) | Inside radius of gravel part                                                 |
| Outside radius of casing 2  | \( r_4 \)  | Outside radius of casing 2/                                                  |
| Inside radius of cement part | \( r_4 \) | Inside radius of cement part                                                 |
| Inside radius of wellbore \( (R_{out}) \) | \( r_5 \) | Inside radius of wellbore \( (R_{out}) \)                                   |
| Specific heat capacity of Zone I | \( C_{pl} \) | Specific heat capacity of Zone I                                             |
| Specific heat capacity of gas | \( C_{pg} \) | Specific heat capacity of gas                                                 |
| Inside radius of casing 1   | \( r_2 \)  | Inside radius of casing 1/                                                   |
| Inside radius of gravel part | \( r_3 \) | Inside radius of gravel part                                                 |
| Inside radius of casing 2  | \( r_4 \)  | Inside radius of casing 2/                                                  |
| Inside radius of cement part | \( r_5 \) | Inside radius of cement part                                                 |
| Interface position          | \( S \)    | Interface position                                                           |
| Temperature of the heat source | \( T_i \) | Temperature of the heat source                                               |
| Temperature in Zone I       | \( T_1 \)  | Temperature in Zone I                                                        |
| Temperature in Zone II      | \( T_II \) | Temperature in Zone II                                                       |
| Ratio of mass of the methane gas trapped inside the MH to the mass of hydrate | \( F_{gH} \) | Ratio of mass of the methane gas trapped inside the MH to the mass of hydrate |
| Initial temperature of hydrate | \( T_0 \) | Initial temperature of hydrate                                               |
| Temperature at the interface | \( T_s \) | Temperature at the interface                                                 |
| Temperature of gas at STP conditions | \( T_{STP} \) | Temperature of gas at STP conditions                                          |
| Time                        | \( t \)    | Time                                                                         |
| Symbol | Description |
|--------|-------------|
| $I$ (β) | Dimensionless constant in equation S22 |
| $I_1$ (β) | Dimensionless constant in equation S23 |
| $K$ (β) | Function in equation S21 |
| $k$ | Permeability |
| $k_I$ | Thermal conductivity of Zone I |
| $k_{II}$ | Thermal conductivity of Zone II |
| $k_c$ | Thermal conductivity of cement |
| $k_g$ | Thermal conductivity of gravel |
| $k_s$ | Thermal conductivity of casing |
| $L$ (β) | Function in equation S18 |
| $M$ (β) | Function in equation S19 |
| MH | Methane hydrate |
| $m$ | Gas molecular mass |
| $N$ (λ) | Function in equation S20 |
| $n_r$ | Total moles of produced gas per surface area of the moving interface in the time fraction of “$t, t-1$” |
| $n_n$ | Total moles of produced gas per surface area of the moving interface up to time $t$ |
| $u_r$ | Heat flux from the well |
| $v_f$ | Volume of produced gas per surface area of the moving interface in the time fraction of “$t, t-1$” |
| $v_{np}$ | Total volume of produced gas per surface area of the moving interface up to time $t$ |
| $v_s$ | Interface velocity |
| $\rho_g$ | Gas density |
| $\rho_{II}$ | Hydrate density |
| $\mu$ | Gas viscosity |
| $\lambda$ | Dimensionless variable in equation 18 |
| $\beta$ | Dimensionless constant in equation 19 |
| $\phi$ | Porosity |
| $\alpha_I$ | Thermal diffusivity of Zone I |
| $\alpha_{II}$ | Thermal diffusivity of Zone II |
| $\nu_s$ | Gas velocity |
| $\eta_r$ | energy efficiency ratio |
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