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Effect of heat diffusion in the burden on the dissociation of methane in a hydrate bearing formation

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ABSTRACT

Production of methane from sediments containing methane hydrates has been studied by researchers through the mathematical models of three phase reactive flow through porous media. This article incorporates in the model the unsteady state heat conduction through the burden and a point heat source in the formation, at a distance from the production well. Saturations and pressure in space and time were modelled using explicit finite difference method. The equation for heat conduction in the hydrate bearing formation was solved implicitly. The equation for heat conduction in the burden was solved with a coupling term from the heat balance equation for the pay-zone. A temperature profile within the burden was observed within few metres from the pay-zone. Beyond this region, the temperature did not change to any appreciable extent. The conduction of heat in the burden resulted in a more uniform temperature along the length of the pay-zone. Consequently, the movement of the dissociation front was found slower, and the production rate decreased. However, at a later stage, the pay-zone temperature was found less uniform along the length axis. The production rate recovered somewhat at this stage. The effect of thermal diffusivity of the burden on the temperature profile and the production rate is presented in this article. The presence of heat source term resulted in increased gas saturation, reduced hydrate saturation, and a higher pressure near the heating zone. The overall temperature of the pay-zone and the production rate increased due to the presence of the heat source.

1. Introduction

Methane is regarded as a source of energy that is less polluting, and of high calorific value. Methane hydrates, existing as vast reserves in marine sediment contain a very high concentration of methane. These hydrates may play a major role in meeting the ever-increasing demand of energy. Methane may be extracted by de-equilibration through the change in pressure, temperature, or chemical environment. In the first method of de-equilibration, the pressure is reduced to a value, lower than the hydration pressure at the prevailing temperature. In the second method, referred as thermal stimulation, the temperature is raised above the decomposition temperature at the prevailing pressure. During depressurization, ice may form at very low pressure. However, to avoid ice formation, if pressure is maintained at a value, higher than the quadruple point, the hydrate dissociation may slow down. The problem can be avoided by introducing heat either directly or through injection of hot water or steam. The heat loss to the surrounding during the transit from the surface to the pay-zone may become an issue in hot fluid injection. A point heat source, e.g., a burner utilizing a fuel and an oxidant, if placed in the right position can increase the temperature by 5 °C, needed for decomposition (Castaldi et al., 2007). This article discusses the simulation results for methane hydrate dissociation under combined effect of depressurization at the production wells, and heating at the central location.

Production of methane from hydrate was modelled by researchers (Moridis, 2002; Ji et al., 2001; Castaldi et al., 2007; Sun et al., 2005; Phirani and Mohanty, 2009). The recent models work with dissociation thermodynamics, kinetics, multiphase flow, and heat transfer, associated with the hydrate depressurization above the quadruple point. The energy balance in this framework of equations includes heat conduction, convection, and heat of dissociation. In earlier models, the heat loss to the surrounding burden was completely neglected. In recent models, the heat loss was considered to be directly proportional to the difference between the temperature of the pay-zone and the bulk temperature of the burden. When thermal stimulation is also a driving mechanism, and the window of temperature for dissociation is small, the

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heat flow to or from over and under burdens needs to be accounted carefully. This article presents the 1-D simulation of methane dissociation in the pay-zone. The model is based on mass and energy balance in the pay-zone, as elaborated by Sun et al. (2005). Additionally, the model accounts for heat loss to the burden in accordance with the transient heat conduction equation, and the heat injection at a grid. The 2-D temperature profile, encompassing the pay zone and the adjoining rock was developed. The temperature profile in the pay-zone, and the cumulative production of methane with time were studied for different operating conditions, and the strengths of the heat source term. The sensitivity of the profiles to the thermal diffusivity of the burden was evaluated.

2. Methods

Fig. 1 describes the schematic drawing of the one-dimensional hydrate bearing formation. The region between the heating zone and the depressurized production well is considered here with the understanding that the profiles can be extrapolated to the entire pattern, using symmetry. x denotes the distance from the production well in the pay-zone. z denotes the vertical distance from the pay-zone to the overburden. Only the heat flow to the overburden was considered with the understanding that the flow of heat to the under-burden can be accommodated using symmetry of the problem. The hydrate-bearing zone was considered to be in equilibrium initially at hydrate-stable condition with the pressure of P^0 and temperature of T^0, saturated with water, methane gas and methane hydrate. For $t > 0$, a low pressure of $p_o < p_e$ is applied at $x = 0$. This causes depletion of hydrates near the production well, and a simultaneous release of gas and water. With time, the dissociation front moved deep into the pay-zone. At the other end of the medium (i.e., at $x = L$), a boundary condition of constant heat flux was employed.

The governing equations that describe heat and mass balances are listed in the Appendix. The equations were discretized in space and time using finite difference method. The values of model parameters, used for the simulation are listed in Table 1. The mass and energy balance equations were solved sequentially. For each time step, first the dissociation equation was solved explicitly. The mass balance equations were solved simultaneously. The heat balance equation for the pay-zone was solved implicitly. The implicit treatment requires solution simultaneous linear equations of tri-diagonal matrix form. This system of equations was solved using Thomas algorithm. The entire algorithm was implemented using Matlab7.1 from Mathworks Inc.

The heat conduction through the burden was included in the algorithm by coupling the transient heat conduction equation for the burden with that of the pay-zone. The heat conduction equation for the burden is one-dimensional, extending from the pay-zone

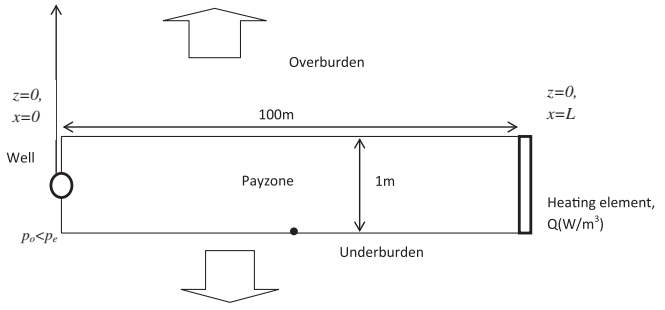

Fig. 1. Schematic drawing of the hydrate bearing formation.

Table 1
The values of system parameters.

Parameter	Value	Parameter	Value
L (m)	100	ρ_s (kg/m^3)	2675.08
n_w	4.0	ρ_w (kg/m^3)	1000
n_c	0.65	ρ_h (kg/m^3)	910
n_g	2.0	S_w^0 (%)	30
p_o (MPa)	2	S_h^0 (%)	69
P^0 (MPa)	15	p_c^e	0.004
Φ (%)	18.8	S_g^0 (%)	1
T_0 (K)	287	S_{wr}	0.2
p^0 (Mpa)	2	S_{gr}	0
k_d	4.4E-16	μ_w (kg/(m s))	0.001
λ (W/m K)	5.57 (dissociated zone)	Cp_h (J/(kg K))	2220
	2.73 (hydrate zone)	Cp_s (J/(kg K))	835
α_b (m^2/s)	1.8	α (W/m^2 K)	5.2
R_τ	1.76E-4		

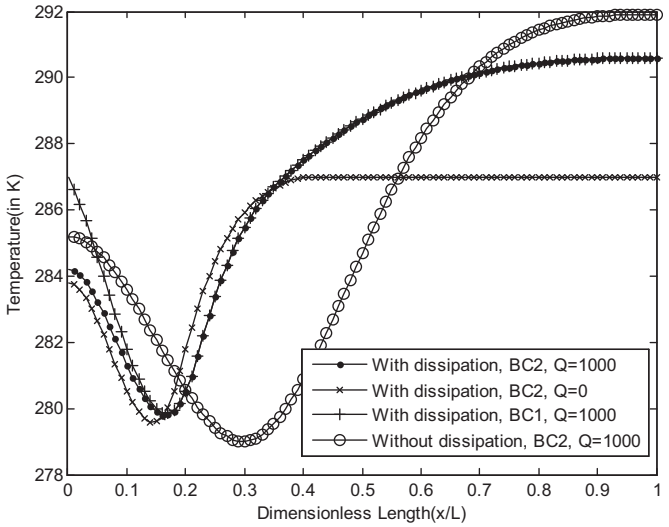

Fig. 2. Temperature of the formation under different operating conditions after 3 days.

into the burden to an infinite distance (referred as z_{max}). The heat conduction equation for the burden was discretized using non-uniform grid spacing of the form $\Delta z(i) = Ae^{bz(i)}$. 100 uniform grids in x-direction along the length of the pay-zone, and in 100 non-uniform grids in z-direction away from the pay-zone were considered.

An iterative procedure was used to compute the temperature profile in the burden at each time step. First, a pay-zone temperature was calculated based on zero heat flow to the burden. Assuming a constant gradient in the burden temperature between the pay-zone and the farthest point away from the pay-zone, the temperature of the z-grid immediately adjacent to the pay-zone was computed. Next, the transient heat balance equation for the burden was solved implicitly starting from the pay-zone side with the updated values of temperatures in the two adjoining grids. The temperature at $z = z_{max}$ was checked. Since this point is far away from the pay-zone, the temperature here should remain close to the initial temperature, T_0. If the check failed, the temperature of the z-grid immediately adjacent to the pay-zone was modified to a pre-specified extent. The procedure was repeated until convergence. Next, the loss or gain term in the pay-zone was computed, and the sequence of governing equations for the pay-zone was solved. The temperature profile in the burden was evaluated for the next time-step, as before. The procedure continued for the subsequent time steps.