Analytical solution for gas production from hydrate reservoirs underlain with free gas

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ABSTRACT

Fast analytical models for predicting hydrate reservoir performance are very attractive, especially in the early phase of development of hydrate reservoirs when data are scarce and a large number of sensitivity studies are required. Recently, a number of analytical solutions have been developed that predict the rate of gas generation (and production) from hydrate-capped gas reservoirs. One of the simplifying assumptions of this research team's previous model – that the decomposition of hydrate is assumed to occur *simultaneously* throughout the hydrate zone – leads to *optimistic* results. To understand just how optimistic previous model's results may be, we present an alternative analytical solution that would lead to *pessimistic* results. Use of a previous optimistic model in conjunction with the current pessimistic one therefore provides bounding upper and lower limits of the rate of gas production from hydrate-capped gas reservoirs.

The model presented here is developed by coupling the energy balance equation of 1D hydrate decomposition ahead of a moving interface with the material balance equation in a volumetric gas reservoir, and includes the thermodynamic relation of hydrate decomposition.

Results are presented to show how this model may be used to estimate a lower bound for hydrate recovery and how these results depend on reservoir and hydrate properties.

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1. Introduction

Gas hydrates are solid ice-like material, where gas molecules are entrapped in the void of an enclosing water cage. This provides a tight structure of gas; upon expanding a given volume of hydrate approximately 150–170 volumes at standard conditions (101.3 kPa and 20 °C) of methane gas are released.

Gas hydrate deposits exist in large quantities in different geologic conditions, such as some ocean sediments and underlying some arctic areas. Methane gas can be released and produced as a result of hydrate dissociation, and different methods have been suggested for enhancing that production. Three widely proposed methods for methane gas recovery from hydrates are (Sloan and Koh, 2008; Pooladi-Darvish, 2004): (1) depressurization, in which pressure is lowered below the hydrate equilibrium pressure at existing temperature; (2) thermal stimulation, in which

temperature is raised above the hydrate equilibrium temperature at prevailing pressure; and (3) inhibitor injection, in which inhibitors such as methanol or brine are used to decompose the hydrate by shifting its thermodynamic-equilibrium curve. Combinations of these methods can also be used.

The thermal stimulation technique has the disadvantage of losing substantial amounts of the introduced energy in the injection path and surroundings. As a result, in this technique, only a small fraction of injected energy is usefully employed to dissociate the hydrate.

The inhibitor injection technique is generally considered only for local dissociation of hydrate (i.e., near wellbore) because large scale use of them as a means of producing natural gas from gas-hydrate reservoirs is associated with high cost and environmental concerns.

Where conditions are suitable, many believe the depressurization technique would be the most economical and practical of the three methods (Grace et al., 2008).

Previous work by this research team (Gerami and Pooladi-Darvish, 2006, 2007) resulted in a model for a flat gas reservoir in communication with hydrates on top, where the decomposition of hydrate is assumed to occur simultaneously *throughout* the hydrate zone. This is referred to as "deep decomposition." The deep-decomposition assumption may be reasonable when there is

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Nomenclature

A	hydrate block surface area in contact with free-gas zone, m^2
a	free-gas–hydrate interface temperature parameter, K/s
c_p	average hydrate-cap heat capacity including rock, hydrate, water, and gas, J/kg K
E_H	gas hydrate expansion factor, std m^3/m^3
G_f	initial free gas-in-place at standard conditions, std m^3
G_g	cumulative gas generation at standard conditions, std m^3
G_p	cumulative gas production at standard conditions, std m^3
H	hydrate zone thickness, m
ΔH	heat of dissociation of hydrate, J/kg hydrate
k_c	thermal conductivity, w/mK
N_a	the ratio of rate of change in sensible heat to rate of heat conduction
N_H	hydration number, *dimensionless*
N_h	ratio of initial gas in the form of hydrate to initial free gas-in-place.
N_p	ratio of normalized gas production to the rate of heat conduction.
p	reservoir pressure, kPa
$\overline{p}$	average reservoir pressure, kPa
q	gas production rate at standard conditions, std m^3/s
r_e	reservoir radius, m
R_h	dimensionless gas generation cumulative
S_{Hi}	initial hydrate saturation, fraction
S_{te}	Dimensionless ratio of the sensible heat of the hydrate cap to heat of decomposition

t	time, s
T	temperature, K
$\overline{T}$	average temperature, K
X	position of the decomposing interface, m
x	spatial position, m
z	compressibility factor, fraction

Greek letters

α	thermal diffusivity, $\alpha = k_c/\rho \cdot c_p$, m^2/s
β	hydrate equilibrium curve constant (8533.80 K)
λ	hydrate equilibrium curve constant (38.98)
ϕ	porosity, fraction
ρ	average hydrate-cap density including rock, hydrate, water and gas, kg/m^3
ρ_H	hydrate density, kg/m^3
η	dimensionless spatial variable
π	3.1415926…
θ	dimensionless temperature
σ	dimensionless interface location
τ	dimensionless time
ξ	dimensionless spatial variable

Subscripts and superscripts

i	initial condition
m	middle point
r	ending state
R	reference state
s	Hydrate-free gas interface

a mobile phase in the hydrate zone and where the thickness of the hydrate layer is small; however, when permeability is sufficiently small and/or the hydrate thickness is sufficiently large, decomposition would occur over only a limited extent of the hydrate volume. Therefore, the deep-decomposition assumption generally leads to optimistic prediction of hydrate reservoir gas production. This paper examines the case of *no* mobile phase in the hydrate cap, leading to hydrate decomposition occurring at a shar-interface between the decomposed zone and the hydrate zone. The actual gas production from real gas-hydrate reservoirs is expected to be somewhere between the cases of deep decomposition as the upper bound (as assumed by the previous model), and the sharp-interface decomposition as the lower bound (as assumed by this model).

This paper focuses on the development of the sharp-interface decomposition model and examines its assumptions. In comparison with many of the other analytical solution with sharp-interface assumption where a constant pressure or temperature was used (Selim et al.,1990; Makogon, 1997; Goel et al., 2001; Ji et al., 2001; Hong 2003; Hong et al., 2003), in this paper hydrate decomposes due to a time dependent pressure reduction in a reservoir. A limited comparison between this model and the previous deep-decomposition model is also presented. A detailed investigation of the range of applicability of each will be presented elsewhere. However, results of one case are shown to demonstrate that depending on the permeability of the hydrate cap, numerical simulation results (that do not invoke assumptions of these analytical models) are bounded by the sharp-interface and deep-decomposition analytical models. We also note that, in the absence of field data, the analytical models may be used to evaluate the recoverability of hydrates and the potential rates of gas production. Such analytical assessments are particularly useful when properties of hydrate reservoirs are poorly known and large number of runs

may be necessary to evaluate the uncertainty in reservoir parameters (Gerami and Pooladi-Darvish, 2008).

2. Scope of the study

Fig. 1 shows a schematic representation of the depressurization method of methane gas production from hydrate reservoirs. A gas reservoir with a saturated hydrate interval at the top is defined here as a hydrate-capped gas reservoir. A well is completed in the free-gas zone. At the start of production, the pressure in the free-gas zone is reduced, causing hydrate to dissociate (Moridis, 2002; Hong and Pooladi-Darvish, 2005). In this model, hydrate dissociation occurs only at the gas–hydrate boundary. Fig. 2 shows a gas–hydrate phase diagram illustrating the dissociation mechanism.

As this figure shows, the endothermic decomposition of hydrate will decrease the temperature of the gas–hydrate interface. A temperature gradient formed in the hydrate cap initiates the conductive heat flow towards the interface. This heat provides the required energy for the dissociation of the solid according to Equation (1).

$$CH_4 \cdot N_H H_2O(solid) \rightarrow CH_4(gas) + N_H H_2O(liquid\ or\ ice) \qquad (1)$$
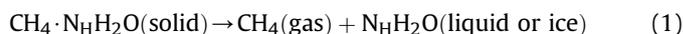
Depressurization can lead to large rates of dissociation when a large area of dissociation exists.

Many foresee that the depressurization method is the most effective and practical method due to its "natural" means of production, with no requirement of an external source to dissociate hydrates (Grace et al., 2008). However, a limitation of this technique is ice formation and/or hydrate reformation which may impair the productivity of the well. On the other hand, this