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Simulation of microwave stimulation for the production of gas from methane hydrate sediment

Jiafei Zhao, Zhen Fan, Bin Wang, Hongsheng Dong, Yu Liu *, Yongchen Song *

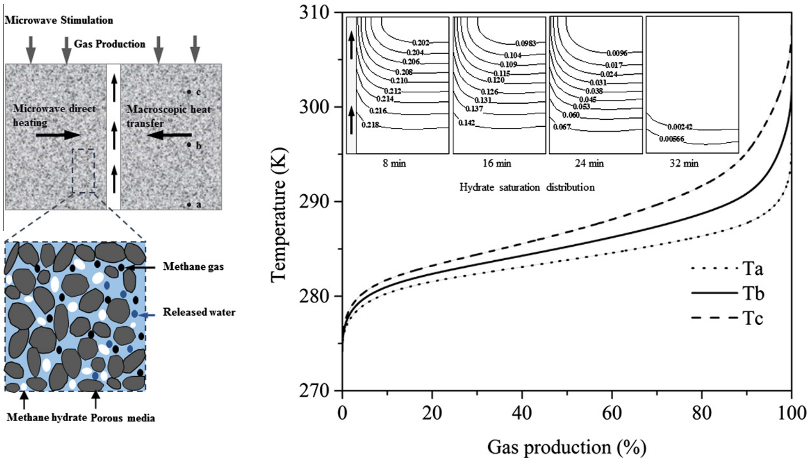
Key Laboratory of Ocean Energy Utilization and Energy Conservation of Ministry of Education, Dalian University of Technology, Dalian 116024, China

HIGHLIGHTS

- Hydrate dissociation behavior was analyzed in porous media by microwave stimulation.
- Microwave stimulation provides sufficient energy conversion for hydrate dissociation.
- Hydrate saturation and specific heat capacity of sediment mainly affect efficiency.
- Heat conduction decreases temperature gradients promoting homogeneous dissociation.

GRAPHICAL ABSTRACT

Schematic diagram illustrating the process of gas production in hydrate-bearing sediment induced by microwave stimulation. Temperature gradients caused by the drop of microwave penetration depth appear in the sediment, leading to a rapid dissociation rate at the upper part of reservoir.



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ABSTRACT

Natural gas hydrates dissociate via an endothermic process. One of the key requirements for any production technique is to supply the heat necessary for this dissociation. In this study, first, a microwave stimulation model for the production of gas from methane hydrate sediment is developed, which includes mass transport, energy conversion and conservation, and intrinsic kinetic reactions as the governing equations. In addition, the theoretical mixing rule of Lichtenecker and Rother is introduced for calculating the average dielectric data of the sediment containing methane hydrates, which affects the penetration of microwaves into the sediment. Next, simulations are performed for investigating gas production, as well as effects of initial water saturation, initial hydrate saturation, and sediment thermal properties induced by microwave stimulation. Moreover, the energy efficiency ratio is employed in the simulation. The simulation results show that microwave stimulation provides timely energy conversion sufficient for promoting the dissociation of hydrates, with rapid, continuous gas production. Temperature gradients caused by the decrease of the microwave penetration depth appear in the reservoir, leading to a rapid dissociation rate in the upper part of the sediment. The energy efficiency ratio for all simulations ranges between 3.752 and 6.452. Hydrate saturation and the specific heat capacity of porous media are two factors that significantly affect energy efficiency. High hydrate saturation contributes to a rapid gas

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* Corresponding authors.

E-mail addresses: liuyu@dlut.edu.cn (Y. Liu), jfzhao@dlut.edu.cn (Y. Song).

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Nomenclature

A	reaction ratio surface area (m^2)
A_y	microwave absorption area (m^2)
C_p	specific heat (J/(kg K))
D_p	microwave penetration depth (m)
E_{mic}	electromagnetic energy released in the reservoir
f	frequency of microwaves
h	enthalpy of phase (J/kg)
K_0	absolute permeability (mD)
k	relative permeability of gas or water
k_0	intrinsic reaction constant
M	molecular weight
$\dot{m}$	mass of phase for the formation or dissociation of hydrates ($kg(s/m^3)$)
N	permeability reduction factor, $N = 15$
N_h	hydrate number, $N_h = 5.75$
n	mole number of cumulative gas production
n_c	empirical constants in Eq. (31), $n_c = 0.65$
n_g	empirical constants in Eq. (7), $n_g = 2$
n_w	empirical constants in Eq. (6), $n_w = 4$
P	pressure (Pa)
P_c	capillary pressure (Pa)
P_c^e	enter pressure in Eq. (30), $P_c^e = 1$ KPa
P_e	equilibrium pressure (Pa)
P_0	initial pressure (Pa)
Q_{CH_4}	heat released by the burning of methane gas from hydrate dissociation
$\overset{\blacksquare}{q}$	energy source (J)
q_{CH_4}	heat released during the combustion of 1 mol methane
R_d	microwave radiation density (W/m^2)
r	radial distance (m)
S	saturation of phase
S_{gr}	gas residual saturation
S_{wr}	water residual saturation
T	temperature (K)
T_e	equilibrium temperature (K)
t	time (s)
V	percentage of each component
v	velocity of fluid phase (m/s)
y	axis distance (m)
z	distance in gravitational acceleration direction (m)

Symbols

$\varnothing$	porosity
$\varnothing_e$	efficient porosity
μ	viscosity (Pa s)
λ	conductivity coefficient (w/m K)
ρ	density of phase (kg/m^3)
σ	gas throttle coefficient
ε'	relative dielectric constant
ε''	relative dielectric loss factor
α	electromagnetic absorption coefficient
β	empirical constants in Eq. (22), $\beta = 0.65$
η	energy efficiency ratio

Subscripts

g	gas phase
h	hydrate phase
in	heat from microwave stimulation
s	sediment phase
w	water phase

generation rate and a long rapid gas generation lasting time, leading to a high energy efficiency. A low specific heat capacity of porous media can decrease the loss of heat to the sediment, increase the gas generation rate, and improve energy efficiency. Furthermore, high initial water saturation can cause a rapid decrease in the microwave penetration depth and lead to large temperature gradients in the sediment. The thermal conductivity of porous media mainly affects gas generation in the latter period of hydrate dissociation. Macroscopic heat conduction in the sediment decreases the temperature gradients in the reservoir and promotes homogeneous hydrate dissociation.

1. Introduction

Methane-hydrate-ice-like combinations of methane and water, which are stable under high pressure and low temperature conditions [1,2], have been viewed as potential energy sources for the 21st century [3,4]. Several recovery methods such as thermal stimulation, depressurization, chemical injection, and CO_2 replacement have been proposed [5,6]. Nevertheless, thermal stimulation and its combination with depressurization are regarded as the most promising choices [7]. However, these methods exhibit disadvantages, such as loss of heat to the surroundings and low permeability, which possibly limit the feasibility of applying these conventional thermal stimulation methods [8]. Thermal stimulation methods involving in situ direct heating are considered to be energy-efficient methods [8–11].

As a form of electromagnetic energy traveling in the form of high-frequency waves and causing dipoles in materials to heat themselves through high-speed rotation, microwaves at 915 MHz and 2.45 GHz are widely utilized to heat materials in the industry and laboratory [12,13]. Because of deep penetration, volumetric heat release, and the absence of coolant, electromagnetic radiation can provide high speed and uniform heat [14]. Applications of microwaves in several areas of the petroleum industry and their corresponding numerical models have been reported [15–18]. Fatykhov et al. have reported that 2.45 GHz microwaves exhibit better performance in propane hydrates or ice melting in pipelines as compared with that exhibited by a natural process [19]. Nomura et al. have developed a process of utilizing 2.45 GHz microwave irradiation for the plasma decomposition of cyclopentane hydrates for producing fuel gas [20]. A patent for the use of exploiting polar material resources for the microwave heating of natural gas hydrates, which involves transmitting temperature and pressure data to control system, and connecting moving floating plate with natural gas well lower limiting pin, has been reported [21]. Experiments on the dissociation of gas hydrates formed from sodium dodecyl sulfate solutions without sediments indicated that microwave irradiation promotes the decomposition of natural gas hydrates [22,23]. He et al. have experimentally investigated the