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Experimental investigation into scaling models of methane hydrate reservoir

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HIGHLIGHTS

- The scaling criteria for methane hydrate reservoir are built.
- The scaling criteria are verified by the experiments in two 3-D simulators.
- The scaling criteria are used for predicting gas production of real hydrate reservoir.
- Methane of 1.168×10^6 m^3 is produced from the hydrate reservoir after 13.9 days.

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ABSTRACT

The Cubic Hydrate Simulator (CHS), a three-dimensional 5.8 L cubic pressure vessel, and the Pilot-Scale Hydrate Simulator (PHS), a three-dimensional 117.8 L pressure vessel, are used for investigating the production processes of hydrate. The gas production behaviors of methane hydrate in the porous media using the thermal stimulation method with a five-spot well system are studied. The experimental conditions are designed by a set of scaling criteria for the gas hydrate reservoir. The experimental results verify that the scaling criteria for gas hydrate production are reliable. The scaling criteria are used for predicting the production behavior of the real-scale hydrate reservoir. In the model of the real-scale hydrate reservoir with the size of 36 m × 36 m × 36 m, methane of 1.168×10^6 m^3 (STP) is produced from the hydrate reservoir during 13.9 days of gas production. It is obtained that the gas recovery is 0.73, and the final energy efficiency is 9.5.

1. Introduction

Natural gas hydrates are crystalline solids composed of water and gas molecules, especially methane. The gas molecules (guests) are trapped in water cavities (host) that are composed of hydrogen-bonded water molecules under a relatively low temperature and high pressure [1]. A large amount of methane gas is trapped in natural gas hydrate reservoirs, and one volume of natural gas hydrate can release 160–180 volumes of natural gas at standard condition. Natural gas hydrates are distributed all over the earth on both the land in permafrost regions and ocean sediments of continental margins. The global resource of natural gas in hydrate deposits is commonly cited as 20,000 trillion m^3, and is considered as a potential energy source [2–4].

The methods for recovering natural gas from hydrates are different and are still under development. The most practical methods are the thermal stimulation method [5–7], the depressurization method [8–11], the chemical injection method [12], and CO_2 replacement method [13]. Till now, experimental investigations and field tests on methane hydrate production under the varied methods have been carried out around the world [14]. The experimental studies of the hydrate dissociation with the different methods in porous media using one-dimensional [6,15], two-dimensional [16], and three-dimensional [17–20] apparatuses have been reported. Meanwhile, The Mallik 2002 well has demonstrated the proof of the concept that it is possible to recover energy from permafrost hydrates combining the dissociation techniques of the depressurization and the thermal stimulation [21–23]. The latest report is found that the world's first offshore test producing gas from methane hydrate is carried out by using a depressurization method in the Nankai Trough, Japan [24]. However, the cost of the hydrate reservoir field test is huge. Therefore, various researches about the hydrate exploitation in laboratory are carried out. Although experimental tests are not sufficient to replace field

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Nomenclature

Abbreviation

CHS	Cubic Hydrate Simulator
PHS	Pilot-Scale Hydrate Simulator

Symbols

V	wellhead
q_i	rate of hot water (ml/min)
T_i	temperature of hot water (K)
x, y, z	coordinates
ϕ	porosity
ϕ_0	total porosity
ϕ_e	effective porosity
s	saturation
P	pressure (MPa)
μ	viscosity (Pa S)
ρ	density (kg m^{-3})
K	permeability (m^{-2})
K_0	maximum absolute permeability (m^{-2})
$\dot{m}$	mass rate (m^3 s^{-1})
h	specific heat (J kg^{-1} K^{-1})
λ	conductivity coefficient (w m^{-1} K^{-1})
q	heat changes on boundary (J)
g	the gravitational acceleration (m s^{-2})
x_p, y_p	coordinates of the production well (m)
x_I, y_I	coordinates of the injection well (m)
r_0	well radii (m)
r_{e0}	effective radii of well (m)
ΔH	enthalpy change of hydrate decomposition (J)
M	molecular weight
N_h	coefficient of dissociation reaction [5.8]
A_s	specific surface area of porous media (m^2)
f	gas fugacity (Pa)
k_d	the dissociation constant
L	length (m)
H	thickness (m)
W	width (m)
θ	gas recovery
ξ	energy efficiency
Q	volume of gas production (m^3)
C_g	combustion heat of natural gas (MJ/m^3)
W	pump work (kw)
m	amount of the phase (kg)
σ	gas throttle coefficient

Subscript

i	initial
I	injection
p	production
g	gas
w	water
h	hydrate
r	rock
eq	phase equilibrium
D	dimensionless
m	model
f	prototype

tests as there are environmental concerns on exploiting these hydrate deposits that cannot be seen in the laboratory experiments. How to use the information obtained from the experimental data to cut down the cost of the field test is a quite significant issue, which requires to be solved in the next step.

Experimental test plays an important role in revealing the mechanism of the physical processes and optimizing the development programs in a short term at a low cost. The principle of similarity or scaling law is crucial for the experimental testes [25]. This method is widely used in the oil industry to preview oil recovery [26–28]. The results obtained from three-dimensional experiments can be enlarged, and the hydrate production in hydrate reservoir can be predicted by using this method. A similarity theory for the natural gas hydrate reservoir has been developed by Wang et al. [29]. However, few literatures about the experimental investigation for the similarity theory can be found.

In this work, a three-dimensional cubic pressure vessel (5.8 L, the Cubic Hydrate Simulator (CHS) [17,18,30]) and a three-dimensional pressure vessel (117.8 L, the Pilot-Scale Hydrate Simulator (PHS) [31,32]) are used for investigating the production processes of hydrate. The gas production of methane hydrate in the porous media is investigated using the thermal stimulation method with the five-spot well system. The experimental conditions are designed by the scaling criteria for hydrate reservoir. Furthermore, the scaling law verified by the experiments is used for predicting the production behavior of the real-scale hydrate reservoir.

2. Experiments

2.1. Experimental apparatus

The schematic of the apparatus [8] is shown in Fig. 1, which has been used to investigate methane hydrate production by huff and puff method [18] and depressurization method [8]. The experimental apparatus involves a high-pressure reactor, a water bath/air bath around the reactor, a back-pressure regulator, a gas and liquid injection equipment, a water/gas separator, a data acquisition system, and some measurement units. The core component of the apparatus is the high-pressure reactor. In this work, two reactors with different sizes, which are the PHS and CHS, are used for investigating the hydrate production processes. The details of the experimental apparatuses have been reported in our previous work [8,10,17,30,32,33].

2.1.1. The Pilot-Scale Hydrate Simulator (PHS)

The PHS is a cylindrical pressure vessel (length 0.60 m, diameter 0.50 m) with the inner volume of 117.8 L. Fig. 2a gives the schematic plot of the inner PHS and the well design in the PHS. From this figure, we can see one central vertical well (V_{inj}) along the centerline of the reactor, and four vertical wells (V_1–V_4) in the four corners of the reactor. There are 147 ($7 \times 7 \times 3$) thermal couples on three layers (Layer A–A, Layer B–B and Layer C–C) in the PHS. As seen in Fig. 2a, the name of thermal couple can be illustrated as follows: as an example, the 49th thermal couples on Layer A–A to Layer C–C are named T49A, T49B and T49C, respectively.

2.1.2. The Cubic Hydrate Simulator (CHS)

The CHS is cubic inside (volume of 5.8 L. The distributions of the thermocouples and production wellheads within the CHS are shown in Fig. 2b. As seen in Fig. 2b, there are 25×3 thermocouples, one central vertical well, and four vertical wells in the four corners of the reactor. There are three layers, which divide the measuring points and the wellheads, named: Layer A, Layer B, and Layer C, respectively. In this work, the heat injection well is the V_{inj} in Layer C, and the gas and water production wells are the V_1–V_4 in Layer A.