International Journal of Heat and Mass Transfer 117 (2018) 940–950

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

A hydrate shell growth model in bubble flow of water-dominated system considering intrinsic kinetics, mass and heat transfer mechanisms

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ARTICLE INFO

Article history:
Received 19 May 2017
Received in revised form 24 July 2017
Accepted 10 October 2017

Keywords:
Hydrate shell
Gas concentration
Bubble flow
Water-dominated
Kick migration
Gas traps

ABSTRACT

The gas hydrate formed in the wellbore or pipeline may pose severe challenges to pressure control and flow assurance. One key issue to address the hydrate problem is the intercoupling of hydrate shell growth characteristics and multiphase flow behaviors, which has not been studied thoroughly in the bubble flow of a water-dominated system. In this study, we develop a fully coupled hydro-thermo-hydrate model considering the interactions of hydrate intrinsic kinetics, mass and heat transfer, and hydrodynamics mechanisms. In the model, the varying concentration of gas on the outside of a hydrate shell, is introduced to describe the dynamic equilibrium between the gas outward diffusion within the hydrate shell, hydrate formation kinetics at the hydrate/liquid interface, and gas dissolution into liquid. The simulation results agree well with the experimental data. Using the proposed model, we study a special kick development mechanism caused by the phase transition of gas traps during deepwater horizontal drilling. The simulated results show that there exists a hydrate phase stability field in the wellbore during deepwater drilling. As the migration of gas traps, the hydrate growth on the bubble surface, which is closely related to the formation and decomposition of hydrate and the dissolution and desolvation of gas, may result in an abrupt and rapid gas kick. The proposed model adds further insights into quantitatively characterizing the hydrate growth and interphase mass transfer rules in the bubble flow of water-dominated systems.

1. Introduction

Formed under low temperature and high pressure, the gas hydrates are crystalline inclusion compounds, in which the gas molecules are trapped in the hydrogen-bonded cages of water molecules [1]. Hydrate utilization technology has been widely used in the field of energy [2–4], such as the development of hydrate resources, solute separation and energy storage. However, as oil and gas exploration enters into the deepwater reservoirs, the thermodynamic and material conditions of hydrate formation are satisfied perfectly in the wellbore and subsea pipelines [5–7]. The formation of solid hydrate will alter the flow behaviors of gas and liquid, which can lead to severe flow assurance problems including the drilled gas kick [6], pipe blockage [7,8], etc. Therefore, it is necessary to study the hydrate phase transition rules on the gas bubbles of a water-dominated system.

The hydrate growth mechanisms are the key issues to address the flow assurance challenge. A wide variety of evidence in the literature indicates that the hydrate formation phenomenon is limited by the mechanisms of intrinsic kinetics, and mass and heat transfer [1,9]. At present, several hydrate kinetics models under different experimental conditions have been developed [10–13], which have been widely utilized to analyze the hydrate formation rules in the water-dominated systems. Using the hydrate kinetics models, Zheng et al. [14], Yapa et al. [5], and Li and Huang [15] simulated the hydrate formation characteristics for the gas bubbles during free rising, and gas bubbles in an intense plume. The hydrate shell growth was found to have an important effect on the migration process and lifetime of a gas bubble. As for the multiphase flow scenarios, Wang et al. [6], Boxall et al. [7], and Wang et al. [8] demonstrated the interactions of gas, liquid, and hydrate phases in wellbore and pipeline considering the hydrate kinetic limitation; moreover, the multiphase flow behaviors of kick migration during drilling, and the flow assurance during pipeline transportation were analyzed. The gas hydrate was observed to occur and cover the bubble surface rapidly in bubble flow (the gas void fraction is less than 25% [16]) of a water-dominated system [17–19]. The hydrate film will not prevent, but only retard, the transports of gas and liquid through it [3,17]. Therefore, the mass transfer process becomes the control step and dominating factor for the hydrate shell thickening.

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https://doi.org/10.1016/j.ijheatmasstransfer.2017.10.045
0017-9310/

Nomenclature

a	profile parameter for low gas fraction in liquid
A	cross-sectional area of fluid flow, m^2
A_p	interfacial area of gas-liquid contact, m^2
A_0	heat transfer resistances between the annulus and surroundings, (K m)/W
B_0	heat transfer resistances between the inner pipe and annulus, (K m)/W
c	reservoir compressibility, 1/Pa
C_g	gas concentration, mol/m^3
C_s	gas concentration on the inner surface of hydrate shell, mol/m^3
C_x	gas concentration on the outer surface of hydrate shell, mol/m^3
C_{w0}	concentration of water, mol/m^3
C_∞	gas concentration in the liquid bulk, mol/m^3
C_0	distribution coefficient
d_c	equivalent diameter, m
D_g	gas diffusion coefficient in liquid, m^2/s
D_h	gas diffusion coefficient in hydrate shell, m^2/s
e_i	internal energy of the ith phase, J/kg
f	fugacity of dissolved gas, Pa
f_{eq}	gas fugacity in three-phase equilibrium, Pa
g	gravitational acceleration, m/s^2
h_i	enthalpy of the ith phase, J/kg
h_{oi}	enthalpy of the ith phase under the influx or leak condition, J/kg
h_c	convective heat transfer coefficients of the fluid, W/(m^2 K)
H	Henry's constant, Pa
ΔH_{sol}	gas dissolution heat, J/kg
ΔH_{hyd}	phase transition heat of hydrate, J/kg
I_{tsfer}	heat transfer rate of the flowing fluid with the surroundings, J/(m s)
$J_{diffusion}$	gas diffusion rate in the hydrate shell, mol/s
$J_{reaction}$	gas consumption or generation rate, mol/s
$J_{dissolve}$	gas dissolution rate, mol/s
k_g	mass transfer coefficient of gas dissolution, m/s
k_e	thermal conductivity of the surroundings, W/(m K)
K	reaction constant of hydrate formation or decomposition, mol/(m^2 Pa s)
K_e	reservoir permeability, m^2
M	molar mass, kg/mol
N	number density of gas bubble, 1/m
Nu	Nusselt number
p	fluid pressure, Pa
p_{res}	reservoir pressure, Pa
Pr	Prandtl number
q	influx rate of fluid from the surrounding, kg/s
r	radial distance, m
r_{ti}	inner radius of the inner pipe, m
r_{to}	outer radius of the inner pipe, m
r_{ci}	inner radius of the outer pipe, m
r_{co}	outer radius of the outer pipe, m
r_w	wellbore radius, m
R	bubble radius
Re	Reynolds number
s	length, m
Δs	length of space segment, m
S	skin factor
t	time, s
T	fluid temperature in the annulus, K
T_t	temperature in the inner pipe, K
T_{ei}	surrounding environment temperature, K
T_D	dimensionless temperature
U	terminal velocity of gas bubble, m/s
U_t	overall heat transfer coefficient in the inner pipe, W/(m^2 K)
U_a	overall heat transfer coefficient in the annulus, W/(m^2 K)
v	velocity, m/s
v_d	gas drift velocity, m/s
x_{sol}	fraction of dissolved gas in liquid, m^3/m^3

Greek letters

θ	angle between perpendicular and flow direction, rad
φ	reservoir porosity
σ_{hl}	hydrate/liquid interfacial tension, N/m
γ	profile parameter reduction term
κ	Euler constant
δ	hydrate shell thickness, m
ρ	density, kg/m^3
ρ_c	average density of hydrated bubble, kg/m^3
μ_f	fluid viscosity at characteristic temperature, Pa s
μ_w	fluid viscosities at surface temperature, Pa s
μ_g	gas viscosity, Pa s
α	volume fraction

Subscripts

g	gas
h	hydrate
l	liquid
m	mixture

Due to the mass transfer limitation, the vertical growth of a hydrate shell is much slower than its lateral growth. The experiments of the hydrate tensile strength and morphology indicate that the hydrate shell can be a porous solid material [18]. Considering the gas diffusion within the hydrate, Holder and Warzinski [20] built the steady-state equation of hydrate shell thickness, and analyzed the rules of hydrate thickening on the bubble surface. Regarding the air bubble in polar ice, Salamatin et al. [21] proposed a coupled model to describe the hydrated bubble behaviors, in which the mass transfer of different phases within the hydrate shell is incorporated. Furthermore, Shi et al. [9], Gong et al. [22], and Turner et al. [23] developed the hydrate inward growth model of water drops in oil emulsions. Gas diffusion across the hydrate shell is revealed as the major factor for hydrate shell growth. However, hydrate formation is a strongly system dependent process [9], affected by the bubble hydrodynamics, gas-water distributions, etc. Therefore, the hydrate shell growth characteristics of the steady bubble or oil-dominated system, which are mainly studied at present [24], can be significantly different with the scenario here. This is because the gas dissolution of the moving hydrated bubble and the dynamic variation of the dissolved gas distribution can affect the driving forces for mass transfer and intrinsic kinetics.

The hydrate shell growth should be intercoupled with the multiphase flow behaviors of the system. The hydrate formation/decomposition can lead to the heat release/absorption and mass transport between different phases, and then influence the variations of volume fractions, pressure, and temperature in water-dominated systems. Conversely, the multiphase flow behaviors control the hydrate phase stability field and the hydrate formation/decomposition rate.