Journal of Petroleum Science and Engineering 98-99 (2012) 122–129

Contents lists available at SciVerse ScienceDirect

Journal of Petroleum Science and Engineering

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

Overview of CSMHyK: A transient hydrate formation model

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ARTICLE INFO

Article history:
Received 6 September 2011
Accepted 26 August 2012
Available online 7 September 2012

Keywords:
flow assurance
natural gas hydrates
multiphase flow
transient gas hydrates modeling
oil-dominated systems
water-dominated systems
gas-dominated systems

ABSTRACT

Deep subsea facilities with high pressure and low temperature operation, encounter formation of gas hydrates as the most challenging problem in flow assurance. CSMHyK is a transient gas hydrate model specially designed for oil-dominated systems that predicts the formation and transportability of gas hydrates in flowlines. This paper presents a description of three sub-models included in the current version of CSMHyK: kinetics model, transport model and cold flow model; the product of intense efforts over a decade of hydrate research, involving over 20 students at the Center for Hydrate Research at the Colorado School of Mines. A set of conceptual pictures is also presented to describe physical phenomena of gas hydrate formation in water-dominated and gas-dominated systems, as the initial step of a development process that aims to extend CSMHyK towards a comprehensive model, to predict where and when hydrate plugs will form.

Contents

1. Introduction

A produced hydrocarbon stream from a wellhead encounters formation of solid gas hydrate deposits, which plug flowlines, as was first revealed by Hammerschmidt (1934) in natural gas transmission lines. Gas hydrates are considered one of the most challenging problems in deep subsea facilities. High pressures and low temperatures of operation in these facilities promote rapid formation of gas hydrates (Sloan, 2005).

Development of a comprehensive transient gas hydrates model that predicts when and where hydrate plugs will form in flowlines will have significant utility for the oil and gas industry. Such a comprehensive model should account for transient mechanisms present in different systems of oil/gas production facilities such as oil-dominated systems (oil as hydrate carrier phase), water-dominated systems (water as hydrate carrier phase), and gas-dominated systems (hydrates deposition on pipe walls). By predicting gas hydrates formation and transportability, the comprehensive model can be applied to design and optimize oil/gas transport facilities, focusing on prevention, management or remediation of gas hydrates in flowlines.

An intense research effort at the Center for Hydrate Research of Colorado School of Mines led to the development of CSMHyK (The Colorado School of Mines Hydrate Kinetics model), a gas hydrate model specially designed for oil-dominated systems,

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http://dx.doi.org/10.1016/j.petrol.2012.08.017

Nomenclature

A_s	surface area between water and hydrocarbon phases (m^2/m)
C_{bulk}	hydrate guest concentration in the bulk phase (kg/m^3)
C_{eq}	hydrate guest concentration in water phase in the presence of hydrate (kg/m^3)
$\bar{d}$	mean droplet diameter (m)
D_A	diffusivity of gas molecules through the hydrate shell (m^2/s)
d_A	hydrate agglomerate diameter (m)
D_p	pipe internal diameter (m)
d_P	hydrate particle diameter (m)
f	fractal dimension
F_a	normalized inter-particle cohesion force (mN/m)
k_1	intrinsic rate constant 1 (kg/m^2/s/K)
k_2	intrinsic rate constant 2 (K)
k_{comp}	heat transfer coefficient of the hydrate shell (J/s/m/K)
k_{hyd}	heat transfer coefficient of hydrate (J/s/m/K)
k_{mass}	mass transfer coefficient (m/s)
k_{water}	heat transfer coefficient of water (J/s/m/K)
h	convective heat transfer coefficient (J/m^2/K/s)
HYD_X_{gas}	molar fraction of hydrate guest in the hydrate phase
HYD_X_{water}	molar fraction of water concentration in the hydrate phase
m_{gas}	mass of gas (kg)
Re	Reynolds number ($\rho_o U D_p/\mu_o$)
r_p	hydrate particle radius (m)
r_w	radius of the water core (m)
t	time (s)
T_{hyd_eq}	hydrate equilibrium temperature (K)
T_{system}	system temperature (K)
U	fluid velocity (m/s)
u	scaling factor to include transport resistances to the model
We	Weber number ($\rho_o U^2 D_p/\sigma$)
ΔT_{sub}	subcooling (K)
δ	hydrate shell thickness (m)
ε	porosity of the hydrate shell
ϕ	hydrate particle volume fraction
ϕ_{eff}	effective volume fraction of the agglomerated hydrate particles
ϕ_{max}	maximum packing fraction
γ	shear rate (1/s)
μ_o	oil viscosity (cp)
μ_r	relative viscosity of the hydrate slurry to the viscosity of the continuous oil phase
ρ_o	density of the oil phase (kg/m^3)
σ	water–oil interfacial tension (mN/m)

which has been incorporated as a plug-in module in a transient multiphase flow simulator (Bendiksen et al., 1991; Turner et al., 2005). CSMHyK was developed for oil-dominated systems based on the conceptual model presented in Fig. 1, where hydrates form at the interface of water droplets entrained in the continuous oil phase by flow shear. In the oil phase, these hydrate-encrusted water droplets can agglomerate increasing into larger hydrate masses, leading to an increase in the slurry viscosity, which can eventually form a plug (Turner, 2005).

This paper presents a description of three sub-models included in the current version of CSMHyK: (1) the kinetics model (Boxall, 2009; Turner et al., 2005) using an intrinsic hydrate kinetic rate equation, (2) the transport model (Davies, 2009) using a set of mass and heat transport equations for hydrate formation, and (3) the cold flow model to calculate stabilized cold flow/slurry flow.

A set of conceptual pictures is presented to explain the physical phenomena of gas hydrate formation in flowlines, and extend the gas hydrate model towards a comprehensive model that includes water-dominated and gas-dominated systems. This paper represents a decade of experimental and modeling efforts to predict where and when a hydrate plug will form in a flowline, via a transient, multiphase model named CSMHyK.

2. Description of CSMHyK

The current version of CSMHyK was developed for oil-dominated systems based on the conceptual model presented in Fig. 1, which represents an approximation to the mechanism of hydrate plug formation and is divided into four main stages:

(1) *Water entrainment*: The water droplets are dispersed in the continuous oil phase by flow shear, as a water-in-oil emulsion.
(2) *Hydrate growth*: A hydrate shell forms at the interface between the water droplets and the surrounding oil phase.
(3) *Agglomeration*: The hydrate-encrusted water droplets can agglomerate, increasing into larger hydrate masses or agglomerates.
(4) *Plugging*: The agglomeration of hydrate particles leads to an increase in the slurry viscosity, which can eventually form a plug.

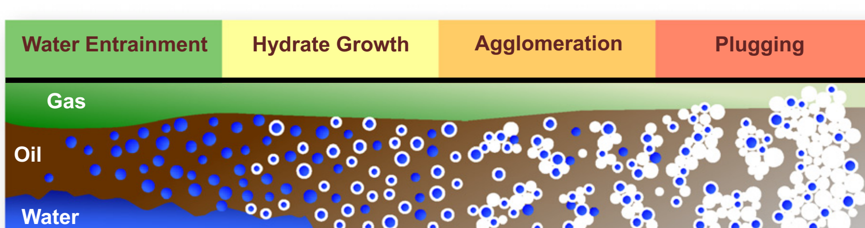

Fig. 1. Conceptual model for hydrate formation in multiphase flow systems consisting of water, oil, and gas; adapted from Turner (2005).