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Modelling agglomeration and deposition of gas hydrates in industrial pipelines with combined CFD-PBM technique

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HIGHLIGHTS

- The CFD-PBM model of the oil–water–hydrate slurry is developed.
- The model is validated with experimental data.
- The model is compared with CSMHyK from Colorado School of Mines.
- The flow patterns are described and analysed.

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ABSTRACT

Hydrates of light hydrocarbons are frequently formed during the subsea petroleum production. These crystalline ice-like solids may accumulate at concentrations sensitive from the flow assurance point of view, increasing the overall pumping costs and imposing sufficient risk of the pipe blockage. Modern trend in the assessment of hydrate-related risks is the development of numerical models of multiphase flows laden by hydrates. The present paper describes a computational fluid dynamic (CFD) model capable to simulate turbulent slurry of oil, water and gas hydrates. The population balance technique (PBM) coupled with CFD enables to predict such details of the process as the formation of hydrate phase, agglomeration of formed solids and granular interactions within the hydrate phase. The simulation results, validated with experimental data in terms of the slurry rheology, highlight flow patterns for a pipe system typical in oil industry. The model is in addition compared to the hydrate kinetics model from Colorado School of Mines (CSMHyK).

1. Introduction

Gas hydrates are formed upon the pressure-driven formation of crystalline water around cages occupied by “guest” gas molecules, for example methane, at temperatures below 10 °C. In nature such conditions are found at the bottom of deep water reservoirs (Sloan and Koh, 2008) and in permafrost (Makogon, 1997). Formation of artificial gas hydrates in pipelines often accompanies petroleum production. Having formed in petroleum lines, hydrates are transported by the flow as solid particles dissipating energy during collisions with the pipe wall and each other, which significantly increases pumping costs and may also form plugs. Therefore their presence is considered to be disadvantageous.

Considering the rheology of a hydrate-particle-laden multiphase flow, it is possible to determine the apparent viscosity of the formed suspension, which is higher than the viscosity in case no hydrates were present. If the local flow conditions favour it, gas hydrates may deposit on the pipe walls forming solid obstructions and even plugging the pipes (Sloan and Koh, 2008; Balakin, 2010). This occurs mainly due to gravity or centrifugal forces in elbows, but deposition is also promoted by agglomeration of hydrate crystals in cases where they are cohesive (Dieker et al., 2008). This problem is increasing as production lines become longer and exploration moves to colder environments, indicating the need for a reliable predictive tool, enabling accurate assessment of hydrate plugging risks. Modern tools of this kind involve computational fluid dynamics (CFD).

Early CFD-modelling of hydrates in pipes, from the 1980s, were based on the “moving mesh” principle, where the formation of a hydrate obstructions was modelled by morphing the boundaries of the computational domain to follow the surface of the obstruction.

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Nomenclature

B	breakage rate ($1/m^3$ s)
$\hat{B}$	breakage rate constant (s^{y-1}/m^3)
c_p	specific heat (J/kg K)
C_D	drag coefficient
d	diameter (μm)
D	rate of strain tensor with components $D^{l,m}$ (1/s)
f	fractal dimension
$f(r)$	particle size distribution function ($1/m^3$)
F_a	adhesive force (N)
F_{int}	solid pressure force per unit volume (N/m^3)
g	acceleration due to the gravity (m/s^2)
h	specific enthalpy (J/kg)
k	turbulent kinetic energy (m^2/s^2)
k_{CH_4}	growth rate constant (kg/m^2 s K)
M	interphase momentum transfer term (N/m^3)
M_i	$= \int_0^\infty r^i f(r)dr$ ith moment of particle size distribution (m^i/m^3)
$\dot{m}$	gas consumption rate (kg/m^3 s)
n	stoichiometric coefficient
N	rate of hydrate shell formation ($1/m^3$ s)
O	inter-phase energy transfer term (W/m^3)
p	pressure (Pa)
Pr	Prandtl number
q	heat transfer coefficient (W/m^2 K)
Q	energy source term (W/m^3)
r	particle radius (r)
Re	Reynolds number
t	time (s)
T	temperature (K)
Δt	time step (s)
u	local phase velocity (m/s)
$\bar{u}$	mean flow velocity (m/s)
W	molar mass (kg/mol)
We	Weber number
x^l	Cartesian coordinates (m)
y	breakage rate parameter
C_μ, C_1, C_2, σ_k, σ_ϵ	turbulence model coefficients

Greek letters

α	collision efficiency
γ	shear rate (1/s)
δ	Kronecker delta
ϵ	turbulent energy dissipation rate (m^2/s^3)
ϕ	volume fraction
κ	von Karman constant
λ	thermal conductivity (W/m K)
μ	dynamic viscosity (Pa s)
μ_a	apparent viscosity (Pa s)
ρ	density (kg/m^3)
σ	surface tension (N/m)
σ_t	turbulent Prandtl number
$\underline{\underline{\tau}}$	stress tensor with components $\tau^{l,m}$ (Pa)
ξ	latent heat (J/kg)

Subscripts, superscripts

0	primary particle
a	agglomerate
CH_4	methane
e	effective
eq	equilibrium
hyd	hydrate
H_2O	water
i, j	phase index
k	component of water–hydrate phase
l, m	coordinate index
max	maximum
o	oil
p	particle
r	relative
T	transposed
t	turbulent
$w–h$	water–hydrate

Bondarev et al. (1982) modelled crystallization of hydrates from the flow of wet natural gas to the cold walls of an industrial line considering the one-dimensional Stefan problem of the process. The simulations showed peculiar periodic variations of the thickness of the hydrate layer formed, which were explained by the competing influence of the Joule–Thomson effect in the gas phase and diminishing heat transfer in the hydrate phase. The authors indirectly confirmed the simulation results by observations of industrial systems similar to the one they had simulated. The model was not, however, able to predict such details of the flow as the radial profiles of the gas velocity, temperature and turbulence intensity. Sean et al. (2007) report a three-dimensional numerical model of the dissociation of a gas hydrate obstruction under the influence of a laminar flow around it. The reduction of the obstruction size was accounted for by moving the boundaries of the computational mesh. Although this model was validated against experiments, the overall process geometry and the problem complexity was rather far removed from industrial conditions. It should be noted, in general, that the Stefan problem for the growing hydrate boundary describes a mechanism, which is not entirely consistent with the plug formation scenario relevant for the petroleum industry. In the petroleum industry gas hydrate shells are formed at the surface of droplets dispersed in the oil phase (Zerpa, 2013). Techniques based on the Stefan problem are, however, relevant for studies of hydrate plug dissolution.

A set of one-dimensional CFD-models for gas hydrate flow assurance was developed in Colorado School of Mines (CSM) (Zerpa et al., 2012; Zerpa, 2013). The models were able to predict the kinetics of hydrate phase formation based on “pressure–volume–temperature” (PVT) data and flow patterns computed by the dynamic multiphase flow simulator OLGA (Kinnari et al., 2008). The technique was incorporated into OLGA as an additional routine named “The Colorado School of Mines Hydrate Kinetics” (CSMHyK) model, which is presently considered as one of the most realistic and complete dynamic hydrate prediction tools, validated with experimental data on the industrial scale. CSMHyK accounted for many details of the process-related phenomena, adopting a rheological approach to describe hydrate slurries reported by Sinquin et al. (2004), which was further updated in CSM by a set of in-house empirical relations for the adhesive force between hydrate particles and the hydrate primary particle size. These expressions were utilized for computation of the average size of hydrate agglomerates and subsequently the apparent viscosity of the slurry, which was finally returned to OLGA. Thus the entire model couples the particulate and continuous phases making it possible to predict the sudden viscosity increase due to hydrate