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Pressure drop in hydrate slurries: Rheology, granulometry and high water cut

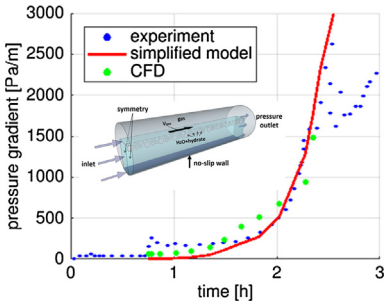
Boris V. Balakin [a,b,*], Anna Kosinska [a], Kirill V. Kutsenko [b]

[a] Western Norway University of Applied Sciences, Bergen, Norway
[b] NRNU Moscow Engineering Physics Institute, Russian Federation

HIGHLIGHTS

- Turbulent flow of water-hydrate slurry is considered.
- Rheological model is formulated.
- CFD model of the process is developed.
- Average size of hydrate particles is estimated.
- Both models are validated against experiments.

GRAPHICAL ABSTRACT



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ABSTRACT

Formation of gas hydrates in systems with high water content is one of the major challenges facing the petroleum industry today. Conventional mitigation using thermodynamic inhibitors is expensive due to large water volumes, while the most recent flow management strategies (anti-agglomerants, cold flow, etc.) have not yet been adopted because the dynamics of hydrate slurry are insufficiently understood. The present contribution examines a flow of gas, hydrates and water using computational fluid dynamics (CFD). The model couples the effective viscosity of gas-water slurry with the average size of hydrate agglomerates and the adhesive force that binds them. The model was validated against experimental pressure drop, demonstrating tolerable discrepancies. According to the simulations, onset of hydrate plugging is most probably related to the formation of a viscous bed at the gas-slurry interphase at hydrate concentrations slightly above 15%. A simplified theoretical approach is proposed for engineering estimates of pressure drop in the hydrate slurry pipes.

1. Introduction

Pipeline plugging by gas hydrates (Sloan, 2003) constitutes an important problem in petroleum flow assurance as the majority of production lines provide perfect thermodynamic conditions for hydrate formation: the presence of water and gas from the reservoir under high pressure and low temperature. Once formed in a pipeline, the adhesive hydrate particles agglomerate and form a solid obstruction that blocks the cross-section. A particular challenge in subsea and Arctic production, hydrate formation is extensively mitigated by means of thermodynamic inhibition (Istomin and Kvon, 2004), resulting in significant costs (above $ 700,000 per day) (Joshi et al., 2013). Low-dosage kinetic inhibitors are not entirely suitable under subcooling below 8 °C (Sloan and Koh, 2000), but anti-agglomerants (AA) are an interesting alternative to monoethylene glycol or methanol. When AA are used, hydrates are formed in the pipe but the inter-particle adhesive forces are moderated so plugging may never occur. Nevertheless, most of

* Corresponding author at: Western Norway University of Applied Sciences, Bergen, Norway.
E-mail address: Boris.Balakin@hvl.no (B.V. Balakin).

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Nomenclature

c	drag function (J/m^4)
C	calibration constant of the pressure drop model
C_D	drag coefficient
C_μ	turbulence model coefficient
d	particle diameter (m)
D	pipe diameter (m)
fr	fractal dimension
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)
I	turbulence intensity
k	turbulent kinetic energy (J/kg)
L	turbulent length scale (m)
M	interphase momentum transfer term (N/m^3)
p	pressure (Pa)
R	rate of strain tensor with components $R^{l,m}$ (1/s)
Re	Reynolds number
S	granular stress (Pa)
t	time (s)
T	temperature (K)
Δt	time step (s)
ΔT	subcooling (K)
u	velocity (m/s)
x^l	Cartesian coordinates (m)
X	parameter of the pressure drop model

Greek letters

α	coefficient of the pressure drop model
γ	shear rate (1/s)
δ	Kronecker delta
μ	dynamic viscosity (Pa s)
μ_∞	limiting viscosity (Pa s)
ρ	density (kg/m^3)
σ_c	tensile strength (Pa)
$\underline{\tau}$	stress tensor with components $\tau^{l,m}$ (Pa)
τ_y	yield stress (Pa)
ϕ	volume fraction
ψ	adhesive force calibration coefficient
ω	specific dissipation rate (s^{-1})

Subscripts, superscripts

I, II	1st and 2nd equilibrium conditions
0	primary particle
a	agglomerate
eq	equilibrium
g	gas
h	hydrate
i, j	phase index
in	inlet
l, m	coordinate index
max	maximum
min	minimum
mix	mixture
r	relative
s	settling
t	turbulent
w	water

the existing AAs condition water-in-oil emulsions i.e. flows with a relatively low water cut, while their efficiency reduces in systems with higher water content. There is a demand for a novel flow assurance technique that is capable of handling gas hydrates in a system with high water-cut production, with low cost and zero plugging risk. This is almost impossible to achieve without a proper understanding of the rheology of flows laden with hydrates, and a reasonable description of hydrate agglomeration process.

Even though plugging the mechanism in hydrate slurries with high water cut are presently little understood, classic experimental studies on the kinetics of hydrate formation are focused on aqueous flow systems. Skovborg (1993) and Herri et al. (1999) produced hydrates in a pressurized agitated vessel, studying the kinetics of their formation and the granulometry of the resultant hydrate slurry. These studies resulted in a set of semi-empirical population balance models (PBM) that related average size of hydrate particles and their volume fraction to the degree of flow agitation. Andersson and Gudmundsson (Andersson and Gudmundsson, 2016) conducted a study on gas-water system rheology in a straight pipe section. They derived an expression relating the effective slurry viscosity to the volume fraction of particles. However, this expression was found to perform less satisfactorily in a similar set of flow loop experiments conducted by Joshi et al. (2013). A number of rheological tests were run by Darbouret et al. (2005) for a laminar pipe flow of low-pressure refrigerant hydrate, and a similar experiment is documented in Balakin et al. (2010) for the turbulent flow of water and freon hydrates. Both studies found that slurries of low-pressure hydrates behave as Bingham fluids. The apparent viscosity was approximated rather well by a power-law rheological expression, similar, for example, to Roscoe and Brinkman. The yield stress was measured at higher hydrate concentrations (i.e. volume fractions). Most of the above-mentioned experimental studies did not entirely decode hydrate plug formation due to a technical inability to reproduce industrial thermodynamic conditions while simultaneously observing the flow.

Numerical simulations of slurry dynamics might, in theory, enable better insight into the process of plugging. Here, the most reliable and widely applied models come from the Colorado School of Mines (Zerpa, 2013). The models are incorporated into the dynamic multiphase flow simulator OLGA as an add-on named "The Colorado School of Mines Hydrate Kinetics" (CSMHyK). Using the flow parameters available from OLGA, CSMHyK estimates the size of agglomerated particles and, applying the concept of effective volume fraction (Zerpa et al., 2012), returns the apparent viscosity to the hydrodynamic model. The model is particularly suited for systems where the carrier phase is presented by water-in-oil emulsions, whereas its performance in flows with high water cut is questionable (Joshi et al., 2013). As has been shown recently, the rheological model incorporated in CSMHyK may deviate from experimental flow loop data with discrepancies above 100% (Qin et al., 2017); the particle-size prediction method also requires improvement (Balakin et al., 2016). The validity of the effective volume fraction concept needs to be better examined because, using this technique, the agglomerating suspensions start to overcome their packing limit at a relatively low agglomerate size (10–12 elementary/primary sizes), which is not entirely realistic. The influence of the fractal dimension on the effective volume fraction is also an open question. Finally, the effective viscosity of hydrate slurry depends on the spatial distribution of particles (Balakin et al., 2016), which is defined by their mobility in the radial direction: this is understandably difficult to reproduce with the one-dimensional simulation approach used in OLGA.