CFD-PBM model for gas hydrate particle size prediction in the turbulent pipeline flow

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Abstract. The combined CFD-PBM model is developed for gas hydrate particle size prediction in the turbulent pipeline flow. The model is based on one-moment population balance technique, which is coupled with the flow field parameters, computed with a commercial CFD software. The current approach is calibrated with five-moment off-line population balance model and validated with experimental data, produced in the low-pressure multiphase flow loop.

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INTRODUCTION

Natural gas hydrates are the product of chemical reaction between gas and water which usually takes place at high pressures and low temperatures. Their appearance in petroleum production and transportation is a great problem for the industry as hydrates, at certain conditions, may plug the pipeline with a solid obstruction. Sloan and Coh [1] in their book consider the scenario, when hydrates, formed in the petroleum line, form shells around the water droplets, suspended in the oil. These solid drops are cohesive and produce aggregates, which significantly increase an apparent viscosity of transported media. The problem of hydrate plugging can be predicted and analyzed on the project stage with the use of computational fluid dynamics (CFD) tools, combined with the model for hydrate population balance (PBM). In the current work we present a combined CFD-PBM model for freon R11 hydrate aggregation and breakage in the turbulent pipeline flow.

MODEL

The current work is based on experimental data, presented in Balakin et al. [4] for the multiphase flow loop with the hydrate of freon R11. The size distribution (PSD) of flocculated hydrate particles was determined in this work by sampling from the water-hydrate slurry for different volume fractions of particles in the system. The samples were taken isokinetically in the turbulent regime, when the slurry was homogeneously mixed over the pipeline cross-section. The mesh of CFD-model, used in current work, mimics the part of flow loop geometry (here we focus on the part of the model, which is shown in Figure 1) and consists of about 67 000 polyhedral control volumes. The set of boundary conditions includes the built-in STAR-CD options for inlet, outlet and no-slip wall. The present research is focused on the homogeneous flow regime so the water-hydrate slurry is considered as a uniform one-phase media which can be described by a set of standard Navier-Stokes equations together with the k-epsilon model for the turbulence simulation [2]. The viscosity of water-hydrate slurry was set to be dependent on the amount of solid in the system according to experimental data [4].
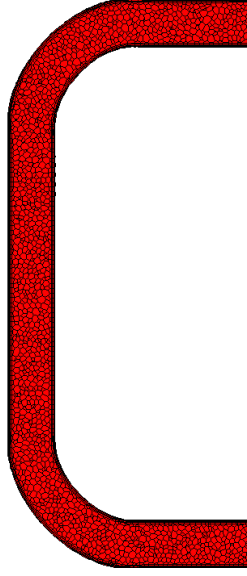
FIGURE 1. Computational mesh. Mid-line cross-section

RESULTS AND DISCUSSION

The kinetics of hydrate particle size are formulated in terms of the moment of their PSD:

$$M_i = \int_0^\infty r^i f(r,x,y,z,t)dr, \tag{1}$$

where $f(r,t)$, m^{-4} is the PSD-function, r, m is the particle radius. The PSD-moments represent per the unit volume of suspension: the number of particles, their size, area and the volume in the order of their numeration from 0 to 3. In the current work we assume that, on the fine mesh, the particles may be considered to be monosized within the control volume, having the diameter:

$$D_{30} = 2 \left(\frac{M_3}{M_0} \right)^{\frac{1}{3}} \tag{2}$$

The third moment, namely, the volume fraction of particles, was kept constant both in our experiments [4] and the current model. The PBM-equation for zeroth moment was given by [3]:

$$\frac{\partial M_0}{\partial t} + \nabla(M_0 U) = B_A + B_B - D_A - D_B, \tag{3}$$

where U is the slurry velocity. The terms B_A and D_A represent the "birth" and "death" of the particles in the interval of sizes from r to $r+dr$ due to aggregation of smaller particles and the aggregation of particles from current interval, respectively. The terms B_B and D_B represent the "birth" of the particles in the current interval due to the breakage of larger particles and the "death" of the current particles due to breakage. According to the literature, these terms may be derived with the use of expressions for solid particles aggregation and collision rates:

$$B_A - D_A = -0.5KM_0{}^2, \tag{4}$$

where K, m^3/s is the collision rate, defined by:

$$K = \frac{4}{3}\gamma\alpha(2\bar{r})^3, \tag{5}$$

where γ, 1/s is the shear rate, α is the probability of successive collision from the aggregation point of view.

$$\gamma = \left(\frac{\varepsilon}{\nu} \right)^{\frac{1}{2}}, \tag{6}$$

where ε, m^2/s^3 is the rate of turbulent energy dissipation per unit mass and ν, m^2/s is the kinematic viscosity of water.

$$B_B - D_B = k_4\gamma^{2.89}M_3, \tag{7}$$

where k_4, s$^{1.89}$/m^3 is the breakage rate constant [3].

The collision efficiency α may be related to the ratio between flow shear force and the attractive force (i.e. capilarly interaction, van der Waals, etc.) [3]:

$$\alpha = k_3 \left(\frac{1}{36\pi\mu\gamma\bar{r}^3} \right)^{0.18}, \tag{8}$$

where k_3, J$^{0.18}$ is the aggregation constant and μ, Pas is the dynamic viscosity of water. The aggregation k_3 and breakage k_4 constants are empirically-based numbers, which are obtained by fitting the PBM-model data to the results of flow sampling in a way, discussed further below. Navier-Stokes equations together with two equations of "k-epsilon" model, Equation 3 are solved with SIMPLE technique by STAR-CD solver.

RESULTS AND DISCUSSION

Direct validation of the proposed PBM-approach was problematic as the experimental data produced did not contain an information on the spatial distribution of particle sizes. However, the off-line compartmental model [3], was used to validate the spatially averaged particle sizes. This model was built on an assumption that the flow loop consists of two compartments (pipeline, where the aggregation is more probable and the pump, where the breakage is dominating) with spatially averaged shear rates and finite residence times. The PBM-model presented in Equation 3 is then sufficiently simplified by neglecting the transport term on the right-hand-side, what forced us to formulate separate equations for the kinetics of 5 PSD moments. As it was mentioned before, the off-line model was validated with the experimental sampling results [4], finding the aggregation constant k_3=1$\times$10^{-7} J$^{0.18}$ and the breakage constant k_4=150 s$^{1.89}$/m^3. The details of validation may be found in [5].

The CFD-PBM model, reported in the present work, was then calibrated with the results of the validated off-line compartmental model. For that purpose a simple one-cell compartment with a constant shear rate was generated in STAR-CD. Figure 2 presents the results of the model calibration for 14% of hydrate in the system and the shear rate of 2158 1/s, intial particle size 48μm. It follows from the Figure that the current model fitts the results of validated one with small underprediction which is explained by the prediction of less PSD-moments, than in off-line. The results
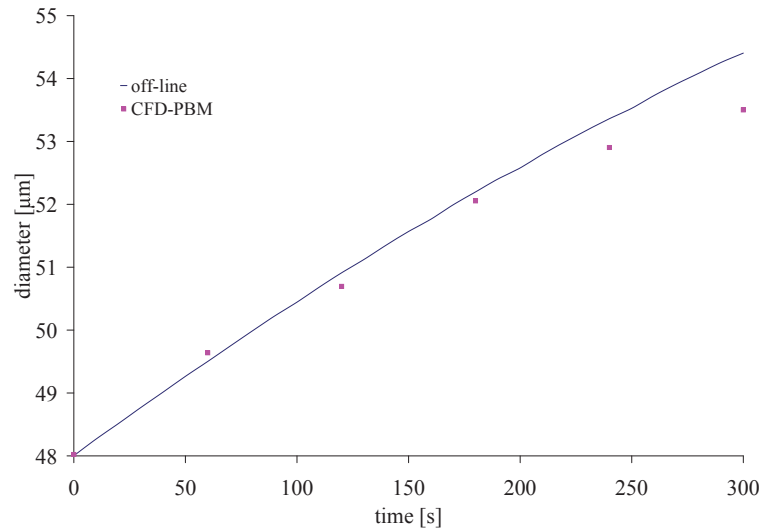

FIGURE 2. Mean particle size as a function of time. Hydrate volume fraction 14%. One-cell CFD model results are compared with off-line PBM-model [3]. Shear rate in the system 2158 1/s

of simulation done with CFD-PBM model are presented in Figure 3 by contours of D_{30} in the midline cross-section of the loop. The system, presented in Figure 3A is aggregation-dominated and the particles increase their size in flow direction as the mean flow velocity is relatively small and the inlet hydrate particle size is low so their collisions are

most effective. The most intensive aggregation goes in the vicinity of the wall as the shear rate there is at maximum and the breakage is weaker than to aggregation.

The opposite process is presented in Figure 3B where the mean flow velocity is 4 m/s and the inlet particle size is relatively large. It is seen from the Figure that the system is breakage-dominated with the decrease of particle size in flow direction. The radial distribution of particle sizes is also different due to the fact that the breakage dominates under the aggregation in the near-wall region.
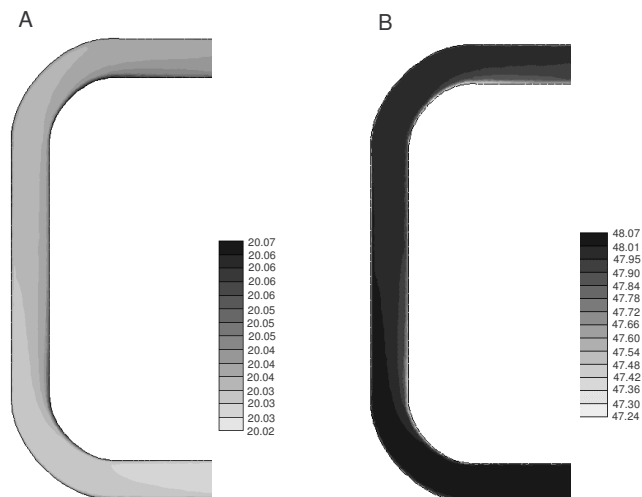

FIGURE 3. Contours of mean particle size in the midline cross-section of flow loop. A: mean flow velocity 1 m/s, inlet particle size 20.02 μm (aggregation-dominated system). B: mean flow velocity 4 m/s, inlet particle size 48.07 μm (breakage-dominated system). Hydrate volume fraction 14%. All the dimensions are in μm

CONCLUSIONS

The combined CFD-PBM model for gas hydrate aggregation in the turbulent flow loop was developed in STAR-CD. The model involves one-moment approach for the hydrate PSD evolution. The results of population balance simulation are calibrated with the off-line two-compartmental PBM-code which was validated with the results of sampling done in experiments. The model is able to predict the spatial distributions of gas hydrate particle size in the pipeline.

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