SPE Brazil Flow Assurance Technology Congress
Rio de Janeiro, Brazil, November 06 – 08 2024

Implementation and assessment of a gas hydrates wall deposition model for gas-dominant pipeflow systems

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Abstract

The present study aimed at investigating a 1-D gas hydrates wall deposition model for gas dominated flow in production lines and its potential to integrate the hydrates plug-in of the commercial simulation software ALFAsim. To do so, a Python-coded prototype implementing it allowed to assess the model's qualitative and quantitative consistencies from predicted fields reproducing flowloop experiments with a gas-dominated system in the annular flow pattern. Two flowloop's outcomes were taken as reference scenarios to validate the implementation and differ from each other mainly due to the presence of a thermodynamic inhibitor, MEG. Numerically computed time evolutions of distributed and integrated quantities across the flowloop exhibited qualitatevely coherent behaviors, and the model's quantitative validation derived from comparisons with empirical head loss buildup profiles and average volumetric hydrate formation rates. The wall deposition model's main outcome predicted spatial distributions of hydraulic diameter for increasing simulated times and congruently reflected the hydrates deposited layer thickening process. In agreement with the theoretical expectation, it corroborated the models's sensitivity to the inhibition effect, retrieving homogeneous and non-uniform profiles along the pipeline length for the cases with and without the inhibitor, respectively, although both simulations featured decreasing length average of the hydraulic diameter.

Keywords

Gas Hydrates; Wall Deposition; Gas-dominated flow

Introduction

The succession of hydrate crystal deposition on pipeline walls depends on mechanisms that directly or indirectly promote the availability of water and hydrate former in such a region, and/or the sedimentation of particles carried within the multiphase flow bulk (which is a function of the established flow pattern) [1].

Regarding the type of multiphase system relative to the predominance of one of the gas, liquid, or oil phases, it is expected that more significant impacts of deposition will occur for gas-dominated scenarios; particularly, concerning the promotion of partial or total line blockages, because of the related processes of jamming, sloughing, and plugging [1,2].

The literature presents still limited modelling alternatives of thew deposition process, reflecting the demand for deeper understanding of its phenomenological and mechanistic aspects [3]. This task reaches even higher complexity levels considering the cross-influence with nucleation, growth, agglomeration, and hydrates agglomerates transportability in oil and gas flowlines [2,3].

The present work's aim is twofold: generating a prototype that implements the Di Lorenzo *et al.*'s [2] gas hydrates wall deposition model; and validating it against data extracted from operations of a gas-dominated flowloop in two scenarios mainly distinguished by the presence of a thermodynamic hydrates inhibitor (THI). The conducted analysis is expected to provide guidance in the incorporation of a wall deposition module in the hydrates' plugin of the commercial simulator ALFAsim.

Mathematical Modelling

To reproduce experimental registers provided by Di Lorenzo *et al.* [2], it has been embedded in the prototype the conceived mechanistic modelling framework, which is based on employing simplified integral conservation equations coupling the spatial and temporal multiphase system's evolution with hydrates formation and wall deposition. Specifically, force and energy balances are applied considering a pseudo-steady-state regime. This means that, for each simulated instant, it holds the assumption that the system attains hydrodynamic and thermal equilibria accordingly to the progression experienced by quantities associated with hydrate formation and deposition along the line.

Force balance

The prediction of pressure gradient derives from a force balance using the classical correlation of Beggs & Brill, and it follows in Eq. (1).

$$\frac{\Delta P}{\Delta x} = -\frac{1}{2} f_{tp} \rho_{ns} \frac{v_m^2}{D_h} \tag{1}$$

where f_{tp} stands for the two-phase friction factor, ρ_{ns}, the non-slip density (computed from the global volumetric fractions of gas and liquid phases),v_m, the mixture velocity, D_h, the hydraulic diameter of the pipe, and P, the system's local pressure.

Energy balance

The integral energy balance (Eq. (2)) returns the temperature gradient along the pipeline, comprehending three contributions affecting the energy transport by the multiphase flow. The corresponding terms relate to: (1) the Joule-Thomson effect, causing cooling of the gas core in response to the experienced pressure drop; (2) heat transfer through the pipe wall with the refrigerant fluid present in the surrounding jacket; and (3) heat release due to hydrate formation, an exothermic process.

$$\frac{\Delta T}{\Delta x} = \beta_{JT} \frac{\Delta P}{\Delta x} - \frac{\pi D_h U (T - T_C)}{\rho_m c_m Q_m} + \frac{1}{\Delta x} \frac{\Delta V_h}{\Delta t} \frac{\Delta H}{c_m Q_m} \tag{2}$$

where β_{JT}, represents the Joule-Thompson coefficient, U, the overall heat transfer coefficient, ρ_m, the mixture density, c_m, the mixture specific heat, Q_m, the mixture's flow rate, ΔH, the enthalpy of hydrate formation, $\frac{\Delta V_h}{\Delta t}$, the volumetric rate of hydrate formation, T, the system temperature, and T_C, the refrigerant fluid temperature.

Hydrates formation and deposition

For modeling hydrate formation, the classical model by [4] was utilized, which is based on the limitation by crystal growth kinetics and has an Arrhenius-type formulation.

The deposition model proposed by [2] primarily yields the volumetric rate of hydrate accumulation on the pipeline wall, as depicted In Eq. (3). It is derived under simplifying assumptions, assuming a uniformly distributed thickness of the deposited layer around the pipe perimeter in each cross-sectional area and considering two contributions to the deposition rate. The deposited layer increment results from the crystallization of the liquid film adjacent to the wall and the migration and adhesion of hydrate particles resulting from the conversion of entrained droplets in the gas bulk. These are associated with the terms represented by $\Delta V_{film} / \Delta t$ and $\Delta V_{part} / \Delta t$, respectively, composing the total deposition rate as indicated in the study.

$$\begin{gathered} \frac{\Delta V_{dep}}{\Delta t} = \frac{\Delta V_{film}}{\Delta t} + \frac{\Delta V_{part}}{\Delta t} \\ \frac{\Delta V_{film}}{\Delta t} = \frac{\Delta V_h}{\Delta t} \left(A_{film}\right); \; \frac{\Delta V_{drop}}{\Delta t} = \frac{\Delta V_h}{\Delta t} \left(A_{drop}\right) \end{gathered} \tag{3}$$

where the parcels retrieving the total volumetric deposition rate refer to the local and instantaneous evaluation of the formation rate model considering the respective interfacial area for the crystallization to undergo: A_{film} and A_{drop}. Their calculation can be done as indicated by Eq. (4):

$$\begin{gathered} A_{drop} = \frac{3\pi}{2} \frac{E}{S} \frac{Q_l}{Q_g} \frac{D_h^2 \Delta x}{d_{32}} \\ A_{film} = \pi D_h \Delta x \sqrt{1 - H + \frac{E Q_l}{S Q_g}} \end{gathered} \tag{4}$$

with Q_l and Q_g denoting the liquid and gas phases flow rates, H_l, the liquid holdup, E, the entrainment fraction, S, the slip factor between phases, and d_{32}, the Sauter mean diameter of dispersed droplets. One can find specific correlations for these quantities in the works of [2,4].

For the case of particles dispersed in the gas depositing, it is defined that only a fraction of the converted droplets into hydrates will contribute to integrating the deposition layer at each temporal and spatial evaluation of the simulation routine. Consequently, an empirical parameter, symbolized by F_d, is introduced, representing the efficiency of hydrate particle deposition. Equation (5) expresses such rates proportionality:

$$\frac{\Delta V_{part}}{\Delta t} = \frac{F_d}{S} \frac{\Delta V_{drop}}{\Delta t} \tag{5}$$

It follows the expression for the total deposition rate $\Delta V_{dep} / \Delta t$:

$$\frac{\Delta V_{dep}}{\Delta t} = -\frac{\pi}{2} D_h \frac{\Delta D_h}{\Delta t} \Delta x \tag{6}$$

Methodology

To verify the potential of the proposed approach for the 1-D modeling of hydrate deposition on pipeline walls, it followed the implementation of the underlying equations within the framework of a simplified prototype in Python.

To support and validate the considered formulation, detailed empirical investigations have been conducted by means of a single pass flowloop operated with a gas-dominated system [5]. The experiments were carried out with low liquid holdups (less than 10%), ensuring the establishment of an annular flow pattern, taking as hydrates former natural gas. Further specifications can be retrieved from the regarded studies [2,5].

Among the operation scenarios outlined in [2], two representative cases of the investigated system were considered. Specifically, the chosen operations for reproduction fundamentally differ from each other concerning the presence of a thermodynamic inhibitor, given by MEG. Table 1 summarizes the specifications regarding the simulated scenarios.

Table 1. Reproduction cases specification.

Parameter	Case 1 – No THI	Case 2 – THI
Tin (°C)	15.5	7.5
Pin (bar)	103.5	111.5
Cmeg (wt%)	0.0	20.0
Tcool (ºC)	12.0	2.0
J gas (m/s)	8.8	8.8
J liq (m/s)	0.18	0.18
Duration (min)	48	37

The implemented prototype outputs profiles of various relevant quantities for analysis, encompassing both spatially distributed and concentrated ones.

Results and Discussion

The initial comparison between the prototype execution outputs and the corresponding reference data involves overlaying curves depicting the evolution of pressure drop across the entire flow loop over the duration of the experiment. Figure 1 agglutinates registers pertaining to experimental measurements and predictions from the numerical modeling reported by [2], along with the prototype implementation.

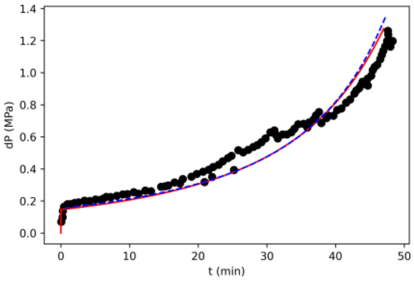

Figure 1. Comparison between experimental values (dots) and simulated pressure drop curves across the flowloop reported by [2] (blue line) and obtained with the prototype for the case 1 (red dashed line).

The extent of quantitative agreement between numerical and experimental points stands out in the graphical comparison. However, capturing the underlying qualitative trend indicates the consistency of the formulation, once it is expected that quantitative accuracy strongly depends on the parameterization resulting from the adjustment pointed out by the authors. The pattern of pressure drop buildup is observed as hydrates formed in the liquid film and entrained droplets lead to thickening of the deposition layer on the pipe walls. This is a consequence of gradually increasing constriction imposed on the flow of the mixture.

Figure 2 presents temporal evolution curves of the volumes of hydrates formed and deposited along the entire length of the flowloop. Qualitatively, there appears to be agreement with the previously discussed pressure drop prediction, as the records show a monotonically increasing variation, indicating progressive accumulation of hydrates in the line, contributing to increased constriction in the flow. Quantitatively, the numerically predicted average volumetric hydrate formation rates approximate the experimentally calculated values. Specifically, relative errors of about 39% are obtained for the result published [2] and 18% for the current prototype, as shown in Table 2.

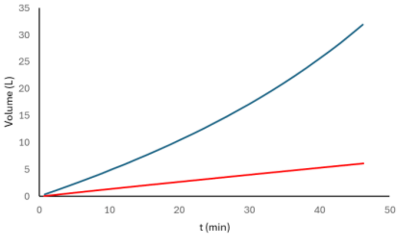

Figure 2. Temporal variation of the volumes of hydrates formed (blue) and deposited (red) along the entire length of the flow loop for the case 1.

Table 2. Average hydrate formation rates simulated and experimentally obtained.

$\Delta V_h \,/\, \Delta t$ – [L/min] Exp	$\Delta V_h \,/\, \Delta t$ – [L/min] [2]	$\Delta V_h \,/\, \Delta t$ – [L/min] Prototype
0.56	0.73	0.66

The prototype execution retrieves as its main outcome the space and time evolutions of the cross-sectional average hydraulic, reflecting the changes in thickness experienced by the deposition layer. Figure 3 shows profiles of this quantity for several recorded time instants.

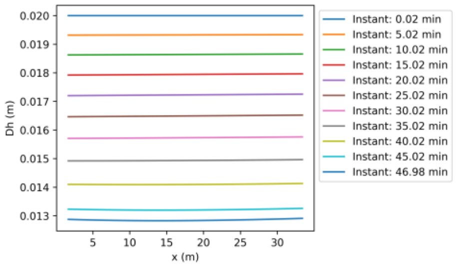

Figure 3. Profiles of hydraulic diameter along the simulated flow loop for different time instances for the case 1.

As explicitly shown in Figure 3 and aligning with theoretical expectations, the average hydraulic diameter across the entire flow loop decreases, reflecting an amplification of the constriction to which the flow is subjected. A highly limited spread of the profiles is observed in each outlined instants, indicating diameters undergoing minimal spatial variation at each time step, despite their length average decreasing significantly and consistently.

Similarly, a graphical comparison followed in Figure 4 between the predicted pressure drop curve and the corresponding measurements for the case 2. Qualitatively congruent trends resulted, with significant accuracy for the adopted parameterization. The achieved pressure drop was approximately 1 MPa, lower than previously obtained, reflecting the impact of thermodynamic inhibition in the predicted deposition extent.

The most prominent discrepancies in the accounting of the THI effect concern to predictions of hydraulic diameter, whose profiles at selected instances are shown in Figure 5. The same trend observed previously of a decrease in the average value along the length over simulated time in response to the thickening of the hydrate deposition layer is evident. However, in the scenario with the inhibitor, there is a noticeable modification in the dispersion of local values, with progressively more pronounced gradients in the direction of increase with distance for later simulated times.

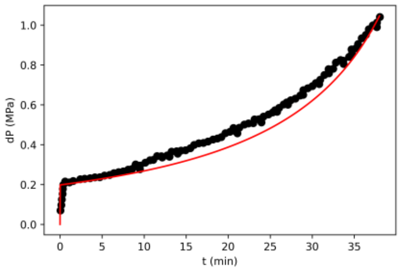

Figure 4. Comparison between experimental values and predicted pressure drop curve.

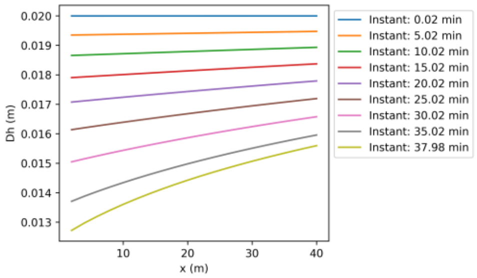

Figure 5. Profiles of hydraulic diameter along the simulated flow loop for different time instants for the case 2.

One may consider the aforementioned behavior as a consequence of a non-uniform thermodynamic inhibition effect along the length of the pipeline due to water consumption with hydrate formation. This results in a gradual enrichment of MEG towards downstream positions as time advances, as visualized in Figure 6. Accordingly, hydrate formation rates, and thus deposition rates, tend to undergo increasing attenuation along the length. This, together with the thermohydraulic conditions, availability of free water, and droplet granulometry, justifies the observed levels of spreading in the analyzed profiles for the recorded instances.

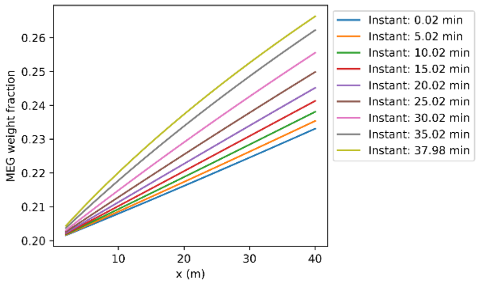

Figure 6. Profiles of MEG weight fraction for different time instants.

Conclusions

In order to verify the formulation for 1-D modeling of hydrate deposition on pipeline walls, proposed by Di Lorenzo *et al.* [2], a simplified prototype was implemented in Python with the considered mechanistic proposition. The resulting prototype enabled qualitative and quantitative evaluations regarding distributions of quantities of interest, as well as reproductions based on comparisons with experimental data of hydrate production and pressure drop buildup predicted in the simulated tests. The assessment took two representative cases of the investigated system, which consisted of a flowloop operating under gas-dominated conditions and in annular flow pattern. Specifically, these scenarios fundamentally differ from each other by the presence of a thermodynamic inhibitor, MEG. The analyses revealed a significant sensitivity of the implemented model to the THI effect, leading to non-uniform distributions of hydraulic diameter along the length of the line in response to non-uniform concentrations with water consumption over the simulated time. The regarded wall deposition model was validated, therefore demonstrating its suitability to integrate the ALFAsim's hydrates plugin and to be tested in field cases.

Acknowledgments

The authors would like to thank Petrogal Brasil S.A. (Joint Venture Galp | Sinopec), for the permission to publish this work, ESSS for making its 1D multiphase flow simulator (ALFAsim®) available, and the Brazilian National Petroleum Agency (ANP) for the financial support (“Compromisso de Investimentos com Pesquisa e Desenvolvimento”)

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