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An optimization approach to reduce the risk of hydrate plugging during gas-dominated restart operations

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ABSTRACT

In this paper, common meta-heuristic optimization techniques are applied for the potential application of reducing the risk of hydrate plugging in gas-dominated flowlines during restart operations. Based upon a hydrodynamic approach first shown in the experimental study of Leporcher et al. (2002), a transient, gas-dominated restart operation is emulated using Computational Fluid Dynamics (CFD) for a pipe section featuring a single low-spot filled with variable heights of free water. A two-phase CFD model has been constructed and validated using OpenFOAM® to simulate the flow. A modification has been made to the solver in order to capture the interfacial area between the gas and water phases at each time step, allowing an estimation of the amount of hydrate growth to be made during the transient and steady state phases of the restart operation. A genetic algorithm has then been used on different types of surrogate models with the goal of minimizing the restart gas velocity such that a defined plugging risk is minimized. Finally, an approach to apply this methodology to actual flowlines is discussed.

1. Introduction

A natural gas hydrate is an ice-like structure that forms when a small hydrocarbon molecule becomes trapped in a larger water cage to form a solid structure. This can happen when contact occurs between the hydrocarbon molecule and free water at high pressures and low temperatures. The formation of hydrates and the subsequent plugging of subsea oil and gas flowlines remains one of the most prevalent flow assurance problems today; where authors such as Sloan et al. (2009) have stated that hydrate plugging constitutes the largest concern by an order of magnitude when compared to asphaltenes, scales and waxes.

From a flow assurance perspective, one of the most critical tasks for a deepwater field operator is to ensure adequate hydrate management during restart operations, particularly after an extended shut-down period when the fluids contained in the flowline have cooled to the ambient temperature at the seabed. During such a restart operation, the cooled fluid is subject to high pressures from the well stream, enabling conditions that are ideal for hydrate nucleation if any free water is present. Depending on the topography of the seabed, the flowline will comprise of multiple bends and low-spots that will contain any free water that has accumulated during shut-down. Hydrates form when the impinging restart gas flow comes into contact with the water and will agglomerate with a high risk of plugging the flowline (Sloan and Koh, 2007).

The conventional strategy to manage hydrates during restart operations is aimed at preventing the formation of hydrates entirely using a combination of chemical inhibition and thermal control. Currently, a paradigm shift is underway that is challenging the notion that complete avoidance of hydrate formation is a necessary step in order to provide adequate flow assurance (Sloan, 2005). Authors such as Turner et al. (2015), Lachance and Keinath (2015), Zerpa et al. (2012), Volk et al. (2007) and Leporcher et al. (2002) have provided the basis to explore alternative solutions that reduce the risk of hydrate plugging in flowlines, without the explicit requirement that hydrates need to be avoided entirely.

In particular, Leporcher et al. (2002) performed two separate restart operations using natural gas and a gas/oil mixture in a 0.0508 m diameter pressurized flow loop, featuring a single low-spot section filled with variable heights of free water to represent an accumulated water phase. Leporcher et al. (2002) observed that high energy restart flows (1 m/s) would evacuate most of the initial accumulated water phase held in the low-spot of the pipe and although hydrate nucleation rapidly took place, no plugging of the pipe occurred. Conversely, the experimental data demonstrated that low energy restart flows (0.001 m/s) actually promote

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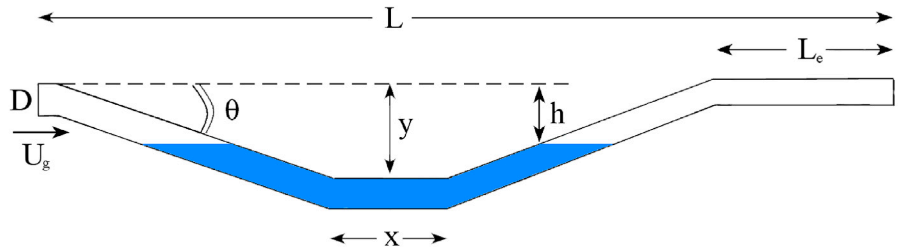

Fig. 1. The pipe geometry used in the optimization study, featuring a single low-spot filled with variable heights of free water (adapted from Leporcher et al. (2002)).

the formation of hydrate plugs, where the most critical case for hydrate plugging to occur was identified by Leporcher et al. (2002) as being when the incoming restart gas passed at low velocity across the bulk of the static water accumulation near the top of the pipe, causing hydrate material to initially deposit on the upper pipe wall with a typical plugging time of approximately 4 h for both of the fluid combinations considered.

The main conclusion provided by Leporcher et al. (2002) was that high energy restart gas flows that quickly wipe off the initial liquid water columns in the low-spot region lead to a reduced risk of hydrate plugging. In a similar experimental flow loop study, Volk et al. (2007) suggested that an actual optimal gas restart velocity may exist that would be high enough to avoid hydrate plugging yet limited to avoid well sanding. Volk et al. (2007) could not determine an optimal restart rate from the available data captured; however, the results from both Leporcher et al. (2002) and Volk et al. (2007) suggest that a time-based hydrate growth model could potentially be used to characterize a meaningful plugging risk during both the transient and steady state phases of a restart operation.

Hydrate growth models are used to estimate the rate at which gas is consumed to become hydrate material, using either kinetic, mass transfer limited or heat transfer limited models. The heat transfer limited models are restricted to estimating the lateral film front growth and are not used in this study, as it can be reasonably expected that the ambient temperature for a subsea flowline will remain essentially constant throughout the length of the flowline until the riser base, such that the heat transfer mechanism will only play a minor role in the overall amount of hydrate growth. For both the kinetic and mass transfer limited hydrate growth models, the hydrate growth rate is a function of the interfacial area between the hydrate forming components and the free water phase, coupled with the degree of subcooling between the hydrate equilibrium temperature at the system pressure and the system temperature.

An example for the comparison of the kinetic hydrate model by Turner et al. (2005) and the mass transfer limited hydrate model by Skovborg and Rasmussen (1994) to experimental data for gas-dominated annular flow can be found in the works of Di Lorenzo et al. (2014) and Aman et al. (2016). Incidentally, both of these studies have used a constant interfacial area, calculated for annular flow based upon a combination of semi-empirical correlations from authors such as Pan and Hanratty (2002) and Beggs and Brill (1973). It is apparent; however, that a constant area approach is not applicable for any kind of transient operation. Instead, the use of Computational Fluid Dynamics (CFD) to model the transient response of the system could potentially be an ideal solution as it can provide an estimation of the time dependent interfacial area, which can be used as the basis for optimization studies involving transient operations.

In this paper, a two-phase CFD-based optimization study of gas and water has been performed on a low-spot bend with the same geometry, fluid properties and conditions presented in the experimental study of Leporcher et al. (2002), with the primary objective to find the restart gas velocity required to minimize the risk of hydrate plugging during a simulated restart operation. The hydrate plugging risk has been defined by a combination of an estimation of the plugging time and the prevention of water accumulation in the upward leg of the low-spot section. Common meta-heuristic optimization techniques have been applied with the focus on adapting the methodology presented in this study to actual flowlines of greater length.

2. Problem description

2.1. Geometric and system parameters

The single low-spot flow loop geometry used in this study has been adapted from Leporcher et al. (2002) and is shown in Fig. 1.

The dimensions D, L, L_e, x, y and θ have fixed values taken directly from Leporcher et al. (2002) and are summarized in Table 1. The dimension h indicates the height of the accumulated water phase in the low-spot section, represented by the shaded area in Fig. 1 and is a variable in this study, along with the inlet gas velocity, U_g. For the purposes of a direct comparison with Leporcher et al. (2002), the dimension h is converted to represent the volume of liquid in the low spot section of the pipe, V, whereby h_{min} corresponds to $V_{\max}$ with a value of 36 L and $h_{\max}$ corresponds to $V_{\min}$ with a value of 7 L.

Using the gas composition provided by Leporcher et al. (2002), the gas density has been derived using the AGA8 guidelines (Starling and Savidge, 1992) at the reported pressure of 70 barg and system temperature of 4 °C. The gas viscosity has been calculated using Sutherland's law. The pipe roughness has been derived from an assumption that the original experimental flow-loop used by Leporcher et al. (2002) consisted of commercially available standard steel sections commonly found in piping applications. The complete set of derived system parameters used in the computational analysis are shown in Table 2.

2.2. Implementation of the hydrate growth model

Following the work of Di Lorenzo et al. (2014) and Aman et al. (2016) for gas-dominated flow, the hydrate growth rate in this study based upon intrinsic kinetics has been estimated using the model developed by Turner et al. (2005). However, due to the variable restart gas velocities considered in this study, the effect of mass transfer will likely also have a prominent role in the amount of hydrate growth observed; as such, the model by Skovborg and Rasmussen (1994) has been used in conjunction with the kinetic model, whereby the total hydrate growth is a summation of the estimations generated from both models. This differs from both studies by Aman et al. (2016) and Di Lorenzo et al. (2014), where both the kinetic and mass transfer limited models were compared directly to experimental data as standalone models.

Instead, in this study the fitting parameter introduced to the kinetic model by Turner et al. (2005) to account for mass and heat transfer

Table 1
Geometric parameters.

Parameter	Description	Value
D	Diameter	0.0508 m
L	Total length	140 m
L_e	Exit length	100 m
x	Low-spot length	3 m
y	Low-spot depth	1.1 m
θ	Low-spot inclination	9°