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Hydrate formation and deposition in a gas-dominant flowloop: Initial studies of the effect of velocity and subcooling

Zachary M. Aman [a, *], Mauricio Di Lorenzo [a, b], Karen Kozielski [b], Carolyn A. Koh [c], Pramod Warrier [c], Michael L. Johns [a], Eric F. May [a]

[a] School of Mechanical and Chemical Engineering, University of Western Australia, 35 Stirling Hwy., Crawley, WA 6009, Australia
[b] CSIRO-Energy, 26 Dick Perry Avenue, Kensington, WA 6151, Australia
[c] Center for Hydrate Research, Colorado School of Mines, 1600 Illinois St., Golden, CO 80401, United States

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ABSTRACT

Gas hydrate formation is a critical flow assurance risk in oil and gas production, as remediation of blockages may require weeks of operating downtime and represent a significant safety hazard. While many studies over the past two decades have focused on quantifying hydrate blockage risk in crude oil systems, there is a dearth of information available with which to assess hydrate growth rate or blockage severity in natural gas systems, which typically operate between stratified and annular flow regimes. In this investigation, a single-pass gas-dominant flowloop was used to measure hydrate growth and particle deposition rates with variable liquid holdup (1–10 vol%) and subcooling (1–20 °C). A particular focus of this study was the impact of reducing the gas phase velocity to achieve lower liquid entrainment and, therefore, decrease hydrate formation rate. Reducing the gas velocity from 8.7 to 4.6 m/s at a constant subcooling around 6 °C reduced the total formation rate by a factor of six. At these conditions, the sensitivity of hydrate formation rate to velocity was about 40 times greater than the sensitivity to subcooling. This reduction in gas velocity also halved the estimated rate of hydrate deposition on the pipeline wall. Finally, new observations of hydrate wash-out are reported, whereby significant localized hydrate deposits were effectively removed by modulating the subcooling of the flowloop wall from 6 °C to 3.5 °C. The results provide new insight to inform the next generation of predictive hydrate growth and deposition models for gas-dominant flowlines.

1. Introduction

Gas hydrates are ice-like solids, where molecular cages of water surround light hydrocarbon species (e.g. methane) at high pressure and low temperature (Sloan and Koh, 2007). In gas pipelines operating at high pressure, hydrate can become thermodynamically stable with sufficient cooling, which may result in pipeline blockage under extreme conditions (Sloan, 2000). Managing the risk of hydrate blockage in gas pipelines is a leading flow assurance concern for new and existing subsea developments; particularly with increasing exploration in deep water, long residence times and cool seafloor temperatures together increase the rate of hydrate growth and, by extension, blockage risk. Thermodynamic hydrate inhibition, where anti-freeze chemicals are injected to disrupt the hydrogen-bonded cage network, is typically used to suppress hydrate stability, but the high cost of this technique may readily outweigh production revenue in deep-water environments (Creek et al., 2011). Increasingly, the flow assurance community is turning toward a risk management approach, which focuses on the prevention of hydrate blockage while allowing some hydrate to remain stable in the line; to succeed in this approach, engineers must first understand the mechanism by which hydrates block gas pipelines (Sloan and Koh, 2007).

For the past twenty years, the community has focused on understanding the mechanism by which hydrate blockages form in oil-dominant flowlines, which have been tested at both the laboratory (Webb et al., 2013) and pilot scale (Grasso et al., 2014). However, the mechanism of hydrate blockage formation in gas flowlines has received much less attention. Zerpa et al., (2012) proposed such a mechanism (Fig. 1), but significant research into the contributing phenomena is still required to validate it and enable quantitative predictions. In gas flowlines, fluids are typically

* Corresponding author.
E-mail address: zachary.aman@uwa.edu.au (Z.M. Aman).

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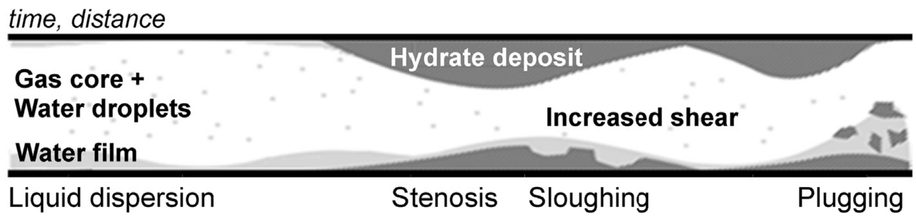

Fig. 1. Conceptual model for hydrate plug formation in gas-dominant systems, adapted from Zerpa et al. (2012).

transmitted in stratified-wavy or annular flow regimes, with liquid entrainment in the gas stream occurring at high gas velocities. During continuous operation under hydrate-forming conditions, crystal formation may occur on the pipe wall (wetting film) and in the flowing gas (entrained droplets). The growth of hydrate particles, and subsequent deposition on the pipe wall, result in the localized build-up of a solid hydrate deposit at the pipe wall ("stenosis"). This deposit imposes a large frictional pressure drop on flowing fluids, and may result in downstream Joule-Thompson cooling (Sloan, 2000) that further increases the hydrate growth rate. As the deposit thickness grows toward a critical limit, the increased shear stress applied by flowing fluids may result in the mechanical fracture ("sloughing") of hydrate from the wall, allowing hydrate aggregates to enter the flow field and accumulate downstream.

Dorstewitz and Mewes (1994) investigated the effect of heat transfer on hydrate formation using a 15 mm diameter flowloop, where hydrates were formed with a low-pressure refrigerant gas. The measured increase in frictional pressure drop was attributed to a decrease of the hydraulic diameter due to hydrate deposition, the thickness of which was modelled using a simple correlation for turbulent flow in pipelines. By applying an energy balance to the system, the authors concluded that hydrate growth in the flowline was limited by heat transfer to the pipeline wall. Rao et al. (2013) studied hydrate deposition on the outer surface of a cold steel tube under high pressure, using a Jerguson-type visual cell with continuous circulation of water-saturated methane. The thickness of the deposited hydrate layer was observed to increase over time until the outer surface of the hydrate film was limited by heat transfer through the hydrate deposit.

Di Lorenzo et al. (2014a, 2014b) reported the first pilot-scale data for hydrate blockage formation in a gas-dominant, single-pass flowloop, which demonstrated hydrate blockage rates similar to what has been reported for industrial cases (Sloan, 2000). Recently Sinquin et al. (2015) and Cassar et al. (2015) reported on hydrate blockage behavior in a 50 mm gas-dominant recirculating flowloop, and noted that a strong plugging tendency existed in the annular flow regime when compared to experiments with stratified flow. Di Lorenzo et al. observed that hydrate growth in annular flow was dominated by the kinetic conversion of entrained water droplets, with the hydrate growth rate in the annular water layer reduced by mass transfer limitations. The experiments performed to date with the single-pass flowloop consistently used a high gas velocity (8.7 m/s), which resulted in significant water entrainment (estimated at 18%). The aim of present work was to investigate the rate of hydrate growth and deposition at entrainment fractions below 10%, which are more representative of industrial systems, over a range of subcoolings similar to those investigated previously.

2. Experimental method

2.1. Gas-dominant flowloop

This study deployed the single-pass, gas-dominant Hytra flowloop, located in Perth, Western Australia, which has been described previously by Di Lorenzo et al. (2014a,b). A photograph of the test section and a simplified process flow diagram are shown in Fig. 2.

The test section was comprised of a grade 316 stainless steel 2.54 cm (1″) outer diameter pipeline, with two straight sections joined by a horseshoe-shaped bend; the total flowloop length was 40 m (131 ft). The loop also contained a "U-shaped" low spot that was 2 m (6.6 ft) long and 0.9 m (3 ft) deep; the low spot was not used in the present study. The temperature of the test section was controlled through a 10.2 cm (4″) pipe-in-pipe co-current glycol jacket with external insulation. A chiller unit was used to control the glycol jacket temperature, the set point of which can vary from −10 to 30 °C (14–86 °F) with a differential of 2 °C (3.6 °F); in the current configuration, the pipe wall thermal control results in temperature oscillations of ±1.5 °C (2.7 °F). Although this can be undesirable and efforts are underway to improve temperature control in the jacket, this oscillation provided a unique insight to hydrate deposition behavior that is discussed below.

The test section was equipped with seven RTD sensors to measure the temperature, with an accuracy of ±0.15 °C (0.27 °F). Each RTD was mounted in a thermowell and spaced approximately 6 m apart (labeled P-T 0–6 in Fig. 2). Each RTD sensor tip was flush with the top pipe wall, and each thermowell also contained a pressure transmitter with an uncertainty of ±0.3 bar (4 psi). The four high-pressure viewing windows at various positions along the test section (VW 1–4 in Fig. 2) were equipped with high-speed cameras for a visual confirmation of flow patterns and hydrate deposition in each test. The gas flow rate was measured by a turbine flow meter (GFM in Fig. 2) with an uncertainty of ±0.3%, and the liquid flow rate was measured by a positive displacement gear flow meter (LFM in Fig. 2) with an uncertainty of ±1%. All pressure, temperature, and flow rate measurements were recorded at 1-s intervals through a custom data acquisition program. The operating specifications of the Hytra flowloop are summarized in Table 1.

2.2. Flowloop operating procedure

In these experiments, domestic gas was used as a proxy for natural gas. Its composition is given in Table 2. In the pressure-temperature region used for this investigation, structure II (sII) gas hydrates are the thermodynamically preferred structure. For a given experiment, the hydrate equilibrium temperature was estimated using the cubic plus association (CPA) model set in the software package Multiflash 4.4 (Multiflash® for Windows, 2012) from the average flowloop pressure (as discussed below).

Before each experiment, the flow line was flushed of any residual water from previous tests by prolonged gas circulation at high pressure. Once the flowline was fully emptied, the water collected in the gravimetric separator was discharged into a tank at atmospheric pressure for disposal. Next, the flowloop was pressurized with natural gas (Table 2) to 103.4 bar (1500 psi). To begin each experiment, the test section was cooled to the set-point temperature under continuous gas flow without any liquid water

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