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Medium Scaled Testing of Cold Flow

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Abstract

This paper presents experimental results of liquid dominated cold flow production in a medium scale test rig. The term “cold flow” is a flow assurance method suited for long tieback subsea oil- and gas fields that are exposed to the risk of hydrate formation and wax precipitation. Use of the technology reduces both costs and carbon emissions compared to conventional flow assurance measures [1-2]. A cold flow unit placed downstream the subsea wellhead efficiently cools the well fluids to ambient conditions and converts wax and hydrates into small and inert particles suspended into the remaining liquid flow. The resulting slurry in addition to any residual gas can be transported in the pipeline, at ambient seabed temperature, without the use of any chemical injection, pipeline insulation, or pipeline heating techniques. The paper is structured into four main parts: 1) Introduction to the cold flow technology and cold flow concepts 2) Methodology of the tests 3) Results and discussion of test results, and 4) Conclusions. Cold flow slurry was produced with WCs ranging from 5 % to 22 %. The effective slurry viscosity was estimated through internal looping of the cold slurry in the flow loop. The relative viscosity for a solid load up to 22% was approximately 2. Shut-in and restart experiments indicate that relatively low pump pressure was required to initiate the flow. Downstream pigging indicated no re-depositing of particles on the pipe wall.

Keywords

Subsea production, flow assurance, wax-hydrate slurry

Introduction

The cold flow technology has been in development for about 30 years [3]. The concept had been under development, testing, and research [4-13]. The initial idea was developed for hydrates but was later modified to include asphaltenes, wax, and scaling using the same principle [14].

The method is based on controlled cooling of the warm stream of hydrocarbons downstream from the subsea wellhead in a dedicated cooling section. A portion of the cold stream, referred to as “seeding”, taken from the end of the cooling section is recycled to near the inlet of the cooling section. The seeding stream contains hydrate and wax crystals, which initiate new growth of solids in the bulk flow rather than on the internal pipe wall surface. The hydrate seeding particles have a hydrophilic surface [3] that attracts the water in the well stream.

The water will coat the hydrate particles forming a water film and, as the flow is cooled, the hydrate particles will absorb the water film. The water is converted into new hydrates by growing on existing hydrate particles. No free water will be encapsulated inside the hydrates. The process forms small, dry, and inert particles that can be transported at cold temperatures in the remaining liquid, forming a slurry. The particle load in the liquid affects the effective viscosity of the slurry. An operational envelope based on GOR and WC has earlier been developed by [1].

The initial cold flow concept by SINTEF was a relatively long recycle loop (>1 km). The length of the loop, along with the size of the recycle pump, made the concept challenging. Additionally, experimental tests showed build-up of wall deposits, indicating that the seeding mechanism was not entirely effective, in particular in the presence of wax. The technology gap was addressed by the new concept proposed by Empig. This concept uses a compact cooler with a smaller recycle pump and a low-energy inductive heating coil that is continuously moved along the cooler pipes to remove any inner pipe deposits. The coil heats a small pipe segment at time, and deposits are torn off the pipe wall in solid form by the shear forces of the flow.

Methodology

Description of the flow loop

A relatively large flow loop, shown in Figure 1, is built at SINTEF’s Multiphase Flow Laboratory in Trondheim, Norway. The dashed yellow boxes and their corresponding numbered label are described as follow: 1) a heated reservoir tank, 2) gas, oil, and water feed lines with pre-cooling, 3) the cold flow cooler unit including a robot used to move the induction coil along the pipes, 4) pump or seeding flow, 5) downstream pipe-in-pipe pigging section, 6) viscosity measurement section, 7) sampling point, and 8) re-heater.

These components can be organized into three systems: a) reservoir, b) cold flow unit, and c) downstream section. Each system has specific objectives: a) to simulate fluids at reservoir conditions, b) to produce a stable and inert slurry for different values of GOR and WC, and c) to investigate the downstream slurry properties. Further details about the facility can be found in [12-13].

The reservoir tank operates at around 70 to 75 °C and 75 to 80 bar. The tank is used for storage of gas, oil, and water and in addition to being a reservoir it functions as a separator for the returning flow. The three phases can individually be pumped into the flow loop. Flow meters are installed on each line for measurement of mass flow and density. Manipulation of GOR and WC is done by controlling the pump rates. For the experiments described in this paper, the gas compressor was not used. Pre-cooling of the feed flow is employed to reduce the fluid temperature to 40 °C before it is mixed with the seed flow. This pre-cooling step is essential as it aligns the operational conditions more closely with a temperature that can be brought to ambient temperature within the cooler length. At the end of the flow loop, a re-heater is used to restore the fluids to reservoir conditions and melt hydrates and wax formed.

The cold flow unit consists of items 3 and 4, which are employed to produce a stable slurry using seeding, and a passive cooler including a robot for localized induction heat. The passive cooler is submerged into a 40-foot container filled with cold water at a temperature of 1 °C. The cold water is continuously replaced to maintain its temperature. The cooler is made from a 300 m long 2-inch pipe. The internal surface of the pipes is kept clean through the moving induction coil operated by a gantry robot system installed on top of the container. Figure 2 shows the container, the cooler pipes, and the robot system. A centrifugal pump (item 4) is used to inject the seed flow into the unit.

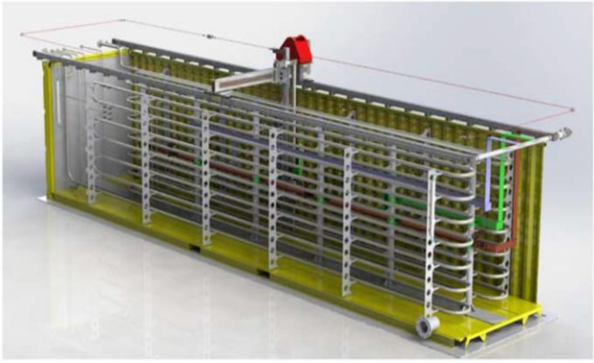

Figure 2. The container with the cooler unit including the robot system.

A downstream section comprises items 5, 6, and 7. Item 5 is a pipe-in-pipe section that can be pigged to check for downstream pipe wall deposits. The annular temperature of the pipe-in-pipe section can be manipulated by a glycol cooling system, which can provide extra cooling to stress test the slurry. A viscosity measurement section (item 6) is utilized to investigate the effective viscosity of the slurry. Sample points (item 7) are available to analyze the slurry.

Description of fluids

The experiments apply an unprocessed crude oil from a field in the Norwegian continental shelf. This oil has also been used in previous test campaigns, ref. [12]. In the reservoir tank, this oil is stored with brine (3.5 wt.% NaCl) and a gas mixture containing methane and propane, which are hydrate formers. Only the oil and water phase were pumped through the flow loop in the tests described. The oil phase, which contains dissolved gases, has a GOR of 110 Sm^3/Sm^3. The wax appearance temperature (WAT) and the hydrate equilibrium temperature (HET) of this system are approximately 31 °C and

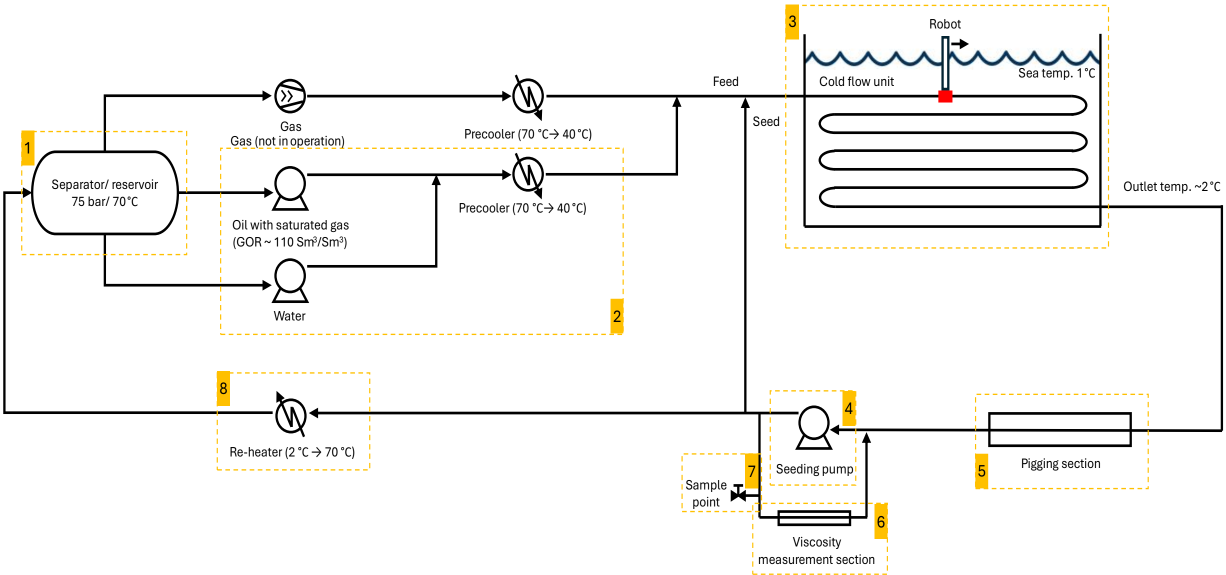

Figure 1. Overview of the flow loop used in the experiments.

20 °C (at 75 bar), respectively. The oil precipitates approximately 5 wt.% wax at 2 °C according to its wax precipitation curve.

Viscosity measurement

A viscosity section (item 6) is used to estimate the slurry effective viscosity across a range of solid loads. This section consists of a straight, vertical pipe which is equipped with sensors that measure mixture density, flow rate, and pressure drop to estimate the viscosity of the slurry.

A portion of the slurry flows through a 2-meter vertical and straight piece of tubing with an inner diameter for 0.012 m. A Coriolis meter measures the mass flow and the density of the slurry passing through the section. A differential pressure sensor, mounted over the tubing section, measures the pressure drop across the tubing. The hydrostatic difference is subtracted from this value. The flow rate through the tubing section is set to ensure turbulent and homogeneous flow conditions.

The viscosity measurements are done at approximately 70 bar and 2 ºC. The measurements are repeated for several flow rates. The fanning friction factor is calculated using the Darcy-Weisbach equation. Subsequently, the corresponding Reynolds number is estimated by applying the Blasius correlation for turbulent flow. Finally, the effective viscosity is calculated from the definition of the Reynolds number.

Results and Discussion

Production of cold flow slurry

The experimental cold flow unit is relatively short to effectively cool down high flow rates at reservoir conditions. To ensure the fluid was cooled to seabed temperatures, a high flow of seeding stream was used compared to the incoming feed stream. The inlet temperature of the cold flow unit was approximately 15 °C, after feed and seed stream were mixed. Figure 3 shows the bulk flow temperature along the unit during production of slurries with 0, 5, and 15 % WCs.

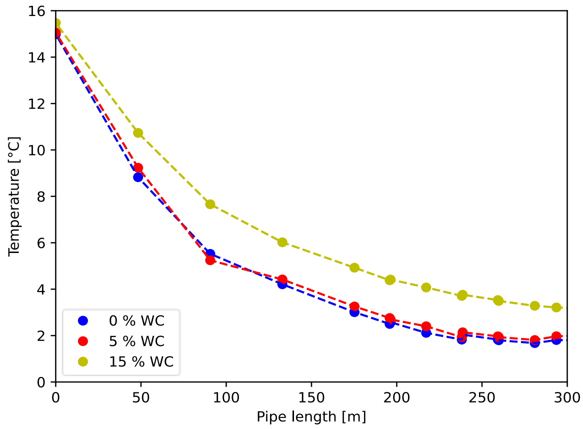

Figure 3. Bulk flow temperature along the unit during production of slurries with 0 (blue), 5 (red), and 15 (yellow) % WCs. Flow velocity was 1.5 m/s.

The pressure drop through the cold flow unit increases with increased WC due to more hydrates formed and consequently increased effective slurry viscosity, as shown in Figure 4 (blue bars). The solid deposits (wax and hydrates) on the internal pipe surface act as an insulation layer. When the induction coil moves along the pipe, the deposits are released, and the outside pipe temperature will increase due to increased radial heat flux. Figure 4 (orange bars) also shows the increase in outside pipe temperature after the robot passes a pipe segment for different WCs. The results suggest that an increase in WC reduces the temperature raise, indicating less deposition within the unit.

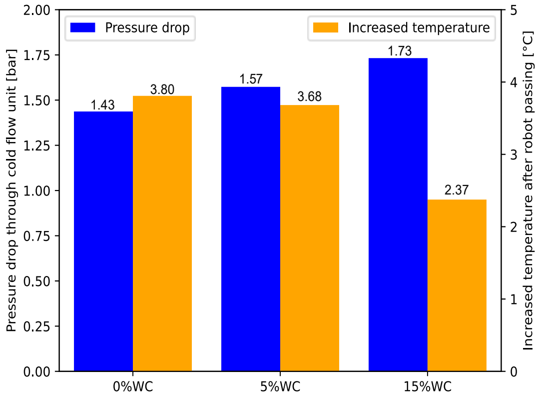

Figure 4. Blue: Pressure drop through the unit for different WCs. Orange: Increased pipe temperature after the robot passes a pipe segment for different WCs. Increased temperatures indicate the release of pipe deposits. Flow velocity was 1.5 m/s.

Viscosity of slurry

Figure 5 shows the estimated relative viscosity of the slurry vs. volumetric solid fraction. Additionally, the Thomas model [15] illustrates estimation of the relative viscosity. The volumetric solid fraction is estimated from the sum of wax and the hydrate particles (based on WC). Based on the GOR and WCs that were tested, it is assumed that all water is converted into hydrates, supported by the cold flow operational envelope given in [1].

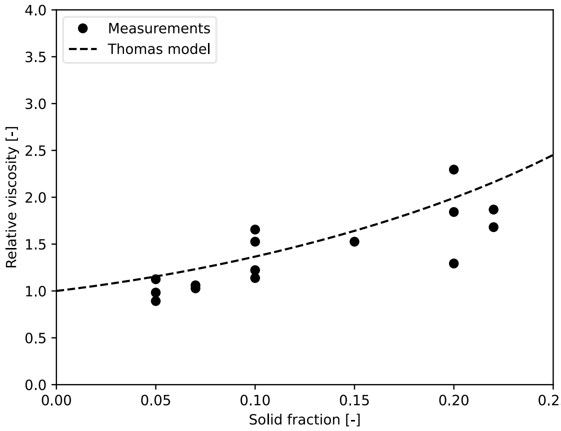

Figure 5. Estimates of relative viscosity vs. slurry solid fraction. The dashed line corresponds to the Thomas model [15] prediction.

Looping and verification of viscosity

After a period of generating cold flow slurry, most of the experiments were shifted into looping mode, *i.e.*, the cold slurry was looped internally in the unit and no warm feed was injected into the cooler. The looping mode simulates the transport of the cold slurry in downstream section to the processing facility. Figure 6 shows the measured pressure drop (blue line) through the 300 m long unit during a looping experiment with 5 % WC slurry. The flow velocity was 1.5 m/s. The figure also shows the calculated pressure drop (orange line) based on the estimated viscosity for 5 % WC cold slurry (2.6 cP). The fluid velocity and density were used to calculate the pressure drop employing the Colebrook equation. A pipe roughness of 0.15 mm was used. Additionally, pressure drop contributions from the 180° pipe bends in the unit (20 in total) were added by utilizing a resistance coefficient of 0.35 per bend [16].

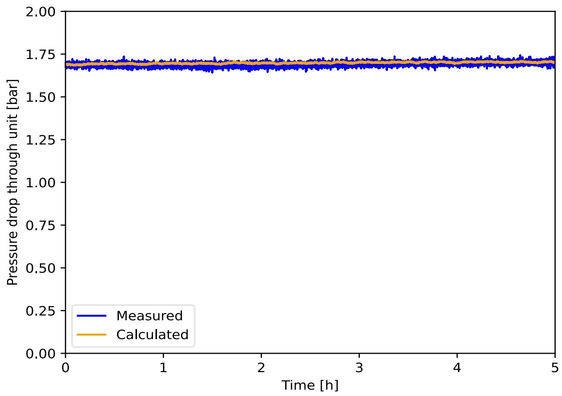

Figure 6. Pressure drop through the unit during stable flow of approximately 1.5 m/s at 2 °C and 5 % WC slurry. The blue line is the measured pressure drop, while the orange line is the calculated pressure drop based on the estimated viscosity.

Shut-in and restart

Figure 7 shows the flow velocity and pressure drop across the cold flow unit during a restart after a long shut-in lasting 137 hrs.

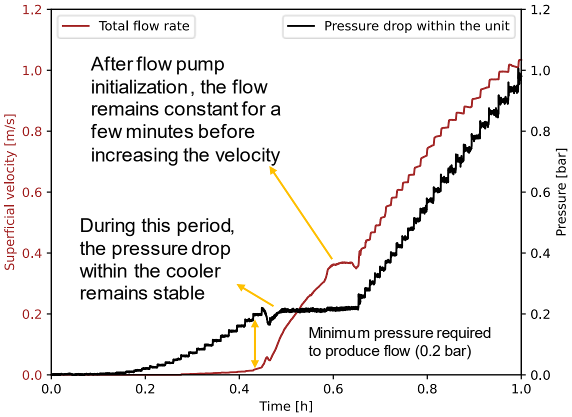

Figure 7. Total flow rate and pressure drop within the cooler during restart experiment after 137 hrs. of shut-in, for a slurry produced with 5% WC.

The slurry was kept cold (1-2 °C) and pressurized (70 bar) during the shut-in. The flow started at approximately 0.15 bar, for a slurry generated with 5% WC. The low restart pressure did not indicate any agglomeration during the shut-in. The slurry was considered easy to restart. Test with 22 % WC also indicated low pressure was required to restart the flow.

Downstream pigging and slurry samples

Figure 8 shows the pig after a reference test without any measures taken (left) and after a test using cold flow (right). Additionally, real in-situ WC was verified with samples taken of the slurry. These procedures were implemented to analyze and visualize the cold flow slurry.

Figure 8. Pigging of downstream section. Left: Reference test. Right: Use of cold flow (seeding and robot), 0 % WC.

Conclusions

The flow loop can produce cold flow using the seeding method combined with a moving induction coil along the unit for internal pipe cleaning. This is verified by 1) Clean downstream pig, 2) Low restart pressure required after shut-in, indicating no agglomeration. Increased WC demonstrated a beneficial effect in reducing the amount of pipe deposits within the unit, mainly wax precipitation. The relative viscosity, estimated under turbulent and homogeneous flow conditions, indicates a flowable slurry with predictable viscosity. The modeling, based on experimental data, well reproduces the pressure drop during looping of cold slurry.

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