Use of Under-inhibition in Hydrate Control Strategies

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ABSTRACT

An under-inhibited system is defined as a system where an insufficient amount of thermodynamic hydrate inhibitor (THI) is present to prevent hydrate formation. Previous studies on under-inhibited fluid systems have shown the following: the hydrate plugging potential will first increase when increasing the inhibitor concentration from zero, then decrease beyond certain inhibitor concentrations. In this work, under-inhibited systems at relatively high inhibitor concentrations are studied. Experimental results on mono-ethylene glycol (MEG) are presented and discussed. At a relatively high inhibitor concentration but still under-inhibited, there seems to be an upper subcooling boundary below which transportable hydrate slurry could be produced. The basic principles behind the observed good transportability of the hydrate slurries are further analyzed. A prediction is made for MEG under-inhibited systems regarding the subcooling limit for making transportable hydrate slurries. The authors expect that the results from this work can be transferred to other THI systems, however an individual mapping of the relationship between the inhibitor concentration and the subcooling will be needed for each inhibitor. The principles of this work have important bearings on the practical inhibition strategy. The main benefits will be reduced chemical volumes, enabling of marginal field developments and increased operational robustness.

Keywords: Hydrate transportability, under-inhibition, thermodynamic hydrate inhibitor

INTRODUCTION

Hydrate control engineers have many different methods to avoid blockage of flowlines and process equipment by hydrates. One of the most used methods is the application of thermodynamic hydrate inhibitors (THI). THIs shift the hydrate formation boundary to higher pressures and lower temperatures by associating with the water molecules and preventing their arrangement into a hydrate lattice [1, 2]. There are mainly two types of THIs: salts and alcohols/glycols. Of the alcohols, methanol (MeOH) and mono-ethylene glycol (MEG) are the most used. Regarding salts, various brine solutions are often used as well intervention or completion fluids. Salts are seldom added into flowlines for hydrate control. However, for certain reservoir conditions, the formation water may contain very high salinities acting as hydrate inhibitors (e.g. in many of the Gulf of Mexico deepwater fields).

Under-inhibited systems are systems with insufficient amount of thermodynamic hydrate inhibitors to avoid hydrate formation. Previous studies have shown that under-inhibited systems have varying hydrate plugging potential depending on the inhibitor concentration and the subcooling [3-8]. Figure 1 illustrates the hydrate plugging potential for MEG under-inhibited systems as a function of MEG concentration. The hydrate plugging potential of MEG under-inhibited systems increases to a maximum at about 10-15 wt% MEG and then decreases at higher MEG concentrations. Above about 30 wt% MEG, the hydrate plugging potential has been observed to be low and the formed hydrates can be transported as slurry particles [7, 8].

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Figure 1. Hydrate plugging potential as a function of MEG concentration.

In our earlier studies [5, 7, 8], focus has been put on mapping the plugging risk of under-inhibited systems and understanding the mechanisms governing plugging and non-plugging behaviors. In this paper, focus will be on the high concentration end of an under-inhibited system in order to identify the transportability limit of such systems. If non-plugging hydrate slurries can be generated and transported over long distances in certain under-inhibited systems, it could offer a new hydrate control solution for long distance multiphase transport. Both existing production facilities and future field development may have large benefits by utilizing the technology.

THEORETICAL BACKGROUND

The surface chemistry of the oil phase could make an oil plugging or non-plugging [8-15]. The hydrocarbon fluid systems studied in this paper are the plugging type oils, like gas-condensates, light oils and some crude oils.

Capillary liquid bridging of hydrate particles has generally been accepted to be the main cause for hydrate agglomeration, where water is the binding liquid [16-20]. Further conversion of the water bridges to solid hydrates are believed to contribute to substantial agglomeration and finally plugging in most fluid systems [7, 8]. In the field of wet granulation [21, 22], where fine powders are enlarged into larger granules by adding a liquid binder, the adhesion of particles through capillary forces is an important mechanism. Permanent bonds will be made by subsequent drying or sintering. The liquid binder content is an important parameter for wet granulation. When increasing the liquid binder content with regard to available pore space from zero, the granule strength will gradually increase until a maximum and then decrease sharply. Above a given liquid binder-to-pore ratio, the capillary adhesion forces will vanish and no agglomeration will occur in a wet granulation process. Figure 2 illustrates the granule strength (i.e. adhesion forces) as a function of the liquid binder saturation state, where the granules are bound by different amount of binder content. For the left two granules illustrated in Figure 2, the spaces between the particles are deliberately enlarged to show the binder connection, most particles will be in close contact in reality. The liquid binder saturation state is defined as the ratio between the liquid binder and the void space between solid particles.

There are many similarities between the hydrate agglomeration and the wet granulation process. When hydrate particles start to agglomerate, the capillary adhesion forces will be very important to keep the agglomerates stable for a certain time. During this time period, stronger bonds between the hydrate particles could be formed creating an extensive hydrate network. When an aggregate collides with another one or the wall, new liquid bridges (and their further conversion to solid ones) could be formed resulting in large lumps/deposits and plugging.

Without the presence of a thermodynamic inhibitor in a fluid system, all of the water has the potential to be converted to hydrates (assuming excess of hydrate formers – i.e. gas molecules). The hydrate particles will agglomerate to lumps by capillary bridges. The water phase wetting the outside of the lumps will continue to react to form
more hydrates, resulting in larger lumps with a dry surface. These lumps would still contain much liquid inside. The formation of a dry skin on the outside of such hydrate lumps will seriously limit further hydrate growth. However, as these lumps collide with each other or the pipe wall, the encapsulated water may be released. The free water can then rapidly convert and bind lumps together or depositing on pipe walls, plugging the pipeline.

In an under-inhibited system, the inhibitor concentration will increase until the full inhibition state is reached or hydrate formation is stopped due to plugging. Thus there will always be a free water phase surrounding the hydrate particles/lumps.

- At low initial inhibitor concentrations (e.g. at about 10 wt% MEG), the free water to solid hydrate volume ratio may lie in the proper range for high capillary adhesion forces. This resembles the third picture from left in Figure 2, where the liquid saturation state is approaching 1, with very high capillary binding forces. The wetted hydrate surfaces will have strong tendency for deposition and agglomeration, giving higher plugging potential than an uninhibited system.

- At higher initial inhibitor concentrations (e.g. >30 wt% MEG), the free water to solid hydrate volume ratio becomes too high and capillary adhesion forces will vanish. No substantial liquid or solid bridges will be formed between hydrate particles, but mainly hydrate in water suspensions. This resembles the rightmost picture in Figure 2, where the liquid saturation state is beyond 1, with minimal capillary binding forces.

For a suspension (slurry flow), its viscosity will depend on many factors like the particle volume fraction, particle size distribution, particle agglomeration properties and flow/shear rate. The Krieger & Dougherty viscosity model has often been used to predict the viscosity of suspensions [23, 24]:

\[
\eta_{\phi} = \frac{1}{(1 - k\phi)^{\eta/M}} = \frac{1}{\left(1 - \frac{\phi}{\phi_M}\right)^{\eta/M}}
\]

Where \([\eta]\) is the “intrinsic viscosity”, \(\phi\) is the volume fraction of the slurry particles and \(\phi_M\) is the characteristic slurry fraction when the suspension viscosity becomes infinite. For systems with narrow particle size distributions, high agglomerating tendency and at low shear rates, the \(\phi_M\) value can be below 0.64 which is the value for randomly close-packed hard mono-sphere systems. For systems with wide particle size distributions, low agglomerating tendency and at high shear rates, the \(\phi_M\) value can be above 0.74 which is the value for densely packed hard mono-sphere systems. For the \([\eta]\phi_M\) product, a higher value leads to faster viscosity increase with increasing solid concentrations than a lower value.

Figure 3 a & b show the relative viscosity of a slurry suspension as a function of the solid volume fraction based on the Krieger & Dougherty viscosity model. As shown in the figures, the viscosity can increase rapidly with increasing solid concentrations for low \(\phi_M\) systems. While for high \(\phi_M\) systems, the suspension viscosity can be rather low at quite high solid concentrations.

![Figure 3](image-url)
Most slurry systems will have a weak viscosity increase when increasing the solid fraction until a certain value, then a sharper increase will follow. With narrow particle size distribution and highly agglomerating particles, the slurry viscosity may increase dramatically at low flow rates, making jammed/plugged systems at lower solid concentrations than other systems. On the other hand, for fluid systems with wide size distribution and non-agglomerating particles, the slurry viscosity can be kept relatively low until very high solid concentrations.

The hydrate behavior in an under-inhibited system can be impacted both by the capillary adhesion forces as well as the free aqueous to solid volume ratio. With high capillary adhesion forces and high particle in aqueous concentration, the fluid system will have very high plugging potential. With low capillary adhesion forces and low particle concentration in the aqueous phase, a transportable slurry system will be formed instead.

**Apparent “solid” volume versus pure hydrate volume**
When water droplets are converting to hydrate particles, hydrate starts to form from the outer surfaces (i.e. at the water/oil or water/gas interfaces). Collision with other particles or wall may release some of the water trapped inside the hydrate shells. It is generally believed that some water cores will remain inside the hydrate particles, as illustrated in Figure 4. For aggregates, water as well as oil and gas may be entrapped inside the aggregates, giving much larger “hydrate” volume than the pure hydrate amount. For irregularly shaped particles/aggregates, water may also fill in the existing capillary channels. This will result in a much larger apparent solid volume than the pure hydrate volume.

Figure 4. Illustration of a hydrate slurry particle with a water core.

Figure 5 shows the estimated slurry concentrations when all available water is converted to hydrates at different subcooling conditions for pure hydrate volume and for hydrate volume with 20% bound water. By assuming some of the free aqueous phase is bound to hydrates, the apparent “solid” volume in the free aqueous phase will increase, as shown in the figure. In the estimations of the apparent solid volume in this paper, only the extra volume by bound water is considered, no gas or oil volume is included.

![Figure 5. Estimated solid concentration for pure hydrate volume and for apparent solid volume with 20% bound water when all available water has been converted to hydrates.](image)

**Estimation of particle packing fraction and aqueous saturation level**
When solid particles are packed in a closed volume, the solid particles can only occupy a certain volume, and the rest is defined as the void space. The fraction of volume occupied by the solid particles in the total volume is defined as the packing fraction. The packing fraction can vary depending on the particle size distribution and the packing pattern. For mono-sized spherical particles, the highest packing fraction is 0.74 (i.e. densely packed system). For non-agglomerating and poly-dispersed particle systems, the packing factors can be higher. On the other hand, an agglomerating system will have a lower packing factor than 0.74. The void space between particles/aggregates will be primarily filled by water. If the amount of free water (excluding the entrapped water) equals to the void space, the aqueous saturation level will be 1. A smaller amount of free water than the void space will lead to an aqueous saturation level less than 1 and vice versa larger than 1 for a larger amount of free water.
EXPERIMENTAL
Description of the Statoil Flow Simulator
Only the main features and the typical operating conditions of the Flow Simulator used in the study are given here. More detailed description of the Flow Simulator and the general procedures during hydrate tests have been presented earlier [7, 8]. The 2” Flow Simulator is a wheel-shaped loop mounted on a horizontal shaft (see Figure 6). The wheel can be rotated at different velocities and operated at different temperatures and pressures. The main purpose of the Flow Simulator is to simulate multiphase flow inside a pipe without pumps, which is the normal way of inducing flow in flow loops. A high-pressure window (PMMA) allows visual inspection using a video camera.

Figure 6. Schematic of the Flow Simulator.

The liquid loading inside the Flow Simulator is typically 40 vol% and fill the whole cross section of the lower part of the wheel. During rotation the liquid will be pushed upwards the rotational direction, while the gravitation balances it downwards. At low velocity, there will be little mixing of the liquid and gas phases, giving a flow pattern equal to two-phase oil-water flow. At higher velocities, gas will start to mix into the liquids and the flow pattern will be more of a slug type. If the velocity is further increased, liquid carry-over will start to appear. The point where the liquid starts to follow the rotation of the wheel is dependent on the liquid viscosity. Once the liquid starts to follow the rotation of the wheel, the Flow Simulator is no longer simulating any flow. Thus, there is a limitation of the Flow Simulator with respect to fluid (including particles) viscosity.

Details of the experiments and data analysis
Regarding the oil phase, several gas-condensates have been tested. These condensates are of the plugging type, where a hydrate inhibitor is necessary to avoid hydrate plugging. The made-up gas composition is 74.5:17.5:8 (mol%) of methane, ethane and propane respectively. MEG has been used as the inhibitor in most of the experiments. Based on the total composition of the gas, oil and the aqueous phase, the hydrate equilibrium conditions for the experiments have been calculated using a thermodynamic package.

The wheel and shaft of the Flow Simulator, together with the motor, is resting on three weighing cells, making it possible to measure the separate masses of oil, water and gas components loaded into the wheel. Hence in addition to calculate the hydrate boundary, the water to hydrate conversion during an experiment can also be estimated. Figure 7 shows an example of an experimental pressure-temperature (P-T) curve when the fluids in the Flow Simulator are gradually cooled to 3°C. The experimental and calculated P-T curves follow closely to each other until hydrate formation starts, in which the experimental pressure drops sharply. The pressure will continue to decrease as hydrates continue to form, until either the system has reached the complete conversion state, or mass transfer limitation has become the main obstacle. The complete conversion state for a particular test is that when all available water has been converted to hydrates according to the total fluid composition, e.g., when reaching the selv-inhibited state for a system containing a THI. In many experiments, the fluid system does not reach the complete conversion state, as gas components are unable to meet unconverted water encapsulated inside hydrate particles, agglomerates or lumps. The quality of the calculated water to hydrate conversion depends on the precision in both the experimental composition and the equation of state used for flash calculations. In this work we have used PVTsim with the Soave-Redlich-Kwong equation of state, with its known limitations for water containing systems [25].
Mainly two types of experiments were performed in the Flow Simulator: 1). Dynamic cooling tests (DC): the Flow Simulator was in rotation as the fluid was cooled from 55°C to a preset temperature. The temperature was kept constant throughout the rest of the experiment. A shut-in (2–4 hours) followed by a restart could be performed during/after hydrate formation to check the agglomeration tendency of the hydrate particles if settled. 2). Shut-in/Start-up tests (SS): the temperature was decreased from 55°C to 30°C while the Flow Simulator was in rotation. At 30°C, the Flow Simulator was stopped and the system continued to be cooled to a preset temperature. The system was kept stagnant at these conditions for minimum 12 hours, followed by a start-up. In some experiments, one or two extra shut-ins (2–4 hours) and restarts were performed some time after the first ordinary start-up.

**Evaluation of hydrate plugging potential**

The hydrate plugging potential was determined by a combination of visual observations and torque measurements. The torque is measured in two ways: the mean torque and the maximum torque per rotation (which is the top 10% highest readings from one rotation). For the system shown in Figure 8, the torque increased sharply as hydrate formation started and then decreased after reaching a maximum value. This indicates some agglomeration first followed by break-up of larger agglomerates to smaller ones. For some oils and at high water cut, the oil phase viscosity may also increase temporarily due to under-saturation of gas during the rapid hydrate formation period [26]. So the torque changes in the period 400-900 minutes may be partially caused by the change in pure oil viscosity. After 900 minutes the torque continued to decrease although the pressure was stabilized, indicating continued break-up of aggregates.

Figure 7. Pressure-temperature relation, the corresponding hydrate dissociation curve and the complete conversion curve for a fluid system in the Flow Simulator.

Figure 8. Data logging during a Flow Simulator experiment.

Figure 9 shows representative logging for a system forming first deposits and then hydrate plug during an experiment. Hydrate formation was detected as the pressure decreased quickly while the torque values increased (around 880 minutes). The maximum torque value increased much more than the mean torque value, indicating unevenly distributed deposits along the Flow Simulator. Partial hydrate plugging was detected as the mean torque curve peaked and then dropped to a lower level (around 990 minutes), while the maximum torque showed high readings. Such torque pattern is expected for plugs following the rotation of the Flow Simulator. Around 1090 minutes, the Flow Simulator was completely plugged.

Figure 9. Torque development where a plug was formed at the end of an experiment.
Deposits and plugs could sometimes be observed through the high pressure window. The deposits, lumps and plugging situations could be temporary in an experiment, and the agglomerates may gradually break-up as more hydrates were formed. Occasionally, rather fine dispersions could be made at the end of an experiment if the Flow Simulator was allowed to rotate for a longer period after observation of lumps, deposits or plugging. For most of the systems studied, the hydrate plugging tendency was highest when the hydrate formation rate was high and there were large amount of unconverted water due to liquid and hydrate bridging [7, 8]. An extra shut-in during the fast hydrate formation period could easily provoke a hydrate plug after the system was started up again.

For certain systems, the torque change is hardly noticeable upon hydrate formation and no visual signs of hydrate agglomeration could be observed either. However, agglomeration may still occur if a shut-in was performed during the fast hydrate formation period, lowering the transportability of the system.

RESULTS AND DISCUSSIONS

Hydrate formation kinetics

Formation kinetics (which is, influenced by e.g. subcooling, contact area and flow rate) will impact the particle growth and the produced slurry system. Generally speaking, the initial water conversion (or hydrate formation) rate increases with increasing subcooling, see Figure 10. As shown in the figure, the un-inhibited and 10 wt% MEG systems show similar water conversion rates, whereas the systems containing 20 and 30 wt% MEG show slower conversion rates. However, for the un-inhibited system, the water conversion rate levels off and decreases at high sub-coolings, whereas for all of the under-inhibited systems the water conversion rate increases monotonously with increasing subcooling. This may indicate that there are less mass transfer limitations in the under-inhibited systems at high subcoolings (no sign of heat transfer limitations during the experiments). In un-inhibited systems, hydrate plugging will easily occur at high subcoolings. This will seriously reduce the further contact between water and oil/gas and hence reduce the hydrate formation rate. See [7] for more details.

Figure 10. Water conversion rate as a function of subcooling.

High hydrate formation rate may lead to more occluded water/oil in hydrate lumps/aggregates and hydrate bridging, resulting in high apparent solid/slurry concentrations. While low hydrate formation rate may create smaller particles with less bound water/oil, hence lead to lower apparent solid/slurry concentrations.

Under-inhibited low MEG concentration systems

The results for the low inhibitor concentration region have been presented earlier [5, 7, 8], as summarized in Figure 1. The hydrate plugging potential is the highest in the low inhibitor concentration range (e.g. around 10 wt% MEG), which is higher than an uninhibited system. The results are based on experimental data and observations made on several fluid systems in both the Flow Simulator and flow loops.

The amount of water bound to hydrate particles may vary depending on many factors. Experimental data/observations suggest that lower MEG concentrations, higher subcoolings and lower flow rates may lead to a larger amount of bound water. Since it is difficult to measure or estimate the exact water volume bound to the solid hydrate phase, a sensitivity test has been performed for the 10 wt% MEG system. By assuming 0, 20% and 40% of the water volume is bound to the solid phase, the apparent “solid” volume concentration in the free aqueous phase can be estimated at different subcoolings. Similarly, the free aqueous saturation level in the void space of the packed “solids” can also be calculated. Extensive agglomeration is generally observed in the 10 wt% MEG systems, so the solid packing fraction has been assumed to be 0.57 in the calculations. Figure 11 shows the theoretical
calculation results for the 10 wt% MEG system at complete conversion. The free aqueous saturation level is in the vicinity of 1 for most cases except at 0% bound water and very low subcooling, indicating that capillary adhesion could be a strong acting mechanism for hydrate agglomerations in 10 wt% MEG systems. In addition, the resulted solid concentration in the free aqueous phase is very high for most subcoolings. These two factors support the experimental findings that about 10 wt% MEG systems show highest plugging potential than other MEG concentrations tested.

Figure 11. Aqueous saturation level and solid in aqueous concentration as a function of subcooling. The particle packing factor has been assumed to be 0.57 due to agglomerating particles.

Under-inhibited high MEG concentration systems
Table 1 shows the experimental results for 30 wt% MEG systems. There seems to be an upper subcooling (ΔT) limit below which transportable hydrate slurry could be produced.

Under otherwise similar conditions, higher subcooling systems will always give higher hydrate plugging potential. Based on experiences from different test facilities and field operations, a shut-in/start-up test is generally more stringent than a dynamic cooling test under same subcooling and flow conditions. So the hydrate plugging potential is always higher during a cold start-up after a long shut-in as compared to gradual cooling to the seabed temperature during production. Increasing water cut (up to 50%) has also been observed to increase the hydrate plugging potential in the Flow Simulator. The results for the 30 wt% MEG under-inhibited systems in Table 1 are in good agreement with these general trends.

Table 1. Summary results of under-inhibited fluid systems with 30 wt% MEG.

<table>
<thead>
<tr>
<th>WC [vol%]</th>
<th>Type</th>
<th>ΔT [K]</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>SS</td>
<td>2.5</td>
<td>Transportable</td>
</tr>
<tr>
<td>11</td>
<td>DC</td>
<td>3.1</td>
<td>Transportable</td>
</tr>
<tr>
<td>11</td>
<td>DC</td>
<td>3.9</td>
<td>Transportable</td>
</tr>
<tr>
<td>11</td>
<td>DC</td>
<td>4.1</td>
<td>Transportable</td>
</tr>
<tr>
<td>11</td>
<td>DC</td>
<td>7.4</td>
<td>Lumps, soft plug at restart</td>
</tr>
<tr>
<td>11</td>
<td>SS</td>
<td>4.0</td>
<td>Transportable</td>
</tr>
<tr>
<td>11</td>
<td>SS</td>
<td>4.5</td>
<td>Transportable</td>
</tr>
<tr>
<td>11</td>
<td>SS</td>
<td>7.5</td>
<td>Lumps, almost plugging</td>
</tr>
<tr>
<td>11</td>
<td>SS</td>
<td>7.5</td>
<td>Lumps, almost plugging</td>
</tr>
<tr>
<td>50</td>
<td>DC</td>
<td>3.1</td>
<td>Transportable</td>
</tr>
<tr>
<td>50</td>
<td>DC</td>
<td>5.3</td>
<td>Minor lumps, borderline</td>
</tr>
<tr>
<td>50</td>
<td>DC</td>
<td>7</td>
<td>Lumps, almost plugging</td>
</tr>
<tr>
<td>50</td>
<td>DC</td>
<td>7</td>
<td>Lumps, almost plugging</td>
</tr>
<tr>
<td>50</td>
<td>SS</td>
<td>7</td>
<td>Lumps, almost plugging, more severe</td>
</tr>
</tbody>
</table>

Figure 12 plots the experimental results for the 30 wt% MEG systems. The predicted upper subcooling limit for good transportability is also shown in the figure, by assuming transportability limit of maximum 43 vol% particles and 20% bound water in the hydrate particles. The water cuts in the tests were from 11 to 50% and both dynamic cooling and shut-in/start-up test results are plotted on the graph. So there is a subcooling region where both borderline and less transportable results could be obtained depending on the water cut and the type of experiment. The observed hydrate behavior seems to agree well with the predicted transportable and less transportable regions for 30 wt% MEG systems. Tests have also been performed at other MEG concentrations (e.g. 40 wt% MEG) in the Statoil Flow Simulator. We have also access to data generated in other test facilities (e.g. loop). Most of these results are in agreement with the results presented here.
As mentioned earlier, the measured torque differences before, during and after hydrate formation can be used to indicate the viscosity change of non-plugging fluid systems. Table 2 shows the ratio of average torques after and before hydrate formation ($Q_{\text{after}}/Q_{\text{before}}$) during several dynamic cooling tests with 30 wt% MEG. The torque change will depend on the water cut and subcooling, since these will directly correlate to the amount of hydrates formed. For fluid systems making transportable hydrates, the total torque (viscosity) increase after hydrate formation seems to be small as shown in Table 2, even at high water cut.

Table 2. Torque change due to hydrate formation in some Flow Simulator DC tests at 30 wt% MEG.

<table>
<thead>
<tr>
<th>Subcooling [K]</th>
<th>WC [vol%]</th>
<th>$Q_{\text{after}}/Q_{\text{before}}$</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>11</td>
<td>2.5</td>
<td>Transportable</td>
</tr>
<tr>
<td>3.9</td>
<td>11</td>
<td>2.8</td>
<td>Transportable</td>
</tr>
<tr>
<td>4.1</td>
<td>11</td>
<td>2.8</td>
<td>Transportable</td>
</tr>
<tr>
<td>7.4</td>
<td>11</td>
<td>5</td>
<td>Lumps, soft plug at restart</td>
</tr>
<tr>
<td>3.1</td>
<td>50</td>
<td>2.5</td>
<td>Transportable</td>
</tr>
<tr>
<td>5.3</td>
<td>50</td>
<td>5</td>
<td>Minor lumps, borderline</td>
</tr>
<tr>
<td>7.0</td>
<td>50</td>
<td>10</td>
<td>Lumps, almost plugging</td>
</tr>
</tbody>
</table>

When increasing the MEG concentration, the relative amount of water phase able to convert to hydrates will decrease. This will increase the aqueous saturation level far beyond 1 and decrease the slurry concentration correspondingly. Figure 13 shows the estimated values for the 30, 35 and 40 wt% MEG systems. In the calculations, it has been assumed that 20 vol% of the aqueous phase is bound to hydrate particles. Experimental observations have shown fine slurry particles in such high MEG concentration systems, so the particle packing factor in the calculations has been assumed to be 0.8 (corresponding to non-agglomerating and widely sized particle systems). Above 30 wt% MEG concentration, the aqueous saturation level in void space is much larger than 1, even by assuming a rather large amount of bound water to hydrate particles. Hence capillary adhesion will be absent or very low in such systems. Hydrate plugging may however still occur when the slurry concentration in the aqueous phase is too high at very high subcoolings, causing too high viscosity or jamming of the slurry system.
sizes, hence the amount of water bound to the particles and the aggregate sizes. A too low flow rate, hilly terrain and tall riser may result in locally very high water cut or particle settling, increasing the possibility of local jamming.

Similarly to MEG, it is expected that other thermodynamic hydrate inhibitors like methanol and salts will also make transportable hydrate slurry systems when slightly under-inhibited in the high concentration region. However, the inhibitor concentration and the subcooling relationship for good hydrate transportability will vary from system to system and need to be mapped for each application. Which inhibitor concentration (or under-inhibition level) is optimal for an application will depend on the system subcooling, the possibility of local water/hydrate accumulation, flow rate etc. Detailed system analyses should be performed to check local variations on water cut and liquid hold-up along the pipeline.

Under-inhibition can offer a new hydrate control measure for multiphase flow. Both existing production facilities and future field development will have large benefit for utilizing the technology. For very long distance multiphase transports, both gas-condensate and oil-dominated well streams, a lower necessary inhibitor rate in the pipeline means smaller injection pipe size and inhibitor regeneration units. This may have vital importance for the economy of a new field development. With a fixed inhibitor capacity (new or existing flowlines), an increased production rate can be obtained, or the oil production rate can be maintained at increased water production. With uncertain and varying water production rates, under-inhibition could also be used as a buffer to increase the robustness of the production. For high salinity systems, if the under-inhibition condition mainly produces transportable hydrate slurries, inhibitor injection or an inhibitor line may be avoided. This may improve the field economy and reduce the chemical discharge to the environment substantially.

CONCLUSIONS
This paper has studied the transportability limit for under-inhibited fluid systems at high inhibitor concentrations. Both experimental data and theoretical analyses results have been presented. At a high inhibitor concentration but still under-inhibited, there seems to be an upper subcooling limit below which transportable hydrate slurry could be produced. A prediction has been made for MEG under-inhibited systems regarding the subcooling limit of hydrate transportability. It is expected that the conclusions from this work can be transferred to other THI systems, however an individual mapping of the relationship between the inhibitor concentration and the subcooling will be needed for each inhibitor. The principles of this work have important bearings on the practical inhibition strategy. The main benefits will be reduced chemical volumes, enabling of marginal field developments and increased operational robustness.

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