LIFE OF FIELD COOLDOWN IN A DEEPWATER DEVELOPMENT

Abstract

Transient multiphase flowline simulators can help engineers understand many different Flow Assurance issues and have proved to be a useful tool during the design of many oil and gas developments. However not all transient issues benefit from being studied using such complex and costly tools, either because the problem is straightforward or an accurate solution is not required or the simulator is not best suited to model the physical phenomenon of interest.

Cooldown of subsea flowlines can be one such issue. This case study was motivated by experience gained in the design of a large West African deepwater development. It shows how the requirement for expensive transient simulations can be minimised when assessing the key Flow Assurance issue of cooldown, leaving time to study more important aspects of the system. Rather than focusing on the minutiae of gas-liquid distribution and cooldown time, it is suggested that time is better spent on the bigger picture in front-end design, answering important questions such as how does operability affect the NPV of the project?

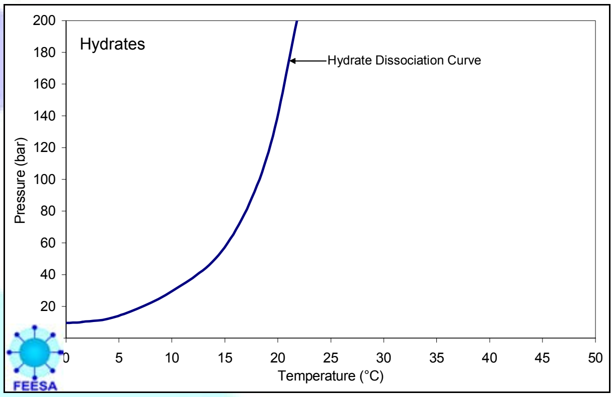
The Cooldown Problem

When a flowline is shut down, liquid settles into dips and gas migrates to the raised sections and the system then gradually cools to the ambient temperature. As gas has a much lower heat capacity than either oil or water, gas filled sections cool much quicker than liquid filled sections.

Cooldown is a particular cause for concern in deepwater developments due to the potential for hydrate formation which are then difficult to remove. Hydrates are crystalline solids formed when water molecules encage light hydrocarbons such as methane, ethane, or propane which are stable at high pressures and low temperatures. Figure 1 is a plot of a typical hydrate dissociation curve, to the left hand side of which hydrates may exist, this is often referred to as the ‘hydrate envelope’.

In many deepwater oil developments, hydrates are avoided during normal operation using insulation to maintain the fluid temperature above the hydrate dissociation temperature at the operating pressure. On shut down however, if the fluids are kept at pressure they may cool down into the hydrate envelope. Blowdown may alleviate this problem by reducing the settle-out pressure and thus the hydrate formation temperature, possibly to below ambient, making hydrate formation impossible in the stagnant system.

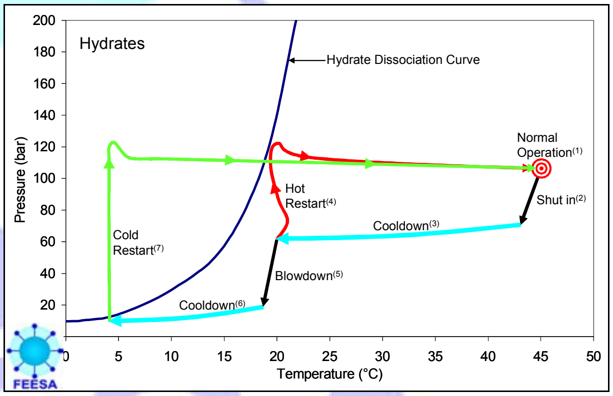
Figure 1 Typical Hydrate Curve



However, for the hydrate curve displayed in Figure 1, the flowline pressure would have to be reduced to below 11 bar to avoid hydrates completely at the seabed temperature (4°C). This may not be possible if watercuts and thus hydrostatic head on shut down are high, and is also difficult to predict. Also, the pressure surges generated on start up can lift the flowline fluid pressure into the hydrate envelope before hydrate inhibitors, or heat can enter the system.

This problem is illustrated in Figure 2 below where the pressure-temperature paths of a flowline section during various operations are plotted with the hydrate dissociation curve of Figure 1.

Figure 2 Example p-T Paths



The flowline section of interest is the coldest section of the flowline during steady state conditions. This is usually the riser base, but not always, particularly in daisy-chained flowline systems. The following points arise from Figure 2:

1. The flowline section begins at the ‘Normal Operation’ point, and is assumed to be at steady state (in this example 45°C, 105bara).

2. The flowline is then shut in, either deliberately or as part of an unplanned event, and the section of flowline quickly finds its static ‘settle-out pressure’.
3. The flowline then cools to the ambient sea temperature (typically 4°C). The pressure may drop slightly as some of the gas condenses.
4. The last possible opportunity to carry out a ‘hot restart’ (a restart without entering the hydrate envelope) is, in this case, once the flowline has reached about 20°C. During this restart the flowline section initially increases in temperature, due to the passage of warmer liquids from upstream in the flowline. The pressure increases sharply on restart as the riser fills with liquid restart surges. This hydrostatic head can be significant (>100bar) in deepwater (>1000m) systems.
5. Blowdown or depressurisation is another hydrate avoidance operation that is often used in shallow water systems. In Figure 2, it is carried out as an alternative pathway to a hot restart at 20°C.
6. The subsequent cooldown and blowdown may drop the system pressure to below the hydrate dissociation pressure at seabed temperature (11bar in this case).
7. When the complete flowline has cooled to 4°C, a cold restart may be performed. In common with the hot restart described above, this pressurises the system up to approximately 120 bar which is some 16°C into the hydrate envelope. This could potentially lead to hydrate blockage if the produced fluids in the flowline are not dosed with a sufficient quantity of hydrate inhibitor.

From Figure 2, it is clear that following a shutdown, there is a minimum flowline temperature for ‘hot restarts’ below which there is a risk of forming hydrates on restart, even following a blowdown. Obviously, it is important for the operators of such flowlines to know how long this ‘cooldown time’ is. Indeed, a minimum specified cooldown time may be a design constraint placed upon the system which may determine the level of flowline insulation required. Flowline insulation can be a major contributor to the CAPEX of a subsea development and thus the issue of cooldown should be addressed early in the design. Ideally therefore, a quick and efficient method for calculating cooldown time using typical tools available during conceptual design is essential.

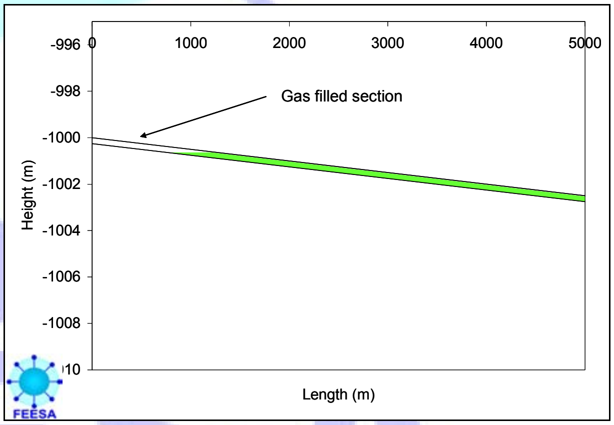
Calculating Cooldown Time

The cooldown time of a section of flowline depends on the following:

1. Flowline design. The steel wall thickness and the thicknesses and physical properties of the insulation and other coatings.
2. Content of the coldest flowline section. The section that will reach the minimum temperature first.
3. Initial temperature of the coldest section of flowline.
4. Ambient temperature.

The flowline design and ambient temperature are usually known or specified. However, predicting exactly where the gases and liquids settle in a flowline (and thus the location of the coldest section) is difficult. First, there is the difficulty of correctly specifying the geometry. Any dip or hump of the same order of magnitude as the diameter can affect the location of gas filled sections, thus flowline topographies must be modelled to the nearest inch to have a chance of correctly estimating the distribution of phases. This has been illustrated below in Figures 3 and 4. In Figure 3 a straight line topography (5km long, 5m decline) has been plotted along with the phase distribution (liquids as green shaded). As would be expected, the liquids run to the lowest sections. However, such a geometry is unlikely to occur in reality since seabed or land topographies are not generally perfectly flat. Usually installed pipelines will follow an undulating profile with frequency and amplitude determined by the local terrain.

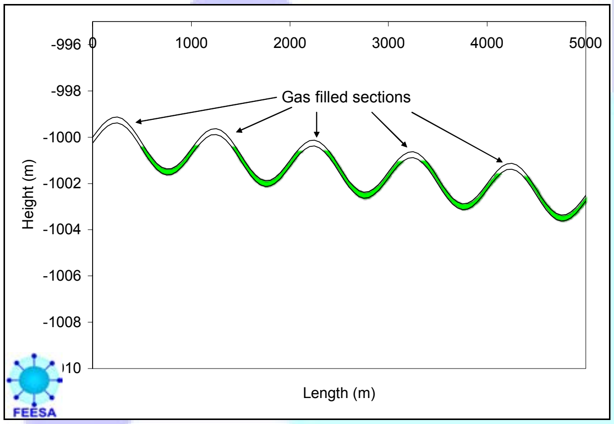
Figure 3 Straight Line Profile Phase Distribution



In Figure 4 a ‘1 in 1000’ sinusoidal undulation (amplitude 1m, wavelength 1km) has been added. This is a very gentle undulation that is only visible when the axis scales have very different magnitudes (as in Figure 4). However, this minor change produces a very different settle out phase distribution as shown. Gas filled sections are now much closer to the exit and are therefore in colder sections of the flowline on shut in and thus the two geometries have markedly different cooldown times.

Therefore, in order to predict the cool down characteristics of the coldest section, it is necessary to have a detailed profile of the pipeline in its installed condition. Clearly these data are not available during the design phase which presents a conundrum to those advocating the full transient multiphase simulation approach!

Figure 4 Undulating Profile Phase Distribution



Moreover, even if accurate topographical data are available, the phase distribution in a flowline operating in an unsteady flow regime (e.g. slug flow) depends on the history of the flow and the exact instant that the flowline is shut in. For example, whether a flowline has a large slug in its riser or not could determine whether the riser base section is liquid filled, or not.

Furthermore, the accuracy of the transient multiphase simulator must also be called into question. The exact way in which the multiple phases interact on shut down of a system like that described in Figure 4 is difficult to predict, particularly with the transient multiphase flow simulators that have been tuned almost exclusively to steady state flowing systems. Evidently, what is required is a more pragmatic approach!

In summary then, it is clear that trying to predict where gas filled sections occur after a shutdown is futile but that their location can have a large impact on the flowline cooldown time. But for most design purposes, it is acceptable to calculate the cooldown time to the nearest hour. Therefore, as a conservative approximation, it is pragmatic to assume that the cooldown time should be calculated based on the coldest section of flowline being occupied by gas.

With this assumption, the cooldown time for a given flowline to a specified temperature in specified ambient conditions is now only a function of the lowest initial temperature in the flowline, i.e. the lowest steady state temperature before shut-in.

Thus with a knowledge of how a gas filled flowline section cools as a function of initial temperature, a good estimate for the cooldown time of the flowline can be calculated.

Such a knowledge can be obtained through analytical or numerical simulation. The detail required in such simulations depends upon the complexity of the insulation system, but for a simple radially symmetric insulation system (such as a bonded SPU insulation) a simple transient radial heat transfer model can be used.

If an analytical model cannot be derived to get an expression of cooldown time as a function of initial temperature, results from a numerical simulator may be correlated to something with the correct functional form. It has been found that Newton's Law of Cooling provides a very satisfactory functional form for many insulation systems. This law yields the following expression:

$$t = B\ln\left|\frac{T_1 - T_\infty}{T_2 - T_\infty}\right| \qquad \text{Equation 1}$$

Where t is the time taken to cool from T_1 to T_2 in an ambient temperature of T_∞. B is a constant for a particular insulation type and flowline content that can be derived analytically, or tuned to the results from a numerical simulator.

For this case study, a 12-inch nominal flowline with a 2.5 W/m^2/K overall heat transfer coefficient produces a cooling constant (B) of approximately 13 hours. Although it should be noted that the result obtained is also dependent on the wall thickness, which of course depends on the flowline mechanical design.

With a cooling constant of 13 hours, the cooldown time from 45 to 20°C is 12 hours. For this system then, step (3) in Figure 2 will take about 12 hours; i.e. from a 45°C initial temperature the operator has 12 hours in which to begin a hot restart. Results from the transient simulation of a gas filled section, initially at 90°C are shown in Figure 5. Figure 6 shows a plot of cooldown time to 20°C as a function of initial temperature, i.e. Equation 1.

Equation 1 can then be applied to the results from steady state simulations to study cooldown time over a wide range of parameters such as flow rate, watercut and GOR. Indeed in this case study, the whole field life was covered with the use of a Life of Field simulator.

Figure 5 Flowline Cooldown

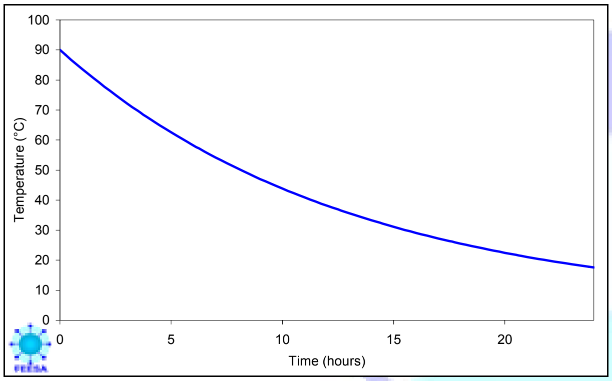
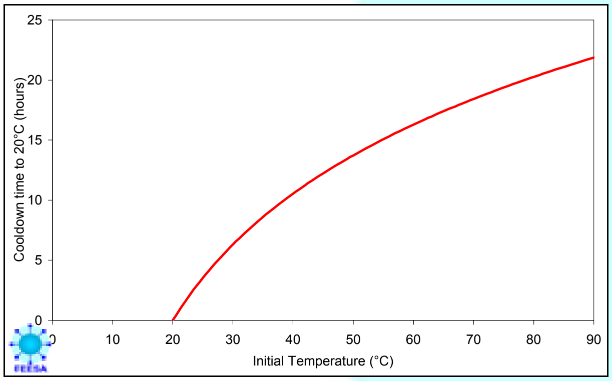


Figure 6 Cooldown Time Versus Temperature



Life of Field Cooldown Time

For this case study, a Life of Field (LOF) simulator was used to simulate the entire daisy-chained flowline system, including the wells such that the only thermal boundary conditions imposed were those of the reservoir and ambient temperatures. Well oil, gas and liquid flow rates were set to those predicted by an integrated reservoir model. Flowing wellhead temperatures were predicted by the model rather than being set to some arbitrary conservative value, thus providing an improved understanding of the temperature variations through field life. In order to assess the sensitivity of the thermal performance to lower well productivities a range of turndown cases was studied. These turndown cases included those plotted in Figure 7, where the minimum temperature in the flowline is plotted along the production profile for a range of turndown cases (20, 40, 60, 80 and 100% of the production profile). For Figure 8 Equation 1 is used to estimate the cooldown time (to 20°C) for all of these cases. As can be seen, even if this system produces 50% of the expected production profile the cooldown time of the flowline only drops by about 2 hours. However, as seen in Figure 8, cooldown time is nonlinear with turndown and at production of less than 50% the system thermal performance drops quite sharply.

Figure 7 Example LOF Turndown Temperatures

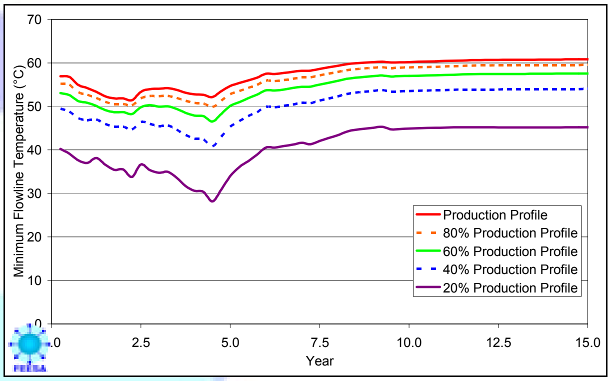
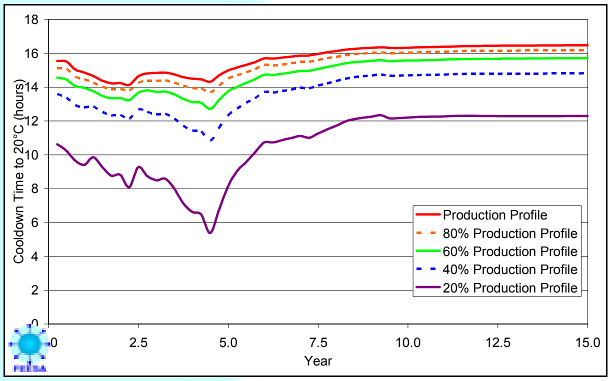


Figure 8 LOF Cooldown Time on Turndown



Conclusion

Though cold flow and active heating systems have been researched over the past few years, the economics of some field developments still favour passive insulation systems. Consequently, the subject of cooldown time will remain an issue for engineers and must be assessed early in the conceptual design.

Due to the inherent difficulties in predicting reliable cooldown times with transient multiphase flow simulators, a method has been proposed which minimises the effort required while still producing satisfactory and conservative results. This method allows a wide range of parametric studies to be carried out in order to gain a better understanding of the thermal performance of the system and its robustness to design uncertainties.

Finally, it is interesting to note that the method also offers a satisfactory procedure for calculating online cooldown times from measured flowline temperatures without the need for a transient simulator.