• STABILIZATION OF TERRAIN INDUCED SLUG FLOW IN MULTIPHASE PIPELINES

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ABB has developed a feedback control algorithm who stabilises terrain induced slug flow at the multiphase Hod Valhall pipeline in the North Sea. The Hod Valhall site is operated by BP Amoco. The control algorithm has been tested on site twice in 1999, and a prototype has been in operation since January year 2000. Results from the on-site tests and rigorous dynamic multiphase fluid flow simulations show:

- **Active control using the choke on the pipeline can stabilise the slug flow experienced at the pipeline**
- **Stabilising the flow causes smoother operation of the pipeline and the wells connected to the Hod platform**
- **At the Valhall platform the slug controller causes smooth operation of the separators and compressors, i.e.:**
  - **improved separation**
  - **no compressor trips**
  - **reduced fuel consumption in the compressor drives (reduced CO_2 emission)**

This paper demonstrates the potential for dynamic feedback control on unstable fluid flow. To our knowledge, results like these have never been published before.

INTRODUCTION

Multiphase pipelines connecting remote wellhead platforms and subsea wells are common today on offshore production facilities in the North Sea. The use of multiphase pipelines to connect remote wellhead platforms, subsea separtion units and subsea wellhead frames, too existing production facilities will only increase in the future. Long distant tie-in lines from the subsea processing units directly to on-shore processing plants are seen as realistic in the future.

One of the most challenging tasks in operation and control of off-shore processing plants and subsea separation units is disturbance rejection in the feed to the separation process. That is, to reject flow variation at the outlet of the multiphase pipes connecting wells and remote installation to the processing unit. The unstable behaviour of slug flow in multiphase pipelines is destructive for both operation and the producing facility at an offshore installation. Severe slugging can even cause platform trips and plant shutdown. Frequently, we see compressor trips due to large and rapid variation in the feed rates to the separators, caused by unstable multiphase fluid flow.

A lot of effort has been spent trying to avoid the operational problems with severe slugging and reduce the effects of the slugs by installing slug catchers (on-shore) or increase the size of the first stage separators to provide buffer capacity. In this paper we will classify these efforts as ''design changes''. For already existing installations where problems with slug flow are present and for compact separation units these design changes are not appropriate.

One approach to tackle the operational problems caused by slug flow is to reduce the effect of the slug on the operation by feed forward control. The approach taken is to detect the build-up of slugs and to prepare the separators to receive the slug. The simplest solution is to use feed forward control to the separator level and pressure control loops. However, as the slug frequency increase the feed forward control loops needs to react faster, and there is certainly a limit to how fast masses can be moved around in the separator train. In addition, feed forward control is very little robust with respect to model uncertainty (see Skogestad and Havre, 1996). In this paper we label these efforts as ''feed forward slug control''.

A common engineering approach is to use the pipeline choke valve to reduce the effect of the slug based on detecting the slug. In this paper we label this approach ''the slug engineering approach''.

However, we find that the feed forward slug control approach is not robust enough, and the slug engineering approach is not working for the Hod Valhall pipeline.

Instead, the approach taken at the Hod Valhall pipeline is to stabilise the terrain induced slug flow. This approach comes rather unexpected on both control engineers and mechanical engineers with fluid flow background. The reason is that the mechanical engineers are not aware of what can be achieved with feedback control and the theory for fluid flow processes is to complicate to be covered in control engineer's undergraduate studies.

The main objective with the work on terrain induced flow at the Hod Valhall pipeline is to overcome some of the operational difficulties caused by terrain induced slug flow in the pipeline.

Then it is important for ABB to extend some of the experience we have gained and the results we have achieved at the Hod Valhall pipeline to other types of slug phenomena. For instance riser induced slug flow and combinations of hydrodynamic induced slug flow and terrain induced slug flow (the latter occurs frequently in pipelines connecting wells to the production facility).

To overcome the difficulties with slug flow and provide control solutions which stabilises unstable multiphase fluid flow regimes might be one of the key tasks for the feasibility of compact separation units for topside and subsea use.

The objective with this paper is to present what we believe are some unexpected results on stabilisation of terrain induced slug flow in the Hod Valhall pipeline.

The outline of the paper is as follows:
First we give a brief description of the Hod Valhall site. Then we present a mental model of the cycle that appears in terrain induced slug flow. Then a brief description of multiphase simulator set up follows. We use multiphase flow simulator to give better view of what happens in the pipe. We go through the SlugCon approach for stabilising terrain induced slug flow. Demonstrate the controller on the multiphase simulator, describe some field tests performed (results and impacts). Then we finally conclude.

HOD VALHALL SITE

The Hod-Valhall site consists of the unmanned wellhead platform Hod, a 13km long multiphase pipeline and the production platform Valhall (see Figure 1 and Figure 2). The gas oil and water produced in the wells connected to the Hod platform is transported through the multiphase pipeline from Hod to Valhall. At the Valhall platform the gas oil and water in the pipeline are merged together with the production coming from the Valhall wells.

The sea depth at the Hod and the Valhall platforms are approximately 70 meters. The pipline profile is shown in Figure 3. From Hod towards Valhall the flow goes upwards the first 2.8 kilometres, then mostly downwards before the riser at the Valhall platform. From the multiphase fluid flow simulations slug flow (the flow regime) appears in the pipe at the highest point (2.8 kilometres from Hod) and in the riser up to the Valhall platform.

The pipeline instrumentation include pressure and temperature transmitters at the Hod end of the pipeline, pressure transmitter at the pipeline before the pipeline choke at the Valhall end of the pipeline. The feed from the wells connected to Hod flows through a test separator at the Hod platform. Before the gas and oil outlets are merged and enters the pipeline to Valhall, the gas and liquid flow rates are measured separately (see Figure 2).

Figure 4 shows dynamic multiphase flow simulations[1] of the Hod/Valhall pipeline. The pipeline inlet and outlet pressure, together with the pipeline outlet flow rates (gas and liquid) are shown. The main problem with slug flow is the varying flow rate at the pipe outlet. Despite the fact that the wellhead platform Hod produces less than 5% of the wells at the Valhall platform the slugs are large and intense enough to cause considerable operational problems at the Valhall platform. These problems includes:

- Large disturbances to separator train:

[1] The pipeline is simulated in the dynamic multiphase flow simulator OLGA, using the ABB developed OLGA/MATLAB link.

  - Poor separation due to rapid varying separator feed rates (water in oil). In particular poor oil water separation at second stage has been a problem in the past
  - Loss of products (oil in water)
  - Possible violation of environment restrictions (oil in water)
- Large and rapid varying loads to compressors: causing
  - Inefficient compressor operation
  - Possible compressor trips due to rapidly varying compressor loads.
- Large pressure variations in Hod wells. The large oscillation in the pressure seen at the Hod end of the pipeline can also be seen in the Hod wells containing bottom hole pressure transmitters.

TERRAIN INDUCED SLUG FLOW CYCLE

The terrain induced slug flow cycle can briefly be describe as follows:

1) Liquid build-up: Terrain induced slug flow is initiated with a period where liquid in terms of oil and water is accumulated in lower parts of the pipeline or bottom of riser.
2) Pressure build-up: At a certain time the liquid block the passage for the gas. In this situation a small amount of the gas bubbles through the liquid plug, however the main part of the gas accumulates upstream the liquid plug causing the pressure to increase.
3) Mass acceleration: At a certain pressure the liquid plug starts moving due to forces acting on the plug. ← Er det denne du mener vi glemte?
4) Mass transportation: Depending on the pipeline geometry downstream the liquid plug and the operation conditions the liquid plug may die out or it may be transported to the outlet of the pipeline/riser.
5) As the gas and liquid is transported out of the pipe the upstream pressure and the liquid flow cease.

The whole process repeats itself and the result is an unstable multiphase flow pattern where the liquid flow rate varies from zero to a significant value (when the liquid plug passes a fixed point in the pipeline) in a short period of time.

In the third step the pipeline is exponentially unstable (accelerates), and ~~. Unfortunately, this is where we are going to operate the pipe. Luckily, the pipe does not blow up (like Chernobyl). T~~the trajectory goes through an exponentially unstable manifold (manifold in mathematical terms, zone ~~or subspace~~ or phase in everyday English) into a stable manifold. This causes a limit cycle, which is known as terrain induced slug flow. It is also worth noting that the pipe stays within the unstable manifold for a very short period of time, ~~. A~~and that different parts of the pipe may be in the unstable manifold at different times as the slug moves along the pipe from its origin to the outlet or it ceases out.

Another ~~(very~~ well known~~)~~ example of a limit cycle (~~one which is a bit more dramatic~~) appearing in practical process control is ~~the~~ a compressor surge.

MULTIPHASE FLUID FLOW SIMULATION

The Hod Valhall pipeline has been simulated in the multiphase fluid flow simulator OLGA. Application specific data entered into the simulator includes:

- Fluid characterisation of the Hod oil
- Pipeline profile and diameters
- Data for pipeline choke and its position

A lot of data has default values (that is not collected for the particular case):

- Pipe roughness
- Heat transfer properties for the pipe material (the simulation is set up to simulate no heat transfer between the pipe and it's surroundings)
- Slip rate/interfacial friction between liquid and gas

Simplifications in terms of the flow into the pipe at the Hod end are made.

Although the model is simplified compared to the real pipeline it is capable to simulate terrain induced slug flow with approximately the same frequency as experienced at the pipeline. Some discrepancies were observed between real pipe data and simulations in the pressure at the inlet of the pipeline (Hod). In particular the pressure difference across the pipeline was significant larger in the real pipe than in the simulation. This can be traced back to different sources. We note that no effort was put into tuning the multiphase model to the real pipeline data, since this is generally a large and difficult exercise.

Figure 4 shows simulation of the pipeline with constant feed rate (3kg/s) at the inlet without control. From this figure it can easily be seen how the liquid pipe outlet flow rate (green line in the bottom part of the figure) is zero for some time period (about 2 hours). In that period the upstream (the liquid plug) builds up. Then the pressure upstream the liquid plug rises above the hydrostatic pressure of the liquid column in the riser the liquid accelerates and the pressure rises at the pipe outlet. The liquid is the transported to the outlet of the pipe, and the pressures decrease as the gas and liquid escapes the pipe. Then the whole process repeats.

In the multiphase flow simulator the pipeline is divided into sections of varying length. Each section contains mass in terms of liquid and gas, and across the section boundaries gas and liquid are transferred. Within the sections we can therefor record the several variables, one of these is the liquid volume fraction. Similarly, we can record the mass flow rates at the fixed points in the pipe corresponding to the positions where the sections starts and ends.

Figure 5 shows pipeline profile plot of the liquid volume fraction sampled each minute through one slug cycle. The intention is *not* to show what happens at the different *time* points *rather* to show what happens at different *positions* (fixed distance) in the pipeline through a slug cycle. Positions where the difference between the maximum and the minimum liquid volume fractions are large are positions who have the potential for initiating terrain induced slug flow. Also note that none of the sections contains only liquid at any time.

Figure 6 shows pipeline profile plot of the liquid volume flow rate sampled each minute through one slug cycle. The figure illustrates how the liquid flow rate varies at different positions in the pipeline through a slug cycle.

THE SLUG CONTROLLER

The appealing approach for engineers to deal with slug is to try to detect the slug, limit the size of the slug and thereby limit the effect it has on the separator train and compressors in the production facility (''the engineering approach''). The approach taken in the slug controller developed by ABB is different than the ''engineering approach'' in the sense that it tries to stabilise the unstable flow pattern.

The slug controller software consist of:

- Slug controller service:
  - Dynamic feedback control: The feedback controller ensures stable operation of the pipeline.
  - Feed forward control: Adjust nominal operating point of the dynamic feedback controller so that it operates in the proper operating region.
  - Slug signature: The software contains a block for detecting slugs, this is used to monitor the performance of the dynamic feedback controller
- Operator interface:
  - Functionality for starting and stopping the controller.
  - Functionality for starting stopping logging.
  - Displaying trends etc

The effect of the slug flow is evident in the measurements from the pipeline instrumentation (see Figure 2, Figure 4 and). Figure 7 shows the feedback control structure of the slug controller in the most general manner, in which it utilises pressure and temperature measurements at the inlet and outlet of the pipeline. The slug controller then uses a combination of the measurements to stabilise the pipeline. If flow measurements are present at the pipeline, then these are used to in a feed forward manner to adjust the nominal operating point of the controller.

Figure 8 Shows the slug controller in operation on multiphase flow simulation. In the first eight hours the controller is in manual and the characteristic pressure swings in the pipeline inlet and outlet pressure can be seen in the firs eight hours. The controller starts at time 28h and it uses the next 5-7hours to stabilise the pipeline in the simulation. The controller seem to have settled for a constant output value at time 38hours (10 hours from it started). However this is not true, if the controller output was zoomed up one would see that the controller constantly makes small movements in the output around the mean value. The reason is that the pipeline is operating in an unstable open-loop operating point. To demonstrate that controller act in unstable operating point in the pipeline the controller is set in manual at time 45h. The controller output after time 45hours is the mean value of the last 3 hours controller output. Then the slug flow slowly builds up. The reason why the slug the slow return to the slug flow regime is the low flow rate through the pipe and the large amount of mass which has to be moved around in the pipe. We note that the slow dynamics to the return to the slug flow regime has nothing to do with the dynamics one have to deal with in order to stabilise the pipeline. These have two different sources that have little to do with each other, and are completely different with respect to speed of response.

To prove global stability is in general a difficult task, and for a complicated process like multiphase slug flow it seems impossible since the model in these cases are so complicated. From Figure 8 it seems reasonable to assume that the pipeline is stable at least at the output (since the flow rates and the pressure is stable in the time period 40 to 45 hours), but also at the input since the input pressure is stable. However, the pipeline is quite long and someone can claim that internal stability might occur in the pipe. Figure 9 shows profile plots of the liquid volume fraction, sampled with 60 seconds sample time in the time period 41 to 45 hours. That is, 241 profile plots are shown in the main figure, all staying on top of each other. The implications are:

- Stability in the whole pipeline is achieved
- The hold-up profile shown in Figure 9 is unique for the pipeline combined with the controller and can only be achieved with use of dynamic feedback control. That is, the hold-up profile shown in Figure 9 can not be achieved without control since no open-loop stable solution exits for the pipeline with the same boundary conditions.

In a similar manner Figure 10 shows the profile plot of the liquid flow rate. The profile plots are again sampled once each minute in the time period from t=41h to t=45h, which gives 241 profile plots shown in the main figure. Since the pipeline is set up with constant inlet feed rate the steady-state solution is to have constant liquid flow rate through the pipe, which is shown in the main part of Figure 10.

Two notes from control theory about stabilisation of unstable systems:

- In order to stabilise and unstable system the control loop needs to have a minimum bandwidth (see Skogestad and Postlethwaite, 1996, chapter 5, page 184). In practical terms this means that the measurement, the controller and the actuator (valve) have to react faster than instability is developing, otherwise the control loop can not contract the instability. This mean that one can *not* have any unnecessary delays in the control loop.
- For unstable systems the sensitivity to measurement noise can be quit high (see Havre, 1998, section 4.5.2, page 78 and section 4.6 page 82). The consequence of this is that the inputs easily go into saturation with the resulting loss of stability. It is therefor important to minimise the amount of measurement noise. This also makes the control loop respond faster.

The two results above have just recently been proved mathematically and are therefore quite new results in control theory. They both play an important role in stabilisation of terrain induced slug flow.

ACKNOWLEDGMENTS

The first author is grateful to Prof. Sigurd Skogestad at NTNU for his eager to understand stabilisation of unstable chemical and now fluid flow processes. Finally, I would like to thank him for his contributions in reviewing this paper.

The first author is also grateful to BP Amoco for going away from the engineering approach to slug control, listing to the ideas on stabilisation and their willingness to test out these ideas on their site.

ABB gratefully acknowledge this.

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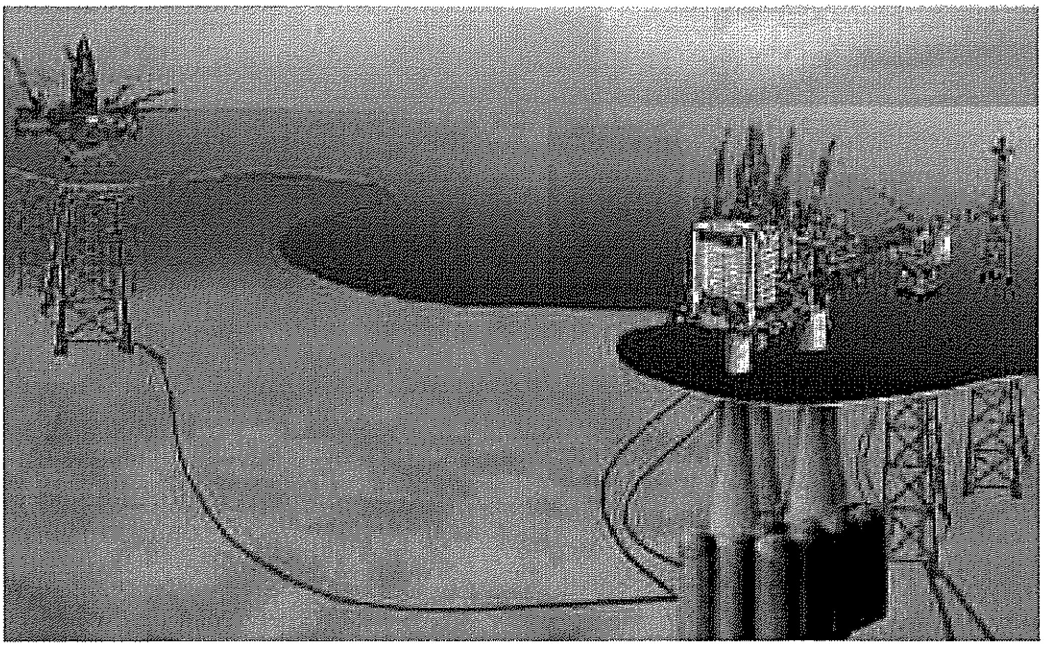

Figure 1 Multiphase pipelines connecting installations in offshore oil production is common in the North Sea.

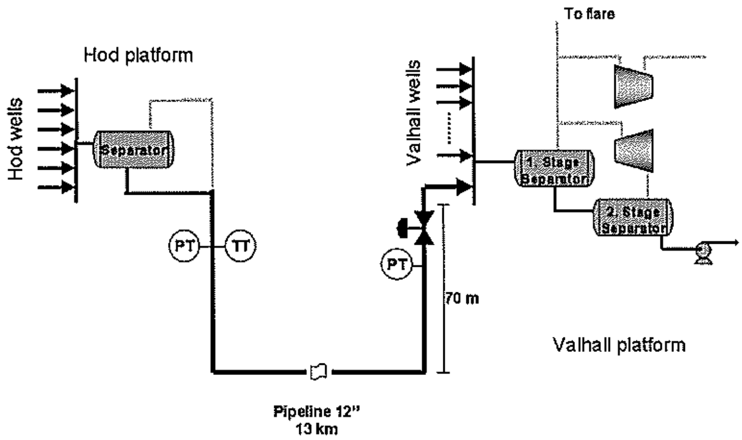

Figure 2 Topology of Hod-Valhall site.

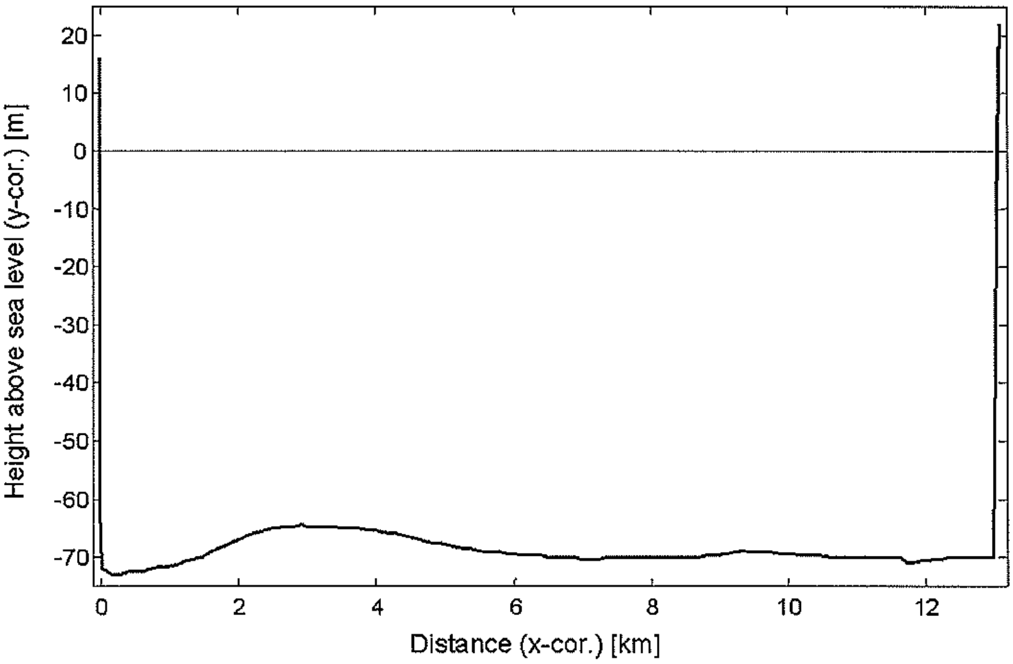

Figure 3 Hod-Valhall pipeline profile.

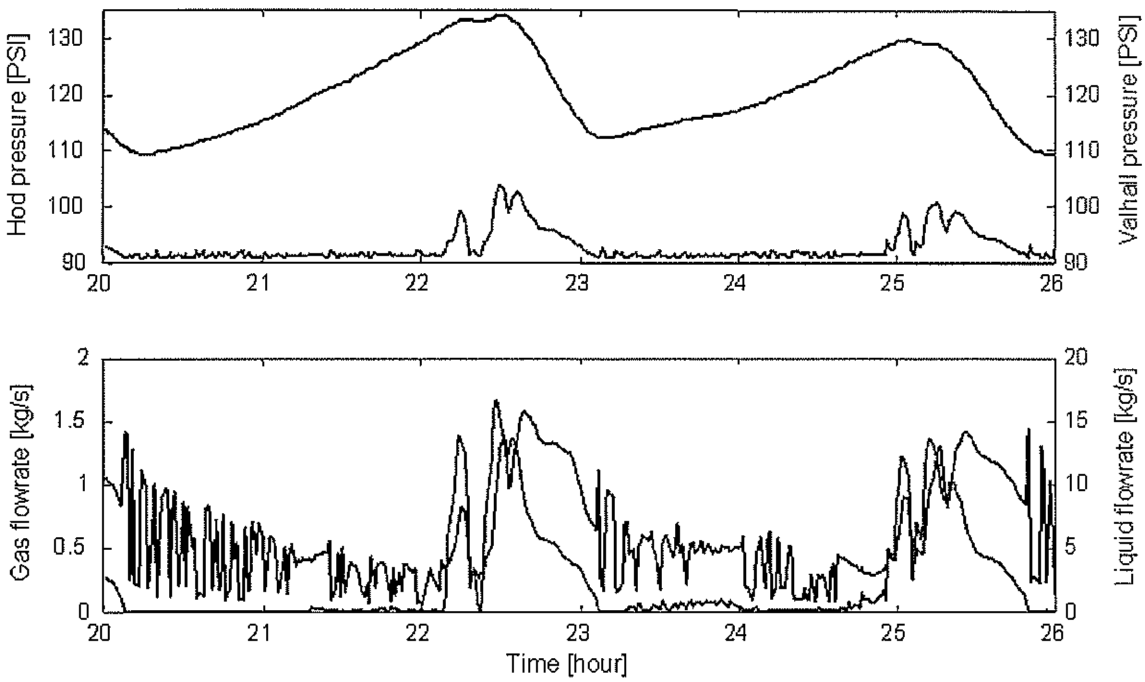

Figure 4 Open loop simulation of Hod Valhall pipeline Two slug cycles are shown. Upper part of the figure shows pipe inlet (Hod, blue) and outlet (Valhall, green) pressure. Lower part shows gas (blue) and liquid (green) flow rates at the outlet of the pipe.

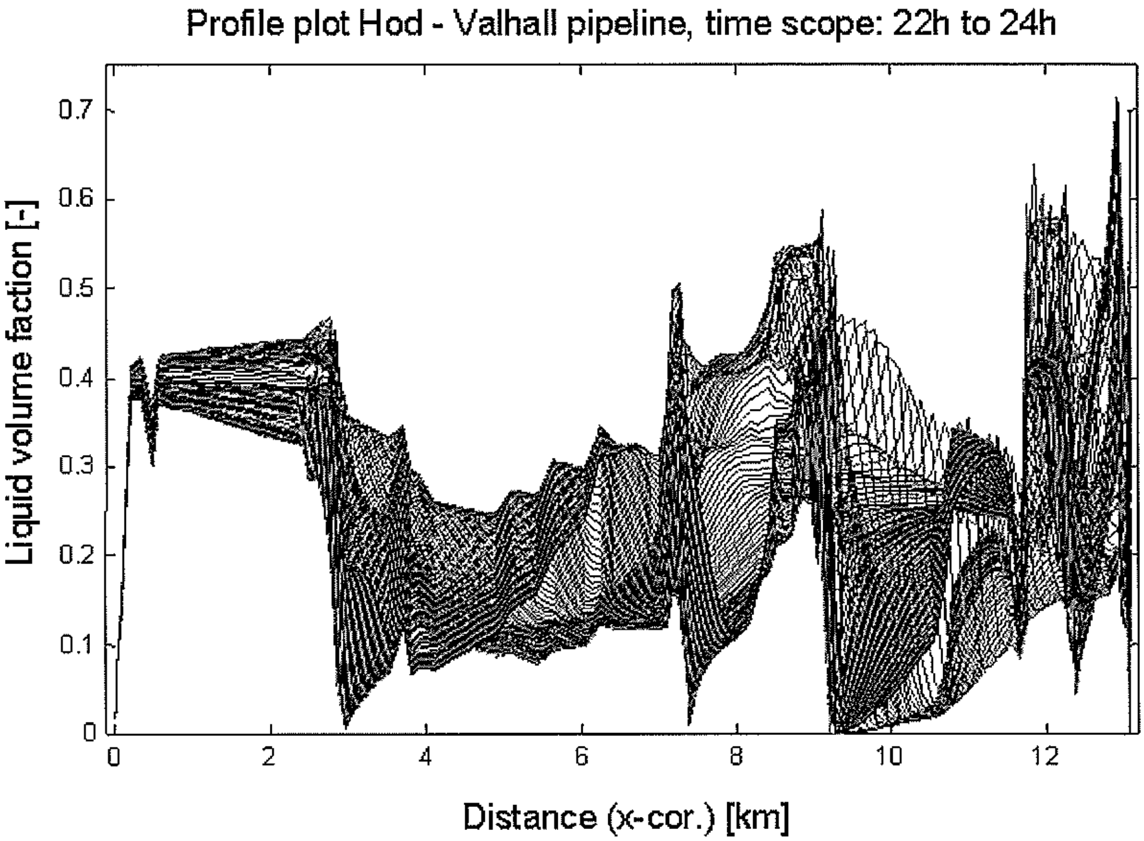

Figure 5 Pipeline profile plot of liquid volume fraction through a slug. Each line represents the liquid volume fraction pipeline profile at given time point. The sample time between each line is 60 seconds.

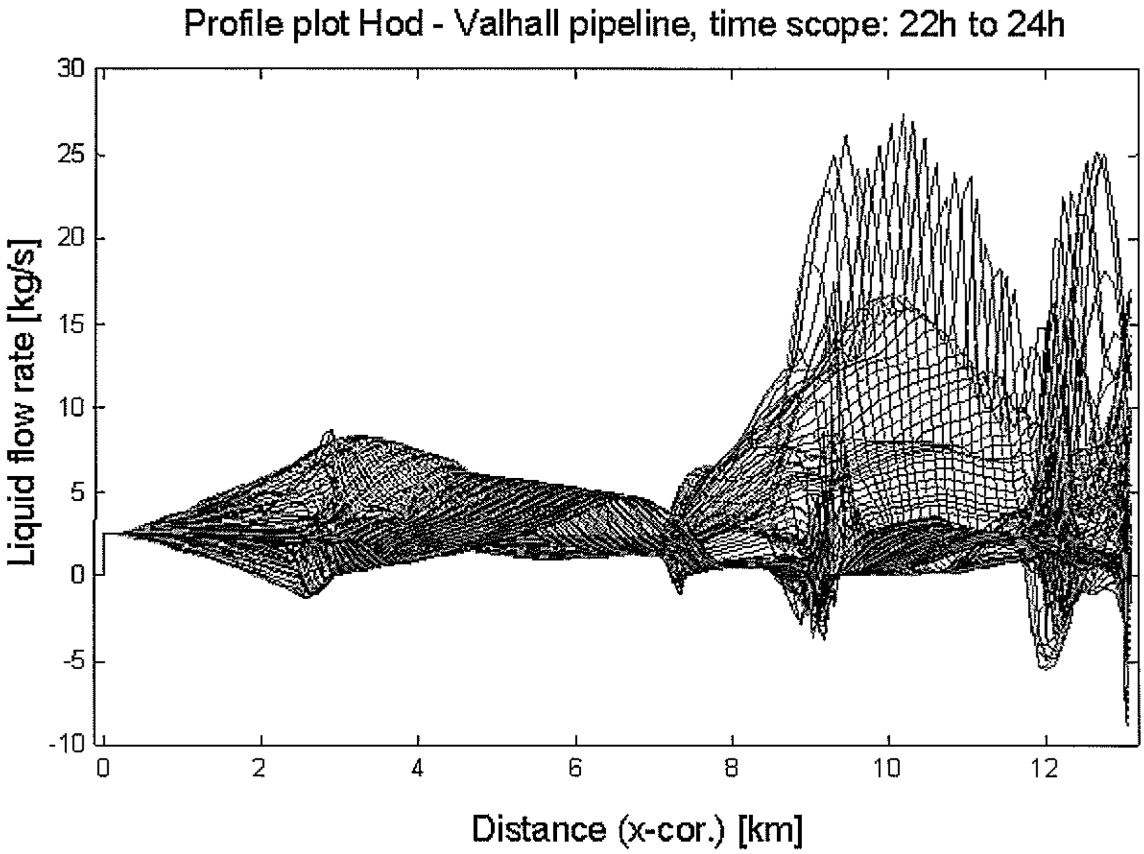

Figure 6 Pipeline profile plot of liquid flow rate through a slug. Each line represents the liquid flow rate pipeline profile at given time point. The sample time between each line is 60 seconds.

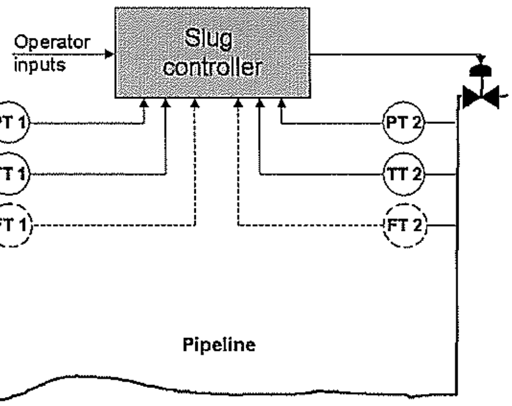

Figure 7 The slug controller feedback structure for stabilisation.

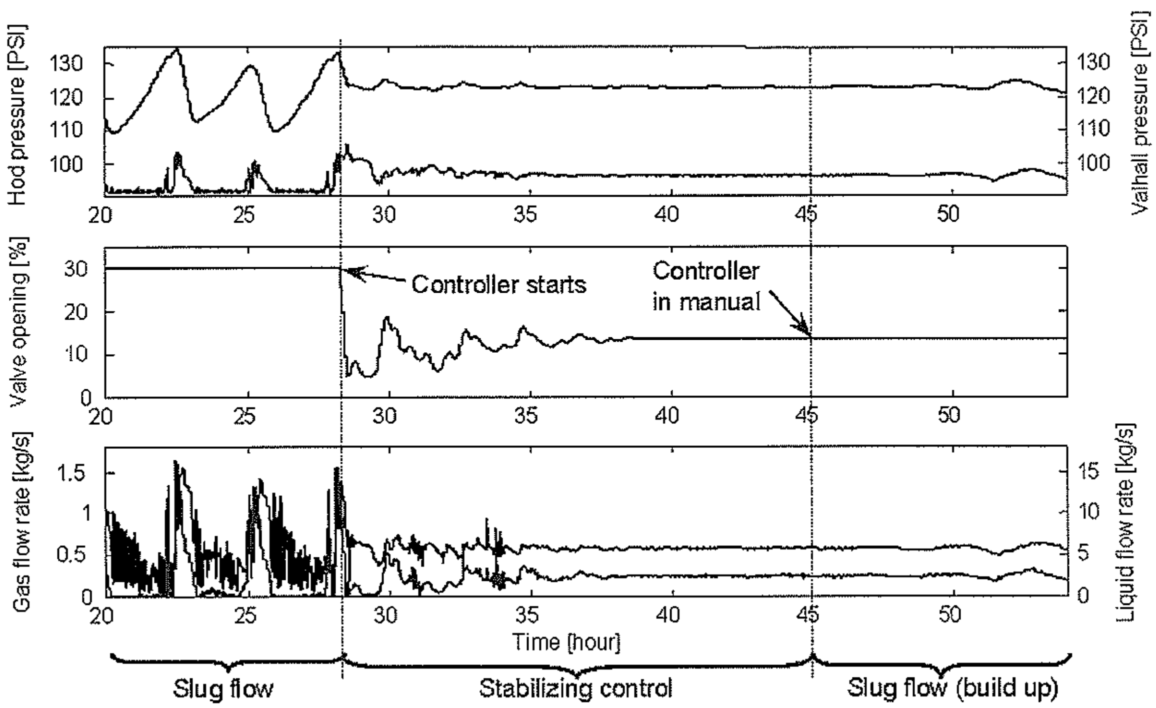

Figure 8 Stabilising control of terrain induced slug flow. Controller starts at t=28h, runs util t=45h, then valve kept constant and slug flow slowly builds up.

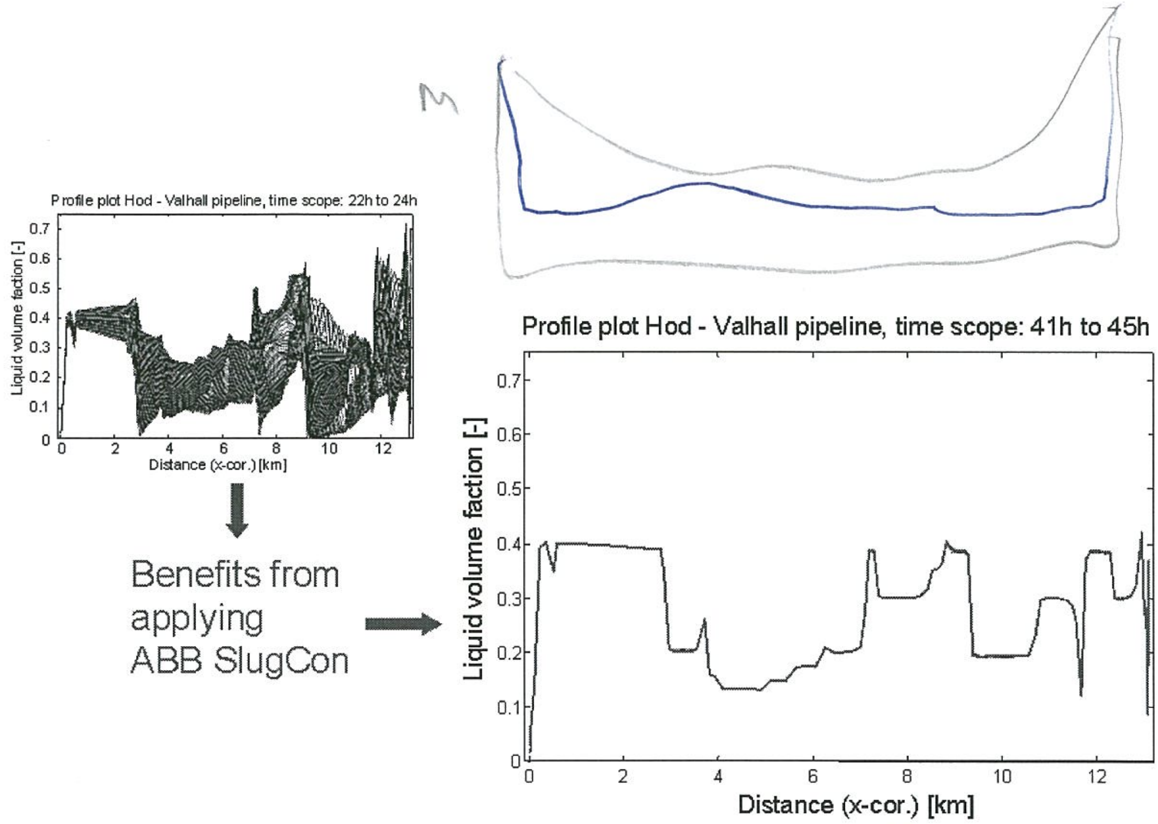

Figure 9 Pipeline profile plot of liquid volume fraction. Upper ~~right~~ left without slug control, same as Figure 5. Main figure, with slug control, 241 profile plots are shown. The sample time between each plot is 60 seconds, all lines on top of each other. Implications the whole pipeline is stable.

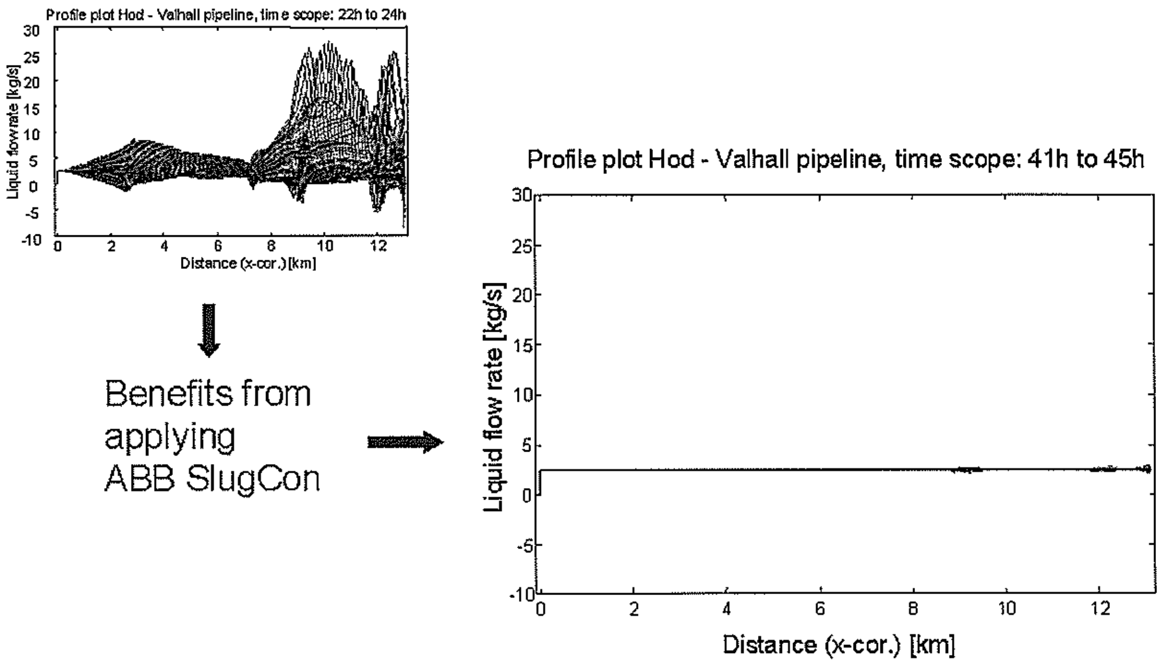

Figure 10 Pipeline profile plot of liquid flow rate. Upper right without slug control, same as Figure 6. Main figure, with slug control, 241 profile plots are shown. The sample time between each plot is 60 seconds, all lines on top of each other. Implications the whole pipeline is stable.