

Advancing Asset Reliability and Process Monitoring using Fiber Optics Technology

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Abstract

The pressure letdown area of alumina high temperature Digestion facilities is subject to highly erosive flow conditions emanating from elevated velocities of flashing/boiling abrasive slurry. As part of continued improvements in the design and asset reliability of these facilities, advanced measurement techniques using optical fiber have been employed to refine our understanding of the fluid mechanic behavior across critical components such as control valves and chokes. Incorporation of these findings into current mathematical models allows for real-time, accurate assessment of flow conditions within the piping system which can then be used to predict rates of erosive wear. Following this primary focus, other areas of application for fiber optic measurement techniques were explored, including alternative level/interface detection methods and detailed temperature profiling of piping and equipment. This paper reviews the application of fiber optic sensor technology in the execution of these aims.

Keywords: Asset Reliability, fiber optics temperature detection, two-phase / three-phase flow, level measurement.

1. Introduction

This paper introduces advanced fiber optic measurement techniques, and summarizes two trials that apply Fiber Bragg Grating technology to two industry challenges.

Firstly, Fiber Bragg Grating technology is applied to provide detailed thermal profiling of the interconnecting flash tank slurry piping of Bayer Digestion facilities. Results of this trial are used to study the fluid dynamic fundamentals of two-phase flashing slurry systems, with focus on the flow characteristics of mechanical chokes/orifices. Findings are then incorporated to provide accurate slurry piping velocity profiles, detailing the onset and development of abrasive two-phase flashing flow throughout the piping system. This forms the basis of a Digestion Asset Reliability System, where real-time piping component wear rates and residual life are graphically and interactively provided.

Secondly, Fiber Bragg Grating technology is assessed for its suitability as an alternative level detection method for process tanks or vessels. Here, the fiber sensors are mounted on the external wall of a vessel, providing a non-intrusive alternative to traditional level detection methods. Two vessels of varying wall thickness are trialed, and the impact of wall thickness on level responsiveness is assessed.

2. Technology Overview - Fiber Optics Based Sensing

Various fiber optics based sensing technologies are commercially available and widely used in industries such as oil & gas, structural health monitoring, aerospace, space and marine. Commonly, optical sensor based technologies are deployed for applications requiring long distance pipeline or structural monitoring, allowing detection of leaks, deformation (strain) of

structures or vibration. Hatch has previously applied fiber based sensor technologies for shorter distance & detailed applications such as furnace refractory condition monitoring via tap-block temperature profiling [1].

Fiber optic sensing technologies take advantage of one or more properties of light to allow measurement of various external environmental parameters throughout the length of the fiber cable itself. That is, temperature, strain or vibration may be profiled over large distances using passive optical fiber cable.

Broadly, there are three categories of established optical fiber based sensing technologies:

1. Single-point, where a single sensor is typically located at the end of the fiber cable (Fabry-Perot),
2. Multi-point, where two or more discrete sensors are positioned at the required points along the fiber cable (Fiber Bragg Grating),
3. Distributed, where the entire fiber cable length is ‘profiled’ for the particular measurement (Rayleigh, Raman and Brillouin).

Table 1. Comparison of optical sensing technologies [2].

Technology	Topology	Range	Temp.	Strain	Pressure	Vibration
Fabry-Perot	Single-Point	< 10 km	Yes	Yes	Yes	Yes
Fiber Bragg Grating	Multi-Point	< 50 km	Yes	Yes	Yes	Yes
Rayleigh	Distributed	< 70 km	Yes	Yes	No	No
Raman	Distributed	< 20 km	Yes	No	No	No
Brillouin	Distributed	< 50 km	Yes	Yes	No	No

Hatch performed a review of the various technologies listed in Table 1, and took part in laboratory trials to witness temperature and vibration measurement capabilities and accuracies. Following this technology review, Hatch selected a highly accurate Fiber Bragg Grating (FBG) based system for this trial campaign. FBG technology offers a lower cost option for shorter distances at a much higher spatial accuracy, enabling specific point measurements at any required location or interval along the length of the optical fiber.

2.1. Fiber Bragg Grating Technology

Fiber Bragg Grating technology provides a high-speed, multi-point sensing method that allows for discrete point temperature measurements at any predefined location along a fiber cable. Bragg Grating refers to the modification of optical fiber where a series of ‘mirrors’ are inscribed into the fiber core at each required measurement location. This creates a refractive index perturbation that reflects light back up the fiber cable at a wavelength specific to each inscription. Therefore, by inscribing each Bragg Grating with a different signature wavelength, multiple sensors can be located along a single fiber cable or a series of cables daisy-chained together.

The selected FBG technology provider utilizes a highly precise tunable laser that sweeps through the measured wavelength spectrum at a rate of up to 8 kHz. With every sweep, each sensor location (Bragg Grating) along the fiber cable reflects its specific wavelength back up the cable, generating an array of discrete wavelength peaks for interpretation. The reflected wavelength of each Bragg Grating will deviate from its signature in response to thermal expansion or physical stretching (strain) of the glass fiber core, and this deviation may then be accurately converted to temperature or strain data via well-established correlations [3]. Figure 1 demonstrates this mechanism, where change in temperature or strain can be seen to deviate (increase) the wavelength of the reflected light.

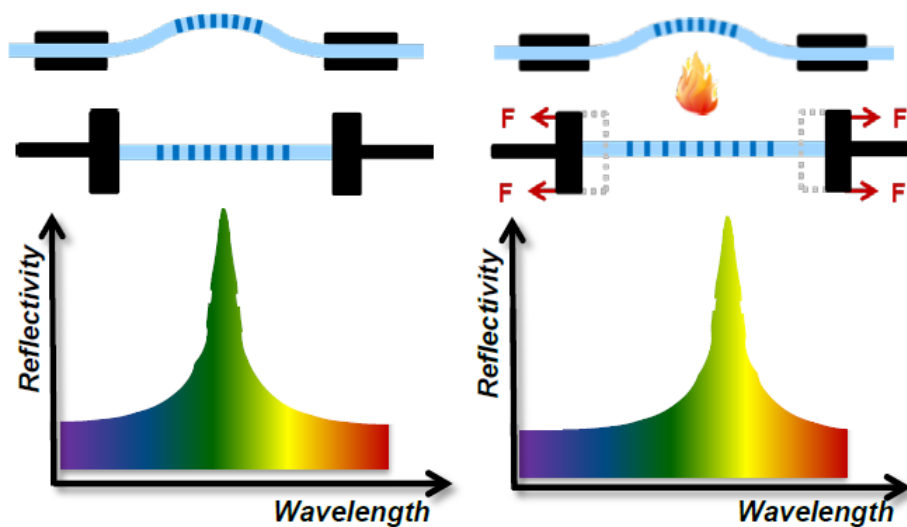


Figure 1. Sensing mechanism of Fiber Bragg Grating [5].

A key drawback of the FBG mechanism is its inability to distinguish between temperature and strain. This implies that accurate temperature measurements may only be made when strain effects are limited or accounted for. This is often addressed in the design of the sensor cables, whereby a lubricated sheath is used to separate the glass fiber core from the external protective jacket, allowing unobstructed movement of the core in response to thermal expansion.

In addition to measurement of temperature and strain, FBG technology has successfully been deployed (via additional passive FBG based sensors) for measurement of pressure, acceleration, above-sea and sub-sea acoustics and tilt [4, 5].

3. Digestion Facility Asset Reliability

The pressure letdown area of alumina Digestion facilities is subject to highly erosive flow conditions emanating from elevated velocities of flashing/boiling abrasive slurry. Consequently, slurry piping and fittings within these facilities, including valves, piping spools, control elements and other wear consumables, are subject to continual non-destructive testing (NDT) for wall thickness measurement as well as regular internal inspections and change-outs.

To develop a predictive real-time asset reliability model for these facilities, a fundamental understanding of the fluid-dynamic behavior of these fittings in two-phase flashing fluid flows is required. Once developed, this may be used to supplement routine NDT information to contribute to integrity of residual life data and assist with spares inventory management. It may also be used to set operational limits such that conditions that are predicted to lead to elevated erosion rates are avoided or limited (where possible) in time exposure.

A series of plant trials were undertaken to refine existing two-phase hydraulic models and estimations of pressure loss for key pressure dissipating piping components such as restricting orifices, control valves, and general piping fittings.

The complexities of two-phase flashing slurry systems have long been studied, and several mathematical two phase fluid flow models have been explored to accurately represent digestion hydraulic systems. A key hydraulic input relates to the discharge coefficient (flow characteristic) of chokes such as restricting orifices. The dimensionless discharge coefficient

effectively de-rates the calculated mass flux of a ‘non-ideal’ choke from that predicted using ideal nozzle models. Specifically, the discharge coefficient accounts for number of non-ideal impacts of geometric & friction influences, viscous flow effects and heat exchange [6, 7]. This information is readily available for single phase liquid or vapor systems [8], which Hatch has validated as part of previous investigations. However, for saturated or two-phase flashing slurry systems, where phase change occurs throughout the choke, the single-phase discharge coefficients are no longer relevant. The two-phase coefficients are particularly complex to predict via direct pressure measurement, mathematical approximations, CFD or otherwise. They are also dependent on the fluid state at the choke inlet (subcooled, saturated or two phase) and are therefore dynamic parameters.

This fiber optic trial aimed to empirically quantify the relationship between fluid state at the choke inlet and hydraulic performance characteristics (discharge coefficient) of the choke for two-phase flashing slurry systems.

3.1. Trial Overview

A series of FBG temperature sensor cables were temporarily mounted to the interconnecting slurry piping between two high pressure flash tanks operating in the vicinity of 2,500 kPa gauge (~235 °C). Sensor cables were mounted along strategic piping spools (see Figure 2 & Figure 3), with an additional 3 single point FBG sensors installed for cross reference. Particular focus was placed on obtaining high-quality temperature data immediately upstream of the restricting orifice, and downstream at a sufficient distance to allow for pressure recovery and dissipation of eddies generated at the orifice outlet. This measurement of differential temperature may then be used to calculate differential pressure across the choke, hence a measure of its actual pressure dissipating duty.

Sensors were also positioned such that the fluid ‘quality’ (vapor extent) could be calculated at the inlet to the choke. This included vapor exiting the upstream flash tank, as well as subsequent flashing occurring within the underflow piping. Based on this data, calculated vapor fractions at the inlet to the orifice ranged from 0.1 to 3 % by mass (**Figure 4**).

In total, 73 discrete FBG temperature sensors were installed throughout the flash tank slurry piping network and connected to a FAZ Technology I4 FBG interrogator unit.

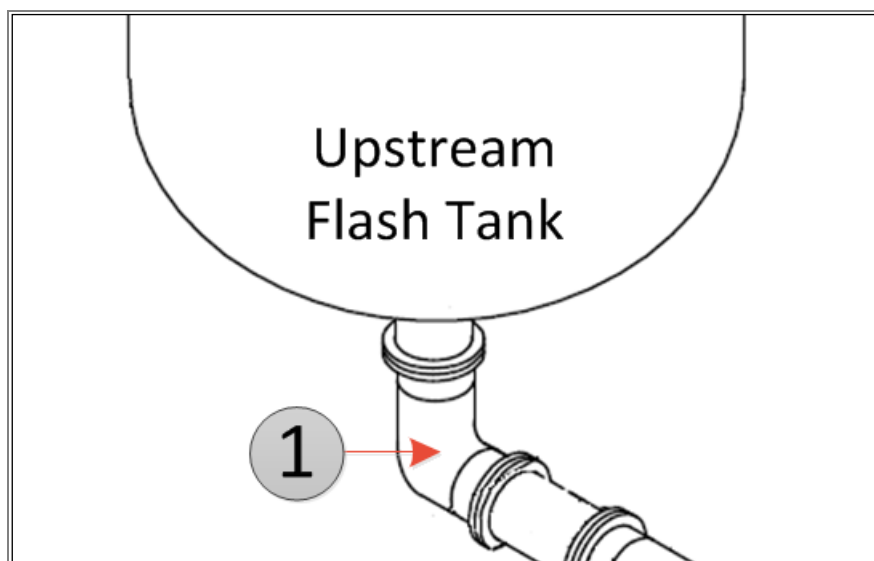


Figure 2. Temperature sensor locations – outlet of upstream flash tank.

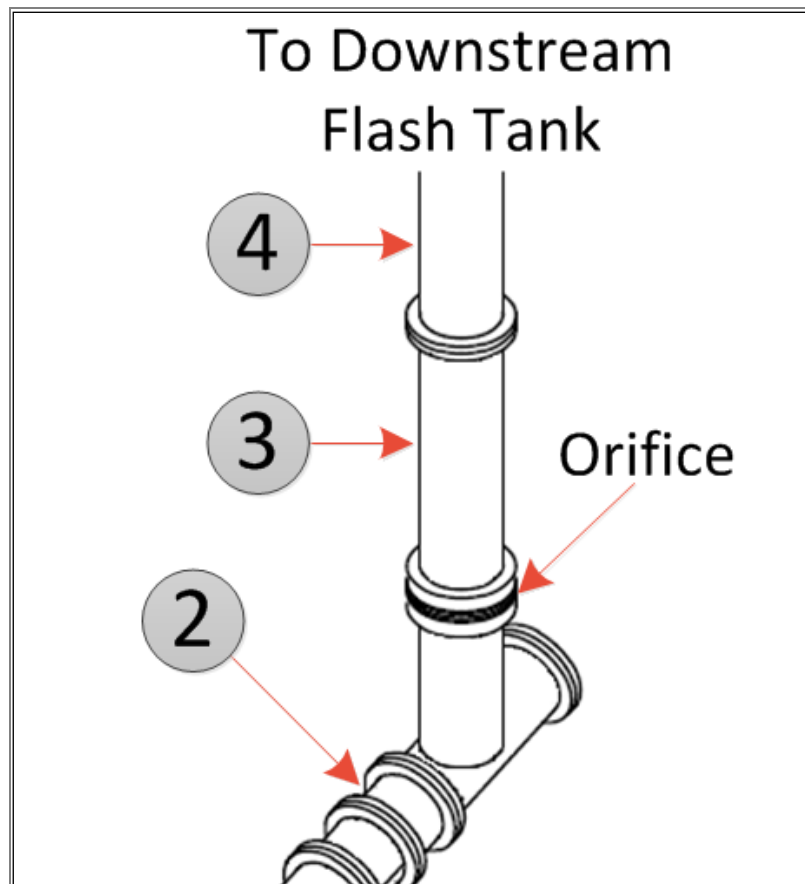


Figure 3. Temperature sensor locations – restricting orifice.

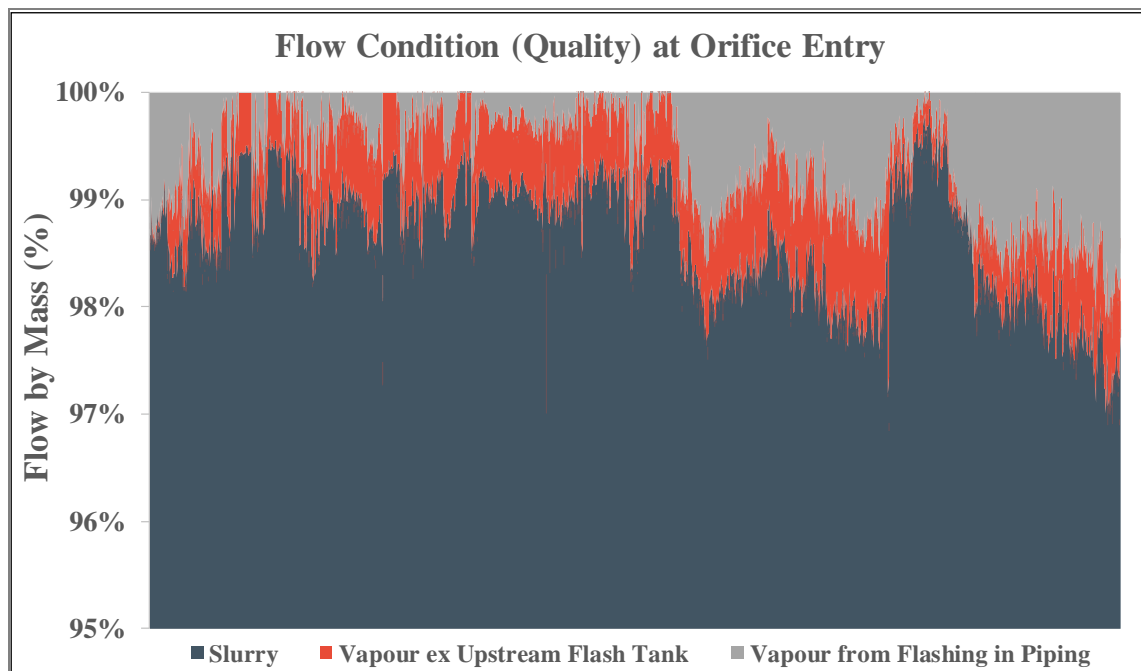


Figure 4. Flow condition (quality) at orifice entry.

3.2. Findings and Results

Figure 5 shows the orifice differential pressure, as measured via differential temperature across the orifice, along with the calculated discharge coefficient over the duration of the trial. Further to this, **Figure 6** compares the discharge coefficient to the fluid quality.

These unfiltered results suggest that discharge coefficients tend from 0.7 at low quality, towards 1.0 as vapor quality increases. Note that this trend is aligned with general literature values for single phase subcooled liquid discharge coefficients (0.62) and single-phase vapor/gas coefficients (0.975).

These trial results for the flashing caustic slurry align well with current mass flux based model theory for two-phase flashing systems across a restricting orifice.

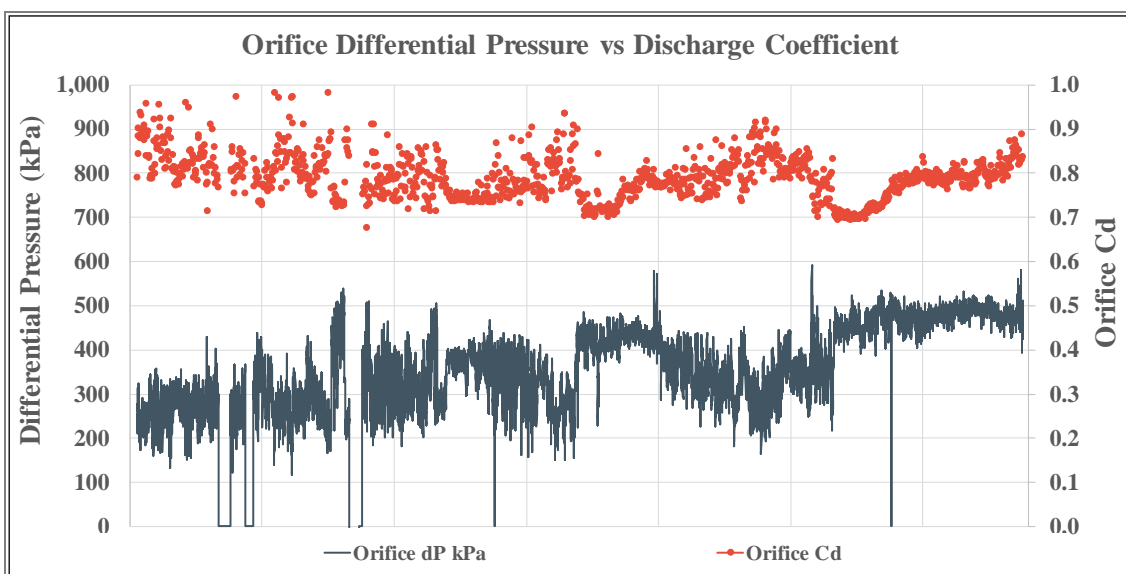


Figure 5. Orifice differential pressure vs. discharge coefficient.

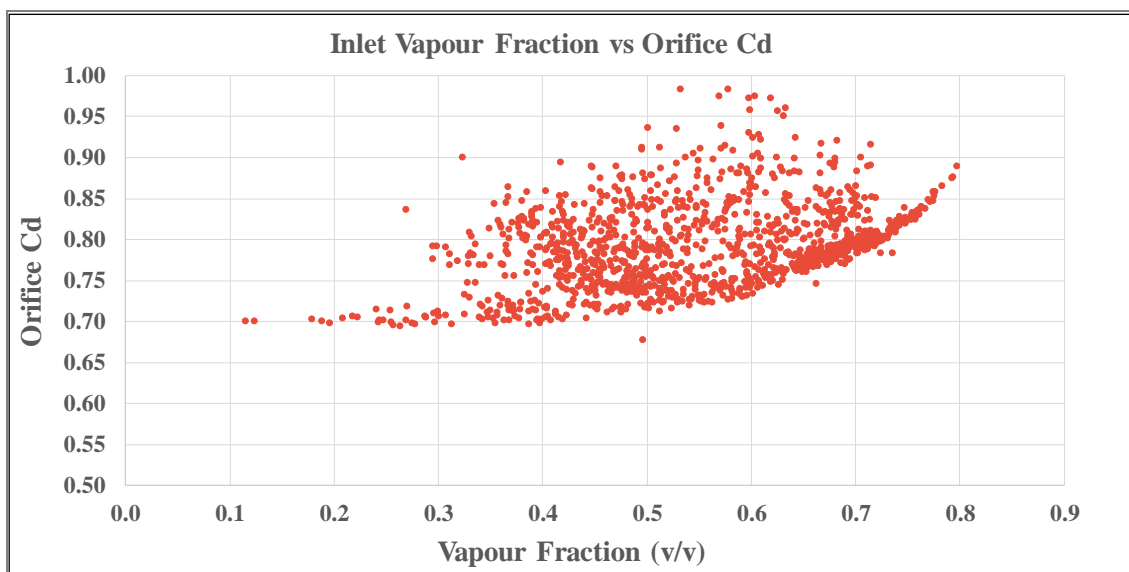


Figure 6. Vapor fraction at orifice inlet vs. discharge coefficient.

3.3. Industrial Application – Digestion Asset Reliability Model

This campaign of plant trials undertaken by Hatch empirically assessed various aspects of two-phase flashing slurry systems. Findings from these trials are used to confirm fluid dynamic fundamentals such that they can be accurately modelled across a range of process operating conditions experienced within Bayer Digestion facilities.

This layer of integrity allows these models to form the basis of a predictive real time Digestion facility asset reliability tool which can supplement periodic NDT data in the refinery setting. Key aspects of this system are as follows:

1. Real-time visual status of the piping system velocity profile, including onset and development of two-phase flashing flow.
2. Visual status of piping component residual life.
3. Consolidation of piping component maintenance data, such as:
 - a. changeout history & photos
 - b. NDT thickness results
 - c. predictive wear rates of piping spools, fittings and control elements
 - d. estimates of remaining life
4. Links to spares inventory management/procurement systems.
5. Links to maintenance scheduling systems.

The piping system assessed within this trial (Figure 2) has been incorporated into a demonstration Digestion Asset Reliability model to visually monitor velocity profiles during a typical equipment rotation. This dynamically demonstrates (visually) the impact on piping velocity profiles and consequently, wear rates for each piping component. Of key interest is the location of onset of two phase flashing, indicated by a local acceleration in piping component velocity.

In addition to utilization of this model as an asset reliability tool, this model can now assist with:

1. hydraulic debottlenecking to unlock production constraints
2. Alerting to transient state conditions (e.g. scale restrictions etc.)
3. Eliminating unplanned outages from erosion events not captured by periodic NDT campaigns
4. Refining the hydraulic design of the interconnecting piping to reduce vapor short-circuiting of the condenser circuit, thereby improving energy recovery and reducing Digestion energy consumption
5. Provide operational guidance on boundary conditions for process parameters such that conditions leading to excessive erosion and/or vapor bypassing may be reduced or eliminated.

4. Level Detection

FBG technology provides quasi-distributed temperature detection, enabling thermal profiling along piping or equipment. This capability lends itself to live detection of thermal gradients such as those that may be present at the level interface of a process tank or settler.

A level detection trial was conducted on a process vessel where a temperature gradient was visible at the level interface via thermal imaging. Key objectives of this trial were to:

1. Independently validate readings from the existing guided wave radar level instruments.

2. Observe level dynamics during normal operation, particularly the degree of surging.
3. Prove the application of Fiber Bragg Grating temperature detection technology for the indication of vessel level where a temperature gradient exists across the level interface.

4.1. Trial Overview

The subject equipment for this trial were accumulator vessels installed on the suction and discharge of triplex piston positive displacement pumps. These are enclosed pressure vessels with an operating level spanning approximately 2.0 m. Level of the process fluid (a Bayer slurry operating at $\sim 80\text{ }^{\circ}\text{C}$) is controlled via the injection or venting of an inert gas. A thermal gradient is therefore present between the process fluid and gaseous space above it, allowing the level interface to be thermally detected.

A 2.0 m long FBG cable was externally mounted on the wall of each vessel spanning the operating level range. Sensors were spaced at 10 cm intervals along the cables, which totaled 21 discrete temperature measurement locations per vessel.



Figure 7. FBG sensor cable mounted to pump discharge accumulator.

An independent guided-wave radar level indicator was also present on each vessel. The relative level of each FBG sensor was converted to a level percent consistent with the ranging of the radar. Results of this trial compared radar readings to the actual location of the level interface as detected by the FBG system, hence assessing the calibration of the radar.

4.2. Findings and Results

Figure 8 displays the typical vessel wall temperature data captured from an accumulator vessel using a FAZ Technologies I4 FBG interrogator unit. Here, sensors are numbered in order of ascending vessel level such that Sensor 01 is located at approximately 30 % level and Sensor 21 is located at approximately 105 % vessel level.

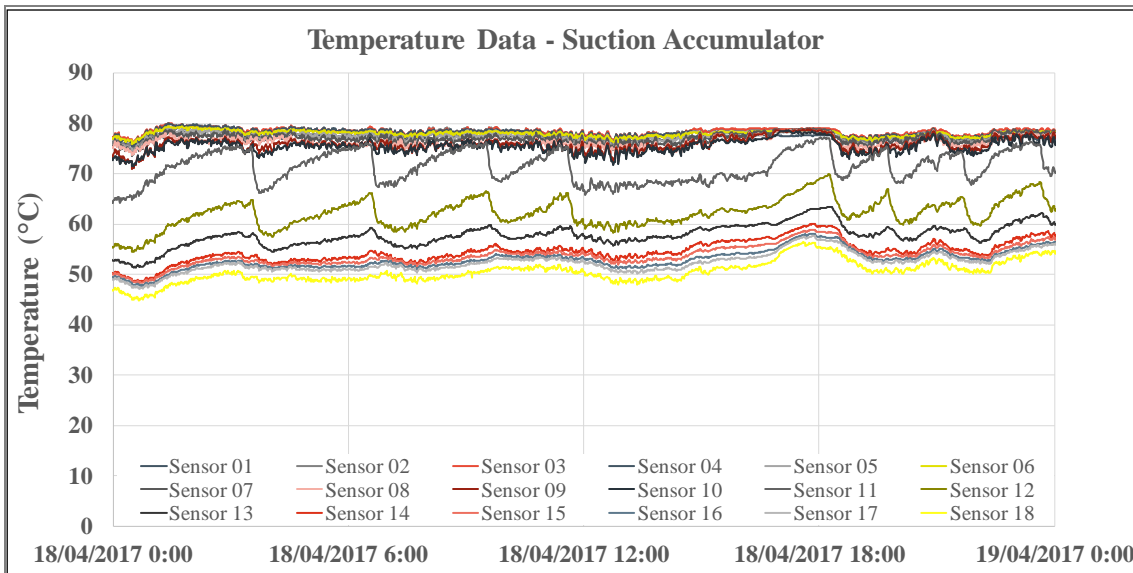


Figure 8. Temperature data for suction accumulator vessel wall.

Sensors 10 and below maintain at the slurry temperature, while sensors 14 and above maintain at the cooler air temperature at the top of the vessel. Sensors 11, 12 & 13 fluctuate in accordance with the moving level interface.

The level interface can be further visualized by converting the temperature data to a color scale, similar to that produced via thermal imaging. Figure 9 shows this for a snapshot of the suction accumulator FBG data.

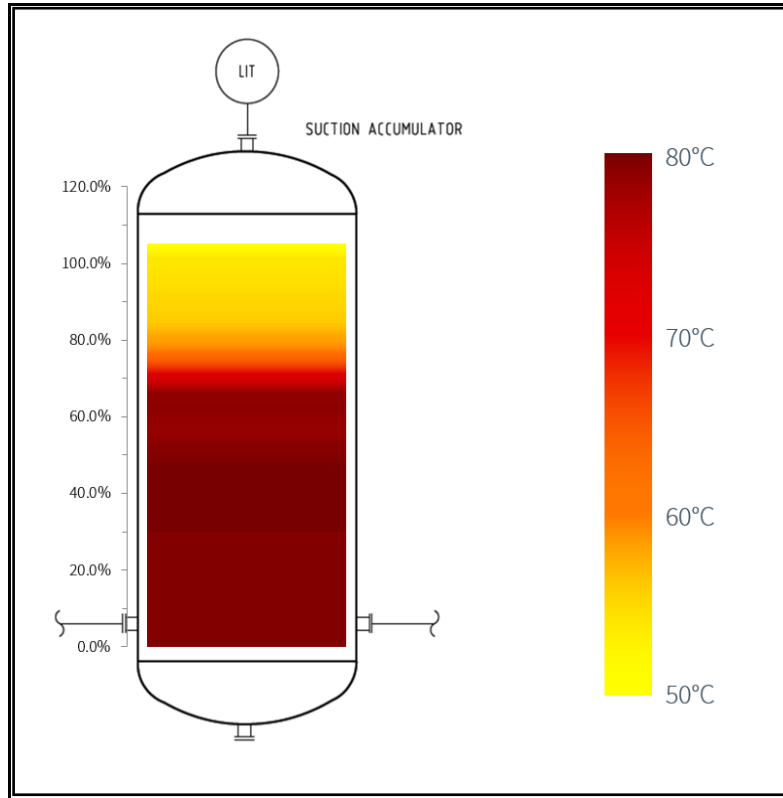


Figure 9. Suction accumulator temperature profile.

Given the 10cm resolution of temperature sensing points (as per the FBG cable sensor spacing), the actual level in Figure 9 may vary between 66 – 71 %. The temperature gradient was then assessed to determine the location of the level interface between two sensor points. This produced reasonably continuous level data that closely matched the radar indicated level. This data was then back-checked against visual temperature profiles (e.g., Figure 9) to ensure no level offset. Figure 10 below shows the results of this interpolated level indication compared to the radar data for the suction accumulator.

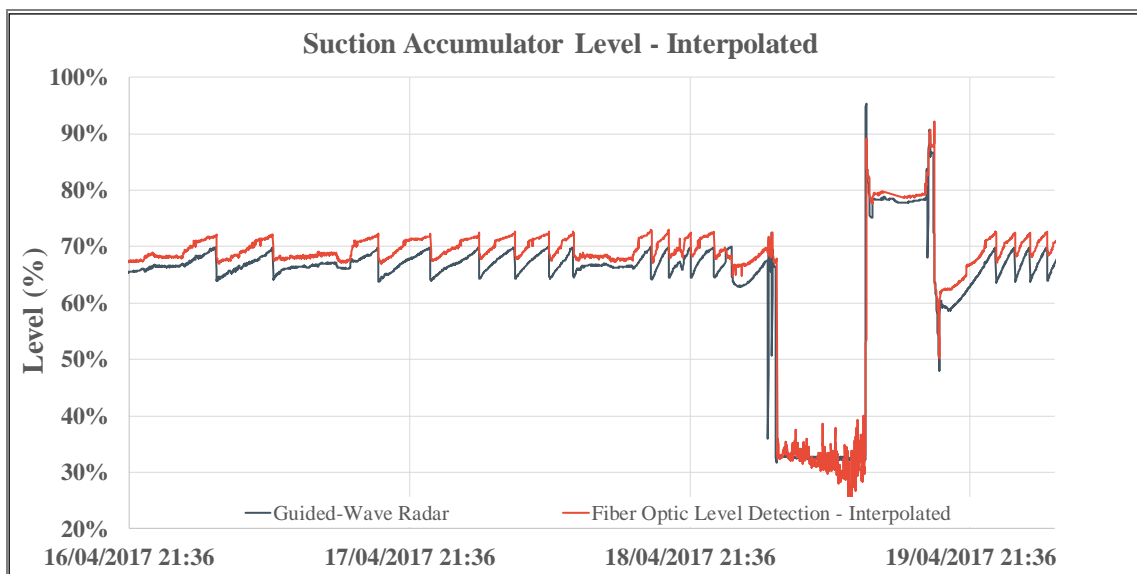


Figure 10. Suction accumulator interpolated level assessment.

As seen above, some noise was present in the FBG level indication during periods where the vessel was offline and drained, due mainly to the limitations of the trial installation.

A key unknown of this trial installation was the impact of thermal inertia and thermal resistance introduced by the accumulator vessel wall, as well as the steel armoring and internal sheathing of the sensor cable. While the FBG technology provides near-instant temperature responsiveness, the above introduces lag in temperature change at the FBG sensor following a change in level. Of particular interest was the impact of the different wall thicknesses of the suction accumulator compared to the thicker walled discharge accumulator. This was assessed by comparing radar level output to the thermal gradient change of the sudden level dampening seen during inert gas injection. A 1 – 2 minute delay was observed in FBG response for the suction accumulator, and a 3 – 4 minute delay was observed for the thicker walled discharge accumulator, both of which are limited by the data resolution of 1 minute.

There is significant scope to reduce this lag through improvements to the installation and calibration of the fiber system. Inaccuracies were minimized as far as practicable for the trial installation, namely ensuring consistent contact between cable sensor locations and vessel wall surface, and minimization of external thermal interference via the use of insulation and tape. Further improvements may be made for permanent installations, allowing detection of much finer temperature gradients, hence reducing lag, eliminating noise, and improving responsiveness.

4.3. Industrial Application – Non-Intrusive Level Detection

The above results empirically prove the application of Fiber Bragg Grating technology for level measurement applications where a thermal gradient exists at the level interface. Results also show that this system may be mounted external to the vessel, such that the instrument detection is non-obtrusive into the process stream.

This method for level measurement may be beneficial in applications where:

- process conditions or vessel internals cause interference with traditional level detection methods.
- the process fluid is incompatible with the materials of construction of internally mounted level instruments.
- it is desirable to access and maintain the level sensor without the need to take the process equipment out of service (as required with internally mounted instruments).

5. Conclusion

This paper has summarized findings of trials applying advanced fiber optic measurement techniques to two industry challenges:

1. Assessment of fluid dynamic fundamentals of two-phase flashing slurry systems.
2. An alternative level detection method utilizing externally mounted sensors on services where a thermal gradient exists at the level interface.

Findings of the first objective of this trial aligned well with current mass flux based model theory for two-phase flashing systems across a restricting orifice. This validation, along with findings of additional fluid mechanic trials, form the basis of an empirically confirmed Digestion Asset Reliability Model that may be used for predictive maintenance activities.

This trial campaign also provided highly encouraging results in the application of FBG technology for level detection applications where a temperature gradient exists across the level interface. This method has the key advantage of being externally mounted to the vessel wall, ideal for applications where traditional level detection may be problematic (due to aggressive process conditions, convoluted vessel internals, or process interference) or intermittent (such as settler interface divers). The ability to externally mount the sensors provides a maintenance/accessibility advantage, potentially leading to reduced vessel downtime that may be experienced due to failures of traditional internally mounted sensors. Results of this trial encourage further trials of additional level detection applications, including settler solids interface detection.

6. Acknowledgement

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7. References

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