CONNECT AND PROTECT

INTELLIGENT PIPELINES FOR TEMPERATURE CRITICAL FLUIDS

nVent
RAYCHEM

Abstract –Pipeline transport for temperature-critical fluids such as sulphur, paraffinic or heavy crude oil, phenol, caustic, asphalt, vacuum gas oil, chlorine and sulphuric acid pose many challenges for pipeline system designers and end user operators. Each of these fluids offer unique critical issues in the performance and operational life of the pipeline, but all share a common goal of safe and reliable operation. While most attention has historically been placed on assuring that the required pipeline temperature is achieved during normal operations, a failure to address the safe, reliable operation during a no-flow, heat up or cool down scenario could result in a plant shutdown due to a pipeline rupture or damage from fluid physical state changes that occur as a function of temperature. In some cases, these fluid state changes may result in excessive pipe movement and/or pipe anchor failures. In worst-case scenarios, the failures may result in catastrophic events such as the discharge of volatile liquids and gases, or toxic fumes – resulting in damage to the environment and even the possible loss of life.

Figure 1. Alaskan Cross-Country Pipeline

The current best practice is to employ skilled operators (who may or may not be specially trained) to manage the proper operation of these critical pipelines. Until now, the ability to implement an automatic program for critical pipeline operation has served as an idyllic vision rather than reality. This paper presents a new and unique system design approach utilizing customized operational software for the safe and reliable transport of these critical fluids. Pipeline operating data are extracted using state-of-the-art technologies such as fibre optic Distributed Temperature Sensing (DTS) and other advanced instrumentation methodologies during the commissioning/start up and during unique operating activities such as heat-up, re-melt, or other fluid state changes. To automate these processes, predictive modelling, transient analysis and improved software solutions are used to create a dynamic, real-time model for the various fluids as they heat-up or transform through various phase changes inside the pipeline. The result is an intelligent flow assurance management program that can assist pipeline operators during all phases of pipeline management, especially during critical stages of pipeline operations.

INTRODUCTION

This paper presents a new and unique approach for a safe and reliable automated flow assurance program without the requirement for continuous operator assistance. By utilizing pipeline operating data extracted from the commissioning and initial start-up activities, it is possible to create an automated program to perform the heat-up of solidified or semi-solid process fluids, identification and location of potentially hazardous temperatures and the real time detection and location of pipeline leaks, should they occur throughout the operational life of the pipeline. In the unique case of an intentional re-melt process, the potential exists for re-melting to occur at different rates in various portions of the line. In such cases, it is imperative to perform the re-melt in a manner that does not cause overpressure or other pipeline failure modes to occur.

With recent developments in predictive modelling, transient analysis and improved software solutions, it is now possible to create a dynamic, real-time model for fluids as they transform through their phase changes inside the pipeline. Then, state-of-the art technologies such as continuous fibre optic Distributed Temperature Sensing are combined with other advanced pipeline instrumentation methodologies to provide key inputs for customized algorithms to drive logic-based decisions during operations.

The organization of this paper is intended to 1) provide the basic pipeline design requirements necessary to collect the data that will allow an automated re-melt, temperature monitoring and/or leak detection program to be developed and 2) to discuss the creation of a data driven software platform which allows for fact-based decision making by pipeline operators when managing the pipeline in various flow regimes.

CRITICAL DESIGN AND OPERATIONAL ISSUES TO BE CONSIDERED FOR TEMPERATURE-CRITICAL FLUIDS

When planning a new temperature-critical fluid pipeline, there are key aspects to consider early in the project cycle, which will ultimately determine the long-term operational benefits of the completed asset. The physical properties of the fluid and its narrow operating temperature zone create many design challenges. Sulphur, for example, will begin to solidify at temperatures around 119°C. Most sulphur pipelines are operated at a temperature between 135°C and 145°C. Similarly, 50% caustic will freeze at 18°C and is typically maintained between 25°C and 32°C – as it will cause accelerated corrosion in the pipeline wall above 49°C. These types of temperature sensitive fluids are often referred to as “temperature critical fluids” due to their unique and challenging design requirements.

There is a symbiotic relationship between three Design Criteria categories that must be understood and carefully considered when designing piping systems for critical fluids:

- Pipeline Mechanical Design - Pipe material, configuration issues, supports, anchors and expansion loops and pipe movement.
- Fluid Material Properties - Physical characteristics that drive design considerations.
- Pipeline Heating System - Its design and the integration of other applicable technologies that can collect valuable data for an automated re-melting, heat-up, cool-down and/or monitoring program.

Refer to the Pipeline Design Triangle in Figure 2.

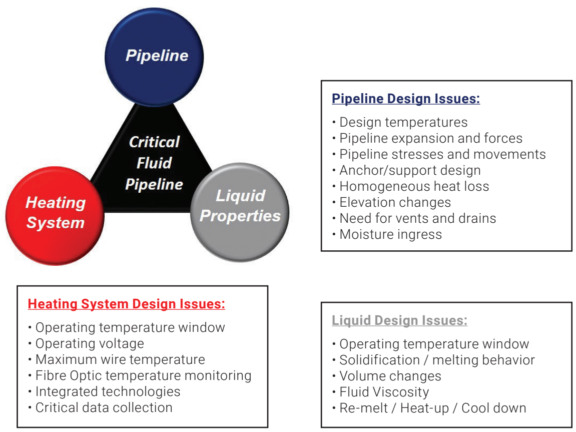

Figure 2. Pipeline Design Triangle

To construct a world-class critical fluid pipeline requires the early understanding of these key design criteria drivers. It then becomes imperative to incorporate these ideas and philosophies into the project requirements at an early stage; usually, this is during the front-end engineering design (FEED) study for a large pipeline project. Key issues must be proactively addressed at the early stage; otherwise, it may be too late to incorporate certain features later, leaving the asset owner to ultimately deal with the result of poor planning. Some of the key design considerations are addressed in this paper.

FLOW REGIMES

It is important to recognize that every critical fluid pipeline will almost certainly experience multiple flow regimes during its operational life:

- Flowing – moving fluid, (temperature above freezing)
- Stagnant – liquid not flowing, but still in a liquid state, (requiring flow to resume)
- Plugged – portions of the pipeline have experienced fluid solidification, (sometimes accompanied with the formation of void spaces)

Each flow regime must be handled in a very different way by pipeline operators; utilizing appropriate data collected from the pre-commissioning activity onwards. The third regime (a plugged pipeline) is the most critical and troublesome issue for critical fluid pipeline operators when trying to re-establish flow.

Some common types of critical fluids that fall into this category include:

- Sulphur – a solid at ambient temperatures, it generally melts and flows above 119°C. However, above 160°C its viscosity increases dramatically making it difficult to flow.
- Phenol – typically processed at 60°C during manufacturing; it solidifies below 41°C.
- Paraffinic Oils and Crude – depending on the oil characteristics and wax appearance temperature, these typically begin to congeal or solidify below 40-60°C.
- Asphalts and Bitumen – will solidify below 138-160°C.
- Vacuum Gas Oil – has a pour point between 43-52°C, depending on composition.

The viscosity of these fluids all change dramatically with temperature, which makes the flow regimes more complicated as a function of temperature. Plug formation and re-melt scenarios must be taken into account for all operating conditions. Further, overheating of petroleum-based fluids can result in fire hazards, and overheating phenol can result in toxic vapours, systemic poisoning and possible death as it is rapidly absorbed through the skin.

CRITICAL TEMPERATURE REGIMES

Chlorine Gas – carbon steel piping in the presence of dry chlorine gas above 150°C will auto ignite causing a chlorine/iron fire.

- Caustic – depending on the temperature and concentration of caustic, carbon steel piping is susceptible to stress corrosion cracking and embrittlement. For example, the high temperature limit for 32% to 50% caustic is 40°C. Caustic will also degrade if it exceeds a strict temperature range, rendering it useless for some commercial applications.
- Sulphuric Acid – temperatures above 38°C will cause significant corrosion in carbon steel piping.

Pipeline failures for these types of fluids can result in significant business interruption, environmental and/or public relations issues.

COMMON FAILURE MODES FOR CRITICAL FLUID PIPELINES

Those who have experienced a pipeline rupture will readily admit that the subsequent forensic root cause analysis is a complex and arduous task. It requires a deep understanding of the many intricacies and complexities of the asset, a pipeline's design basis, construction records, and circumstances leading up to a rupture event. Generally, for critical pipelines it is either the solid-to liquid phase change, (i.e., the accompanying expansive forces from the volume increase) or the corrosive critical temperature, which creates problems for operators sometimes leading to a catastrophic pipeline failure.

History has shown that some of the most common pipeline failures are caused by:

- Pressure build-up in the pipeline due to a lack of pressure management.
- Welded pipe shoes or a faulty anchor design, drawing heat away from the pipe, (often up to 75% additional heat loss).
- Insufficient thickness and/or poor field installation of thermal insulation.
- Inability to monitor the pipeline temperature along the entire length of the pipeline; e.g., when localized heat losses create cold zones along the pipeline.
- Excessive pipeline movements from temperature cycling.
- “Runaway heating” (overheating) at voids/empty zones, which are present in the pipeline due to either elevation or fluid solidification.
- Absence of a clear and methodical re-melt procedure.

HEAT LOSS MANAGEMENT AND A UNIFORM THERMAL PROFILE

When heating a pipeline for any service, but particularly so for very high operating temperatures, it is imperative to maximize the efficiency of the thermal envelope around the pipeline. Embedded in this discussion is the idea of creating a “uniform thermal profile”, where ideally no heat sinks occur along the pipeline that would cause excessive amounts of heat to be lost in localized areas. For example, this situation can occur when components such as pipe supports and anchors are designed solely to minimize the pipe movements, without regard to preservation of thermal heat loss.

In addition, poorly installed or water-soaked thermal insulation can jeopardize the pipeline heat loss uniformity. Management of heat loss to achieve a uniform thermal profile is critical for peak pipeline performance, because without it pipeline management becomes difficult, or even impossible! This key aspect is addressed in the next section with the concept of an “Intelligent Pipeline”.

INTELLIGENT PIPELINE FEATURES

The introduction of “Intelligent Pipelines” incorporating state-of the-art bundled technologies occurred in 2012 as a dramatic and significant milestone in the heating of long molten sulphur pipelines. This unique technology integration concept has proven to be a winning Flow Assurance formula that has been implemented to make many types of critical fluid pipelines more reliable and more predictable to operate.

Technology bundling for critical fluid pipelines as illustrated in Figure 3, incorporates a “fit-for-purpose” integration of applicable state-of-the-art technologies for pipelines:

- Heating technology (electric skin-effect technology).
- Pre-insulated piping to achieve a homogenous thermal profile for the entire pipeline.
- Fibre optic sensing system such as Distributed Temperature Sensing (DTS) to monitor the pipeline temperature.
- Engineered pipe supports and anchors that minimize localized heat loss.
- Computational modelling/transient analysis which provides foundational data to create an effective pipeline management software.

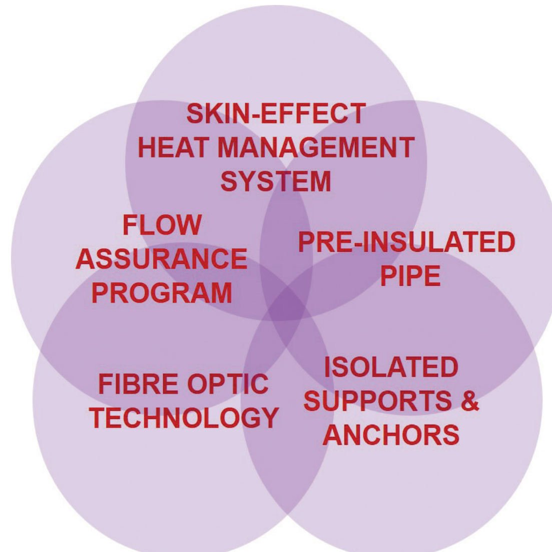

Figure 3. Intelligent Pipeline Critical Components

Together, all of these system components and customized procedures create tremendous synergies in the operation and preventative maintenance of critical fluid transport pipelines.

SKIN-EFFECT TRACE-HEATING SYSTEM

Skin-effect based trace-heating systems have existed for more than fifty years with significant increased usage over the past 10 to 15 years. Skin-effect trace-heating systems as indicated in Figure 4 utilize a medium voltage wire (operating up to 5,000 volts) inside a carbon steel tube welded or banded to the carrier pipe. The conductor and the tube are connected together to make a circuit that, depending on the application, can be as long as 30km. The relationship between the tube size, the conductor size and the applied voltage determines the output power. The heat generation is based on the electrical phenomenon of Ohm’s law, skin-effect and proximity effect in ferromagnetic conductive materials under alternating current of commercial frequency.

Like heating cables, skin-effect technology is very efficient since all of the heat is generated inside the thermal insulation envelope. The low impedance and high voltage capability of the skin-effect heater enables it to operate over long circuit lengths at relatively high power.

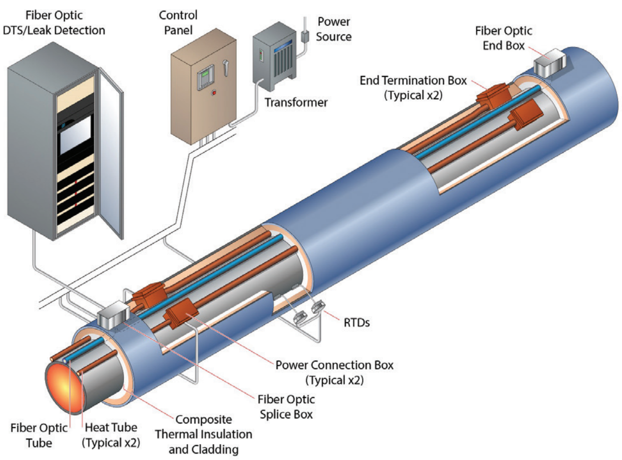

Figure 4. Skin-Effect Trace-Heating System (with Fibre Optic DTS) on an Intelligent Pipeline

PRE-INSULATED PIPE

Today's best available pre-insulated piping technology provides predictable heat loss and offers a homogenous thermal profile for the pipeline. The bundling of pre-insulated pipe with skin-effect trace-heating is a natural fit. Some major advantages of utilizing a pre-insulated piping system include:

- Superior product quality; factory tested and inspected.
- Construction schedule improvements; ease and quickness of installation.
- Lower installed cost vs. field insulated and fabricated piping systems.
- Durable construction.
- Reduced maintenance.

Figure 5 includes a photo of pre-insulated pipe segments that incorporate both skin-effect heating tubes and fibre optic DTS tubes in their construction.

Figure 5. Samples of Pre-Insulated Piping Sections

FIBRE OPTIC DISTRIBUTED TEMPERATURE SENSING

The ability to gather real-time thermal intelligence data can be highly valued by pipeline operators, enhancing the safety and reliability of the pipeline.

Various fibre optic technologies exist for pipeline monitoring, including Distributed Acoustic Sensing (DAS), Distributed Vibrational Sensing (DVS) and Distributed Temperature Sensing (DTS).

For most Distributed Sensing techniques, a pulsed laser is coupled to an optical fibre through a directional coupler. Light is backscattered as the pulse propagates through the fibre's core owing to changes in density and composition as well as molecular and bulk vibrations. In a homogeneous fibre, the intensity of the sampled backscattered light decays exponentially with time. Because the velocity of light propagation in the optical fibre is well known, the distance can be calculated from the deterministic collection time of the backscattered light. Thus, the measured parameter and distance can be identified simultaneously.

A major component of the fibre optic based measurement system is the interrogation electronics. This is comprised of a light source (High Intensity Laser) and a specialized OTDR (Optical Time Domain Reflectometer) with software to analyse specific spectral signals for distributed or point measurement information.

In the case of DTS, this system provides "thermal intelligence" by monitoring the temperature along the entire pipeline, giving operators a clear and visual understanding of the thermal profile of the pipeline and how the heating system is operating. Figure 6 shows a typical DTS system GUI (Graphical User Interface) for pipeline temperature monitoring.

With DTS, a temperature profile is generated along the entire pipeline, greatly assisting in daily decision-making to operate the pipeline efficiently and safely. The inclusion of fibre optic DTS also offers accurate historical records by recording the critical fluid temperatures during routine operations and excursion events. DTS is particularly important during the re-melt processes or for the identification of critical temperature excursions of critical fluids.

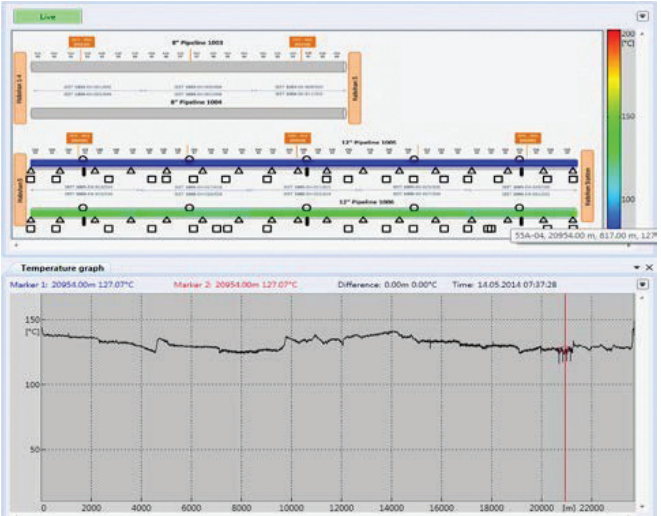

Figure 6. Sample GUI Screenshot of DTS Temperature Profile

A side benefit of DTS is the identification and location of fluid leaks in the piping system. Whenever a leak occurs, it is typically accompanied by a localized temperature anomaly near the leak. It may be a local warming (warm liquids) or cooling (pressurized gases), but in both cases, the DTS is an efficient means to detect the leak and its location. (It is also possible to incorporate communications fibre in the cable to serve as a data highway along the pipeline).

THERMALLY ISOLATED PIPE SUPPORTS AND ANCHORS

While normally specified by piping or pipe stress engineers only to carry structural loadings, these critical items are often overlooked from a thermal standpoint. Thermally isolated pipe supports and anchors are critical for uniform heat loss along the installed critical fluid pipeline, serving to eliminate localized "heat sinks" which can result in pipeline failure. It is extremely important to eliminate any metal-to-metal contact. Figure 7 shows a photo of a thermally isolated pipe anchor.

Figure 7. Engineered Thermally Isolated Pipe Anchor

FLOW ASSURANCE PIPELINE MONITORING SOFTWARE

In conjunction with DTS, it is possible to join a modelled software solution of the piping system that can be utilized to create real time monitoring dashboards specific to the critical fluid of interest, while also accurately predicting the formation of "hot or cold spots" under various operating conditions. This allows for proactive intervention and the implementation of corrective action plans.

For temperature-critical fluids, severe consequences may occur if temperatures fall below or rise above certain critical limits. In particular, localized temperature excursions may develop during very low flow or stagnant conditions due to a variety of reasons or factors. The various scenarios could include power outages, heating system inoperability, disparate ambient conditions, unintended heat sinks, nefarious activity, and breaches in the thermal insulation and/or outer jacket.

For transport lines, it is common for pipes to encounter road crossings, above and below ground installations, elevation changes, submerged applications and many other unique field situations in a wide variety of combinations. The challenge is to stay within the critical fluid temperature-operating envelope during all flow regimes and at every pipe location.

The inclusion of fibre optic DTS also offers accurate historical records by recording the critical fluid temperatures and their location during both routine operations and excursion events.

PIPELINE MANAGEMENT FLOW ASSURANCE SOFTWARE

By introducing the recent advancement of an artificial intelligence AUTO-Melt™program that works with DTS, the critical fluid re-melting process becomes much more predictable, with much less left to "chance". This new diagnostic and predictive pipeline management program is based on pipeline and other dynamic data and information gathered from the intelligent pipeline approach for critical fluids such as those mentioned earlier.

Some of the important features and components are discussed in the following sections. These components include custom algorithms and a customized pipeline management console based on core logic modules. The program identifies and collects relevant dynamic data and relies on powerful customized software to create a pipeline management program that is timely, automated and relevant.

Predictive Pipeline Behaviour Using Custom Algorithms

Historically, the management of critical fluid pipelines has been left largely to the shift operator who uses his judgement and experience to make appropriate decisions. This is a highly manual and operator-dependent approach, with limited or no real-time data used to drive decisions. It becomes, many times, a "best guess" approach to managing the pipeline that will lead to poor pipeline behaviour, and possibly pipe rupture.

It is possible to create a data driven, operating methodology for a critical fluid pipeline that combines data generated from various integrated technologies to feed custom algorithms. The result is a sophisticated proprietary software framework with asset mapping, parameter benchmarking, dense data collection and specialized data manipulation techniques, all delivered through a dedicated "custom dashboard" on a master data management display console.

Master Data Console – A Pipeline Management Tool

The new development of special algorithms created from data gathered during testing (pre-commissioning), commissioning and pipeline start-up can be applied to a predictive pipeline behaviour model. This breakthrough has resulted in the creation of a new specialized software framework for the management of critical fluid pipelines.

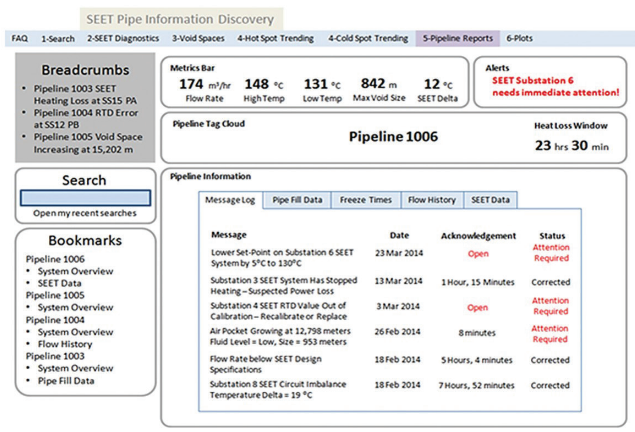

Figure 8. Sample Pipeline Management Portal Screen

The data processing contained in the algorithms goes well beyond the classical pipeline temperature monitoring, which is often limited to providing pre-alarms or alarms when the pipeline temperature has moved out of the acceptable range for some portion of the pipeline.

Core Logic Module for the AUTO-Melt™ Program

The pipeline management program's data collection and data analysis are contained in the system's many logic modules, which are used in the support of the day-to-day operation and maintenance of the pipeline.

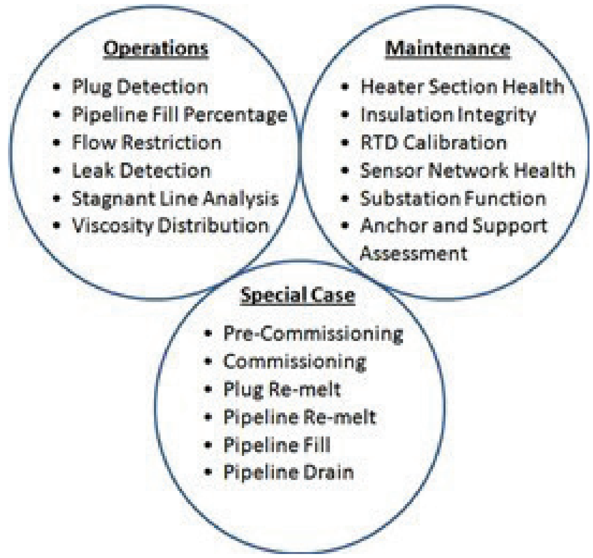

Figure 9. Core Logic Modules for the Automated Pipeline Manager

The modules generally fall into one of three categories, as shown in Figure 9 above.

Building Custom Algorithms

The customized algorithms built into the software framework make use of a variety of sensor inputs. These inputs may include both distributed and discrete measurements. Example inputs are shown in Figure 10.

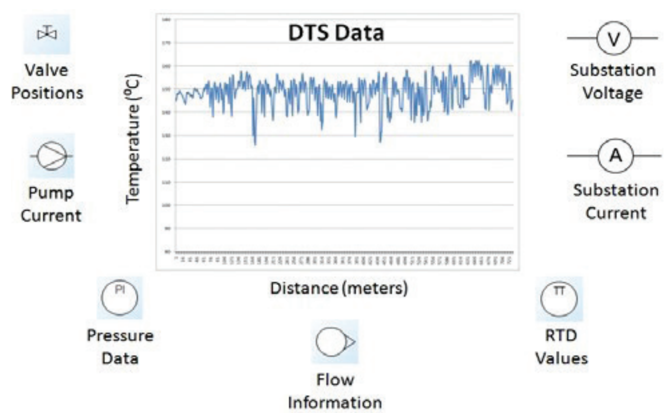

Figure 10. Core Logic Modules for the Automated Pipeline Manager

Customized "Smart Dashboard" to Assist Operator Decision Making

Information generated by the Operations, Maintenance, and Special Case logic modules is organized and presented at the system console using a custom "Smart Dashboard" user interface. This interface allows control room personnel to quickly identify the current state of the pipeline and to initiate appropriate responses or actions recommended by the software.

Using conventional navigation tools, users can toggle between a wide range of advanced data summary and analysis screens. The software sends automated messages, as required, to notify personnel of conditions on the pipeline that require attention or intervention.

Post Mortem Case Study Using Actual Pipeline Data

For various reasons, long sections of a critical fluid pipeline demonstrated a thermal transition to the solid state, (e.g., the entire pipeline was de-energized for an extended period, resulting in the solidification throughout multiple heating zones).

When the algorithms detected that fluid solidified over longer sections of the pipeline, the system automatically shifted into full re-melt mode. First, a logic module determined the fill percentage data for the solid fluid at one-meter intervals along the entire pipeline. This provided the basic information needed to monitor the re-melt process.

The pipeline and drainage cool down module classified the solid pipeline fill percentage into four categories as referenced in Figure 11 below.

76 to 100%
51 to 75%
26 to 50%
1 to 25%

Figure 11. Pipeline Volume Fill Percentage

An example screen from the pipeline management console is shown in the illustration below (Figure 12). The entire pipeline had cooled below the critical fluid freezing point resulting in the formation of voids in the line due to the combined effects of a varying pipeline elevation and the reduced volume of the fluid during the phase change.

The critical fluid flowed to the low elevations along the line as it cooled and reduced in volume; voids tended to move to the pipeline profile high points as referenced by the elevation profile (blue line) shown above the top of the display. This brings up a very important point – pipeline elevation matters during a phase change event, especially when there is a change in volume occurring.

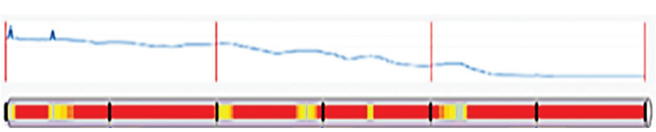

Figure 12. Cooled Pipeline

In the display above, the portions of the pipeline that are mostly filled with the solidified fluid are shown in red while the pipe that is empty is shown with no colour. The graphic also displays some of the pipeline in the colours ranging from red to yellow. These areas of the pipeline contain solidified fluid, but the pipe is less than 75% filled, (i.e., partially full). All of this information is critical when embarking on the process of re-melting the pipeline contents.

How the AUTO-Melt™ Program Works

To begin the re-melt process, the AUTO-Melt™ system utilizes the various heater zones and power levels available to achieve a uniform pipeline temperature that is just below the critical fluid melting point (in the pipeline sections that contain fluid that is in the solid state). If this is not achievable, the heating system will revert to the temperature maintenance mode and notify operations and maintenance staff of the existing non-uniformity issues, (specifically locating any problem areas to within +/- 1 meter). Any such issues must be resolved prior to the progression of the automated re-melt program.

Once an acceptable pre-melt temperature profile has been achieved, the pipeline management system will provide an operator prompt to verify that all pipeline valves, vents, and drains are properly set to the open position. This will provide the maximum available volume to accommodate the fluid expansion during phase change. Only after the operations staff have acknowledged this prompt will the system begin to increase the temperature of the pipeline toward the melting point.

As the temperature of the pipeline increases, the fluid melt algorithm tracks the progress (on a meter-by-meter basis) of the phase change from solid to liquid. This data is analysed for uniformity at the critical pipeline sections (those with low available expansion volume), as identified by the algorithms.

The pipeline management system controls the heater zones and available power levels to synchronize the phase change along the key pipeline sections. If, at any point throughout the automated re-melt process, the algorithms are unable to achieve a spatially uniform phase change, the system will hold the pipeline temperature below the melting point of the fluid and notify operations and maintenance personnel of the pipeline locations (by specific meter marks), where the required uniformity cannot be achieved. The system will only re-start the automated re-melt process engine after control room personnel have verified that the identified uniformity problems have been properly resolved.

When the system has verified that the re-melt is complete, operations personnel will be instructed to close any pipeline vents and drains, and the heater set point can then be increased to the stagnant critical fluid target value. Once the pipeline heaters are cycling normally at the stagnant critical fluid set point, the pumps can be started and the control software returned to its normal operating and maintenance mode.

OTHER PARAMETER MONITORING

In the previous section, customized software is described for monitoring flowing, stagnant, and plugged scenarios, and in particular for automating re-melt procedures. This AUTO-Melt™ system applies to many types of critical temperature/viscosity dependent fluids such as sulphur, heavy or paraffinic oils, phenol, asphalt and VGO where plugs can form due to cold spot formation.

However, other critical fluids (such as chlorine and sulphuric acid) may never freeze, but they exhibit severe corrosive consequences if overheated; (caustic has both plugging and corrosive potential). The Flow Assurance design and operating procedure aspects described in the previous sections also readily apply to these types of critical fluids, but in slightly different ways.

Critical Temperature Monitoring

In the case of fibre optic DTS, this system provides "thermal intelligence" by monitoring the temperature along the entire pipeline, giving operators a clear and visual understanding of the thermal profile of the pipeline and how the heating system is operating.

In particular, localized high temperature excursions due to risers, elevation changes, excess thermal insulation or external sources of heat may develop during stagnant flow. The software model of the piping system can accurately predict "hotspots" under various operating conditions and can be utilized to create real time monitoring dashboards specific to the critical fluids of interest.

Leak Detection

A strong side benefit of DTS is the ability to identify and locate fluid leaks or ruptures in the piping system. For leak or rupture detection of heated fluids being transported through a pipeline, it is possible to identify excursion events using temperature differentials and anomalies along the pipeline alignment.

DTS can give "real time" notifications of the location of a leak or rupture, within minutes of the occurrence. This allows a pipeline company's emergency response plan to be enacted and to initiate prescribed release mitigation measures. This is a huge benefit for pipelines who must comply with CPM (Computational Pipeline Monitoring) requirements, both in the United States and abroad.

The detection of leakage along a pipeline (while also monitoring temperature) requires special processing to discriminate an actual leak from environmental temperature fluctuations. The temperature evolution associated with a leakage has been extensively studied for different types of fluids (hot water, oil, brine, phenol, gas, etc.). Leak rates for critical fluids depends on their physical properties, but in all cases, the DTS is an efficient means to detect the leak and its location.

A series of well-designed algorithms for the DTS data provides a high confidence level in notification and alarming functions. Continuous "polling" by the DTS system provides 24/7 surveillance and gives the pipeline operator a higher level of confidence to manage the pipeline, through the automatic notification/alarming functionality that is provided with customized software.

CONCLUSION

Heated critical fluid pipelines are at the threshold of achieving great milestones in design, operations, preventive maintenance, safe re-melting and monitoring of the fluids during all stages of their operation and lifetime. A new wave of technology allows pipeline operators to use "fact-based" logic in both routine and emergency decision-making for a variety of scenarios. With the help of pipeline operating data, new software and custom algorithms offer greater reliability and safety for the difficult re-melt process and predictive monitoring tasks. This concept will revolutionize the transportation of critical fluids in pipelines.

The main conclusions from this paper can be summarized as follows:

- Pipelines should be designed to minimize aspects that might create a non-uniform temperature profile.
- It is highly recommended that fibre optic temperature monitoring be incorporated into the pipeline design early in the project requirements phase.
- A predictive pipeline model can be constructed from customized asset data collected during the testing, start-up and commissioning phases of the project.
- It is possible to use algorithms and analytics to assist pipeline operators in the daily and emergency management of critical fluid pipelines, including temperature excursions, re-melt and even pipe leaks.

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