Fiber Optic Temperature Control for Jafurah Project Sulfur Pipelines[1]

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Abstract

Temperature control and heat sensing of pipelines have always been critical challenges for the oil and gas industry, especially when precise operation is essential to maintain plant operations. This is specifically true in the case of molten sulfur lines, where its characteristics vary significantly with changes such as sulfur solidification in pipelines at low temperature. Recent advancements in temperature sensing and pipeline heating systems have been addressing these challenges, and one of the latest technologies in the market is the skin effect heating system with temperature sensing using fiber optic technology. Using the fiber optic as the temperature sensors is a main factor in this system. The fiber optics utilize the optical properties of the cable to measure temperature, which eliminates the need to have the sensing element in direct contact with the process. This makes this technology ideal for molten sulfur transfer lines. The fiber optic temperature sensing is part of the Skin-Effect Tracing System, which provides the temperature reading to adjust the electrical heating. This technology offers several benefits such as eliminating the need to provide temperature sensing inside the pipeline, and the use of fiber optic sensors allows for more accurate and reliable temperature readings to ensure the safe and reliable transportation of molten sulfur. Additionally, the closed-loop temperature controlling will improve the operation reliability by applying an optimum cost-effective heating system.

Overall, the skin effect heating system with fiber optic temperature sensing technology represents a significant advancement in temperature control and pipeline heating systems for the oil and gas industry. Its ability to provide precise temperature control, prevent pipeline failures, and reduce energy costs makes it a reliable and cost-effective solution for molten sulfur transfer lines.

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1. Introduction

Pipelines transporting molten sulfur face a unique set of operational challenges due to the material's sensitivity to temperature variations. Sulfur must remain above its melting point throughout transport to prevent solidification, which can cause blockages, disrupt flow, and require costly maintenance interventions. This creates a critical need for heating systems that not only maintain sufficient temperature uniformly over long distances but also allow operators to monitor thermal conditions accurately along the entire pipeline. Traditional approaches, such as steam tracing and conventional electric resistance heating combined with discrete temperature sensors, have been used extensively but are limited in their ability to provide comprehensive, real-time temperature profiles. These methods often rely on point measurements, which can leave undetected cold spots and result in inefficient energy use. Recent technological advances have made it possible to integrate skin-effect electric heating with distributed fiber optic temperature sensing. This integration offers new opportunities for maintaining uniform temperatures and enables continuous monitoring of thermal performance along every segment of the pipeline. As a result, operators gain better control, improved safety, and the potential for significant reductions in energy consumption and maintenance costs.

This paper examines the heating and monitoring requirements specific to molten sulfur pipelines, evaluates the limitations of conventional technologies, and explores the principles and expected advantages of combining skin-effect heating with fiber optic distributed temperature sensing as an integrated solution.

2. Characteristics of Molten Sulfur and Heating Requirements

Molten sulfur is used extensively in the oil and gas industry but presents handling challenges due to its physical properties. Sulfur melts at approximately 120°C, and in molten form must be maintained between 120°C and 160°C for efficient storage and transportation [1]. If the temperature drops below the melting point, even briefly, the sulfur solidifies, leading to blockages that can interrupt operations and require significant effort to remove. To ensure continuous transport, it is necessary to maintain molten sulfur at a stable temperature, typically above 130°C, along the entire length of the pipeline. Any partial cooling can result in partial solidification and subsequent operational disruptions. Molten sulfur pipelines are generally installed above ground to facilitate inspection and maintenance. This configuration supports reliable heating and insulation performance and allows straightforward access for repairs and servicing of external heating systems such as skin-effect heating or steam tracing. In contrast, buried pipelines are subject to greater heat loss to the surrounding soil, which increases the energy required to maintain the target temperature.

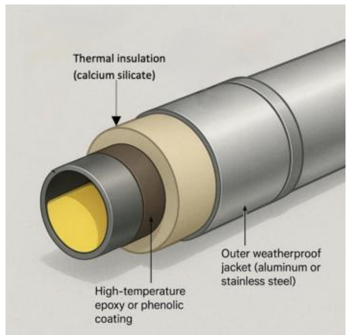

Figure 1: Sulfur Pipe Coating Layers

As figure.1 illustrate, Pipelines used for molten sulfur are externally coated and insulated to reduce thermal losses and protect them from environmental conditions. Typically, a high-temperature epoxy or phenolic coating is applied directly to the steel surface to provide corrosion protection. This coating serves as a base layer over which thermal insulation materials, such as mineral wool or calcium silicate, are installed. An outer weatherproof jacket, often aluminum or stainless steel, protects the insulation from mechanical damage and environmental exposure. However, insulation alone is insufficient to maintain the required temperature, particularly in cold climates or fluctuating conditions, making external heating essential to ensure reliable molten sulfur transport.

In any molten sulfur pipeline system, the external coating and insulation arrangement not only provides protection and thermal performance but also defines how future technologies, whether for heat injection or temperature monitoring, can be installed. It is important that these systems, such as heating elements or fiber optic sensors, are applied in a manner that does not compromise the integrity of the corrosion protection coating. Therefore, when discussing the installation of technologies along these pipelines, it will be clarified how they are positioned or secured in relation to the protective coating and insulation layers to ensure long-term performance and system reliability. These requirements make molten sulfur pipelines a demanding application where precise heating and temperature control are critical. The heating system must maintain uniform heat distribution and provide continuous monitoring to prevent cold spots, reduce operational risks, and ensure safe and reliable operation.

3. Conventional Heating and Sensing Technologies

Before the introduction of modern systems such as skin-effect heating combined with fiber optic temperature sensing, pipelines transporting temperature-sensitive materials relied on traditional heating and sensing methods. One of the most common methods is steam tracing, where small steam lines run parallel to the pipeline to transfer heat by conduction. While steam tracing is widely used, it presents several challenges: it requires a continuous steam supply, is susceptible to heat loss along the length of the pipeline, and is labor-intensive to install and maintain. Failures or leaks in the tracing system can lead to local temperature reductions, which are particularly problematic in molten sulfur service due to the risk of solidification.

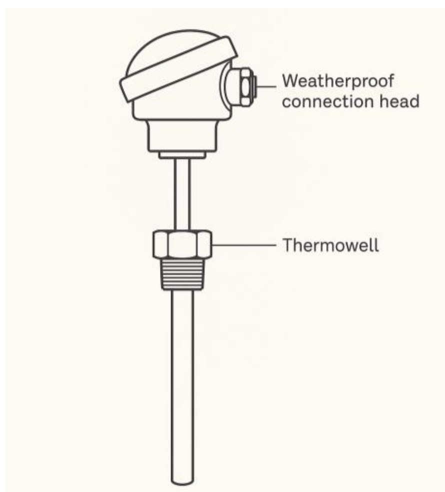

Figure 2: RTD Probe with thermowell

Another conventional method is electric resistance heating, where electric heating cables or tapes are applied externally to the pipeline. These systems enable precise heating control but typically rely on discrete point sensors, such as thermocouples or resistance temperature detectors (RTDs), for feedback. RTDs *(figure.2)* typically consist of a probe mounted via a thermowell or attached directly to the pipe surface using either clamps or being welded, providing temperature measurement at a specific location [2]. Since these sensors measure temperature only at selected points, they can fail to detect uneven heating or localized cold spots along the pipeline length. Conventional temperature

sensors also present limitations. When installed directly on or inside the pipeline, they can be intrusive, require regular maintenance, and are susceptible to damage or calibration drift. For externally coated and insulated pipelines, accessing these sensors for inspection or repair introduces additional complexity and maintenance demands.
Due to these limitations, conventional heating and sensing systems often struggle to achieve uniform and reliable temperature control over extended pipeline distances. This increases operational risks, particularly in molten sulfur pipelines, where maintaining continuous flow depends on strict temperature management to prevent solidification. This does not include specialized systems such as skin-effect heating, which will be discussed separately.

4. Skin-Effect Heating System Overview

The skin-effect heating system is a specialized form of electric resistance heating designed to provide efficient, uniform heating along long pipeline lengths, making it particularly suitable for applications such as molten sulfur transport. It operates based on the principle that alternating current tends to flow near the surface of a conductor at higher frequencies, a phenomenon known as the "skin effect" [3].

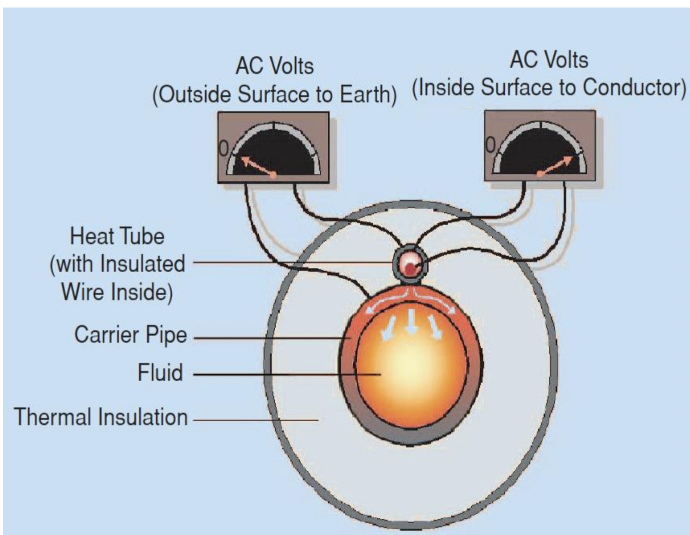

Figure 3: Cross Section of Pipe with STS (Source: Research Gate [3])

In a typical skin-effect heating system, a carbon steel heating tube is installed parallel to the pipeline, with an insulated electrical conductor running inside this tube. The conductor is connected to a power source at one end of the circuit and electrically bonded to the heating tube at the far end, forming a return path for the current. As current flows through this circuit, heat is generated by resistive losses along the heating tube itself, which is in continuous contact with the pipeline, enabling uniform heat transfer over long distances. This method allows heating transfer to up to 25 km from a single feed point and minimizes voltage drop and heat loss compared to conventional heat tracing [4].

In reference to table.2 of Appendix A, Skin-effect offers several advantages compared to conventional heating methods. Skin-effect heating can maintain consistent temperatures across extensive pipeline runs, with minimal voltage drop or heat loss along the length of the circuit. It is robust, durable, and well-suited for externally coated and insulated pipelines because it can be installed without penetrating the pipe wall or compromising the corrosion protection layer. Additionally, the system can be designed for minimal maintenance requirements, as all electrical connections and terminations are located at accessible endpoints. Because of these characteristics, skin-effect heating systems have become a preferred solution for pipelines that transport molten sulfur. Their ability to provide reliable, continuous heating ensures that the pipeline temperature remains above the sulfur melting point, preventing blockages and ensuring uninterrupted operation.

5. Fiber Optic Temperature Sensing Technology

Fiber optic cables are flexible strands, *a strand refers to an individual optical fiber within a cable assembly*, typically made from glass (silica) that guide light along their length by total internal reflection. A standard fiber optic cable consists of a core (the central light-carrying region), a cladding (a material with lower refractive index surrounding the core to keep light confined), and protective coatings or jackets for mechanical strength and environmental protection There are two main types of fiber optic cables: single-mode fibers (SMF), which have a small core diameter and allow only one propagation mode of light, and multi-mode fibers (MMF), which have larger cores allowing multiple light paths. Below table.1 provide a comparison between single-mode and multi-mode fiber optic cables highlighting structural, optical, and performance characteristics [5].

Table 1: Comparison between SMF vs. MMF

Feature	SMF	MMF
Core Diameter	9 microns	50 to 100 microns
Distance Capabilities	Up to 40 kilometers	Up to 2 kilometers
Bandwidth Capacity	Up to 100 Gbps	10 Gbps to 400 Gbps
Cost	more expensive	less expensive
Applications	Long-distance networks, high-bandwidth applications	Shorter-distance applications,

Fiber optics are widely used in telecommunications, medical imaging, sensors, industrial instrumentation, and data transmission systems because they offer high bandwidth, immunity to electromagnetic interference, and durability in harsh environments. Among these diverse applications, one particularly valuable use is in temperature sensing for industrial pipelines. Fiber optic temperature sensing is a modern and increasingly applied technology that enables distributed temperature monitoring along the entire length of a pipeline. Unlike conventional point sensors such as thermocouples or RTDs, fiber optic systems can provide continuous, high-resolution temperature profiles, making them particularly suitable for critical applications such as molten sulfur pipelines. It works based on optical phenomena such as Raman or Brillouin scattering. As light pulses travel along the fiber, a portion of the light is scattered back due to temperature-dependent variations in the fiber's material properties. By analyzing the time delay and spectral characteristics of this backscattered light, the system can determine the temperature at multiple locations along the fiber with high accuracy [6]. This technology offers several advantages over traditional sensing methods since they are immune to electromagnetic interference, resistant to corrosion, and capable of operating reliably in harsh environments. Their distributed nature eliminates the need for multiple discrete sensors and allows early detection of localized cold spots or uneven heating along the pipeline.

In molten sulfur pipeline applications, fiber optic sensors can be installed in different configurations. They may be attached to the pipeline exterior, embedded near the heating system, or even positioned inside the skin-effect heating tube to monitor both the heating element and the adjacent pipeline temperature. Careful consideration is required to ensure that the fiber optic cable installation does not interfere with the performance of the skin-effect heating system or compromise the protective coating and insulation layers. The relationship between fiber optic sensor placement and the heating system is essential because their integration directly influences the overall performance of molten sulfur pipeline heating and monitoring. Thus, the proper installation and use of fiber optic temperature sensing would enhance the performance of skin-effect heating systems by enabling precise, real-time monitoring and control. This capability improves the reliability and safety of molten sulfur transport by ensuring that the entire pipeline length remains above the sulfur solidification temperature.

a. Integration: Skin-Effect Heating with Fiber Optic Sensing

The integration of skin-effect heating systems with fiber optic temperature sensing provides a comprehensive solution for maintaining and monitoring pipeline temperature in molten sulfur transport applications. Each system individually addresses key challenges: skin-effect heating ensures uniform temperature is provided, while fiber optic sensing offers continuous, distributed temperature monitoring, but when combined, their capabilities are enhanced. Successful integration requires careful consideration of installation practices and component interaction. Fiber optic cables must be positioned so that they accurately monitor pipeline or heater temperatures without compromising the integrity of the heating system or the pipeline's protective coating and insulation. Common installation strategies include routing the fiber optic cable along the outer surface of the pipeline, embedding it within the insulation layer, or placing it inside the skin-effect heating tube itself.

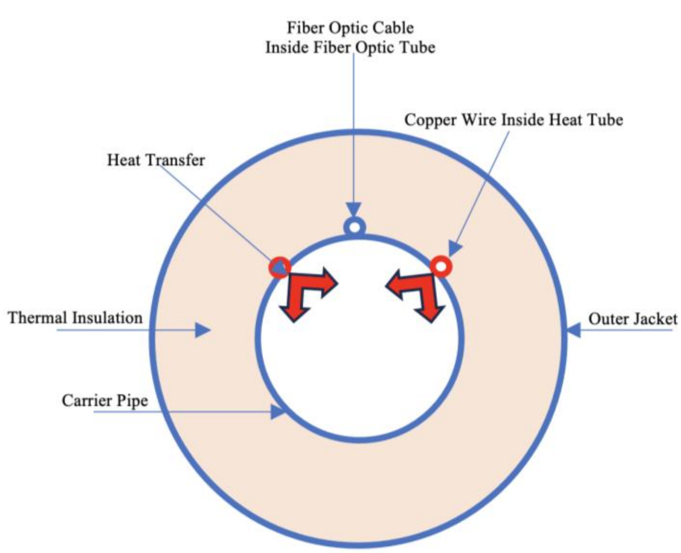

Figure 4: Cross Section of STS and Fiber Optic Installation

In figure 4, the Skin-Effect Trace-Heating (STS) system consists of a heat tube welded along the carrier pipe. This weld serves as a heat transfer path to the carrier pipe. Within this heat tube, a specially designed, high-temperature, copper wire fully insulated acts as the conductor carrying electrical power. Electrical current flows through this conductor to a termination point at the far end of the pipeline, then returns through the heat tube itself. Because the conductor is enclosed in a steel tube, an inductive effect concentrates the return current on the inner surface of the heat tube, creating resistive heating along its length. This heat is efficiently transferred to the carrier pipe through the welds. A fiber optic cable also installed near the heat tube to enable continuous, distributed temperature monitoring along the pipeline [7]. Together, these components ensure precise, reliable heating and control throughout the entire system. In these applications, single-mode fiber optic cables are typically used due to their superior performance in distributed temperature sensing (DTS) systems. DTS relies on Raman or Brillouin backscatter analysis, and single-mode fibers are preferred because it eliminates modal dispersion by supporting only one propagation mode. This ensures a clean, consistent backscattered signal, allowing precise temperature measurement over long distances. Multi-mode fiber, in contrast, allows multiple light paths that would result in dispersion, signal distortion, and reduced accuracy, particularly for extended sensing ranges [8].

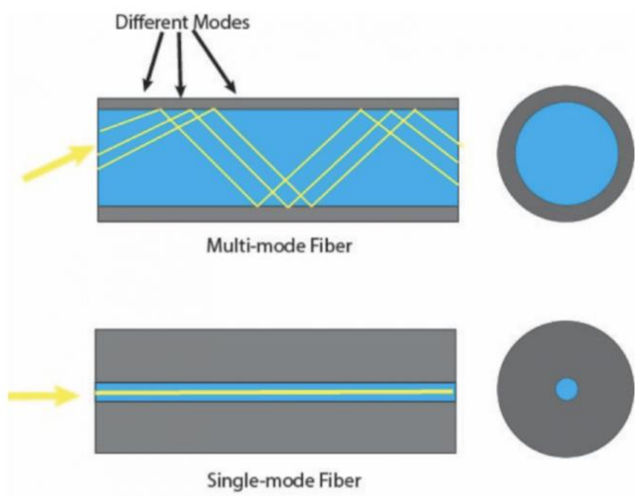

Figure 5: Conceptual Diagram Modes behavior SMF vs. MMF (Source: Linden Photonics [8])

For deploy-ability in harsh field conditions, the fiber must be coated within a mechanically robust, high-temperature jacket. This often involves using armored or loose-tube designs to protect the cable during installation and operation. Additionally, although the fiber core is typically standard telecom-grade silica, it must be enclosed in buffer and jacket materials rated for sustained exposure to temperatures above 120 °C, to ensure reliability near heated sulfur pipelines and skin-effect heating elements. Such high-temperature fiber optic cables are commonly rated for continuous operation at or above 150 °C, with stainless steel armor and heat-resistant housing like Hytrel or PTFE providing the necessary protection [9]. The integrated system enables closed-loop control where temperature data from the fiber optic sensor network informs adjustments to the skin-effect heating power. This ensures that the pipeline temperature remains within the desired operational range along its entire length, improving operational reliability and reducing energy consumption. Furthermore, distributed sensing allows for the detection of localized cold spots or areas of insulation failure that may not be apparent with conventional point sensing systems. Proper integration also facilitates safer remelting procedures since the skin-effect heating system itself is capable of performing remelting by delivering sufficient heat to re-liquefy solidified sulfur along the pipeline length when operated at higher power output [3]. This remelting function requires careful control because of the different thermal properties of solid sulfur and the potential for localized overheating, particularly in void spaces. Integration with distributed fiber optic sensing improves this process by enabling precise, real-time monitoring during reheating operations. Integrating skin-effect heating with fiber optic temperature sensing creates a robust, efficient, and reliable solution for temperature management in molten sulfur pipelines, supporting both operational performance and safety objectives.

b. Performance Results and Discussion

The integrated skin-effect heating and fiber optic temperature sensing system has delivered significant performance benefits for molten sulfur pipelines. It is designed to maintain uniform temperatures above the sulfur solidification point along the entire pipeline length, with DTS. This capability enables early detection of localized cold spots or insulation decay that could result in heat loss or operational interruptions. A key performance feature of this system is its ability to pinpoint the exact location of temperature irregularity. This is achieved through the principle of time-domain reflection measurement: a short laser pulse (e.g., 10 nanoseconds long) is injected into the fiber, and as the light pulse travels through the fiber, it is scattered back at every point due to Rayleigh, Raman, and Brillouin scattering phenomena.

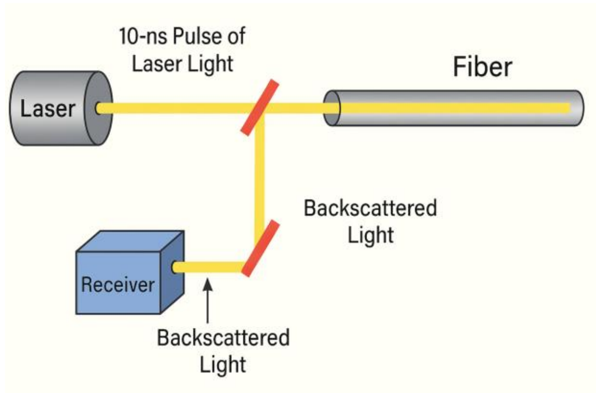

Figure 6: Schematic representation of the principle of DTS

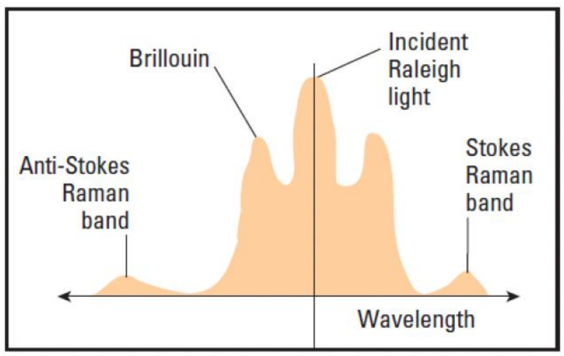

Figure 7: Spectra of Back-scattered light (Source: Research Gate [10])

The backscattered light returns to the detector with a delay corresponding to its point of origin along the fiber. Since the speed of light in the fiber is known (approximately 2×10^8 m/s), the system can calculate the distance precisely using the formula:

$$D = \frac{\text{Speed of light in fiber } \times \textit{Time delay}}{2}$$

The division by two accounts for the round-trip travel of light in the fiber: the measured time delay represents the time for light to travel to a scattering point and return to the detector. For example, if a backscattered signal is measured with a time delay corresponding to 4 km of light travel, the actual distance to the scattering point is 2 km, because light must travel to that point and then back again. Dividing the total distance by two yields the correct physical location along the fiber.

The fiber itself acts as a continuous sensing element, not a set of discrete sensors, enabling measurement of temperature at intervals. The DTS system processes backscatter data from thousands of locations along the fiber and maps them to a temperature profile versus distance. This allows the operator or control system to visualize the entire pipeline's thermal condition, and if a cold spot appears, such as due to degraded insulation or heater failure, it can be located precisely relative to the starting point of the fiber.

c. Example: Jafurah GUI

Assuming the fiber optic cable runs along a 2 km sulfur pipeline in the Jafurah Project, the Graphic User Interface (GUI) reports temperature at 2-meter intervals. The section between 755m and 760m shows a drop below the target temperature. The GUI of the Sulfur Lines System clearly highlights this anomaly at approximately 757 meters along the pipeline (measured from the defined 0 m origin point), enabling maintenance to quickly locate, inspect, and resolve the issue.

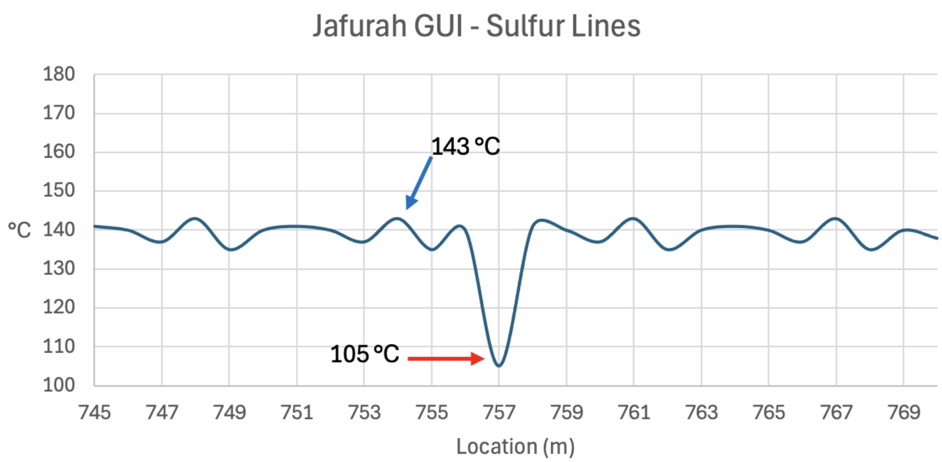

Figure 8: Example of GUI Behavior of Fiber Optic Response to Heating Failure in a Pipeline

In a closed-loop configuration, this real-time location-specific temperature feedback allows dynamic adjustment of heating power, reducing unnecessary energy consumption during stable conditions while ensuring adequate heating during periods of higher heat loss. Additionally, during remelting operations following an extended outage, this system is expected to enhance safety and reliability by ensuring uniform reheating and minimizing risks such as localized overheating, pressure buildup, or pipe damage.

6. Conclusion

The integration of skin-effect heating with fiber optic distributed temperature sensing represents a significant advancement in the management of molten sulfur pipelines. This combined system is expected to deliver uniform temperature control, precise real-time monitoring, and enhanced energy efficiency compared to traditional methods. The ability to detect localized cold spots, dynamically adjust heating output, and safely manage critical operations such as remelting after an outage positions this technology as a robust, reliable, and cost-effective solution for modern sulfur transport systems.

As fiber optic sensing and skin-effect heating technologies continue to mature, their adoption in the oil and gas sector is likely to expand, supporting safer operations, reduced maintenance requirements, and improved system performance over longer pipeline distances and in more demanding environmental conditions.

7. Acknowledgment

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8. References

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During the preparation of this work, the author used ChatGPT's assisted tools for editorial support, translation of text, and illustration of selected figures. All AI-generated content and figures were reviewed, verified, and modified by the authors to ensure accuracy, originality, and compliance with ethical standards.

Appendix A

Table 2: Comparison of Key Characteristics of Conventional Heating Methods & Skin-effect heating systems for molten sulfur pipelines

Feature	Steam Tracing	Electric Resistance Heating	Skin-Effect Heating
Heating principle	Heat transfer from steam pipes	Heat from resistance cables/tapes	Heat generated along steel heating tube (skin effect)
Typical monitoring method	Point sensors (RTDs, thermocouples)	Point sensors (RTDs, thermocouples)	Distributed sensing or endpoint monitoring
Temperature uniformity	Moderate; potential heat loss along length	Moderate; voltage drop limits long runs	High; uniform along entire length
Distance limitations	Practical for short to moderate lengths	Limited by cable length and voltage drop	Long pipelines (up to ~25 km from one feed point)
Installation complexity	Labor-intensive; piping and insulation required	Easier than steam; discrete cable routing	Straightforward; runs parallel to pipeline
Maintenance requirements	High; leaks, steam supply issues	Moderate; periodic sensor and cable checks	Low; few mechanical connections
Compatibility with coatings	May require penetrations at supports and sensors	May require penetrations at supports and sensors	Fully external; no pipe wall penetration required

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