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(Research Article)

Enhancement performance oil pipeline utilizing nanotechnology

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Abstract

Oil and gas pipelines are a critical part of the global energy supply and are also essential to economic viability across the world. Many pipelines around the world are reaching, or have reached, their useful life; this increases the risk of a logistical failure in the transportation infrastructure. Pipelines are subject to a variety of mechanisms that contribute to their deterioration, specifically; corrosion, erosion, fouling and material fatigue. These mechanisms diminish the overall efficiency of pipelines while simultaneously exposing them to new safety and environmental liabilities. Historically, there are many forms of protection against deterioration that were used to protect pipelines; however, those methods have not provided long-term performance and durability guarantees. Nanotechnology could be a method to address the need for increased pipeline integrity and to extend the service life of pipelines. The use of nano-coatings along with barriers created from nano-composite materials will provide enhanced protection against corrosive agents through low permeability and extremely protective layers. Self-healing nano materials will add to the reliability of pipelines through the ability to naturally repair micro-damage to the pipelines without assistance from the outside world. Nanotechnology-enabled catholic protection systems will provide improved corrosion control while using less energy and providing greater efficiency. The use of Nano fluids will improve flow assurance by reducing frictional losses, preventing deposits from developing and aid to enhancement of thermal stability of fluids in a pipeline system, as such will possess the ability to sustain optimal flow conditions and minimize the risk of blockages and or efficiency loss over time.

Keywords: Nanotechnology; Pipeline; Integrity; Mitigation; Nanosensors

1. Introduction

Pipelines are critical infrastructure for the transportation of oil and gas, connecting production sites to consumers. A significant portion of the about 2.2 million kilometers of oil pipelines worldwide operates under severe conditions, which can lead to degradation and even failures. Pipeline integrity problems have severe impacts in terms of lost product, shutdown of production, clean-up deployment, and potential catastrophes. These events lead to massive economical impacts, but also safety concerns. In Europe, 82% of such transport installations are aged over 10 years, and 30% over 30 years, putting the integrity and safety of a large part of this infrastructure at risk. Different degradation mechanisms, corrosion, fouling, erosion and material fatigue have been identified as causes of pipeline integrity failures. Various approach are proposed to slow down or mitigate such degradation, including (i) modification of the transported fluid to meet more stringent pipeline specification to reduce fouling and corrosion, (ii) lining the pipeline or using a different material for the construction of the pipeline to slow down the deterioration, and (iii) internal and external coating to apply anticorrosion protection, thermal insulation and fluid drag reduction as the following figure 1.

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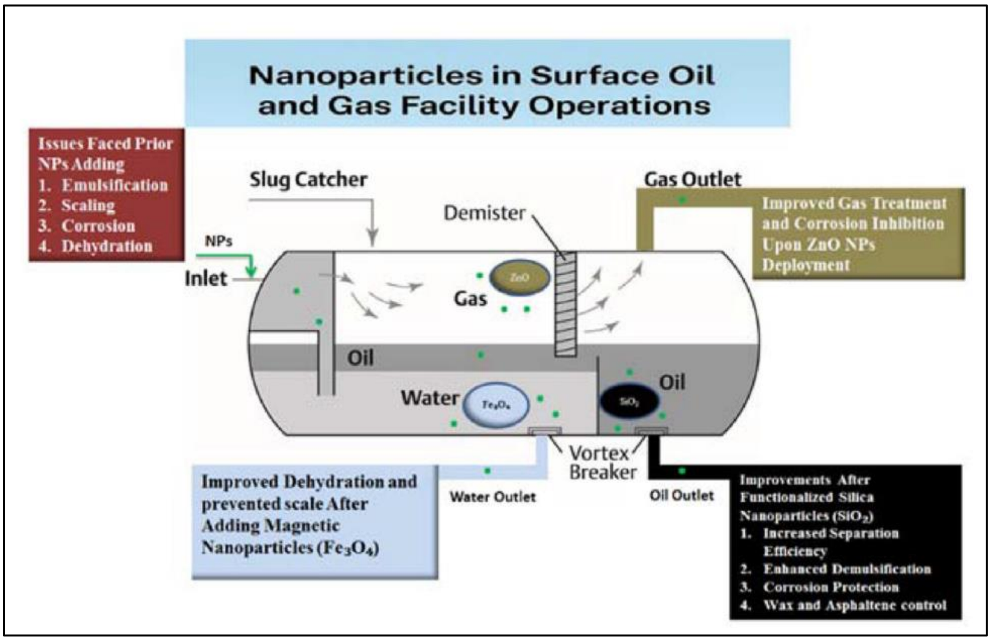

Figure 1 Nanotechnology applications in surface facility processing, enhancing separation, flow assurance, and corrosion protection [2]

Nanotechnology has recently become a valuable method to propose additional options to tackle pipeline integrity and safety. The emergence of new nanocrystalline materials or nano-sensors, open new opportunities in investigations or interventions on pipelines to increase safety on existing assets [1]. The field of nanotechnology has shown promise in addressing major problems and improving drilling effectiveness. An overview of the difficulties encountered during oil and gas well drilling operations and the demand for creative solutions opens the debate. This paper explores how nanotechnology is transforming the oil industry and enhancing performance as a whole. Nanotechnology offers transformative potential in enhancing petroleum surface facility operations through improved efficiency, system protection, and environmental compliance. Nanomaterials, due to their unique size-dependent properties, provide advanced functionality in phase separation, corrosion inhibition, scaling mitigation, and gas treatment.

2. Fundamentals of Pipeline Degradation and Failure Mechanisms

Oil and gas pipelines are important components of the global energy infrastructure. Pipeline systems are designed to ensure the integrity, safety, reliability, and performance in transporting hazardous hydrocarbons and other chemicals. It is important to understand various degradation mechanisms encountered by pipelines over operation time. Pipeline degradation leads to accommodation of operational problems such as the increased frequency of inspection or repair activity, longer maintenance durations, reduced throughput, and production interruption [3]. Many degradation mechanisms such as corrosion, erosion, fouling, and material fatigue can occur in the pipeline, depending on the operational conditions and the nature of transported fluid. The selection of material and the application of protection strategies are often determined by the specific degradation mechanisms anticipated based on the sources of degradation [4].

Surface oil and gas production facilities are essential for separating and managing multiphase fluids before downstream transportation. However, as operational complexity rises and infrastructure ages, conventional technologies increasingly fall short of sustainability and efficiency goals, particularly under stricter environmental regulations [9]. Initially, the pipeline gets covered by soil that contains moisture and other ions, such as sulfate, carbonate, chloride, and others. Afterward, these ions react with the layer of dirt around the external surface of the pipeline to form an corrosive cell in the presence of oxygen. This causes the pipelines to corrode from the outside, resulting in dimension reduction or perforation of the wall. Nanotechnology offers potential solutions to improve drilling efficiency, boost production rates, and reduce environmental effects in the oil and gas industry [5]. Extra layers of protection are often applied to the external surface of the pipelines. The pipelines are also internally protected using various methods. Selection of these methods depends on the fluid composition and operational conditions, such as temperature and pressure. The optimal explanation of corrosion formation in pipelines is fluid-induced corrosion. External corrosion under buried soil and internal corrosion under harsh environments as in pipeline systems can be prevented. Overlay of certain grades of steel or metal can provide a protective barrier so that fluid cannot directly contact with the original pipeline material, while coatings can protect the pipelines from such a risk [2]. Preventive actions are often selected based on the fluid composition and the supplying materials.

Erosion is defined as the process by which a material is worn away from the surface, usually due to the abrasive action of mechanical forces. The materials removed from the surface are known as "erosion products" or "erosion debris". Erosion can occur at the solid-liquid-gas interface when solid particulate matter or other abrasive materials are transported. The main concussion sources of erosion are the particle impingement, cavitation, vibration, and hammering of hoses. Erosion tends to deepen pre-existing surface defects rather than creating new ones. The location of erosion can define the orientation of the imposed shock loading. The targets of erosion generally are external surfaces of a pipeline. An artificial or naturally occurring nanoparticle with a size between 1 and 100 nm may be used in nanotechnology for a variety of applications [13]. Due to their special qualities, nanoparticles are useful in various applications in the oilfield, such as sensing or imaging, improved oil recovery (EOR), gas mobility control, drilling and completion, produced fluid treatment, and tight reservoir applications3. Nanotechnology-Based Solutions for Corrosion Mitigation [7] Nanostructured coatings improve catholic protection by making it possible to use lower levels of current density and providing a means for real-time monitoring of pipeline integrity [4]. These technologies can complement or enhance the effectiveness of traditional corrosion prevention methods and increase the overall integrity of pipelines.

3. Self-Healing Nanomaterials for Pipeline Linings

Pipeline degradation represents any type of deterioration of the structural integrity of an underground or aboveground oil piping system. It can be manifested when pipelines deteriorate due to corrosion, erosion, fouling, or fatigue. Pipeline failure can occur when the following operating conditions are not controlled: temperature, pressure, vibration, and the spread of substrate materials. Deteriorating pipelines may affect oil fields economy. They can interrupt production or transportation of oil and cause environmental disasters or accidents. Some oil companies have already lost million of dollars because of disrupted production and transportation. Conventional approaches to prevent degradation and enhance the service life of pipelines include cathodic protection, chemical inhibitors, and the application of coatings. However, such techniques do not completely eliminate pipeline degradation. Therefore, developing coatings that decrease erosion and corrosion, prevent fouling, and avoid fatigue when a pipeline is externally or internally damaged is a promising approach. Nanotechnology, using materials on the nanometer scale, is aimed at enhancing and improving the properties of materials, coatings, and chemical compounds. Nanotechnology has proven to be a useful, effective, and promising technology to address the aforementioned degradation mechanisms in oil pipelines [6].

3.1. Nanostructured Cathodic Protection and Sensing

Nanostuctured coatings can be used for both sacrificial and impressed current cathodic protection systems. The functionality can also be combined with sensing capabilities [5]. Nanoparticles or nanostructures are incorporated into the polymer coating to provide cathodic protection to buried pipelines. The coating is not only resistant to corrosion but also allows the current to reach the substrate and provide protection. When using impressed current cathodic protection (ICCP), the coating can reduce the required amount of current and maintain an effective protection system. Enhancement of nanoscale cathodic protection system for both sacrificial and impressed current protection is elaborated..nano Coatings containing particles capable of providing cathodic protection are also developed. Such coatings can provide corrosion protection. They can be used as an anti-corrosive layer in combination with other anti-fouling systems. Energy harvesting naturally drives these functionalities in buried pipelines [7].

4. Methodology

The oil and gas industry has a drawback of flow assurance in transporting and processing fluid materials, which often degrades the pipeline and causes a drop in production, thus hindering transportation. This often results in economic burdens and safety risks due to a lengthy intermittent period in re-establishing the production line subsequently. Flow assurance occurs when asphaltenes and paraffin wax particles are flow hindered and deposited on pipe walls when oil cools below a certain temperature resulting in process shutdown; drag reduction happens due to rough surfaces of pipes and turbulence-inducing fittings on pipeline process. Nanotechnology-Driven Flow Assurance and Drag Reduction are focused on high performance in oil extraction and transportation that utilize nanomaterial-based techniques, mainly for polymer conformance control, interfacial tension reduction and nanofluids to reduce friction pressure loss, product viscosity and improve fluid drainage under surface and down-hole for improved recovery efficiency, safety and economic returns [8] constantly. To address the uncertainties in high-importance production and ultimately solution that can be established within pipeline and requires less field personnel [9] different types of nanoparticles to modify and enhance the basic properties using lab designed dual-purpose fracturing fluids in field test.

4.1. Nanofluids for Hydrodynamic Optimization

Nanofluids can modify the rheological and thermal transport properties of petroleum fluids and thus have a high potential for flow assurance, drag reduction, particle deposition mitigation, and transport optimization of solid particles and wax in pipes and tubes [8]. Different types of nanomaterials with high thermal conductivity/rheological performance and compatibility to petroleum fluids, such as metal oxides, nanohybrids, graphite, carbon nanotubes, graphene, and metallic nanoparticles can be used to prepare nanofluids [10]. Consequently, the development of nanofluids related to the above aspects, including nanoparticles used, base fluids employed, stability, rheology, heat transfer, compatibility with oil and gas pipeline infrastructures, and safety in this specific oil and gas industry, is an important task. The approach combined the use of silica (SiO_2) nanoparticles, kerosene, and the anionic surfactant SDBS. Prior to application, the silica nanoparticles were thoroughly characterized using thermogravimetric analysis (TGA), X-ray diffraction (XRD), atomic force microscopy (AFM), scanning electron microscopy (SEM), and energy-dispersive X-ray spectroscopy (SEM-EDX). These techniques confirmed the particles' thermal stability, crystalline structure, nanoscale morphology, and elemental composition, validating their suitability for crude oil modification.

4.2. Surface Nanotexturing to Minimize Erosion and Fouling

Surface nanotexturing can also minimize erosion and fouling, prolonging the service life of pipelines. Oilfield applications often experience particulate matter, such as sand, that, with time and part exposure, could progressively erode pipeline surfaces built with carbon steel or plastic. These deposits lower flow capacity, increase downtime, escalate operating costs, and affect overall production rates [9]. Pipelines constructed from either carbon steel or plastic experience significant erosion from abrasive particles over time in the petroleum industry.

5. The Result and discussion

Pipelines transporting oil are subject to heightened challenges that can develop gradually into cumulative damage subsequently leading to, corrosion, erosive wear, and/or fatigue. This may result in significant losses of both internal/external wall material that often goes undetected for long periods. There are several factors that promote accelerated deterioration such as irregular process performance characteristics, inappropriate material selection, rough surface finish, and harsh environmental conditions - all of which will hinder the ability to identify or address the root causes of degradation. Therefore, an effective structural health monitoring (SHM) system is imperative to provide an early warning of the existence of damage. The validation activity classifies methodologies according to their performance and confirms the robustness of physics-based models with substantial dependence on the addressed aspects of the problem, especially for integrity-risk modelling that is deemed a key factor to promptly exploit the potential gain of the system [14].

Table 1 Mechanisms Pipeline Degradation

Degradation Type	Main Causes	Affected Area	Impact on Pipeline	Detection Method	Severity (1–5)
Corrosion	H_2O, CO_2, H_2S	internal	wall thinning, leakage	EIS, UT sensors	5
Erosion	sand, particles	internal	material loss, cracks	flow sensors	4
Fouling	wax, asphaltenes	internal	flow restriction	pressure drop	3
Fatigue	Presser and vibration	structure	cracks, rupture	strain sensors	5

Pipeline degradation mechanisms are corrosion, erosion, fouling, and fatigue affecting various system components. Corrosion and fatigue have the highest severity ratings, indicating they are the most critical threats to pipeline integrity as the following in figure 2

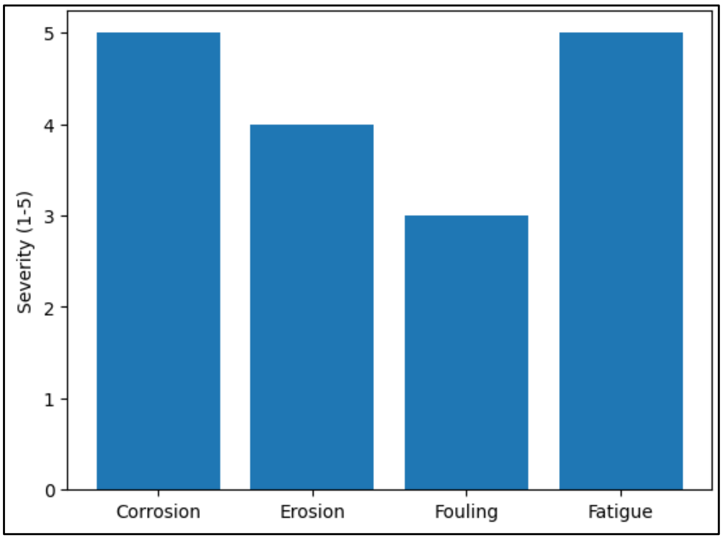

Figure 2 Pipeline degradation mechanisms

Table 2 Solutions Nanotechnology

Nanotech Solution	**Material Type**	**Function**	**Key Benefit**	**TRL Level***
Nanocoatings	TiO_2/GO, PVA/PANI	corrosion protection	barrier + hydrophobic	6–8
Self-healing coatings	polymer nanocomposites	damage repair	autonomous healing	5–7
Nanofluids	CNT, graphene	drag reduction	lower pressure loss	6–9
Nanotextured surfaces	nano-patterned steel	anti-fouling	reduced deposition	5–7
Nanosensors	nanowires, CNT	Monitoring	real-time diagnostics	7–9

Different nanotechnology solutions such as nanocoatings and nanosensors offer protection monitoring and performance enhancement. These technologies increase pipeline efficiency and reliability with higher TRL levels indicating readiness for real-world application as showing in figure 3.

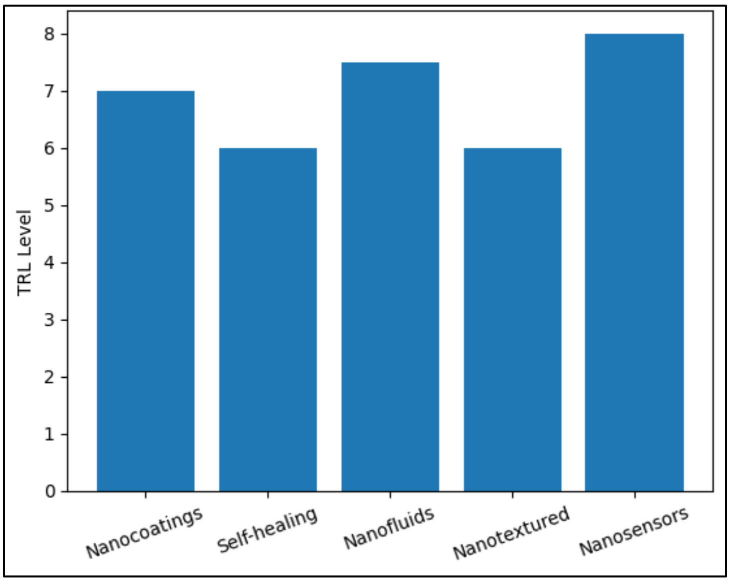

Figure 3 Technology readiness level (TRL)

Table 3 Performance improving

Parameter	Traditional Methods	Nanotechnology-Based	Improvement (%)
Corrosion rate (mm/year)	0.5–1.2	0.1–0.3	60–80% ↓
Maintenance frequency	High	Reduced	30–50% ↓
Flow efficiency	Moderate	High	20–40% ↑
Leak detection time	Slow	Real-time	70–90% faster
Operational cost	High	Medium	25–45% ↓

Nanotechnology has a significant performance enhancement effect by reducing corrosion maintenance frequency operational cost improving flow efficiency allowing faster leak detection than conventional methods as showing in figure 5.

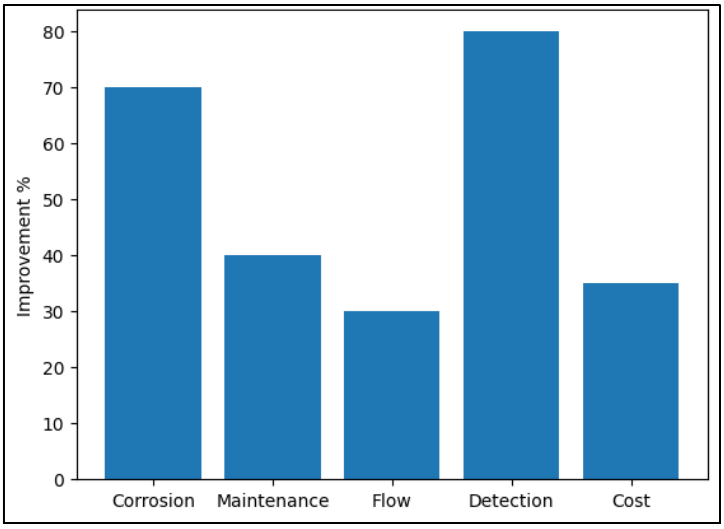

Figure 4 Performance improving

Table 4 Predictive Maintenance for Nanosensor Data

Parameter	Sensor Type	Unit	Threshold	Action
Strain	CNT sensor	microstrain	>2000	inspect
Crack growth	nanowire grid	mm	>2 mm	repair
Corrosion rate	electrochemical nanosensor	mm/year	>0.3	apply coating
Temperature	nano-thermal sensor	°C	>80	reduce flow
Pressure drop	nano-pressure sensor	Bar	abnormal	clean pipeline

Nanosensors continuously monitor parameters like strain temperature corrosion rate to provide early damage warning. Defined threshold values help initiate actions before failures occur thus enhancing safety as showing in figure 5.

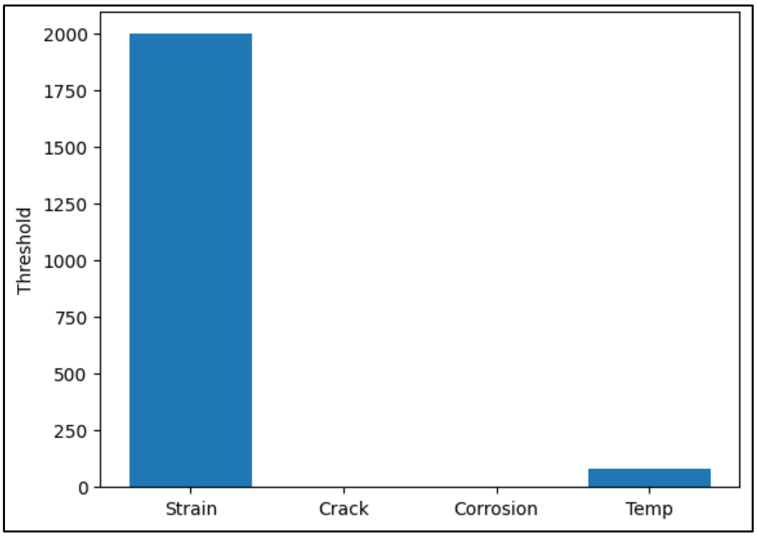

Figure 5 Sensor threshold values

Table 5 Analysis Impact Economic

Factor	Without Nanotech	With Nanotech	Savings
Annual maintenance ($)	10M	6M	40%
Failure cost ($)	50M	15M	70%
Downtime (days/year)	20	8	60%
Pipeline lifespan (years)	25	40	+60%

Finally, the use of nanotechnology helps in reducing maintenance and failure costs as well as minimizing downtimes besides increasing the lifespan of pipelines hence making it an economical long-term investment as showing in figure 6.

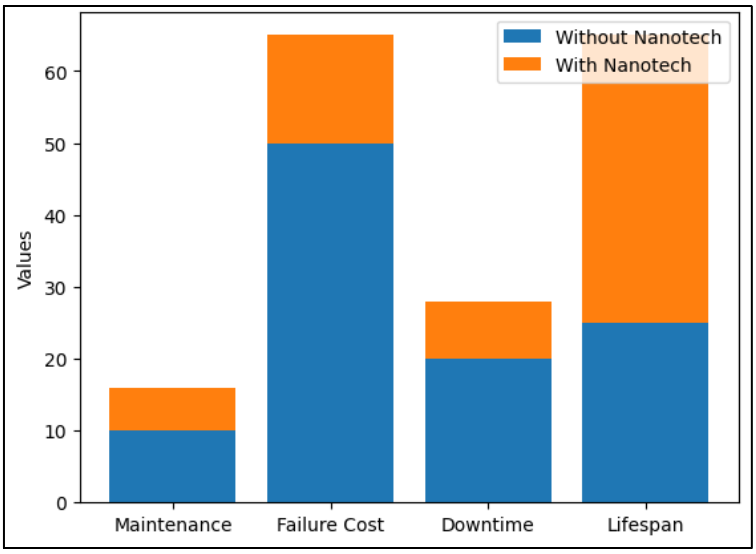

Figure 6 Economic Impact

6. Conclusion

Pipeline deterioration is a major issue which creates significant financial and ecological threats to the economy and environment through leaks and rupture. Existing methods to monitor and/or mitigate the degradation of pipelines have had limited success and/or impact. There is great potential for nanotechnology to address these limitations and improve pipeline performance, safety and effectiveness, but there is uncertainty about the barriers to and generalizability of nanotechnology benefits for pipelines. Nanotechnology is capable of providing better solutions for the mitigation of pipeline corrosion, the assurance of flow in pipeline operations, and preventing leaks from pipelines. The properties of nanomaterials provide a novel mechanism for creating coatings and linings that include self-healing functions, as well as the capability to build cathodic protections systems that operate in harsh environments and include sensing functions. The hydrodynamic properties of petroleum-based fluids can be enhanced using nanofluids, due to the ability to extend the service life of oil pipelines without the need for mechanical cleaning. Also, surface nanotexturing of pipeline materials can control their interaction (i.e., build-up of fouling and erosion) with crude oil transported through the pipelines. Nanoscale sensors have greater degrees of sensitivity and a wider range of sensitivity than bulk sensors, making it easier to detect cracks and strain in the pipeline and allowing for real-time monitoring without affecting the integrity of the pipeline.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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