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MINI REVIEW OF MAGNETIC FLUX LEAKAGE DETECTION TECHNOLOGY FOR LONG-DISTANCE OIL AND GAS PIPELINES

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Abstract:

Long-distance oil and gas pipelines are a crucial means of energy transportation, and leaks in pipelines can lead to significant environmental and human losses. Therefore, it is necessary to adopt defect detection technology to regularly inspect pipelines, ultimately achieving the purpose of maintenance and repair of oil and gas pipelines. This paper introduces common types of defects in oil and gas pipelines, as well as commonly used defect detection methods. It focuses on the principle of magnetic flux leakage detection, analyzes factors affecting the results of magnetic flux leakage detection, and prospects the future development direction of magnetic flux leakage detection technology.

Keywords:

Pipeline Defects; Non-Destructive Testing; Oil And Gas Pipelines

Introduction

Pipelines are considered a relatively safe, reliable, and cost-effective means of energy transportation Yani, Jingping, Bo, & Guoliang (2023).According to current data, over 70% of the world's oil resources and over 90% of natural gas resources are transported through long-distance pipelinesNuan (2022).Since the first recorded use of oil pipelines in Pennsylvania in 1859, the total length of oil and gas pipelines worldwide is sufficient to circle the Earth 30 times.

However, due to the long transportation distances, diverse geographical terrains along the pipeline routes, and the extended service life of some pipelines, various defects such as corrosion, deformation, and cracks inevitably occur during the use of oil and gas pipelines. In recent years, various pipeline leakage incidents have become increasingly common. These incidents not only cause economic losses to the affected countries but also result in severe environmental pollution, which is vital for our survival, posing significant health hazards to human beings (Aljaroudi, Khan, Akinturk, Haddara, & Thodi, 2015).

Due to constraints imposed by existing detection technologies and methods, once steel pipes are put into use, it becomes challenging to assess their health condition accurately. Blind excavation, scrapping, and maintenance without scientific basis can lead to significant waste of manpower and financial resources. Consequently, the precise identification of steel pipe defects becomes even more urgent and prominent.

Common Types of Pipeline Defects and Detection Methods

Common Types of Pipeline Defects

Corrosion is one of the most common defects in pipelines, caused by chemical reactions between the pipeline surface and the medium, resulting in thinning or perforation of the metal. Factors such as high salinity soil, high temperature and humid environments, friction and vibration during pipeline transportation, structural defects in pipe materials, and coating damage can accelerate the corrosion process of pipelines. The presence of corrosion reduces the strength and durability of the pipeline walls.

Cracks are linear defects in pipelines, typically occurring inside the pipeline when stress is concentrated, or external pressure exceeds its bearing capacity. Common forms of cracks include longitudinal, circumferential, and compound cracks. Cracks may also occur in welded seams and heat-affected zones at pipeline connections, potentially leading to pipeline rupture.
Wear is damage to the inner surface of a pipeline caused by the friction of fluid or particles flowing inside the pipeline, which may result in thinning of the pipe wall.

Holes are small openings or voids in the inner or outer walls of a pipeline and are a relatively common form of defect. There are mainly two reasons for their occurrence: one is material defects, bubbles, or uneven composition during the manufacturing process; the other is improper welding operations during pipeline joints, resulting in welding pores or slag inclusions. The presence of holes may concentrate stress in the pipeline, leading to the risk of cracking.

Welding depressions are caused by improper welding operations resulting in undercut or incomplete penetration defects; protrusions are caused by welding producing weld beads. Depressions and protrusions can concentrate stress in the steel pipe, reduce the load-bearing capacity of the joints, lead to cracks, and result in fracture failure.

Common Pipeline Defect Detection Methods

In general, pipelines go through a relatively long period from the appearance of defects to failure. Therefore, effective identification of pipeline defects becomes crucial for accident prevention (Zhao, Wei, & Yang, 2020).

Non-destructive testing (NDT) is a method of detecting defects in materials, components, or parts without causing damage to them, utilizing various technological means and principles of physics and chemistry. In contrast to NDT, other testing methods are essentially destructive. Therefore, they can only be performed on a batch sampling basis rather than on materials or products put into use.

There are many non-destructive testing methods, with over 70 varieties identified according to research and analysis conducted by NASA (NDT, 2017). However, some of the more commonly used methods in practical applications include Ultrasonic Testing (UT), Radiographic Testing (RT), Magnetic Particle Testing (MT), Penetrant Testing (PT), and Eddy Current Testing (ET).

The working principle of ultrasonic testing technology is based on the phenomenon of sound wave reflection. Ultrasonic testing has high accuracy and can detect defects such as dents and cracks in pipelines Pengcong (2020) Xiangyu, Yehui, & Jinlu (2022) . However, the detection process is complex and demands high environmental conditions. For crude oil transmission pipelines, the significant differences in density and uniformity of the crude oil medium can greatly affect the detection accuracy. Additionally, when the pipe wall is heavily waxed, ultrasonic waves will be absorbed by the wax. Therefore, ultrasonic testing technology needs to be tailored to the actual conditions of oil and gas pipelines to fully realize its valueZhitao & Wenxin (2021) Wei (2004) .

Eddy current testing can comprehensively detect internal and external defects in ferromagnetic materials without the need for contact with the workpiece or the use of coupling agents. It is an efficient and highly reliable non-destructive testing method. Traditional eddy current testing exhibits skin effect, which means it can sensitively detect defects near the inner surface of pipelines. However, it is challenging to detect defects deep within thick-walled pipelines and determine the parameters of these defects. Currently, far-field eddy current testing technology can overcome skin effect, penetrating through the pipe wall to inspect the exterior surface of pipelines. Pulse eddy current technology has the advantages of fast response and strong defect detection capabilities, which can also compensate for the shortcomings of eddy current testing in detecting deep defects within pipelines Xiangyu et al. (2022) .

Radiographic testing relies on the differential absorption of electromagnetic or particle radiation by various components, densities, and thicknesses of the workpiece to detect characteristics such as quality and size. It is suitable for oil and gas pipelines made of any material. The drawback is that X-ray equipment requires significant investment and is heavy, making it unsuitable for defect detection in long-distance pipelines. In addition, the depth of defects cannot be measured, and it cannot identify small linear defects perpendicular to the direction of the radiation. Moreover, radiation poses a certain risk to the environment and personnel involved in the testing process. The recovery of developing and fixing solutions is challenging, and direct discharge can lead to environmental pollutionJunming (2022) . In practical applications, to achieve better pipeline inspection results, X-ray testing technology is often combined with ultrasonic or other detection techniques Zhitao & Wenxin (2021).

Magnetic particle inspection is widely used for non-destructive testing of surface and near-surface defects in ferromagnetic materials. Its principle involves the magnetization of ferromagnetic workpieces by an external magnetic field. When there are defects in the workpiece, the magnetic flux lines deform locally, forming detectable magnetic leakage fields. After applying magnetic particles to the inspected workpiece, the particles will accumulate at the defect locations, making them visibleXu (2021) . However, magnetic particle testing is only suitable for detecting surface and near-surface defects in ferromagnetic materials such as carbon steel, martensitic stainless steel, and precipitation-hardened stainless steel. It cannot detect defects in non-ferromagnetic materials such as aluminum, magnesium, austenitic stainless steel, etc. Additionally, it is not suitable for detecting buried deep internal defectsWikipedia (2022) .

Not all non-destructive testing methods are suitable for defect detection in long-distance pipelines. Due to constraints imposed by the pipeline's location and the limitations of relevant detection technologies, most inspection techniques do not yield satisfactory results for identifying defects in long-distance pipelinesWan, Wang, & Yang (2021) .

Magnetic flux leakage (MFL) detection is currently the most widely used non-destructive testing method due to its numerous advantages. It requires low environmental conditions inside the pipeline, does not require coupling, has a wide range of applications, is cost-effective, has a high defect detection rate, and offers good value for money. Moreover, it can be implemented for online inspection without affecting the transportation of long-distance pipelinesLin et al. (2022) .

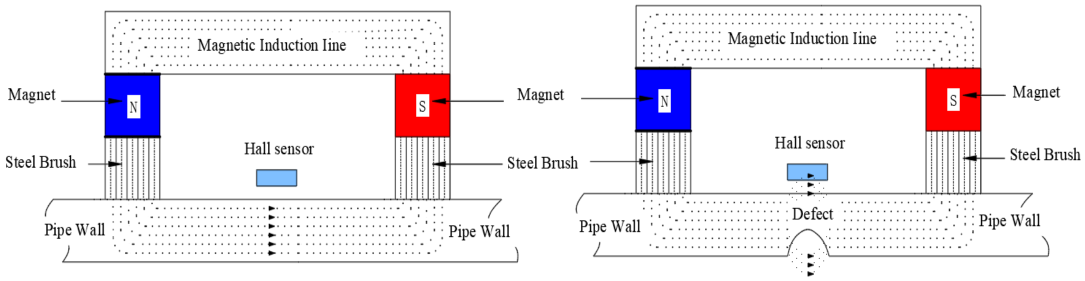
Principle of Magnetic Flux Leakage Detection and Analysis of Factors Affecting Detection Results

Magnetic flux leakage (MFL) detection technology is a non-destructive testing method that utilizes magnetic phenomena to detect surface and near-surface defects in ferromagnetic materials. It is based on the high magnetic permeability characteristics of ferromagnetic materials and has evolved from magnetic particle testing technologyLiu (2010) . It can detect various types of defects and provide a rapid and relatively inexpensive assessment of ferromagnetic materials. The typical application of magnetic flux leakage (MFL) detection is to inspect steel billets, steel structures, rods, and round steel to ensure the integrity of the finished products. Additionally, it can be used to inspect steel pipes, steel cables, and large storage tanks such as gas tanks and oil tanks.

Principle of Magnetic Flux Leakage Detection

The basic principle of magnetic flux leakage (MFL) detection for steel pipes is illustrated in Figure 1. A strong magnetic field is generated using a permanent magnet, and the steel brush is used to magnetize the wall of the ferromagnetic steel pipe to saturation. When there are no defects on the pipe wall, the magnetic field distribution is uniform, as shown in Figure 1a.

When anomalies such as defects, weld beads, or cracks exist on the pipe wall, there will be magnetic flux leakage in these areas, as shown in Figure 1b. By detecting the magnetic leakage field with a magnetic sensor probe, defects in the steel pipe can be discovered. During result analysis, information such as slope, amplitude, and cycle from the data curve can be used to determine the extent of corrosion, the type, and size of defects in the pipeline.



（a）Magnetic field distribution without defect

（b）Magnetic field distribution with defects

0: Schematic of Magnetic Flux Leakage Detection For Steel Pipes

Analysis of Factors Affecting Magnetic Flux Leakage Detection Results

The defects formed by natural corrosion in steel pipelines are diverse and lack regularity. According to the corrosion assessment standards for steel pipelines, corrosion defects can be evaluated based on three geometric parameters: equivalent width, equivalent length, and maximum depth. These parameters directly influence the magnetic flux leakage signals of defects.

The Impact of Defect Length on the Magnetic Flux Leakage Field.

As shown in Figure 2, with the steel pipe defect lengths set at 2mm, 4mm, 6mm, 8mm, and 10mm, all with a depth of 5mm and other external dimensions and parameters unchanged, as the defect length increases, the span of the defect magnetic leakage field increases while the amplitude decreases. Overall, there is an approximate linear relationship. When the defect length varies within a small range, the change in the magnetic leakage field of the defect is more significant, with the amplitude showing a larger linear proportion to the defect length. However, when the defect length is relatively large, the change in the magnetic leakage field amplitude becomes smaller, with a smaller linear proportion to the defect length.

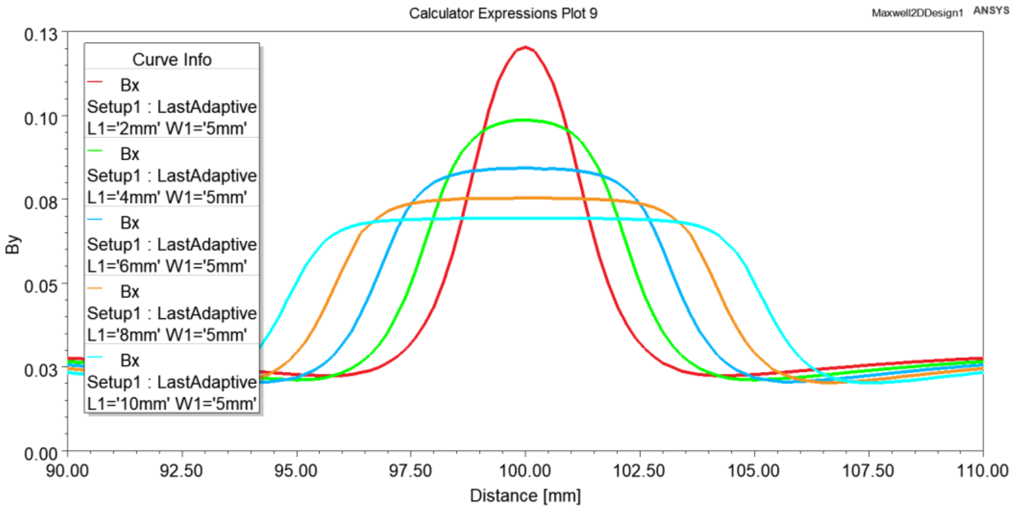


Figure 2: Axial Components of Magnetic Leakage Signals For Defects Of Different Lengths

The Effect Of Defect Width On Leakage Magnetic Field

It is generally believed that variations in defect width mainly affect the peak spacing of the radial component of the leakage magnetic fieldYongliang, Cheng, Zhijun, Xuefeng, & Yuzhuo (2021), When the magnetization direction is perpendicular to the defect width direction, defects with larger width and smaller length exhibit a more pronounced leakage magnetic field. With increasing defect width, the circumferential distribution of the leakage magnetic field increases, and simultaneously, the amplitude of the leakage magnetic field also increases.

In the quantitative detection of leakage in boiler water-cooled wall defects conducted by Du Peng et al. from Hebei University of Technology, the threshold value for the separation of the magnetization device and sensor was set at 4mm, with defect widths of 1, 2, 6, 12, and 20mm. It was observed that the intensity of the leakage magnetic signal did not continuously increase with the increase in defect width. In fact, it was found to decrease to some extent after reaching a certain level (Figure 3). The background magnetic field remained constant, while the signal profile widened gradually with the increasing defect width. The slope of the signal's inclined portion increased gradually up to a certain level and then remained relatively constant.

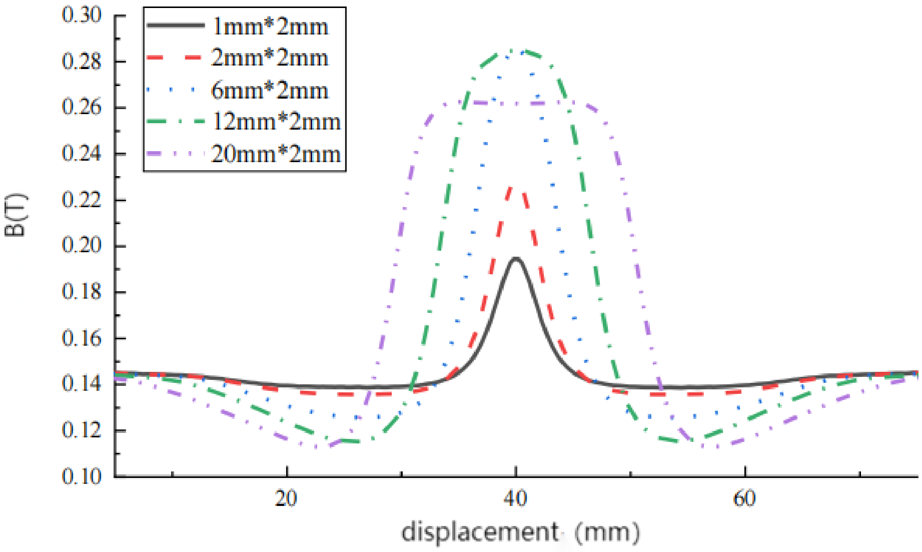


Figure 3: Magnetic Leakage Signals of Different Defect Widths

The Influence Of Defect Depth On The Leakage Magnetic Field.

Among numerous references, the study on defect depth is the most extensive. The extent of damage and corrosion in pipelines is primarily associated with the dimension of defect depth. In their study on the leakage magnetic field signals of defects at different depths in 20# steel, Jiang Qi and colleagues from Tianjin University found that JiangQi (2002), with the defect width and length unchanged, the amplitude of the leakage magnetic field signal increased with the increase in defect depth, exhibiting an approximate linear relationship. During the depth range of 10% to 50%, the amplitude of the leakage magnetic field increased rapidly, while it increased more gradually from 50% to 80% of the depth. However, for defects of the same depth, when the length and width of the defects varied, the waveform amplitude and shape of the leakage magnetic field also varied significantly, with notable differences. Therefore, considering the influence of defect depth on the leakage magnetic field requires a comprehensive consideration of the defect's length and width. Typically, for defects with fixed length, those with higher aspect ratios (width-to-length ratio) exhibit steeper signals and higher amplitudes. Conversely, the opposite is also true Wenlai (2009).

The Influence Of Surface Roughness On Leakage Magnetic Signals.

Research conducted by Yang YunYun (2017) and colleagues from Huazhong University of Science and Technology in China found that two geometric features of rough surface contours form opposite magnetic field disturbances: at the troughs of the contour elements, some magnetic flux lines from the adjacent interface of the workpiece "leak" into the air, forming a magnetic field intensity distribution larger than that caused by the background magnetic field induced by the magnetizer; at the peaks of the contour elements, some magnetic flux lines from the air near the interface are "drawn" into the interior of the workpiece, forming a magnetic field intensity distribution smaller than the background magnetic field. The typical characteristic shape of surface leakage magnetic field signals caused by surface roughness is an approximate sine wave.

The Influence Of Temperature On Leakage Magnetic Signals.

Research has shown that with increasing temperature, both the peak value of the Bx component and the peak-to-valley height of the By component increase simultaneously. This is because as the temperature of the tested material rises, the permeability decreases. Under conditions of material magnetic saturation, excess magnetic field leaks outside, enhancing the leakage magnetic field at the defect location. In practical detection, this characteristic can be utilized to enhance the leakage magnetic signals for detecting small, subsurface, and internal defects, thereby improving the detection effectivenessDaoyi (2016) .

The Influence Of Lift-Off Distance On Leakage Magnetic Signals.

The lift-off distance of the magnetization device refers to the distance between the magnet and the surface of the tested workpiece. There is a close relationship between the lift-off distance and the degree of magnetization, which directly affects the strength of the leakage magnetic signals at the defect location. In Figure 4, which depicts 100 sets of defects with lengths and depths ranging from 1 to 10mm, with lift-off distances set at 1mm, 2mm, 3mm, and 4mm, the y-axis represents the peak-to-peak magnetic flux density, and the x-axis represents the 100 sets of defects. From the graph, it can be observed that a smaller lift-off distance corresponds to a larger peak-to-peak magnetic flux density. However, reducing the lift-off distance may allow the magnetic sensor to capture more leakage magnetic field information, but it can also increase errors caused by fluctuations in the lift-off distance. Therefore, it is important to select an appropriate lift-off distance based on the actual conditions at the siteZhong-he, Jie-le, & Yu-qi (2021) .

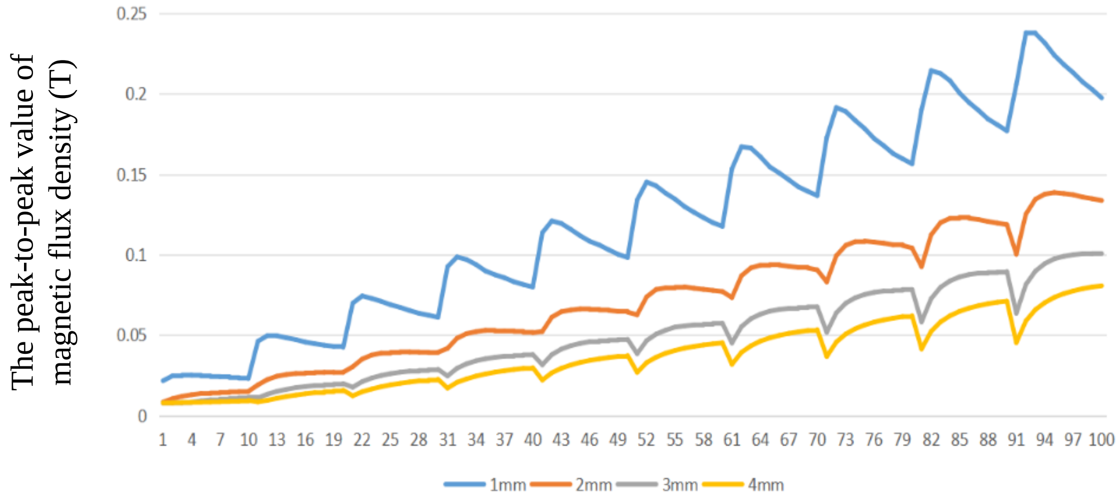


Figure 4: The Peak-To-Peak Magnetic Flux Density

Research Progress of Magnetic Flux Leakage Detection Technology

The theoretical research of magnetic detection is the study and analysis of defect leakage magnetic fields Cui (2022). In 1865, British physicist James Clerk Maxwell proposed a solution based on Maxwell's equations, which became the foundation for the development and theoretical research of magnetic flux leakageLingli (2009). In 1933, Zuschlug first proposed the idea of using magnetic sensors to measure leakage magnetic flux. In 1947, Hastings designed a magnetic flux leakage detection system, which addressed the limitation of magnetic particle testing in detecting defects such as internal wall injuries in pipelines. In 1965, the American company Tubecope Vetco developed the Linalog magnetic flux leakage pipeline inspection device, which effectively detected various defects such as transverse scars and corrosion pits in pipelinesWang (2015). In 1966, Shcherbin and Zatsepin proposed the magnetic dipole model for an infinite rectangular crack to determine the relationship between leakage magnetic field and defect shape. In 1970, SwansonJ invented the Ansys finite element analysis software. In 1972, Shcherbin and Poshagin collaborated to derive the magnetic field distribution of an open-ended finite crack based on the same magnetic dipole model. From then on, magnetic flux leakage detection technology began to be applied internationally and gained widespread recognitionZhang (2011) Wang (2015).

In recent years, the importance attached to the inspection of oil and gas pipelines has been continuously increasing worldwide. Numerous scholars have conducted in-depth research in various fields, achieving fruitful results. Hiroaki Kikuchi and others have utilized GMI sensors to detect defects as small as 100 μm in size and GMR sensors to detect defects with a diameter as tiny as 30 μm. Kikuchi, Tschuncky, & Szielasko (2019).Zheng Fuyin et al. designed a pipeline stress detection system based on the J-A model of magneto-mechanical effects to achieve real-time monitoring of stress in oil and gas pipelines. Ou Zhengyu et al. inserted a magnetic field sensor into the magnetization gap for magnetic disturbance detection, combined with leakage magnetic detection to accurately identify internal and external wall defects with a depth range of 12.5% to 87.5% of the wall thickness. Zhengyu, Zandong, Jisong, & Xiaxi (2023).Cao Hui and colleagues proposed a deviation-based random forest defect three-dimensional (3D) contour reconstruction method. This method utilizes deviation estimation from leakage magnetic signals to reconstruct contour deviations, ultimately achieving accurate reconstruction of the 3D contours of defectsHui & Lijian (2019). Hu Jing and colleagues proposed a theory based on magnetic multipole fields to extract parameter features from defect detection signals of leakage magnetic internal detectors, thereby distinguishing between defects on the inner and outer walls of pipelines. This method overcomes the limitation of detectors requiring hardware sensors, demonstrating high recognition accuracy. It provides guidance for the identification, principle analysis, and differentiation of leakage magnetic defects.Jing, Sijiao, Li, Zhenfeng, & Jianhua (2021).

Future Development Trends and Prospects of Leakage Magnetic Detection

At the end of 2015, the 21st United Nations Climate Change Conference adopted the Paris Agreement. The agreement states that to reduce the ecological risks of climate change to the Earth, global greenhouse gas emissions should peak as soon as possible, with zero emissions of greenhouse gases achieved in the second half of this century. According to statistics from the Energy and Climate Intelligence UnitUnit (2024), as of March 2024, a total of 143 countries and regions have proposed or committed to achieving zero carbon emissions.

From a global perspective, petroleum, and coal account for the largest proportion of primary energy consumption, followed by natural gas and other renewable resources. To adjust and optimize the energy structure, it is necessary to use lower-carbon and cleaner resources such as natural gas or other renewable resources to replace or reduce the use of coal and petroleum. However, achieving carbon neutrality in the short term is a very challenging task, considering factors such as the economic development level of each country, baseline emissions, and the cost of energy transition. For a long time, traditional petroleum resources and emerging natural gas resources will remain the focus of development for most countries.

Detecting pipeline defects using leakage magnetic signal data has always been a highly challenging task. Based on current research progress and hotspots, leakage magnetic detection technology will develop in the following aspects.

1.Integrating leakage magnetic detection with various other detection technologies such as ultrasonic testing and eddy current testing can lead to the development of more intelligent and automated detection systems. This integration helps overcome the limitations of individual detection methods, enhancing the accuracy and sensitivity of defect detection. Furthermore, it can improve production efficiency and quality levels while reducing costs.

2. With the rise of computer technology and the emergence of high-precision sensors, people can easily obtain a large amount of leakage magnetic data, leading to significant advancements in the two-dimensional reconstruction technique of defect profiles. However, two-dimensional reconstruction techniques can only display the cross-sectional information of defects and cannot fully represent the overall appearance of defects. Therefore, three-dimensional reconstruction techniques for defects are expected to become the mainstream research focus.
With the continuous development of algorithms such as deep learning and machine learning, as well as improvements in computer performance, future three-dimensional reconstruction techniques are likely to become more automated. Defect data will be transformed into clear models of the actual morphology of pipelines, significantly reducing manual labor costs.

3. Leakage magnetic detection data processing is a complex process, with the operational environment often being challenging and influenced by various factors. As scientific and technological advancements continue, exploration in oil and gas fields may extend to even harsher environments. To meet the demands of extraction and transportation, composite materials or other alternative materials for pipelines may gradually be adopted. Therefore, future leakage magnetic detection techniques must consider the accuracy of data processing under conditions of weak magnetic fields, thick walls, and severe corrosion effects.

4. Most existing research on leakage magnetic detection focuses on individual rule-based defects. However, in practical applications, defects often appear in clusters and have intricate shapes. Detecting individual defects can be influenced by the leakage magnetic fields generated by surrounding defects, leading to identification errors. Therefore, when constructing a database of leakage magnetic detection features, it is essential to consider the significance of analyzing multiple defects simultaneously.

Conclusion

The review highlights the critical role of pipeline transportation in the global energy infrastructure and underscores the importance of effectively detecting and managing pipeline defects to ensure safety and reliability. Common pipeline defects such as corrosion, cracks, wear, and welding depressions can significantly impact the structural integrity of pipelines, leading to potential failures and environmental hazards. Among the various non-destructive testing (NDT) methods, Magnetic Flux Leakage (MFL) detection stands out for its ability to efficiently identify surface and near-surface defects in ferromagnetic materials. The MFL method's advantages include its cost-effectiveness, applicability to online inspections, and high defect detection rate. However, factors such as defect length, width, depth, surface roughness, temperature, and lift-off distance influence the accuracy of MFL detection. Advancements in MFL technology, coupled with integration with other NDT methods, hold promise for more accurate, efficient, and comprehensive pipeline inspections. As global energy demand evolves and environmental regulations tighten, the development of intelligent, automated detection systems integrating MFL with other technologies will be crucial in maintaining the safety and integrity of long-distance pipelines, contributing to sustainable energy transportation solutions**.** The industry stands to benefit greatly from the widespread adoption of MFL due to its ability to detect defects efficiently, minimizing the risk of pipeline failures and associated environmental hazards. This, in turn, can lead to reduced maintenance costs and fewer operational disruptions, thereby increasing overall efficiency and profitability. Moreover, the integration of MFL with other non-destructive testing (NDT) methods can provide a more comprehensive inspection framework, allowing for early detection of potential issues before they escalate into serious problems. As the industry faces increasing regulatory scrutiny and growing demands for sustainable practices, the adoption of advanced, automated detection systems can ensure compliance with safety standards while also reducing the environmental impact of pipeline operations. Furthermore, the development of intelligent MFL systems can facilitate real-time monitoring and predictive maintenance, enabling operators to make informed decisions and optimize the lifespan of pipeline infrastructure. By leveraging these advancements, the industry can not only improve safety and reliability but also achieve greater sustainability and cost-effectiveness in energy transportation.

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