



OPEN Distributed optical fiber acoustic wave sensor detection technology for gangue slurry pipeline conveying blockage

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The pipeline conveying system as the gangue slurry filling technology lifeline. The occurrence of pipeline blockage will lead to the paralysis of the entire filling system; timely detection of pipeline blockage and early warning are needed to ensure the safe, stable, and efficient operation of the core elements of the coal gangue slurry filling system. Based on this, this paper summarizes and analyzes the classification of pipeline blockage and summarizes the current pipeline conveying blockage detection technologies. It elaborates in detail on the principles and advantages and disadvantages of existing pipeline blockage detection technologies, and points out that distributed optical fiber acoustic wave sensor (DAS), as an emerging fiber optic detection technology in recent years, can achieve high-precision, large-scale, real-time dynamic and distributed acoustic detection, Compared with traditional monitoring for pipeline blockage, it is more suitable for detecting blockage in coal gangue slurry pipeline conveying; then from the sensing principle of distributed fiber optic acoustic wave sensing technology, it discusses the current status of DAS technology application, analyzes the pipeline blockage DAS detection mechanism, and verifies the feasibility of pipeline conveying blockage detection based on the distributed fiber optic acoustic wave sensing technology by building a pipeline blockage DAS detection simulation experiment system; finally, it puts forward the feasibility of distributed fiber optic acoustic wave sensing technology; finally, it puts forward the feasibility of distributed fiber optic wave sensing technology detection. Finally, a pipeline blockage DAS detection and identification system is proposed, the function of each subsystem is introduced, and the core key technology involved in the pipeline blockage DAS detection and identification system is analyzed in detail, and the future development direction of gangue slurry pipeline conveying blockage DAS detection technology is also pointed out in order to provide reference for the development of the subsequent gangue slurry pipeline blockage and other pipeline conveying blockage DAS detection technology.

Keywords Gangue slurry filling technology, Pipeline blockage, Distributed optical fiber acoustic wave sensor technology, Pipeline blockage identification

As the main producing area of coal in China, the western region bears the important task of independent supply of national basic energy^{1,2}. However, with the large-scale and high-intensity mining of coal resources in the West at the same time, the ecological environment also has a certain impact, in which the coal gangue is one of the main sources of ecological impact in the mining area, not only occupies a large amount of land, but also on the air and surface water and so on also caused serious pollution³⁻⁵. With the continuous enhancement of social awareness of environmental protection, the negative effects of environmental pollution caused by coal gangue discharge are more and more difficult to accept, and the green treatment of coal mine gangue is imperative⁶⁻⁸. For this reason, Zhu Lei^{9,10} and others have taken the lead in fully summarizing the characteristics of traditional filling technology on the basis of the combination of high-productivity and high-efficiency mines in the western region of the gangue green, high-efficiency, low-disturbance and low-cost disposal of coal gangue needs, took

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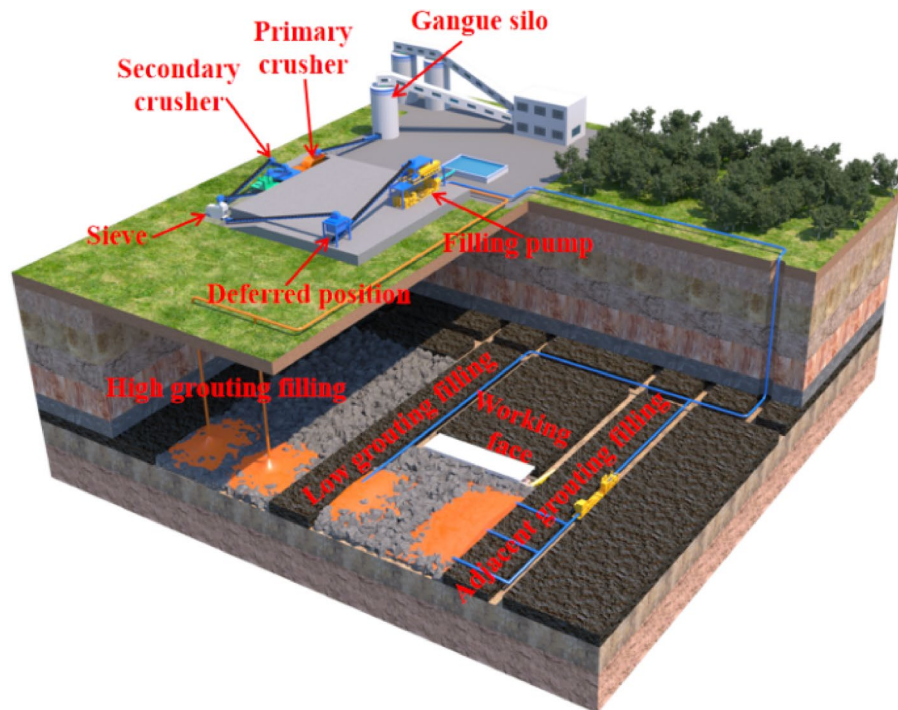


Fig. 1. Schematic diagram of gangue slurry filling technology.

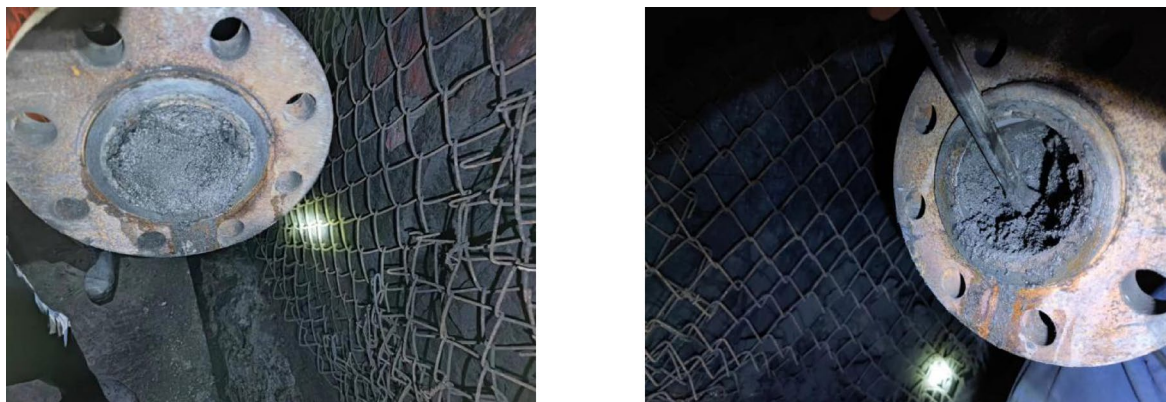


Fig. 2. Physical drawing of pipe blockage.

the lead in proposing the gangue slurry filling technology, the principle of gangue slurry filling technology schematic diagram, shown in Fig. 1. which is mainly composed of a crushing slurry system, pipeline conveying system and multi-bit filling system.

Pipeline conveying system as a gangue slurry filling technology lifeline. The main role is to use the slurry pump to gangue slurry through the pipeline at a suitable conveying speed, safe and stable transportation to the vicinity of the mining area. The pipeline conveying system in the actual operation process, often by the gangue slurry conveying speed, slurry concentration, ionization adsorption between the particles and other factors, may lead to pipeline clogging. Pipeline conveying system clogging, pipeline conveying efficiency will be rapidly reduced, when serious, will lead to the paralysis of the entire filling system; at the same time due to the gangue slurry pipeline conveying distance is longer, if the pipeline can not be timely and accurately find the location of the clogging before the complete clogging, once the complete clogging occurs, it may lead to a large area of the pipeline clogging, which not only increases the difficulty of pipeline cleanup and workload, and when it is serious, it will cause safety accidents and result in a large area of pipelines. This will not only increase the difficulty and workload of pipeline cleaning but also cause serious safety accidents and certain economic losses, as Fig. 2 is a mine in northern Shaanxi Province, filling site pipeline clogging cleanup photos (pipe diameter 125 mm). As an unstable solid–liquid two-phase flow that settles more easily, gangue slurry is still susceptible to clogging by other factors under complex working conditions. Gangue slurry pipeline clogging characteristics, from non-

complete clogging development to complete clogging is a gradual cumulative process, and in the formation of non-complete clogging in the early stage of the pipeline pressure, flow and other indicators of the impact is not obvious, the pipeline can still maintain a certain degree of conveying capacity. Therefore, how to use appropriate detection methods on the pipeline clogging failure to carry out rapid and accurate detection and early warning, minimize the adverse effects of pipeline clogging accident, become the rapid development and application of slurry filling technology is a key issue to be resolved.

In recent years, along with the rapid development of pipeline conveying technology, scholars at home and abroad have carried out a lot of research on pipeline clogging detection, which has made great progress in pipeline clogging detection technology, but in the face of long-distance slurry pipeline conveying, the existing pipeline clogging detection methods are still difficult to realize the shortcomings of dynamic real-time monitoring with no blind time and blind area, so the advantages are not obvious. Distributed fiber-optic acoustic sensing technology as a nondestructive testing technology developed in recent years, in addition to general fiber-optic sensing technology has the advantage of the acoustic signal has a high sensitivity, real-time dynamic detection capabilities and long-distance detection scale advantages, and the same cost can be achieved under the monitoring length and accuracy is much greater than other pipeline blockage detection method, which will gradually become the future trend of gangue slurry pipeline conveying. It will gradually become the trend of future development of gangue slurry pipeline transportation blockage detection.

This paper summarizes the types of gangue slurry pipeline conveying blockage and pipeline conveying blockage detection technology, analyzes the current research status and advantages and disadvantages of pipeline blockage detection technology, introduces the principle of distributed fiber-optic acoustic wave sensing and the current situation of its application in pipeline conveying, puts forward the pipeline blockage detection technology based on the distributed fiber-optic acoustic wave sensing technology, discusses the mechanism of pipeline blockage detection, constructs the pipeline blockage detection and identification system. DAS detection and identification system analyzed the core key technology involved in the system and pointed out the future development direction of gangue slurry pipeline conveying blockage DAS detection technology in order to provide a reference for the subsequent development of gangue slurry pipeline blockage and other pipeline conveying blockage DAS detection technology.

Types of pipeline transportation blockage and the current status of detection

Classification of pipeline transportation blockages

In the process of conveying gangue slurry, the pipeline will form different types of blockage based on the gangue slurry conveying speed, slurry concentration, ionization adsorption between the particles, and other factors. Generally divided into the following categories, namely, pipeline leakage type, slurry over-thickening type, slurry segregation type, foreign matter mixing type and pipeline defects and failures.

(1) Pipe leakage type blockage

When the pipeline leaks, or even leaks slurry, the concentration of part of the gangue slurry in the pipeline near the leakage point will increase, and the fluidity performance will be reduced or even lose fluidity, which will cause the pipeline to be blocked.

Basic features: there are leakage points, and the gangue slurry blockage section is located in the lower section of the leakage point; the more serious the leakage, the blockage section from the leakage point, the general occurrence of pipeline leakage type of blockage pipeline pressure will show a gradual increase in the process.

(2) Slurry over-thickening type clogging

When the gangue slurry concentration is higher than the design value and large to a certain extent, the pipeline conveying resistance will increase dramatically; this problem, if not solved in time, will eventually lead to plugging.

Basic characteristics: the blocked section is close to the filling port, the greater the slurry concentration, the closer the blocked section is to the filling port; if the slurry concentration is higher than the design value to a lesser extent, the problematic slurry can be gradually sent out of the filling tube by adjusting the slurry concentration subsequently to return to normal.

(3) Slurry segregation type clogging

When the gangue slurry concentration than the design concentration is low to a certain extent, or the gangue particle gradation design is unreasonable, it will trigger the gangue slurry water secretion stratification in the conveying process, especially for some reason after a period of time suspension, the slurry will be precipitation buildup, and when it is serious, it will lead to blocking the pipe.

Basic characteristics: gangue slurry segregation-type blockage occurs mostly at the bottom of the drill pipe or the bottom section of the slope.

(4) Foreign body mixing type blockage

In the filling pipeline, if mixed with such as weeds, branches, not stirred gangue powder or more than 1/4–1/3 of the inner diameter of the pipeline of large pieces of material, due to these foreign matter can not be synchronized with the flow of gangue slurry, maybe in a position in the pipeline of a number of pieces of foreign matter accumulation, which will lead to pipe blocking accident.

Basic characteristics: the occurrence of a sudden, generally easy plug pipe in the bent part of the accident, but the probability of a straight section is also relatively large, so it is difficult to determine the location of the blockage.

(5) Foreign body mixing type blockage

Coal gangue slurry conveying pipeline is exposed to the outside for a long time, may be affected by external factors and lead to pipeline clogging, such as valve ageing, pipeline corrosion, pipeline deformation caused by underground construction carelessness, as well as clearing the pipeline operation process of clearing the ball is lost, and other factors may result in pipeline clogging.

Basic characteristics: The location of pipe blockage is difficult to determine due to different external factors.

Current status of pipeline transportation blockage detection research

In recent years, pipeline transportation technology has been developing rapidly at home and abroad with the advantages of low transportation costs, energy saving, and environmental protection, but the phenomenon of pipeline transportation clogging still occurs from time to time. At present, scholars at home and abroad have also carried out a lot of research on the detection of pipeline clogging and formed a variety of pipeline clogging detection and location methods according to the different detection principles and means used in the process of clogging detection can be divided into three categories, one of which is based on the manual inspection method; the second is based on the detection of the hardware method, which is mainly related to a number of disciplines including acoustics, mechanics, optics and electromagnetism; and the third is based on the detection method of software analysis. Pipeline transportation blockage detection method classification, as shown in Fig. 3.

Manual inspection method

Manual inspection method is the earliest method of blockage detection, through the inspection personnel holding portable detection equipment along the pipeline section by section for inspection, the use of percussion audio-audible blockage detection principle to determine the location of pipeline blockage. The advantage of this method is simple, easy to operate, but the method requires a large investment in manpower, and is limited to the pipeline layout environment is simple to detect the pipeline, for buried in the ground below the surface and manpower can not reach the pipeline can not be detected.

Hardware detection method

(1) Stress–strain detection method

Pipeline stress–strain detection method is to pressurize the pipeline before the pipe blockage location, using the pipeline blockage before the location of pressure deformation is greater than the characteristics of the blockage location after the use of stress–strain sensors on the pipeline deformation collection, and stress–strain data processing to obtain the location of the pipeline blockage of a method¹¹.

Chen Baozhong¹² earlier used the stress–strain principle for the study of clogging point localization and tested the 27 km long pipeline from Fushun Petroleum Three Plant to Ethylene Plant, and accurately found the exact location of the clogging point by testing seven points; Hiebert¹¹ designed a method to measure the clogging localization of pipelines for the clogging problem of hydrates in natural gas pipelines. By installing strain gauges upstream and downstream of the faulty pipeline, and then pressurizing the liquid in the pipeline, so that the pipeline produces stress strain, according to the different clogging location produces different size of

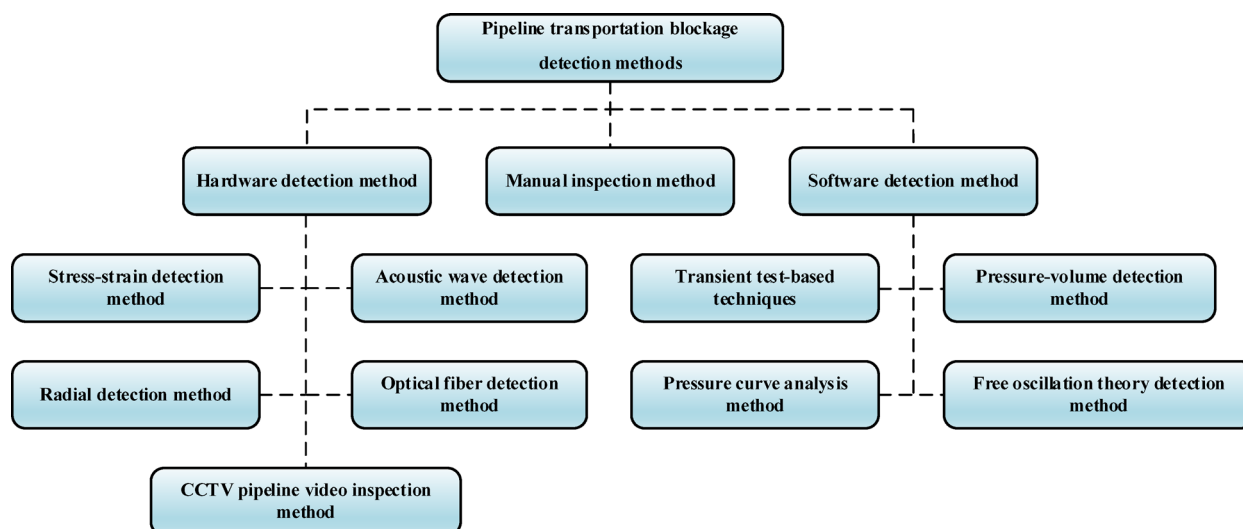


Fig. 3. Classification of pipeline transportation blockage detection methods.

the stress strain, so as to determine the location of clogging in the pipeline. It can be seen that the stress–strain method can realize the localization of pipeline blockage by detecting the stress changes occurring on the pipeline wall. However, this method requires a large number of strain sensors to be arranged along the pipe wall, and it is not guaranteed that the external pressurization will not cause damage to the pipe performance during the measurement process, and at the same time, it is difficult to judge whether the deformation of the pipe is caused by the blockage or the pipe itself by other influencing factors. At present, by the stress–strain detection method of slow response to the blockage, identification of the characteristics of the accuracy is not high, domestic and foreign scholars for the stress–strain detection of the blockage of the research is relatively small. Therefore, the method is not economical and effective for gangue slurry transportation pipeline.

(2) Acoustic wave detection method

Acoustic wave detection method is through the acoustic wave generator to be measured in the pipeline input a section of low-frequency sound waves; the use of acoustic wave in the pipeline propagation will be encountered in the blockage will produce a reflection signal, through the reflection signal contains the time, amplitude, and frequency of the information contained in the analysis of the pipeline blockage of information related to a method.

Since the last century, the acoustic wave detection method has received extensive attention from scholars at home and abroad. In 2008, Shamout et al.¹³ designed a pipeline acoustic wave detection device to realize the detection of pipeline blockage as well as leakage. In the same year, Papadopoulou et al.¹⁴ carried out a series of theoretical and experimental studies on pipeline blockage detection by acoustic wave reflection method, and the results of the studies proved that the technique could be successfully applied to the blockage detection of individual pipelines and pipe networks with large diameters and lengths of more than 5 km. Subsequently, Vialet al.¹⁵ applied acoustic technology to the challenge of pipeline clogging caused by deepwater flow safety and security, especially hydrates and paraffins, and designed and developed a device to realize the effective identification and measurement of clogging in pipelines. The advantage of the acoustic detection method for pipeline clogging is that it does not interfere with the normal operation of the pipeline or damage the structure of the pipeline, and at the same time, it can realize the advantage of clogging detection in complex working conditions. After decades of research, the method has been greatly developed, so that the positioning accuracy has been substantially improved^{16–18}. However, due to the defect of faster attenuation of acoustic wave signal in the pipeline, it is difficult to realize the detection of long-distance pipeline clogging by the acoustic wave detection method. At the same time, although the acoustic wave detection method has been developed more mature, but in the acoustic wave signal feature extraction there is still much room for improvement. In summary, the acoustic wave detection method is difficult to apply to long-distance gangue slurry pipeline blockage detection.

(3) Radiation detection method

The ray detection method is a method to collect information on the internal morphology parameters of the pipeline by transmitting or receiving rays that penetrate the pipeline, and the commonly used rays are γ -rays¹⁹ and X-rays²⁰, etc. The earliest application of the transmission method to pipeline clogging detection applications was by Mcnamee²¹, who used γ -ray imaging to detect damage such as corrosion and clogging of pipe walls in 1970. The results proved that the γ -ray source is characterized by low contrast, and at the same time, it can produce high intensity isotopes, and has good imaging effect on the interior of the pipe. Deng Mingliu et al.¹⁹ also used γ -ray method in 1999 to investigate the plugging of ground pipelines, and the experimental results found that either gas or liquid is applicable, but the method is only applicable to ground pipelines, and it is not applicable to the seabed or the pipelines buried deep in the ground. Subsequently, Wang Mingquan et al.²⁰ applied high-resolution X-ray digital imaging technology to pipeline corrosion detection, which realistically showed the internal scaling, clogging and corrosion of pipelines.

In summary, the ray detection method can obtain the blockage information in the pipeline more intuitively. The ray detection method can be more intuitive to obtain the blockage information in the pipeline, with high detection accuracy, not subject to the pipeline and the advantages of media interference, but the detection process instruments need to be close to the pipe wall, the feasibility of the implementation of the detection of buried pipelines is not high, and the cost is high, so in the later stage of the study, the heat is gradually replaced by other more effective methods of blockage detection.

(4) CCTV pipeline video inspection method

With the development of modern imaging technology is becoming more and more mature, the instrumental imaging detection method such as the emergence of a new army, which is more mature development of CCTV pipeline video detection method^{22,23}, specifically with the video camera and photographic function of the robot placed in the pipeline, through the robot in the pipe at the same time while moving the pipe information collection, and transmitted to the ground through the information comparison analysis, so as to realize the assessment of the pipeline clogging situation. To realize the assessment of pipeline clogging. This technology was first applied in the field in the 1950s in foreign countries. Domestically, Xu Zhou et al.²² took the drainage pipe under a road section in Chengdu City as the research object, and utilized the CCTV pipe TV inspection method to identify the defects of the pipe, and found 39 defects, mainly corrosion and deposition. Along with the rapid development of robotics, this type of system has been installed on various types of pipeline robots to realize the monitoring of the internal condition of the pipeline. Hawari et al.²⁴ realized the recording of the pipeline condition by pairing the image recording equipment with a pipeline operating robot, and instantly sent the data to the ground control center through the transmission cable to determine the status of the pipeline.

Compared with other detection methods, the CCTV pipeline video inspection method has the advantage of being able to realize the visualization of pipeline clogging status to obtain pipeline clogging information is more intuitive and accurate, but the shortcomings are that the pre-data and image acquisition process is cumbersome, and it needs to be processed in order to be compared with the real situation in the later stage, although there are scholars who have been used to identify the method of machine learning and deep learning recognition to replace the artificial identification, only Although scholars have used machine learning recognition method and deep learning recognition method to replace manual recognition, it is only limited to the detection of individual pipelines with a diameter larger than DN225, and often can only be detected after the pipeline is blocked.

(5) CCTV pipeline video inspection method

Optical fiber detection method is to lay optical fibres on the outer wall of the pipeline; when the sensing fibre along the pipeline is subjected to vibration, strain, temperature and other parameters, the phase of light waves propagated in the optical fibre will change, the change in the phase of the light waves will be transmitted through the optical fibre detector photoelectric detectors, photoelectric detectors can be realized from optical signal to electrical signal transformation. The collected signals undergo a series of processing, which can realize a way to provide timely feedback on the abnormal conditions along the pipeline, including pipeline blockage.

Zhao Naizhuo et al.²⁵ by laying multiple sets of optical fibers in the pipeline, due to pipeline clogging will produce stress strain, resulting in blockage at the fiber optic phase modulation, light waves propagate from the phase modulation to the two ends, the photoelectric detector set up at both ends of the pipeline detected signals will be a time difference, which is brought into the formula can be found out the location of the clogging. Guo Guangzhao²⁶ used the distributed fiber optic sensor inspection principle, proposed the use of distributed fiber optic sensor detection signal time difference on the pipeline accident location of the technology, successfully achieved the detection of buried pipeline ice blockage situation and ice blockage point location. Based on optical fibre sensing technology pipeline clogging monitoring method can achieve the full coverage of the pipeline monitoring, with corrosion resistance, high sensitivity, anti-electromagnetic interference and nonintrusive measurement advantages, while the cost of fiber optics is also very low, very suitable for long-distance pipeline monitoring, shortcomings need to be in the pipeline at the same time as the pipeline should be synchronized with the installation of fiber optics in the pipeline, especially in the buried pipeline should be more so.

Software detection method

Detection method based on software analysis, refers to the use of a pipe network data acquisition system on the pipeline pressure, flow rate, temperature, and other physical quantities to be analyzed, on the basis of hydrodynamics, to study its change rule in the steady state or produce transient flow state, so as to achieve the pipeline clogging detection of a method. Mainly Transient test-based techniques, pressure curve analysis method, pressure–volume detection method, and free oscillation theory detection method.

(1) Transient test-based techniques

Based on the transient test-based techniques is through the pipeline at the entrance and exit of the valve for rapid closure or the injection of a certain amount of fluid into the pipeline, breaking the steady state of the fluid in the pipe, resulting in transient pressure fluctuations, the use of sensors to collect the frequency, amplitude, and return time of the pressure return wave, and analyze it, so as to obtain the information of the pipeline blockage of a method, the schematic diagram as shown in Fig. 4²⁷.

Hasan et al.²⁸ first applied the transient flow theory to pipe clogging to obtain the clogging location and clogging intensity; Wang Tong et al.²⁹ earlier applied the transient test-based techniques to the detection of clogging locations in underground pipelines; Stephen et al.³⁰ first applied the inverse transient analysis technique to pipeline detection to accurately obtain the location information of clogging points; Brunone et al.^{31–33}

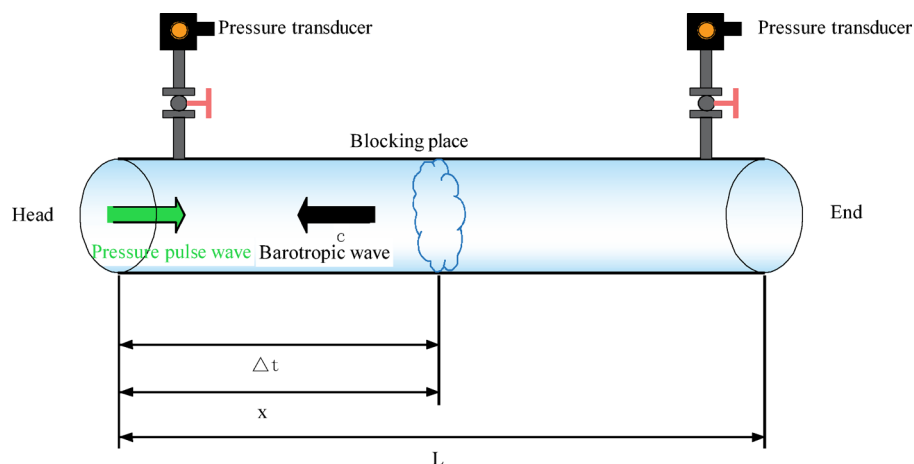


Fig. 4. Transient test-based techniques²⁷.

developed a portable pressure wave generator by establishing a correlation model between partial occlusion characteristics and pressure wave reflection patterns, and verified its effectiveness under laboratory and field conditions. Then Kumar et al.³⁴ proposed an improved reconstruction of features (RMOC) method based on the transient test-based techniques for detecting multi-point partial clogging in elastic pipelines and viscous pipelines vs. extended partial blockage.

Transient test-based techniques have the advantages of short response time, low cost, and wide range of application, and are capable of accurately monitoring and detecting the location of clogged segments within a pipeline. However, in the face of multiple obstacles or different degrees of siltation in the pipeline, based on transient testing technology may be difficult to accurately distinguish the location and nature of each obstacle. In this case, the ultrasonic signals may overlap or interfere with each other, making it difficult for the staff to determine which specific location is clogged³⁵. In addition, the inconsistency of the acoustic wave conduction velocity in multiphase flow will seriously affect the prediction accuracy of this testing method, so this method is also not applicable to the gangue slurry in two-phase flow.

(2) Pressure curve analysis method

Pressure curve analysis method is to identify the clogging point by analyzing the pressure changes in the pipeline, the core of which lies in the use of the law of sudden pressure changes to carry out quantitative and localization analysis of clogging, mainly back pressure method, hydraulic slope curve method, etc. Scott et al.^{36,37} improved the traditional backpressure method and determined the blockage location by comparing the pressure characteristic curves when there is no blockage and when there is incomplete blockage; Liu Enbin et al.³⁸ proposed to use the difference between the simulated value of the pressure difference between the two ends of the pipe before and after the blockage and the actual measured value to detect the blockage of the pipe, and the equipment required for this method is simple and easy to operate, and the economy is relatively high.

In summary, the pressure curve method has the advantages of requiring less equipment (only pressure sensor and valve), simple operation, low cost, etc., and has a better detection effect for the blockage of the extended part of the blockage with a longer blockage length, but there are some shortcomings of the pressure curve analysis method, including affecting the normal production of the pipeline, low detection accuracy, limited ability to detect the blockage of smaller lengths, and at the same time, the pressure sensor provides less effective information, low dimensions, poor adaptability to complex working conditions and blockage conditions, and insufficient detection capability. However, the pressure curve analysis method also has some shortcomings, including affecting normal production, low detection accuracy, limited detection ability for clogging of small length, less effective information provided by the pressure sensor, low dimensionality, poor adaptability to complex conditions and clogging, and insufficient detection ability.

(3) Pressure–volume detection method

Pressure–volume detection method is to fill the clogged pipe leakage of gas or liquid, record the change rule of pressure or flow rate in the pipe, and deduce the volume of the clogged pipe section to realize the clogging point positioning method. The principle of this positioning method is simple, easy to operate, but only applies to completely blocked pipes.

Zeng Doli³⁹ et al. earlier proposed to use the method of oil injection pressure test to detect the completely blocked refined oil pipeline. By injecting oil in the closed space between the blockage and the first end of the pipeline, measuring the relationship between the hydraulic pressure with the volume of oil injection and the blockage location, and calculating the length of the oil injection pipe section, the determination of the location of the blockage point can be realized.

Pressure–volume method of calculation although the theory is relatively simple, the calculation results of higher accuracy, but it also has many shortcomings, often need to carry out field operations, carry more equipment, work intensity, the detection process is time-consuming and lead to a long time of pipeline shutdown.

(4) Free oscillation theory detection method

Free oscillation is a phenomenon in which the inherently damped oscillations of a system decay with time after some excitation. Unlike conventional piping systems, the free oscillation decay of a clogged piping system contains, in addition to the system damping decay, the clogging decay. In the study of pipeline clogging localization, the ratio of the clogging attenuation parameters of the two harmonics is usually studied to determine the clogging location and the degree of clogging^{40,41}. In addition, the pipeline detection technology based on free oscillation theory can not only be used for pipeline clogging detection, but also has more applications in pipeline leakage detection, but the shortcoming is that the detection accuracy is low.

In summary, compared with other pipeline blockage detection methods, the fiber optic detection method has the advantages of high precision, anti-electromagnetic interference, long distance, corrosion resistance, high life expectancy, etc., and the same cost can be achieved under the monitoring length and accuracy is much greater than that of other pipeline blockage detection method, is the trend of the development of the future blockage detection of gangue slurry pipeline transportation.

Distributed fiber optic acoustic wave sensing technology

Distributed fiber optic acoustic sensing technology is a revolutionary new technology, in addition to the advantages of general fiber optic sensing technology, it also has the advantages of high sensitivity to acoustic signals, real-time dynamic detection capability and large scale long-distance detection. Since its introduction in the 1990s, it has been widely concerned by scholars at home and abroad^{42–44}, in recent years, as scholars at

home and abroad continue to deepen the study of the technology, its monitoring of pipeline transportation also shows great potential^{45,46}. Compared with the previous pipeline clogging fiber optic monitoring, in addition to also need to lay the pipeline at the same time need to install the fiber optic synchronization in the pipeline, its advantages make it more suitable for the gangue slurry pipeline transport clogging detection.

Distributed fiber optic acoustic sensing principle

Distributed Optical Fiber Acoustic Wave Sensor (DAS) is based on Phase-sensitive optical-time-domain reflectometer (ϕ -OTDR) technology to realize the monitoring of sound or vibration signals, which can not only measure the intensity of the sound or vibration event, but also obtain its phase and frequency information. The specific principle is that a laser light source emits continuous light, which is modulated into pulsed light by a modulator and enters the sensing fiber through a circulator. Next, the molecules in the sensing fiber scatter with the pulsed light, producing backscattered light. The backscattered light is then converted into an electrical signal by the annulus and an Avalanche Photo Diode (APD). Finally, when the sensing fiber is perturbed by the outside world, it will affect the intensity of the scattered light, thus realizing the location of the perturbation⁴⁷. The sensing principle is shown in Fig. 5.

Distributed fiber optic acoustic wave sensing technology application status

After years of development, distributed optical fiber acoustic wave sensor (DAS) technology has been applied in the fields of oil and gas exploration^{48,49}, natural seismic observation^{50–52} and so on. In recent years, some researchers have also begun to try to apply DAS in the field of pipeline transportation, mainly focusing on external intrusion monitoring, flow rate monitoring, pipeline leakage and so on.

In terms of external intrusion monitoring, a research team from the University of Pittsburgh, USA, laid fiber optic cables on the surface of pipelines, tracked the propagation characteristics of acoustic waves in pipelines through DAS, and analyzed them in conjunction with neural network-based machine learning algorithms to validate the feasibility of their use in external intrusion monitoring of pipelines⁵³. A team from Wuhan University of Technology used two symmetrical fiber-optic cables laid in underground pipelines to localize intrusion damage events, and achieved good localization accuracy in practical tests⁵⁴.

In the field of pipeline flow rate monitoring, Li T et al. carried out non-invasive distributed flow rate monitoring experiments in the laboratory using polyvinyl chloride pipes, and successfully measured the flow rate within the range of 2–3.6 m/s with high accuracy (uncertainty less than 5%)⁵⁵; Li Tongda first realized the distributed measurement of the flow rate of the liquid in the pipeline, and measured the flow rate of the pipeline by using the characteristic of the different speeds of the fluids with different strengths of the pipe wall, and the measurement results were in very good agreement with the real results⁵⁶; then Du Yuankai successfully realized the monitoring of the pipeline flow rate using DAS. The measurement results are in good agreement with the real results⁴⁵.

In terms of pipeline leakage monitoring, Yunjiang Rao's team at the University of Electronic Science and Technology (UEST) applied the DAS system to pipeline leakage monitoring, realizing the leakage monitoring of a 1.6 km-long steel pipe of 91 cm inner diameter, with the lower limit of leakage calibre of 4 mm⁵⁷; Subsequently, Chen Wang et al. proposed an online leakage detection technology for oil and gas pipelines based on the DAS sensing principle, which, combined with wavelet noise reduction algorithms, realized accurate gas leakage monitoring under pressurized conditions of 0.05 MPa. MPa pressurized conditions of gas leakage accurate monitoring, further enhance the DAS-based pipeline leakage detection accuracy⁴⁶; Li Tongda in the pipeline flow velocity of the distributed measurement of the pipeline at the same time, but also synchronized with the pipeline leakage aperture size and leakage localization of the research, and will leakage localization ability to the centimetre level⁵⁶; Ahmed Reda et al.⁵⁸ concluded that fiber optics is the most reliable and accurate pipeline leak detection technology when it comes to pipeline leak detection.

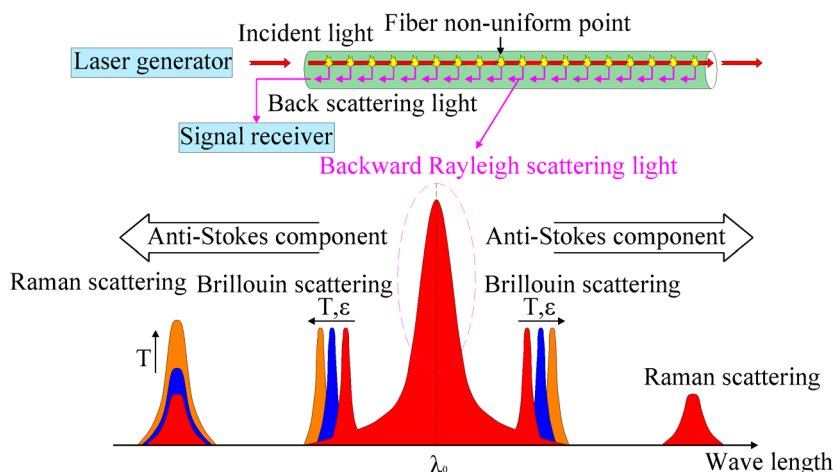


Fig. 5. DAS sensing principle.

Pipeline transportation clogging DAS detection technology

Pipe clogging DAS detection mechanisms

Schematic diagram of the principle of pipeline clogging DAS detection, as shown in Fig. 6. When the gangue slurry pipeline blockage occurs, the pipeline overflow section is reduced, causing fluid throttling flow, under pressure, the pipeline will be accompanied by the occurrence of high-frequency vibration, and produce acoustic signals, these two parts of the signal to the optical fiber, so that the length of the optical fiber and the refractive index will be changed, resulting in the propagation of the guided light in the optical fiber phase is modulated^{59,60}, and its expression for the formula (1).

$$\Phi_s = \beta \Delta L + L \Delta \beta \tag{1}$$

where: Φ_s is the amplitude of the phase change of the light wave; β is the propagation constant of the light wave in the optical fiber.

When the gangue slurry pipeline blockage signal acts on the sensing fiber, it will modulate the phase of light propagating in the fiber, and the phase change of the light wave modulated by the blockage signal is expressed by Eq. (2).

$$\delta \Phi = \Phi_s \sin \omega_s t \tag{2}$$

where: $\delta \Phi$ is the phase of the light wave modulated by the blocking signal; ω_s is the frequency of the blocking signal.

The optical phase difference caused by the gangue slurry pipe blockage signal can be expressed as Eq. (3).

$$\Delta \theta(t) = \theta_1(t) - \theta_2(t) = 2\Phi_s \cos \omega_s \left(t - \frac{\tau_1 + \tau_2}{2} \right) \sin \omega_s \left(\frac{\tau_2 - \tau_1}{2} \right) \tag{3}$$

where: $\theta(t)$ is the optical phase difference caused by the pipe blockage; $\theta_1(t)$ and $\theta_2(t)$ are the optical wave phases before and after the pipe blockage, respectively; τ_1 and τ_2 are the two-time points before and after the pipe blockage.

To facilitate calculations using known parameters, let.

$$\tau_s = \frac{\tau_2 - \tau_1}{2} = \frac{n_s s}{c}, \tau_T = \tau_1 + \tau_2 = \frac{s_2 n}{c}$$

$$\Delta \theta(t) = \theta_1(t) - \theta_2(t) = 2\Phi_s \cos \omega_s \left(t - \frac{\tau_T}{2} \right) \sin \omega_s \tau_s \tag{4}$$

where: s is the distance from the clogging location to the distributed fiber demodulator; τ_T is the total time taken for the light to propagate through the fiber; τ_s is the time taken for the light to travel from the clogging location to the DAS demodulator.

A DAS demodulator can demodulate $\Delta \theta(t)$ from the signal, and by being able to monitor changes in pipe vibration caused by a clogged pipe conveyance, it is possible to measure the location of the clogged pipe and issue an alarm in a timely manner.

Pipe clogging DAS detection simulation experiment

In order to verify the feasibility of DAS to detect the clogging of gangue slurry pipeline, a fiber-optic pipeline clogging detection system as shown in Fig. 7 was built in the laboratory. The system is mainly composed of mixing system, pumping system, pipeline conveying system, clogging system, DAS demodulator, sensing fiber optic cable and so on. Among them, the pipeline delivery system consists of seamless steel pipe with a diameter of 50 mm and a length of 130 m; the clogging system consists of 7 knife gate valves, and the clogging degree of the pipeline can be simulated by adjusting the opening of the knife gate valves; the sensing fiber optic cable adopts a tightly wrapped fiber optic cable with a diameter of 0.9 mm, and the fiber optic cable is glued to the surface of the pipeline using an epoxy resin by 45° helical twisting, and the length of the pipeline is 190 m in total. DAS demodulator is used for the acquisition and demodulation of acoustic signals, the spatial resolution

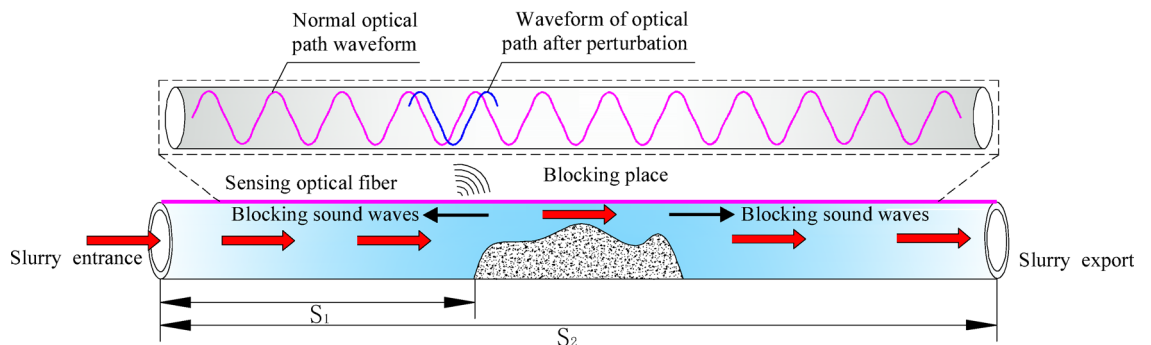


Fig. 6. Schematic diagram of DAS detection principle for pipeline blockage.

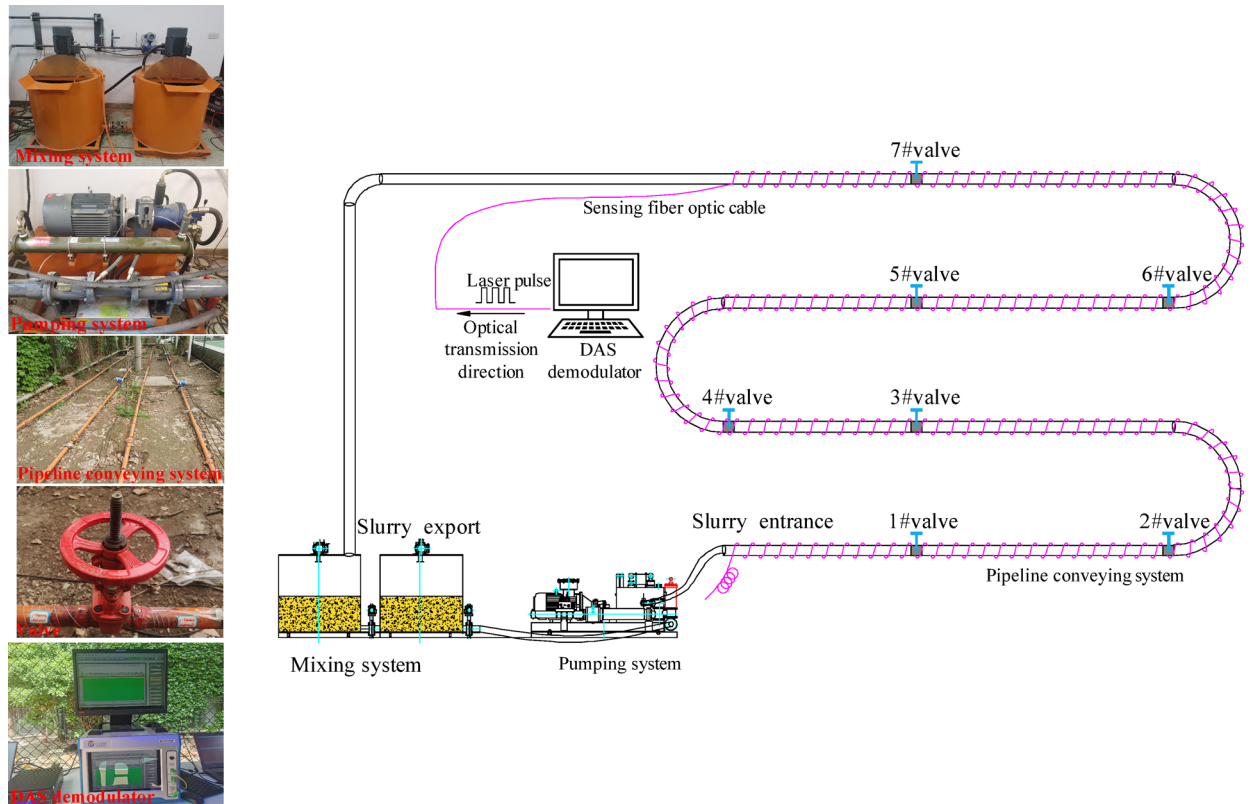


Fig. 7. Fiber optic detection system for pipeline blockage.

of DAS demodulator is set to 2 kHz, and the sampling interval is 1 m, in order to realize the precise positioning of the acoustic wave generation position.

Specific experimental steps are as follows: before the start of the experiment, first open the DAS demodulator, mark the location of the channel where each valve is located, and then use the mixing system to prepare the gangue slurry system, and close the 5 # valve 1/4, then start the grouting pump to start grouting, to be gangue slurry from the slurry outlets, the use of DAS demodulator for the deployment of sensing fiber optic range of the pipeline operation of the monitoring records.

In the experiment, the data within 10 s at 1 m and 2 m in front of and behind the clogging position when the clogging occurs are selected, and the time domain diagram as shown in Fig. 8, is drawn, where the horizontal coordinate indicates the time of the pipe vibration after the pipe blockage, and the vertical coordinate indicates the amplitude of the change of the pipe vibration when the blockage occurred. As can be seen from the figure, the amplitude change in front of the clogging point is larger than that in the rear within the range of 10 s of detection, and the amount of change in front of the clogging point is concentrated in ± 4.0 , and the amount of change in the rear of the clogging point is concentrated in ± 2.0 , which is caused by fluid dynamics and the physical phenomenon caused by the change of pressure, when the slurry in front of the pipe clogging position encounters the clogging, and is not able to continue to move forward to the normal flow, which results in the velocity of the slurry in front of the clogging position Slow down, the pressure gradually increased, the formation of pressure-holding phenomenon, pressure-holding phenomenon makes the fluid in front of the clogging position is in a high-pressure state, this high-pressure state will exacerbate the vibration of the pipeline and the fluid. This shows that when the clogging phenomenon occurs, the pipe clogging position can be accurately identified by using the DAS to monitor the magnitude of the amplitude change of the signal. Based on this, it is also shown that it is feasible to use DAS detection technology to monitor pipeline clogging.

Pipeline clogging DAS detection and identification system construction

Gangue slurry pipeline clogging DAS identification system can be gangue slurry pipeline operation status of real-time monitoring, real-time data uploading, the events occurring along the pipeline to analyze, distinguish between what are normal activities, which are about the pipeline clogging events, timely abnormal information on the pipeline to make early warning predictions, equivalent to the DAS demodulator brain, directly determine the intelligent perception of the entire system, which can significantly reduce resources and staffing.

Pipeline clogging DAS detection and recognition system architecture

The pipeline-clogging DAS identification system architecture is mainly composed of software and hardware such as DAS monitoring equipment acquisition subsystem, data transmission subsystem, fiber optic signal AI

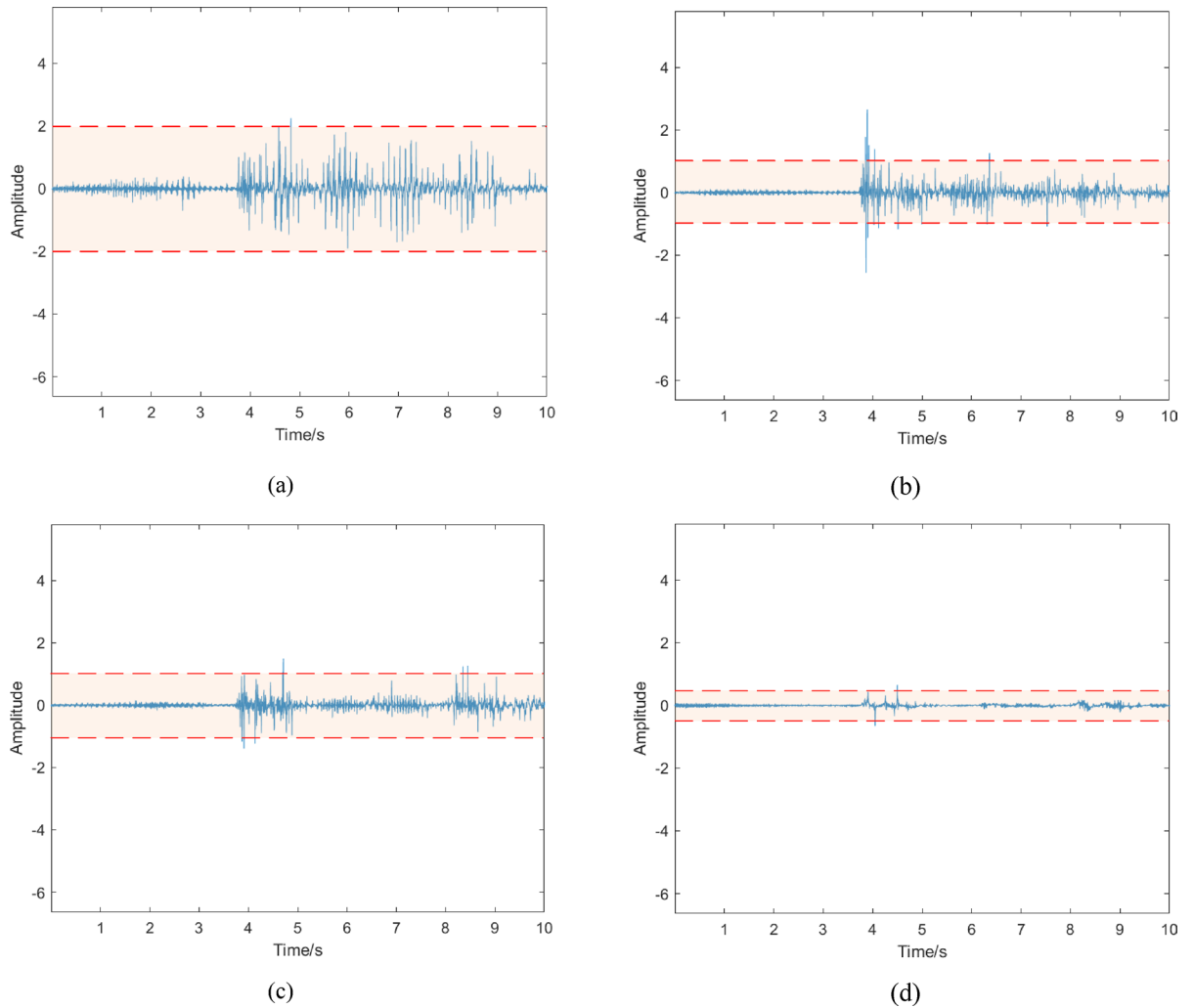


Fig. 8. Time domain diagram before and after blockage location. (a) 1 m in front of the blockage point; (b) 2 m in front of the blockage point; (c) 1 m behind the blockage point; (d) 2 m behind the blockage point.

identification terminal, data storage, analysis and identification model training server, as shown in Fig. 9, and the identification framework is shown in Fig. 10.

The functions of each monitoring system of the gangue slurry pipeline clogging DAS identification system are as follows:

- (1) DAS monitoring equipment acquisition subsystem. It consists of DAS fiber-optic sensors as well as modems, which are used for monitoring and data acquisition of the normal working condition of the gangue slurry transport pipeline.
- (2) Data transmission function. The text data of different DAS monitoring channels in the pipeline monitoring process will be transmitted to the private cloud platform in the data centre via the Internet in real-time for data storage and at the same time, transmitted to the fiber-optic signal AI identification terminal by wired or wireless means.
- (3) Data storage function. A private cloud platform is used to establish a data storage server, which is responsible for storing the received time series data of different channels in the fiber optic vibration signal database server.
- (4) Data analysis and visualization of data analysis server. The data analysis server is responsible for filling in the missing data, removing data noise and visualizing the monitoring data of the original monitoring data of different channels stored in the database, and the system users can view the real-time amplitude data of different monitoring positions in real-time in the form of tables or visualized images through smart terminals such as cell phones or browsers. The vibration signals generated by underground tunnel wind flow, roof water, auxiliary transportation equipment and construction, etc. and the inherent vibration of the grouting pump in the surrounding production environment will also be superimposed on the vibration signals collected by the fiber-optic sensors deployed in the gangue slurry conveying pipeline, which needs to be removed as much as possible as noise signals.

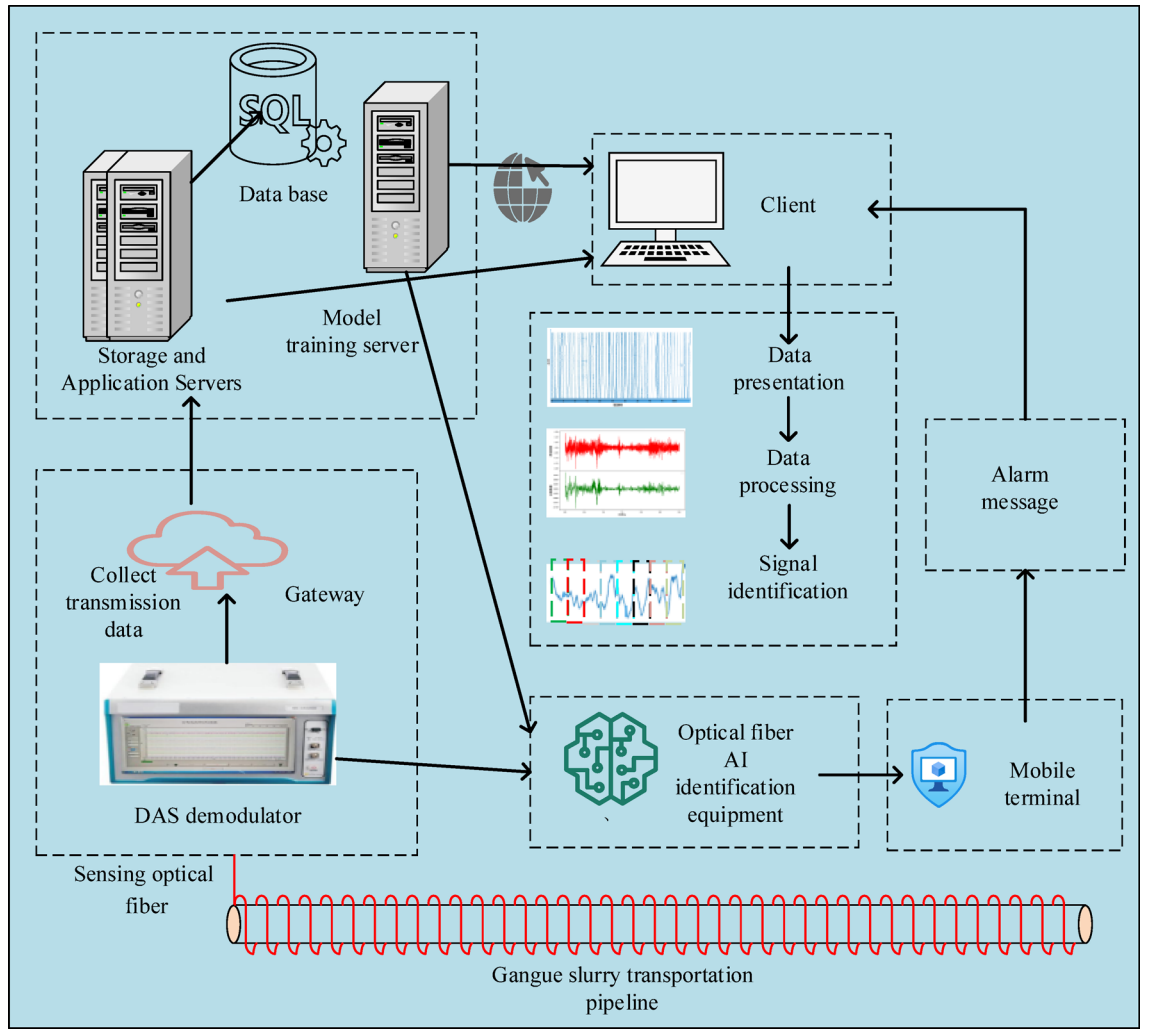


Fig. 9. DAS identification system for pipeline blockage.

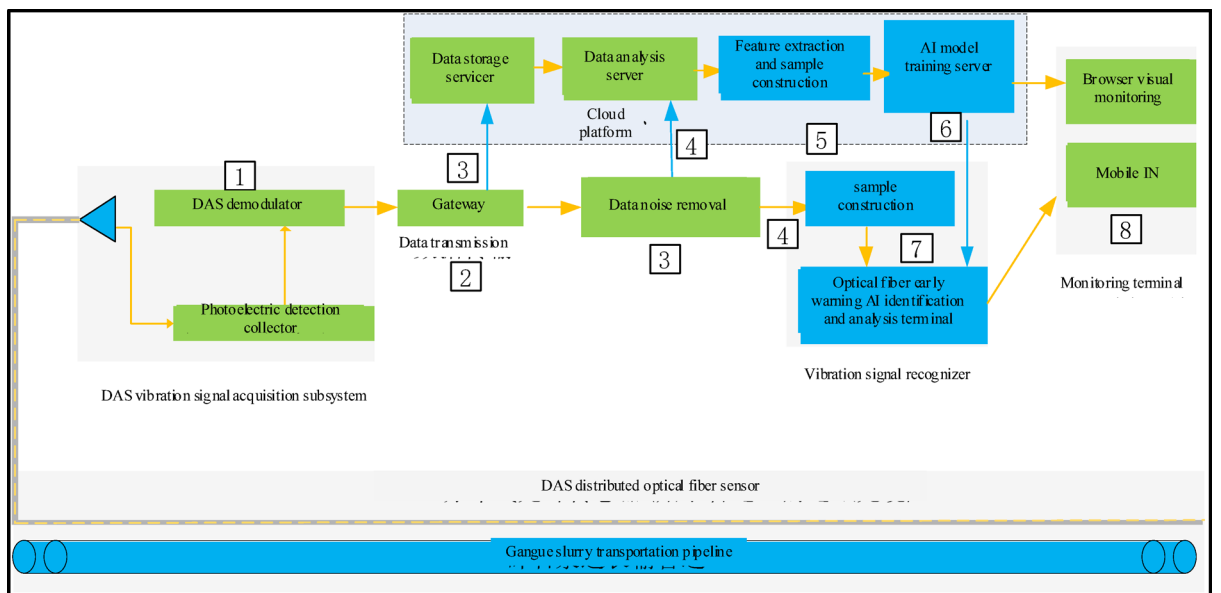


Fig. 10. Pipe blockage identification system.

- (5) Recognition model building and training. The fiber optic AI recognition model server is responsible for storing the sample dataset of all channel time series after removing the noise into the history database according to the channel as well as the time stamp. At the same time, different algorithms are used to extract the time–frequency domain features of the fiber vibration signals and construct the feature mapping matrix and the corresponding recognition labels of different vibration signals. A deep learning recognition model is constructed and trained using the data, and the trained recognition model is downloaded to the fiber optic signal AI recognition terminal.
- (6) Recognition of different vibration signals. The signal recognition module or AI recognition terminal in the monitoring system can be the current collection of all channel data for normal pumping, the surrounding environment of the impact of severe noise, pipeline different blockage status, fiber optic breaks, other and other vibration signals identification, in addition to the normal operating state of the other identified signals for the system end and cell phones and other mobile terminals warning display.

Analysis of key technologies

Coal gangue slurry pipeline clogging DAS identification system can be accurate early warning of pipeline clogging and clogging location fast identification, the key lies in the pattern recognition of the detection signal, and the accuracy of pattern recognition is inseparable from the reliable detection data and the correct feature signals, therefore, the data preprocessing, feature extraction and pattern recognition is the construction of the coal gangue slurry pipeline clogging DAS identification system must overcome the three major. Therefore, data preprocessing, feature extraction and pattern recognition are the three key technical problems that must be overcome to build a DAS identification system for coal gangue slurry pipe blockage.

Data preprocessing analysis

Φ -OTDR based DAS system has the characteristics of high sensitivity and fast response speed, etc. In the actual application of coal gangue slurry pipeline transportation project, it is easily affected by the external random vibration (such as the wind flow in the underground roadway, roof drenching, auxiliary transportation equipment and construction, etc.); at the same time, due to the DAS system itself there is also optical background noise, circuit noise and component thermal noise. The acquired signal contains a large amount of noise, which will greatly limit the sensitivity and positioning accuracy of the Φ -OTDR system. In order to suppress multi-source noise and improve the signal-to-noise ratio of the system, it is necessary to denoise the raw data collected by the DAS system. At present, the signal processing methods commonly used in the field of fiber optic sensing mainly include an IIR filter or FIR filter, wavelet transform threshold denoising, singular value decomposition denoising, and other methods.

Feature extraction analysis

Feature extraction is to extract different types of fiber optic vibration signals can characterize the characteristics of vibration signals, thus making it easy to distinguish between different types of information, the results of feature extraction will directly affect the accuracy of fault identification. According to the different signal processing methods, it is divided into time domain features, frequency domain features and time–frequency domain features. Among them, the time domain feature is the simplest and most direct way of feature extraction, without a variety of transformations, the time domain features of fiber optic vibration have the average value, variance and rms, waveform factor, etc., which can only simply distinguish the amplitude distribution of normal vibration signals and blocking vibration signals; the frequency domain feature is the use of a certain method of converting the time domain signal into a frequency domain signal to determine the frequency of the vibration signals of the pipeline, a feature extraction method, mainly including the frequency domain feature, frequency domain feature, frequency domain feature and frequency domain feature. Frequency domain feature is a way of determining the frequency of pipe vibration signal by converting the time domain signal into frequency domain signal using certain methods, mainly including spectral derived features, features based on Fast Fourier Transform (FFT), features based on form frequency/harmonic frequency, Power Spectral Density (PSD), and Harmonic Line Associations (HLA), etc. Frequency domain analysis is much more concise, and the analysis of the problem is much more profound and convenient. Time–frequency domain features is the use of wavelet transform (from the discrete or continuous wavelet transform (DWT or CWT)) and short-time fast Fourier transform (STFFT) and other techniques to convert the time domain signal into time–frequency information, the pipe vibration signal to determine the frequency and time of a feature extraction, which is both time-domain and frequency-domain features. Generally affected by the external background noise, the time domain signal is difficult to find the relative change of each component, although the frequency domain features can distinguish between the various signals in the various frequency bands, but it is limited to the analysis of the frequency of a particular moment, can not analyze the relationship between the signal frequency and time at the same time, it is easy to miss the vibration characteristics of the information at different times. Therefore, most of the cases need to convert the time domain signal to time–frequency domain signals for time–frequency domain characterization, which has the advantages of both the time domain and the frequency domain, and can get more comprehensive results.

Pattern recognition analysis

Pattern recognition focuses on training the extracted samples and recognizing the classification using a classifier so that it can predict the unknown output of the system as accurately as possible. Pattern recognition is one of the most critical and difficult technologies in the pipeline-clogging DAS recognition system. How to accurately and rapidly capture the signal of pipeline clogging under the conditions of long distances, complex surrounding environment and many destructive factors, guide the system to timely judge the degree of pipeline clogging

and locate the clogging location, and prevent the pipeline from clogging the safety hazards, which is the basic requirement put forward by the system to the pattern recognition technology. At present, the commonly used pattern recognition methods include machine learning algorithms represented by support vector machines and random forests, and deep learning methods represented by convolutional neural networks CNN and long and short time memory neural networks. Among them, the deep learning-based pipeline blockage recognition method has made explosive progress in recent years and is the mainstream technology for pattern recognition in the future.

Conclusions

Compared with the existing detection technology, based on fiber-optic distributed acoustic wave sensing technology gangue slurry pipeline blockage detection technology, can achieve high precision, large range, real-time dynamic and distributed acoustic wave detection, can be gangue slurry filling lifeline safe and stable operation to provide a strong guarantee, has broad application prospects. At present, DAS technology in the field of gangue slurry pipeline blockage detection is still in its infancy, and the cases available for reference are very limited, this paper believes that in subsequent research needs to be carried out from the following aspects of further research:

- (1) Sensing fiber and the object to be measured between the laying process is good or bad, directly affects the signal-to-noise ratio of the DAS monitoring system, the ratio of the accuracy and stability of DAS monitoring plays a crucial role. Therefore, how to effectively improve the signal-to-noise ratio of the DAS monitoring system without affecting the installation and disassembly of the gangue slurry pipeline, more experiments need to be carried out to explore the special distributed fiber-optic sensors suitable for gangue slurry pipeline and the installation process.
- (2) At present, based on the DAS detection of gangue slurry pipeline blockage research is still in its infancy, for the gangue slurry conveying pipeline blockage characteristics of the signal is not clear, should be combined with the gangue slurry in the actual conveying process of the relevant parameters and the possible impact of the noise, to carry out ground simulation experiments and on-site data collection, the establishment of the pipeline blockage DAS characteristics of the data model library, so as to provide a basic guarantee for gangue slurry pipeline transportation clogging early warning system to provide a basic guarantee.
- (3) DAS detects a large amount of data, because each sensing unit on the sensing fiber optic cable collects information at a high frequency, and the distance of the gangue slurry conveying pipeline is at least 5 kms, which will produce tens of megabytes or even hundreds of megabytes of monitoring data per second, and in the face of such a massive amount of monitoring data, how to effectively denoise the DAS monitoring data and automatically capture the characteristic signals to become intelligent processing of DAS data The focus of future retrieval work.
- (4) Although the deep learning-based DAS detection and identification model is more efficient than the traditional machine learning method, and the identification accuracy has been greatly improved, its acquisition of labelled data requires a large amount of manpower, material resources and time costs, how to break through the artificial intelligence and deep learning-enabled gangue slurry pipeline conveying clogging of the intelligent detection and identification technology and improve the pipeline clogging identification model in the training sample is insufficient or even absence of precision and generalization is the biggest challenge at present.
- (5) Facing the application requirements based on DAS detection of gangue slurry pipeline blockage identification and positioning and other functions, in order to ensure the accuracy of detection, identification and positioning on the basis of the realization of DAS technology collected data for rapid processing and analysis, timely detection and early warning of pipeline blockage, reduce downtime and maintenance costs, is a major problem that needs to be solved urgently in the early warning system of gangue slurry pipeline transportation blockage.

Data availability

The primary findings and contributions presented in this study are detailed within the article. For additional queries or information, please contact the corresponding author.

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Author contributions

Conceptualization, L.Z.; Methodology, C.Y.L. and W.Z.G.; Investigation, H.P., T.Q.S and P.Z.; Data curation, C.Y.M. and F.Q.Q.; writing—original draft preparation, F.Q.Q.; All authors have read and agreed to the published version of the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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