Research on the anti-interference identification mechanism of physical evidence traces in complex fire scene of gas explosion

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ABSTRACT Gas explosion fire scenes present a complex physicochemical environment with superimposed thermal, pressure, and electromagnetic fields. Physical evidence is easily affected by high-temperature carbonization, impact deformation, and multi-source interference, making identification extremely difficult. This paper systematically analyzes the characteristics of the fire scene environment and the types of traces, detailing the complex damage, secondary pollution, and shortcomings of traditional techniques. Furthermore, it proposes a systematic anti-interference identification mechanism from four aspects: multimodal detection technology integration, intelligent anti-interference algorithms, standardized on-site operation procedures, and multi-departmental collaboration. Utilizing engineering and science technologies such as GC-MS, CT scanning, CNN, and GAN, this mechanism improves the accuracy of gas explosion evidence identification, providing effective technical support for the scientific investigation and judicial determination of energy safety accidents.

INDEX TERMS gas explosion; fire scene evidence; trace identification; anti-interference mechanism; electromagnetic detection; energy security

I. INTRODUCTION

GAS is a major clean energy source in cities, and its pipeline network is expanding, leading to a rise in explosions that cause serious casualties and property damage. Gas explosions involve various physical and chemical effects, including thermal radiation, blast waves, and toxic gases. Physical evidence is easily deformed, carbonized, or even extinguished under the combined interference of high-temperature combustion, instantaneous overpressure, and firefighting. However, existing trace identification technologies are relatively weak in resisting interference in complex fire environments, requiring theoretical and technical improvements.

This paper systematically studies the anti-interference identification mechanism of gas explosion accident investigation techniques, hoping to promote the development of gas explosion accident investigation technology.

A. BASIC UNDERSTANDING OF TRACE IDENTIFICATION OF PHYSICAL EVIDENCE AT GAS EXPLOSION FIRE SCENES

1) Characteristic Analysis of Complex Fire Scene Environments Caused by Gas Explosion

There are many coupling phenomena in the physical and chemical aspects of gas explosion fire scene. The high temperature (above 1500°C) and overpressure shock wave generated at the moment of explosion act together on the structure at the scene, forming a thermal composite destruction field; the components such as CO and NO_x in the combustion products and the residual gas continuously react, forming a dynamic chemical interference environment. The arc discharge and electromagnetic radiation generated by the short circuit of the electrical circuit also affect the physical morphology and distribution pattern of the traces at the scene, making the fire scene exhibit the characteristics of superposition of three fields: thermal field, pressure field and electromagnetic field, which greatly increases the complexity of the environment [1].

2) Types and Identification Value of Physical Evidence Traces

The physical evidence traces at the fire scene of a gas explosion can be divided into three categories: combustion traces, explosion mechanical traces, and chemical residue traces. Combustion traces include V-shaped carbonization marks, molten metal drip marks, etc., which can reflect the location of the fire and the direction of its spread. Explosion mechanical traces are structural fracture surfaces, fragment splash distribution, and shock wave pressure imprints, which can reproduce the explosion center and overpressure peak. Chemical residue traces use gas chromatography-mass spectrometry to detect residual gas components, providing direct material evidence for source tracing and identification. The three types of traces corroborate each other and have irreplaceable judicial identification value [2]. In order to facilitate a systematic understanding of the core characteristics and identification value of the three types of traces, their main attributes are summarized in the following table.

TABLE 1. Types and Identification Value of Physical Evidence from Gas Explosion Fire Scenes

Trace type	Typical manifestations	Reflecting information	Identify value
Burn marks	V-shaped carbonization marks, molten metal drip marks	Location of fire and direction of fire spread	Determine the ignition point and reconstruct the spread path.
Explosion mechanical traces	Structural fracture surface, debris splash distribution, shock wave pressure value	Location of the explosion center and peak overpressure	Reverse the relationship between explosive yield and energy release
Chemical residues	Gas chromatography-mass spectrometry for the detection of residual fuel components	Gas composition and leak source	Provides direct material evidence for traceability and identification.

3) Analysis of Factors Affecting Physical Evidence and Traces in Complex Environments

The interference factors caused by complex fire scenes to physical evidence traces include physical, chemical and human factors. Physically, high temperature radiation causes traces to carbonize and melt, shock waves cause structural traces to be superimposed and deformed, and fire water flow washes away and destroys the spatial distribution of residues. Chemically, combustion by-products cover the original traces, causing chemical characteristic signals to be distorted. Human factors include the secondary interference caused by the trampling of surveyors, operation of instruments and sample contamination, which seriously hinders the readability and credibility of trace information [3].

Based on the above analysis, the three types of interfering factors differ significantly in their mechanisms of action and degree of influence, as shown in the table below.

TABLE 2. Comparison of Interference Factors in Complex Fire Scenes

Interference Dimension	Main source	Mechanism of action	Effects on traces
Physical interference	High-temperature radiation, shock wave, fire-fighting water flow	Thermal damage, mechanical deformation, scour displacement	Trace carbonization and ablation, spatial distribution destruction
Chemical interference	Combustion byproducts, fire extinguishing agents	Chemical coverage, component reaction	Distortion of characteristic signals and deviation of detection results
Human interference	Personnel trampling, equipment operation, non-standard sampling	Secondary pollution, cross-contamination	Reduced readability and credibility

B. THE REAL-WORLD CHALLENGES OF INTERFERENCE-RESISTANT IDENTIFICATION OF PHYSICAL EVIDENCE AND TRACES AT GAS EXPLOSION FIRE SCENES

1) Combined damage to traces caused by high-temperature combustion and explosive impact

The combined destruction of physical evidence traces by high-temperature combustion and explosion shock waves is the first problem encountered in the current identification work. The large amount of heat generated by the gas explosion (heat flux density can reach more than 100kW/m2) causes organic physical evidence to be rapidly carbonized or gasified, and the trace morphology characteristics tend to be uniform, making it impossible to distinguish the ignition point and the spread path [4]. At the same time, the overpressure shock wave generated by the explosion (peak overpressure of tens to hundreds of kPa) applies instantaneous high strain load to structural physical evidence, causing the fracture surface morphology to be superimposed and destroyed, and the original fracture characteristics cannot be preserved. Thermo-coupling effect can also cause material phase change, such as the melting and recrystallization of metal components, which will cause irreversible changes in the original mechanical trace characteristics [5]. The strong electromagnetic interference (wideband electromagnetic radiation generated by arc discharge) accompanying the high-temperature fire field will interfere with the precision measurement of electronic instruments, thereby affecting the quality of on-site data collection, causing the composite destruction mechanism to be unable to be fully restored, which brings fundamental difficulties to the subsequent judicial identification work [6].

2) Secondary pollution and human interference during the on-site investigation process

Secondary pollution and human interference during on-site investigation can affect the accuracy of trace identification. After the gas explosion accident, multiple teams such as fire rescue and emergency response entered the scene one after another. The operation of personnel trampling, mechanical clearing and fire water flushing inevitably caused physical disturbance to the original traces, causing the spatial distribution of fragments, liquid flow traces and powdery residues to shift or disappear [7]. From the perspective of chemical pollution, after the introduction of exogenous substances such as fire foam and chemical protective agents into the system, they will react chemically with the residual gas components, which will cause deviations in the gas chromatography detection results, thus affecting the accuracy of chemical traceability identification work [8]. In terms of human operation, some investigators did not strictly follow the zoning and grading operation specifications, causing different trace areas to contaminate each other; the non-standard use of sample collection containers will also bring in exogenous pollutants, thus affecting the laboratory test results. The superposition effect of multiple sources of secondary pollution makes trace identification very uncertain, and it is urgent to formulate a systematic pollution prevention operation procedure.

3) Limitations of Traditional Identification Technologies in Complex Environments

Traditional trace identification techniques are clearly insufficient for identifying gas explosion traces in complex fire scenes. Visual observation and ordinary optical photography techniques are very ineffective for identifying hidden traces due to factors such as smoke, carbon deposits, and surface damage. They cannot penetrate the shielding layer to obtain information about the deep structure. Traditional chemical testing methods use only one reagent reaction, which has low sensitivity for detecting gas residues that are degraded at high temperatures and mixed with multiple components, and is prone to missed detection and misjudgment [9]. Electronic data recovery technology may experience the melting of storage media in high-temperature environments, which greatly reduces the success rate of data extraction. In addition, traditional single-modal detection methods lack the ability to fuse multi-source data. In complex interference environments where thermal, force, and electromagnetic fields are superimposed, they cannot perform collaborative analysis and mutual verification of multiple feature dimensions. The scientific nature and probative value of the identification conclusions are insufficient, and they cannot meet the precision requirements of modern fire accident judicial identification [10].

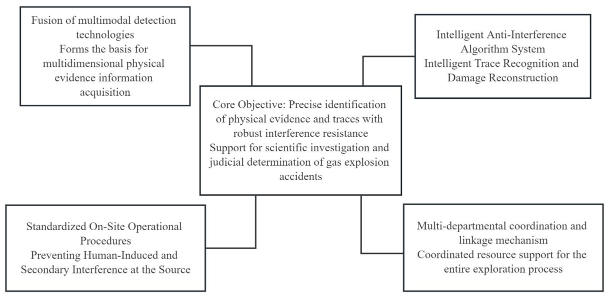
To more intuitively illustrate the limitations of traditional technical methods, the applicable scope and main shortcomings of various technologies are compared and summarized as follows.

TABLE 3. Comparison of Limitations of Traditional Trace Identification Technologies

Technical methods	Applicable Scenarios	Main limitations	Applicability to complex fire scenes
Visual observation and optical photography	Surface Trace Records	Obscured by smoke and carbon deposits, it is impossible to obtain deeper information.	weak
Traditional chemical testing	Single-component residue identification	Low sensitivity and high false negative rate for high-temperature degradation components.	weak
Electronic Data Recovery	Data extraction from electronic devices	High temperatures can damage storage media, resulting in a low retrieval success rate.	extremely weak
Single-mode detection	Specific parameter measurement	Lacking multi-source fusion, it cannot cope with the superposition of three interference fields.	weak

C. CONSTRUCTION PATH OF ANTI-INTERFERENCE IDENTIFICATION MECHANISM FOR PHYSICAL EVIDENCE TRACES IN GAS EXPLOSION FIRE SCENES

To visually demonstrate the overall architecture of the "four-dimensional integrated" anti-interference identification mechanism for physical evidence traces at gas explosion fire scenes, the system framework is constructed as shown in the figure below.



1) Trace Extraction Mechanism Based on Multimodal Detection Technology Fusion

Creating a trace extraction mechanism that integrates multimodal detection technologies is the key technical approach to overcome complex fire scene interference and achieve high-precision physical evidence extraction. Single detection mode is insufficient in information acquisition in complex environments with high temperature, high pressure, and electromagnetic interference. Multimodal fusion can achieve the effect of mutual supplementation of various physical domains. Based on visible light imaging, near-infrared thermal imaging technology can penetrate the smoke and carbon deposit layer, identify the thermal gradient distribution characteristics of hidden combustion traces, and use X-ray computed tomography (CT) technology to non-destructively detect the microcrack distribution and explosion mechanical damage mode inside the structural physical evidence, overcoming the limitation of surface shielding [11]. From the perspective of chemical detection, the combination of gas chromatography-mass spectrometry (GC-MS) and laser-induced breakdown spectroscopy (LIBS) can perform in-situ qualitative and semi-quantitative analysis of gas residues in micro-areas, thereby improving the sensitivity and specificity of chemical tracing. In order to suppress electromagnetic interference, electromagnetic shielding sampling devices and differential signal acquisition circuits are used to effectively suppress the interference of broadband electromagnetic noise on sensor signals and ensure the acquisition accuracy of electrical trace data [12]. After spatiotemporal alignment and feature-level fusion, multimodal data forms a multidimensional evidence information matrix, which greatly improves the coverage and reliability of trace extraction, laying a solid data foundation for subsequent intelligent identification. The various modal detection technologies complement each other in terms of coverage and functional positioning; their core technical parameters and synergistic relationships are shown in the table below.

TABLE 4. Overview of Multimodal Detection Technology Fusion Schemes

Detection mode	Core technologies	Main functions	Anti-interference advantages
Optical imaging	Near-infrared thermal imaging	Penetrate the carbon deposit layer to identify the thermal gradient distribution	Overcoming smoke obscuration interference
Structural inspection	X-ray CT scan	Nondestructive testing of internal microcracks and damage modes	Overcoming the limitations of surface damage
Chemical testing	GC-MS in conjunction with LIBS	In situ micro-area qualitative and semi-quantitative analysis	Improve the detection sensitivity of multi-component mixtures
Electrical data acquisition	Electromagnetic shielding device + differential circuit	Suppress broadband electromagnetic noise and ensure signal accuracy	Effectively isolate electromagnetic interference from electric arc discharge

2) Trace Recognition and Reconstruction Mechanism of Intelligent Anti-Interference Algorithm

After multimodal data acquisition, creating an intelligent anti-interference algorithm system is the technical support for achieving accurate identification and effective restoration of traces. Faced with the complex fire scene noise environment, traditional threshold segmentation and linear filtering methods are difficult to distinguish trace signals from interference signals, and intelligent algorithms with adaptive learning functions are required. From the perspective of signal preprocessing, the multi-scale denoising algorithm using wavelet transform can separate interference components in different frequency domains, retain the high-frequency detail information of trace features, and effectively suppress random noise caused by thermal field fluctuations and electromagnetic radiation. In terms of feature extraction, convolutional neural networks (CNNs) have a strong self-learning ability for the nonlinear features of multimodal image data. After training with a large number of labeled fire scene samples, an accurate mapping relationship between trace morphology features and combustion patterns can be established, overcoming the subjectivity of manual visual analysis. From the perspective of trace restoration, using generative adversarial networks (GANs) to reconstruct damaged and blurred trace images can effectively restore the original appearance of hidden or partially disappeared traces [13]. When multi-source interference causes information distortion, the Bayesian fusion framework can perform probabilistic inference and uncertainty evaluation on multimodal detection data, thereby achieving robust determination of trace attribution. The integrated application of the above algorithm system can greatly improve the accuracy of trace identification at gas explosion fire scenes, providing quantifiable scientific evidence for forensic identification.

3) Standardized On-site Protection and Hierarchical Identification Operational Mechanism

Scientific and standardized on-site protection and hierarchical identification procedures are the institutional basis for controlling interference from the source and ensuring the integrity of physical evidence traces. Establishing a standardized operation mechanism should be implemented layer by layer from three levels: on-site sealing, zoned management, and hierarchical collection [14]. On-site sealing is based on the explosion overpressure attenuation model and thermal radiation zoning theory to accurately divide the sealing boundaries of the core area, buffer zone, and outer area. Strict control is exercised over personnel entering each area to prevent cross-trampling and mechanical interference during the exploration process. In terms of zoned management, non-contact three-dimensional laser scanning and UAV aerial photography technology are used to complete the digital modeling of all spatial data of the core area. Before any physical contact occurs, the original spatial coordinates and morphological information of the traces are fixed and an electronic evidence archive that cannot be tampered with is formed. Different processing measures are taken according to the type of traces and the degree of interference. Carbonized traces in the high-temperature zone are first detected by non-contact spectral detection, mechanical traces are peeled off layer by layer and sampled sequentially, and chemical residues are processed by a combination of low-temperature preservation in anti-pollution sealed containers and precise laboratory analysis, so that the information loss of various traces is minimized at different processing stages [15]. In addition, a full-process operation record and traceability ledger system should be established to make standardized records of the operators, time, methods, equipment, etc. of each link, forming a complete chain of physical evidence preservation, effectively preventing human interference factors from damaging the credibility of the identification conclusion, and improving the probative value of physical evidence in court.

II. CONCLUSION

With the rapid development of modern information technology, the information wave characterized by digitalization, networking, and intelligence is profoundly influencing and changing people's lifestyles. Anti-interference identification of physical evidence traces in complex fire scenes of gas explosions is a comprehensive engineering and technical issue that integrates multiple disciplines such as thermodynamics, electromagnetics, materials science, and intelligent signal processing. This paper systematically reviews the main problems encountered in trace identification under multi-field coupling interference from three aspects: basic understanding, practical difficulties, and mechanism establishment. It proposes a "four-dimensional" identification mechanism supported by multimodal detection fusion, intelligent algorithms, operational standards, and collaborative linkage.

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