International Journal of New Developments in Engineering and Society
ISSN 2522-3488 Vol. 10, Issue 1: 74-80, DOI: 10.25236/IJNDES.2026.100110

Research on the Causes of Chemical Process Explosion Accidents in the Energy Industry and Optimization of Safety Management

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Abstract: *The chemical plants in the energy industry are characterized by high temperatures and pressures, flammable and explosive media, continuous production, and clustered facility distribution, making them a high-risk scenario for major hazardous chemical explosions in China. Current domestic research primarily focuses on general chemical scenarios, with a notable lack of specialized accident tracing studies addressing the production attributes and field operation conditions of the energy industry. The existing safety management system exhibits insufficient adaptability to on-site operational conditions, featuring prominent gaps in preemptive risk prevention and fragmented control measures. Based on the theory of energy accidental release and process safety management theory, this study analyzes the multi-level causes of explosion accidents from six dimensions—human, machine, materials, methods, environment, and management—using typical industry accident samples from the past decade. It identifies shortcomings in the industry's safety management while addressing energy production constraints, proposing an optimized closed-loop safety management system for the entire process and supporting implementation mechanisms. This research provides a theoretical foundation and practical support for process explosion risk prevention in the energy chemical industry, as well as for improving the industry's safety supervision system.*

Keywords: *energy industry; chemical process; explosion accidents; risk prevention and control*

1. Introduction

Against the backdrop of coordinated advancement in the dual-carbon strategy and the new energy system, coal chemical, petroleum refining, natural gas processing, and other supporting energy-related chemical industries have entered a stage of large-scale and intensive development. These high-risk chemical processes often involve highly exothermic reactions, high-pressure and high-density operating conditions, and flammable and explosive hazardous materials, with extremely low fault tolerance in process system operation and prominent explosion risks. In recent years, multiple major and severe production safety accidents in the national energy sector have demonstrated that, compared to traditional fine chemical processes, the long-term full-load operation of energy chemical installations, clustered station layouts, complex field operation environments, and the prioritization of energy supply security significantly amplify the probability of process explosion incidents and domino chain disaster effects, leading to substantial casualties, property losses, and disruptions to regional energy supply chains. Current academic research both domestically and internationally has extensively explored the mechanisms of chemical explosion accidents, risk identification, and safety management, forming mature process safety management and dual prevention control systems. However, most existing findings are tailored to conventional chemical production scenarios, overlooking the unique constraints of energy industry safety production subordinating to energy supply security tasks, and fall short in systematically uncovering management-level vulnerabilities, making them ill-suited for on-site control requirements in energy chemical operations. The prevailing industry practice of emphasizing hardware equipment rectification over process management optimization further exacerbates the difficulty in preventing process explosion accidents. Based on this, this paper takes various chemical explosion accidents in the energy sector as the research focus, analyzing multi-level causes through accident statistics and case reviews, precisely identifying deficiencies in the existing safety management system, and proposing specialized optimization and control strategies adapted to energy production conditions. It aims to provide theoretical foundations and practical pathways for reducing the incidence of process explosion accidents in the energy sector and standardizing the industry's safety governance system.

2. Theoretical basis and analysis of characteristics of chemical explosion accidents in the energy industry

2.1 Definition of relevant core concepts

To clarify the research boundary of this article and unify the academic research standards of the industry, the two core research concepts of the paper are first standardized and defined. One is the chemical process in the energy industry, which is different from small-scale and discrete civilian fine chemical production processes. It is a supporting chemical production system that relies on the energy backbone industry chain such as oil and gas extraction, clean utilization of coal resources, and industrial hydrogen energy preparation; It mainly completes production tasks such as energy raw material purification, chemical reaction conversion, product synthesis, and deep processing. Typical processes include high-risk operations such as petroleum refining and catalytic cracking, coal to low-carbon olefins, and natural gas desulfurization and refining. It has typical industry characteristics of high-pressure sealing, strong exothermic reactions, long-term continuous operation, and strong sensitivity to working conditions disturbances [1]. The second is chemical process explosion accidents. The research scope of this article specifically refers to chemical explosions induced by process parameters deviating from the rated threshold and lack of production process control during the production stage, excluding physical explosions caused by equipment structural pressure failure, explosions in hazardous chemical storage and off-site storage and transportation links; According to the disaster mechanism, it can be divided into three categories: reaction heat runaway explosion, flammable and explosive medium leakage explosion, and safety interlock device failure induced chain explosion. Compared with traditional chemical explosion accidents, process explosions in energy scenarios are characterized by strong domino effects, and disasters are easily transmitted and spread along upstream and downstream clustered production facilities, which can easily lead to secondary derivative accidents and cause phased stagnation of the regional energy industry production chain [5].

2.2 Relevant basic theoretical support

This study builds a logical framework for accident analysis based on classic theories of security system engineering, and selects three major adaptive theories to support subsequent causal tracing research. Firstly, the theory of accidental energy release, as the underlying mechanism theory of chemical explosion accidents, clarifies that the essence of explosion disasters is the accumulation of chemical energy and pressure potential energy within the system breaking through the constraint boundary, resulting in uncontrolled instantaneous release, providing core theoretical support for analyzing the mechanism of process medium leakage and system overpressure explosion [3]. Secondly, the accident chain theory denies the one-sided view that a single fault causes disasters, and clarifies that safety production accidents are the result of the coupling and transmission of multiple factors such as personnel, equipment, work environment, and management system, which is suitable for multi-level accident cause decomposition analysis. Finally, the Process Safety Management (PSM) theory focuses on dynamic risk management throughout the entire industrial production cycle, which is in line with the continuous operation and production characteristics of energy and chemical plants. It is suitable for identifying hidden management hazards such as process deficiencies and inadequate institutional adaptability [4]. By integrating three types of theories, a three-layer progressive analysis model of "hazard accumulation external triggering factors top-level management defects" can be constructed, providing a complete theoretical analysis tool for the systematic disassembly of multi-level causes of explosion accidents and the analysis of industry safety management shortcomings in the following text.

2.3 Statistical analysis of industry accidents and review of typical cases

By organizing the energy and chemical explosion accident records, hazardous chemical industry accident yearbooks, and local emergency supervision public documents publicly announced by the Ministry of Emergency Management from 2015 to 2024, and excluding invalid samples such as storage and transportation, civilian gas, and pure physical explosions, 127 chemical process runaway explosion accidents in energy scenarios were screened for cluster statistical analysis. From the perspective of scene distribution, accidents in the two major sectors of petroleum refining and modern coal chemical industry account for as high as 78.2%, making them high-risk scenarios for process explosions; From the perspective of production processes, accidents mainly occur in three major operational scenarios: chemical reaction parameter regulation, equipment overhaul and technological transformation, and high-risk hot work operations, accounting for 41.5%, 28.3%, and 17.6% respectively. It is worth noting that due to the constraints of regional energy supply guarantee assessment, the proportion of accidents occurring during the continuous operation of enterprise installations at full load and overload exceeds 65%, and the problems of equipment aging and personnel fatigue caused by long-term production significantly increase the accident risk threshold. Two representative major accidents in the domestic industry were selected for a full process review: the uncontrolled explosion of a synthesis kettle reaction in a coal to methanol plant in Northwest China, and the medium leakage explosion of a hydrogenation unit in a refining enterprise in North China. By dismantling the accident chain, it can be found that the direct causes of the two typical accidents are misoperation of process temperature control parameters and corrosion failure of high-pressure pipelines. However, the underlying logic of the accident tracing has common management loopholes such as incomplete identification of hazards in the early stage, the dual prevention mechanism becoming a formality, and the lack of on-site team safety supervision. This paper, based on statistical data and case review results, summarize the three unique characteristics of chemical process explosions in the energy industry: firstly, it has a strong domino effect, and the layout of device clusters is prone to secondary and derivative explosion accidents; The second is that production constraints have strong interference with risk prevention and control, squeezing the redundant space of safety control to ensure supply targets; The third is that implicit management defects are the core fundamental disaster causing factors, and hardware equipment failures are often the direct trigger of accidents.

3. Analysis of the causes of chemical process explosion accidents in the energy industry and shortcomings in safety management

3.1 Multidimensional traceability of chemical process explosion accidents

From the perspective of accident evolution hierarchy, the causative factors of explosion accidents can be divided into surface direct triggering factors, intermediate indirect system factors, and underlying deep root factors, and the influence weights of each factor can be clarified through quantitative analysis. The direct triggering factors are the surface explicit triggering factors in the accident evolution chain, mainly classified into three categories: personnel unsafe behavior, equipment physical hazards, and external work environment interference. At the human factor level, the four shift and three operation shift system commonly used in the energy and chemical industry can easily cause physiological fatigue and decreased sensitivity to working conditions for frontline operators; Violations such as personnel operating illegally, carrying out high-risk special operations without permits, tampering with process operating parameters without authorization, and inadequate performance during on-site inspections are the main human risk sources that trigger process explosions. At the level of unsafe conditions of objects, complete sets of process equipment for refining and coal chemical industries have been in service for a long time under high temperature, strong corrosion, high pressure and harsh working conditions, which are prone to hardware failures such as fatigue aging of pressure equipment, failure of explosion-proof emergency interlock actuators, and data drift of on-site measurement and control sensing instruments, forming a physical explosion hazard that cannot be ignored. At the external environmental level, energy and chemical field stations face complex natural conditions such as thunderstorm electrostatic interference, extreme temperature differences, and accumulation of combustible dust. Such environmental disturbances can disrupt the stable operation of closed chemical process systems, induce chain reactions of flammable and explosive media, and ultimately trigger explosion accidents.

Excluding explicit surface causes, systemic control loopholes that run through the entire lifecycle of chemical processes constitute indirect system influencing factors for accidents. Such hidden dangers cover the entire business process of engineering design, production operation, maintenance, and technological transformation. Firstly, the inherent endowment of process design is insufficient. Some small and medium-sized energy and chemical projects simplify the design of safety ancillary systems such as explosion prevention and pressure relief, emergency shutdown, etc. in order to compress infrastructure investment. During the project safety demonstration stage, the boundary of extreme operating conditions is not fully evaluated, which poses inherent process safety hazards; Secondly, there is a lack of order in the control of production and operation processes. Under the rigid assessment pressure of regional energy supply guarantee, production equipment has been operating beyond the design rated load for a long time, and approval processes such as process changes and abnormal parameter regulation have been virtualized, resulting in the failure of closed-loop processes; The third

ISSN 2522-3488 Vol. 10, Issue 1: 74-80, DOI: 10.25236/IJNDES.2026.100110

issue is the lack of control over shutdown inspection and maintenance operations, inadequate replacement of flammable and explosive media during the equipment overhaul stage, inadequate implementation of physical isolation measures for high-risk process systems, and further amplification of the probability of process explosion accidents due to cross disciplinary high-risk operations.

Digging deeper into the underlying causes of the two types of risks mentioned above, the defects in the systematic safety management system are the core dominant factors that lead to the accumulation and loss of control of multi-level risks and trigger explosion accidents. At present, most energy production enterprises directly apply the general fine chemical industry safety control system, without combining the industry characteristics of prioritizing energy supply and continuous operation of equipment to carry out institutional adaptation and optimization; The implementation of the dual prevention mechanism has become a formality, and the dynamic risk classification control of high-risk processes has failed [2]. The full process control of hidden danger investigation, supervision, and closed-loop rectification is lacking; The specialized training system for grassroots practitioners is severely homogenized, and there is insufficient supply of specialized safety briefings and practical training for energy composite high-risk chemical processes; In addition, the division of responsibilities between industry regulatory authorities and emergency supervision units is blurred, and the ability of multi-party collaborative supervision in the cluster production scenario of chemical industrial parks is weak, amplifying various front-end accident hazards at the top-level.

To further quantify the contribution of various disaster causing factors and accurately locate the core targets of prevention and control, this article uses the LEC hazard assessment method to quantitatively assign values and weight calculations to the multidimensional accident causes mentioned above. The empirical analysis results show that the weight of the impact of management system defects on process explosion accidents is as high as 47.2%, the weight of process system design and operation defects is 29.5%, and the weight of explicit front-end hidden dangers in human machine environment is 23.3%. The quantitative results further confirm that systematic management loopholes are the core target for preventing and controlling chemical process explosion accidents in the energy industry.

3.2 Existing deficiencies in the chemical safety management system of the energy industry

Based on the tracing results of the accident causes, summarize the four common management shortcomings in the industry. Firstly, the adaptability of the top-level standard system is insufficient. The current national standard for hazardous chemical safety in China does not distinguish between general chemical and energy chemical production scenarios. The weight of safety assessment indicators in the energy industry is lower than that of production and supply assurance assessment, and there is a deviation in the guidance of the top-level system. Secondly, the process safety management of enterprises is fragmented, and there is a common control misconception in the industry that emphasizes post emergency response and hardware equipment investment, while neglecting pre risk control and process closed-loop management. Thirdly, the on-site execution ability at the grassroots level has declined, and the transmission of safety management systems from top to bottom has failed. The implementation effect of basic control work such as on-site supervision by teams, daily working condition inspections, and job risk disclosure is poor. Fourthly, the special emergency control system is not perfect, lacking a pre fuse control plan for process loss of control. The existing emergency plan focuses on post accident disposal and cannot prevent secondary disasters caused by domino chain explosions. The closed-loop review mechanism for the entire accident cycle is missing.

4. Optimization strategy and implementation guarantee of chemical process safety management system in the energy industry

4.1 Optimization path of full chain safety management system

We will promote the optimization of the safety management system from six dimensions: top-level system, full process prevention and control of processes, on-site implementation at the grassroots level, digital technology empowerment, emergency closed-loop governance, and industry collaborative supervision. On the one hand, we will establish special safety control rules for high-risk processes in the energy and chemical industry, clarify the regulatory rights and responsibilities of energy and emergency management departments, implement a one vote veto system for high-risk process safety production, optimize enterprise performance assessment plans, enhance the weight of safety indicator assessments, and fundamentally solve the real contradiction of energy supply guarantee tasks squeezing safety

ISSN 2522-3488 Vol. 10, Issue 1: 74-80, DOI: 10.25236/IJNDES.2026.100110

production space from the institutional root; On the other hand, pre risk prevention and control measures are implemented throughout the entire life cycle of project design, production operation, maintenance and technical transformation. By strengthening the redundant design and safety demonstration of process explosion prevention, building a dynamic warning threshold model for process parameters, standardizing the isolation and medium replacement process of high-risk operations, and implementing on-site supervision throughout the entire process, the breeding of explosion risks is curbed from the source of the process; At the same time, we establish a hierarchical and classified job safety training mechanism, carry out scenario-based emergency practical training around explosive hazards, rely on the grid-based safety management mode to consolidate the lifelong safety responsibilities of each position, and remove obstacles to the implementation of safety management systems at the grassroots level; By leveraging industrial Internet of Things and artificial intelligence anomaly recognition technology, a risk digital control platform is built to achieve dynamic classification of hazards, precise tracing of hidden dangers, and real-time risk warning, filling the regulatory gap of traditional manual inspections; At the same time, the enterprise completes the special emergency plan for graded and classified process explosions, supplements early response measures against process runaway, regularly organizes collaborative emergency drills targeting multi-equipment domino accidents within the park, and forms a closed-loop management mechanism covering accident investigation, hazard rectification, effect verification, as well as long-term prevention and control; Finally, relying on the supervision ledger of the chemical industrial park, dynamic supervision of energy installations will be implemented, strict safety access review of high-risk energy and chemical projects will be carried out, and the credit rating of enterprise safety production will be linked to industry supervision constraints, building a multi-party linkage and long-term stable industry safety governance and supervision model.

4.2 Optimization strategy implementation guarantee system construction

In order to ensure the long-term implementation of the optimized safety management plan for the entire chain in energy and chemical production scenarios, avoid common industry problems such as institutional formalism and weakened control execution, and combine the characteristics of the energy industry's supply priority and continuous production conditions, a three-dimensional supporting implementation guarantee system is constructed from four dimensions: system, resources, personnel, and external supervision. At the level of institutional safeguards, it is necessary to improve the top-down safety production internal control management mechanism of enterprises, clarify the list of responsibilities of departments such as process management, production operation and maintenance, and safety supervision, improve the rules and regulations for safety accident classification and accountability, control process approval, and closed-loop supervision of hidden danger rectification, and use rigid internal control regulations to constrain the control behavior of production departments, and eliminate the phenomenon of safety strategies compromising production supply at the organizational level. At the level of resource security, enterprises need to allocate a special budget for chemical process risk prevention and control, and use the funds specifically for the iterative upgrade of explosion-proof equipment in high-risk sections, operation and maintenance of process interlocking control systems, and the construction and iterative operation and maintenance of digital risk control platforms. This will clarify the priority of safety resource allocation and ensure the stable operation of hardware prevention and control facilities and intelligent control systems. At the level of personnel security, we will provide full-time on-site process safety engineers and grassroots safety management personnel, establish a regular assessment and practical training system covering management, technical personnel, and frontline operators, strengthen the practical ability of practitioners in new control processes and digital platforms, and consolidate the grassroots human resources foundation for the implementation of the plan. At the level of supervision and guarantee, third-party security technology service institutions with qualifications for hazardous energy projects are introduced to conduct periodic special verification and on-site supervision of the effectiveness of optimizing the management system implementation, forming a dual supervision mechanism of enterprise internal control and external third-party evaluation, dynamically identifying loopholes in the system implementation, and ensuring the standardized and normalized implementation of the entire chain security management strategy.

4.3 Feasibility analysis of optimization plan engineering

To verify the implementation efficiency and engineering applicability of the full chain safety management optimization system constructed in this article on energy and chemical sites, and in combination with industry production constraints, a systematic engineering feasibility study is conducted from three core dimensions: policy compliance, economic rationality, and on-site production adaptability.

From a policy perspective, at present, the country is vigorously promoting the construction of a new energy security system. The emergency management department has issued multiple industry mandatory guidance standards for the control of high-risk processes for hazardous chemicals and the implementation of dual prevention mechanisms. The optimization strategy in this article fully conforms to the top-level policy guidance of national safety production and comprehensive governance of the energy industry, and meets the safety access and industry supervision standards of chemical industrial parks, with sufficient external policy implementation support. From an economic perspective, this optimization plan adopts a lightweight and hierarchical iterative transformation approach, abandoning high cost transformation models such as large-scale equipment replacement, and focusing on institutional process optimization, existing equipment technological transformation, and incremental upgrading of digital modules, effectively reducing the investment in the transformation of small and medium-sized energy chemical enterprises; At the same time, this plan can reduce property losses, accident shutdown compensation, and administrative penalty costs from the source of explosion accidents. The long-term safety input-output ratio is significantly positive, which meets the economic efficiency requirements of industrial enterprise production and operation. From the perspective of production adaptability, this plan fully considers the rigid operational constraints of continuous production in the energy industry and ensuring the supply of energy for people's livelihoods. All control and transformation processes can be carried out in parallel with normal production operations of the equipment, without the need for complete shutdown and rectification of the equipment, and without disturbing the production rhythm of the main industrial chains of oil and gas refining and coal chemical industry; The plan can be flexibly adapted and adjusted according to the scale of the enterprise station and the type of equipment process, and can cover various application scenarios of large energy and chemical parks as well as small and medium-sized edge stations, with strong universality in project implementation.

5. Conclusion and future work

This article takes chemical process explosion accidents in the energy industry as the research object, and combines safety system engineering theory, industry accident statistical data, and typical accident case review to systematically trace the causes of accidents and analyze the shortcomings of safety management. Three core conclusions are drawn. Firstly, chemical process explosion accidents in the energy industry are different from ordinary chemical explosion accidents, with industry specific characteristics of significant domino effect, strong interference in production conditions, and overlapping risks of equipment clusters. Refining and modern coal chemical industry are high-risk application scenarios for accidents. Secondly, through multidimensional quantitative analysis, it is found that personnel violations, equipment failures, and extreme environments are the direct causes of explosion accidents; The loopholes in process design and operation control are indirect causes, and the inadequate adaptability of the safety management system and the virtualization of control processes are the underlying core root causes of process explosion accidents. Thirdly, based on the constraints of energy supply and production, the five in one full chain safety management optimization system and supporting guarantee mechanism constructed can effectively address the shortcomings of existing industry control, and can directly serve as a practical basis for on-site risk prevention and control of energy and chemical enterprises and special inspections by industry regulatory departments.

Based on China's dual carbon goals and the development trend of new energy system construction, further research can be deepened and expanded from three aspects. Firstly, conduct specialized quantitative research on explosion risk mechanisms for low-carbon emerging energy chemical processes such as green hydrogen and new energy storage electrolytes; Secondly, by combining big data and digital twin technology, an intelligent prediction model for explosion risks in energy and chemical processes can be constructed to achieve accurate pre prediction of hazardous sources; Thirdly, for unmanned intelligent energy and chemical plants, the enterprise conducts research on lightweight remote safety control systems applicable to unmanned operation scenarios, so as to adapt to the future development needs of safety governance in the smart energy industry.

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