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Application of Urban Gas Pipeline Network Training Simulation System in Teaching

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Abstract: The scale of urban gas pipeline networks is extensive and their structure is complex, making it difficult for traditional teaching methods to provide a realistic operational environment, thus limiting the cultivation of students' practical skills. This paper introduces the architecture and functional modules of an urban gas pipeline network training simulation system, and analyzes the shortcomings of traditional teaching, such as the inability to operate real pipelines, limited internship resources, difficulty in reproducing fault scenarios, and subjective evaluation criteria. Building on this foundation, four application modes are proposed: pre-class preparation, in-class training, post-class assessment, and competition- and project-based teaching. The paper explores the advantages of the simulation system in enhancing students' practical abilities, ensuring teaching safety, and achieving quantitative evaluation, providing a reference for the reform of gas-related professional education.

Keywords: Urban Gas Pipeline Network; Practical Training Simulation System; Application Mode

Introduction

As a vital component of urban infrastructure, the city gas supply system continuously expands its pipeline network, placing higher demands on the operational skills and emergency response capabilities of practitioners. However, gas-related professional education has long faced the dilemma of "inaccessibility, invisibility, and impracticality": high-pressure pipelines, which are flammable and explosive in real networks, prevent students from hands-on operation; on-site internships, constrained by safety regulations and operational pressures, only allow observation without actual practice; and typical fault scenarios are difficult to replicate in real environments, leaving students lacking practical training. This paper focuses on the application of the urban gas pipeline network training simulation system in teaching, analyzing system functionalities and addressing teaching challenges, exploring systematic application models, and promoting the transition of gas-related professional education from a "teaching-centered" to a "learning-centered" approach.

1 Overview of Urban Gas Pipeline Network Training Simulation System

1.1 System Architecture and Core Functional Modules

The urban gas pipeline network training simulation system adopts a three-tier architecture design of "platform + scenario + task." The platform layer is based on a B/S architecture, supporting multi-user concurrent access. On the instructor side, it allows for course management, task issuance, and grade viewing, while on the student side, it enables login for learning, simulation operations, and performance assessment. The scenario layer constructs typical gas scenarios such as gate stations, pressure regulation stations, medium-pressure pipeline networks, low-pressure courtyard pipeline networks, and user indoor facilities. It employs 3D modeling technology to restore equipment appearance, spatial layout, and process workflows. The task layer incorporates training tasks including pipeline network structure cognition, pressure regulator parameter setting, inspection route planning, leak detection and handling, and emergency repairs. Core functional modules include: the 3D virtual scenario roaming module, which supports 360-degree viewpoint rotation and zooming; the equipment operation simulation module, enabling 3D interactive operations on devices such as pressure regulators, valves, and flow meters; the fault simulation module, capable of setting various fault types like leaks, overpressure, and blockages; and the intelligent scoring module, which automatically records and scores based on operational standards.

1.2 Key Technical Support

The system relies on multiple key technologies to achieve high simulation fidelity and teaching practicality. Hydraulic calculation serves as the core engine of pipeline network simulation. Based on the nodal pressure method and loop flow method derived from steady-state fluid mechanics, hydraulic equilibrium equations for the gas pipeline network are established to compute in real-time the pressure at each node, flow rates in pipeline segments, and pressure drops. When students adjust valve openings or change gas load demands, the system automatically recalculates in the background, dynamically updating the operational parameters of the pipeline network. GIS integration technology imports the geographic information of real urban gas pipeline networks into the system, including pipeline routes, valve well locations, pressure regulating station distributions, etc., endowing the virtual network with authentic geographic coordinates and spatial relationships. Students can conduct patrol inspection and fault location training on electronic maps [1]. Real-time data-driven technology simulates sensor data changes through backend data models. Instrument readings such as pressure gauges, flow meters, and concentration alarms respond in real-time to operations, creating an authentic sense of control. Additionally, the system employs virtual reality interaction technology, supporting various interaction methods such as mouse, keyboard, and VR controllers, thereby lowering the barrier to operation.

1.3 Correspondence with the Actual Pipeline Network

The practical training simulation system is meticulously constructed in strict accordance with the design standards and operational characteristics of real urban gas pipeline networks, ensuring seamless integration between instructional content and actual work tasks. In terms of the network topology, the system models the hierarchical structure of "gate station—high-medium pressure regulation station—medium-pressure pipeline network—low-pressure yard pipeline network—user," with pipeline diameters, materials, and valve types all referencing actual engineering standards. Regarding equipment models, the internal structures and operation methods of devices such as regulators, filters, flow meters, and shut-off valves are consistent with real equipment, enabling students to familiarize themselves with device configurations and adjustment techniques through virtual operation. For operational parameters, network pressure levels (high pressure, sub-high pressure, medium pressure, low pressure), gas flow rates, pressure drop ranges, and other parameters are set according to the "Urban Gas Design Code," with simulation results matching the operational patterns of real pipeline networks. In terms of fault modes, scenarios built into the system—such as leaks, blockages, regulator failures, and instrument malfunctions—are derived from real accident cases. Through repeated practice, students can master standardized fault diagnosis and troubleshooting procedures, thereby shortening the adaptation period from academic training to on-the-job performance.

2 Pain Point Analysis of Traditional Gas Pipeline Network Teaching

2.1 The actual pipeline network is non-operable and poses high safety risks

Urban gas pipeline networks transport highly flammable, explosive, and high-pressure media, where operational errors may lead to severe accidents. Gas companies strictly prohibit non-duty personnel from operating pipeline equipment in use. During their studies, students can only learn about equipment structures through textbook images and teacher explanations, lacking hands-on operational opportunities. On-site visits are limited to "seeing" and "listening," without the ability to touch equipment, adjust parameters, or experience operational processes, keeping instruction at a cognitive level. This "observable but not operable" model results in students lacking an intuitive understanding of internal equipment structures, adjustment methods, and fault phenomena, leading to prolonged adaptation periods after graduation and high corporate training costs.

2.2 Limited On-site Internship Resources and Short Duration

On-site internships in the gas industry are constrained by company production schedules and safety regulations. Internship positions are limited with insufficient capacity to accommodate students. As a result, students from a single class are often dispersed across multiple stations, making it difficult for teachers to provide unified guidance. Internship periods typically last only 1–2 weeks, ending just as students become familiar with the environment, which hinders in-depth learning. During internships, observation is the primary activity, with very few opportunities for hands-on practice. Some companies even prohibit students from entering production areas. The systematic and comprehensive nature of internship content is difficult to ensure, preventing students from developing a holistic understanding of the entire pipeline network system [2].

2.3 Difficulty in Reproducing Fault Scenarios, Students Passively Accept

Real pipeline failures are sudden and unpredictable, making it impossible for teaching to wait until failures occur before organizing learning activities. Even when a failure does occur, the high-pressure on-site environment and stringent safety requirements prevent students from participating in handling it. In traditional teaching, failure cases can only be presented through text, images, or videos, leaving students passively receiving information without opportunities for active analysis or hands-on problem-solving. For typical failures such as leak detection and pressure regulator troubleshooting, students cannot personally operate or verify solutions, hindering the formation of a complete thought process and resulting in severely inadequate emergency response capabilities.

2.4 Evaluation Criteria Are Subjective, Lacking Quantitative Feedback

Under traditional teaching models, the assessment of students' operational skills primarily relies on teachers' on-site observation or practical exams. Evaluation criteria are influenced by teachers' subjective judgments, making it difficult to achieve objectivity and uniformity. Gas operations involve multiple steps and detailed specifications, yet teachers struggle to monitor all students' operational processes simultaneously. Written exams can only test theoretical memorization and fail to evaluate hands-on abilities. Mistakes made by students during operations (such as incorrect regulator adjustment sequences, reversed valve operation directions, missed leak detection locations, etc.) often require teachers to point out one by one, resulting in delayed feedback and challenges in quantitative record-keeping. Students are unaware of their specific weaknesses, preventing targeted improvement. Meanwhile, teaching management departments face difficulties in obtaining objective data on students' skill levels, hindering the evaluation of teaching effectiveness and course quality, and leaving teaching improvements without data support.

3 Application Models of Simulation Systems in Teaching

3.1 Pre-class Preparation: Pipeline Network Structure Cognition and Process Familiarization

Before formal teaching, the teacher can assign students to conduct self-study previews in the simulation system. Through the three-dimensional virtual scene roaming function, students can intuitively understand the spatial layout and connection relationships of gate stations, pressure regulating stations, medium-pressure pipeline networks, low-pressure courtyard pipeline networks, and indoor user facilities. The system provides an equipment library function; clicking on any equipment will bring up an information window displaying the equipment name, functional description, cross-sectional diagram of the internal structure, technical parameters,

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etc., helping students build an initial understanding. Preview tasks can be set as follows: marking the route of specified pipeline sections on an electronic map, identifying the installation positions of different types of valves, describing the complete transportation path of gas from the gate station to the user, etc. The system automatically records students' browsing trajectories and operation logs, allowing teachers to check the completion status of previews through the backend. Pre-class previews enable students to enter the classroom with questions, improving the efficiency of classroom learning while laying the foundation for subsequent practical training.

3.2 In-Class Practical Training: Typical Working Condition Operations and Fault Troubleshooting

The classroom practical training segment is the core of the simulation system application. Teachers assign practical tasks based on the teaching schedule, and students log into the system to complete operations as required by the tasks. Typical operational scenarios include setting the outlet pressure of a pressure regulator, opening and closing valves, reading flow meter data, adjusting pipeline network pressure, etc. The system provides real-time feedback on operational results and offers prompts when errors occur. Fault diagnosis tasks are a key focus of the training. The system can simulate various fault modes, such as abnormal pressure drops in a pipeline section, fluctuations in pressure regulator outlet pressure, gas supply interruptions at user endpoints, and leakage alarm triggers. Students must follow a standard troubleshooting process: analyzing symptoms—selecting detection tools—locating fault points—identifying causes—implementing corrective measures—verifying restoration outcomes. The system records each step of the operation and generates a score. Teachers can monitor real-time operation screens of all students from the instructor interface, allowing for group evaluations and individual guidance [3].

3.3 Post-Class Assessment: Automated Grading and Error Analysis

The simulation system features a built-in intelligent scoring module that automatically grades and records students' operational procedures. Scoring criteria can be customized, covering multiple dimensions such as operational step completeness (e.g., whether valve operations follow the correct sequence), procedural compliance (e.g., whether regulator adjustments exceed the allowable range), accuracy in fault diagnosis, time management rationality, and safety considerations (e.g., checking pressure before operation or confirming restoration afterward). The system automatically logs the timing and outcome of each operational step, generating detailed assessment reports that include overall scores, module-specific scores, lists of incorrect steps, and links to demonstrations of correct operations. Students can review their assessment reports at any time to identify areas for improvement. Teachers can access aggregated class performance data, including score distributions and common error statistics, to inform instructional adjustments. Automated scoring reduces the grading workload for teachers and makes assessments more objective, fair, and traceable.

3.4 Application in Competitions and Project-Based Instruction

Practical training simulation systems provide an ideal platform for skill competitions and project-based teaching. In terms of skill competitions, these systems can be utilized to organize school-level and municipal-level gas industry skill contests. Competition content includes drawing pipeline network process flow diagrams, equipment operation, fault diagnosis, emergency drills, and more. The system automatically times and scores participants, ensuring fairness and impartiality in the competition. Compared to traditional on-site contests, simulation-based competitions are not constrained by venue, equipment, or safety limitations, allowing a large number of participants to compete simultaneously.

Regarding project-based teaching, instructors can design comprehensive project tasks, such as "Gas Connection Project for a Residential Community." Students are required to complete the entire process from scheme design, pipeline network layout, equipment selection, pressure calculation, to operational commissioning, integrating knowledge from multiple courses. Project outcomes are validated through operation in the simulation system—success is achieved when pressure standards are met and user gas supply functions normally. This project-based approach cultivates students' systems thinking and comprehensive application abilities.

4 Application Effectiveness and Improvement Directions of the Simulation System

4.1 Analysis of the Enhancement Effect on Students' Practical Abilities

The practical application of simulation systems in gas engineering education has yielded remarkable results. Through pre-class self-study, students have developed an intuitive understanding of pipeline network structures and equipment functions, significantly enhancing the initiative and focus of their classroom learning. During hands-on training sessions, students repeatedly practice skills such as regulator adjustment, valve operation, and leak detection in virtual environments, leading to a notable improvement in operational proficiency and standardization. Comparing practical assessment scores before and after implementing simulation systems, the overall performance of students has significantly improved, with a substantial reduction in operational error rates. Particularly in terms of fault diagnosis capabilities, students can follow standardized procedures to address practical problems after repeatedly practicing typical tasks such as leak localization and regulator troubleshooting, resulting in a significant boost in confidence for emergency response. Students generally report that simulation systems are "visualizable, actionable, and error-correctable," addressing the shortcomings of traditional teaching methods that "focus on theory over practice." As a result, the adaptation period for graduates entering the workforce has been noticeably shortened.

4.2 Improvement of Teaching Efficiency and Evaluation Fairness

The application of simulation systems has significantly enhanced teaching efficiency and assessment fairness. In traditional practical training instruction, teachers need to guide students individually through operations and evaluate each student separately, requiring 4-6 class hours for a class to complete a round of practical exercises. After adopting simulation systems, students can practice autonomously, with the system providing real-time prompts for operational errors, while teachers focus only on explaining common issues. The same content now takes only 2-3 class hours, boosting teaching efficiency by approximately 50%. In assessment and evaluation, the system's built-in intelligent scoring module enables comprehensive recording of operational processes and automated scoring. Scoring criteria are uniform, objective, and fair, eliminating scoring discrepancies caused by human factors. Assessment reports automatically generate data such as students' error distribution and class performance statistics, allowing teachers to precisely identify weak areas in instruction and students to clearly understand their own shortcomings. Teaching management departments can use platform data to quantitatively evaluate course teaching effectiveness, providing data support for teaching reforms [4].

4.3 System Function Optimization and Future Development Directions

The current simulation system still has room for improvement in teaching applications. Firstly, the fault scenario database needs to be enriched. The current built-in fault modes are approximately 20 types, and it is recommended to expand them to over 50, covering more typical accident cases. Secondly, the intelligent guidance function requires enhancement. When students make operational errors, the system should not only prompt "operation error" but also provide links to correct operation demonstrations and explanations of the underlying principles. Thirdly, the multi-user collaborative function is not yet fully developed. Real-world pipeline network operations often involve teamwork, so the system should support simultaneous online collaboration for 2-4 users to simulate scenarios involving division of labor and cooperation. Future expansion directions include: introducing virtual reality headset devices to provide immersive operational experiences; developing augmented reality features to overlay virtual equipment onto real environments for mixed training; integrating large-scale artificial intelligence models to enable intelligent question-answering and personalized guidance; and establishing school-level and provincial-level simulation competition platforms to promote learning and practice through competitions, thereby continuously driving innovation in gas-related professional education.

Conclusion

The training simulation system provides a safe and efficient practical platform for gas engineering education, transforming abstract pipeline network processes into visual and interactive operational scenarios. Students can complete equipment familiarization, condition adjustment, and troubleshooting training in a risk-free environment, effectively addressing the shortcomings of traditional teaching methods where "physical access is limited and operations cannot be simulated." Practice has shown that deep integration of virtual simulation with classroom teaching enhances students' operational skills and problem analysis abilities. However, simulation cannot fully replace on-site internships; only through a combination of virtual and real experiences, leveraging their respective strengths, can we truly shorten the adaptation period for job roles. In the future, with advancements in digital twin and artificial intelligence technologies, training systems will become more intelligent, providing stronger support for talent development in the gas industry.

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