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Risk assessment and modeling of chlorine leakage consequences using fuzzy HAZOP technique and PHAST software

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Abstract

Objectives: This study aims to develop strategies for risk management and accurately model the potential outcomes in hazardous zones.
Methods: The initial step of this study involved conducting HAZOP studies to identify all process nodes and deviations in an urban water-treatment plant located in Markazi province. Subsequently, all risks associated with the identified deviations were evaluated using a qualitative risk matrix. To enhance the scientific accuracy of the risk assessment results, the fuzzy HAZOP methodology was employed. Finally, the assessed risks were prioritized with precision, and PHAST software was utilized to visualize critical scenarios and determine the zones of catastrophic consequences.
Results: The initial findings from the HAZOP investigations conducted in the chlorination unit of the treatment facility reveal a total of 41 deviations out of 55 identified risks. Out of these risks, 47 (85%) were classified as high risk (HR), while 8 (15%) were categorized as medium risk (MR). The results of the risk assessment clearly demonstrate that the risks are of significant concern, despite the presence of existing controls. Ultimately, eight scenarios were identified and extracted from the analysis.
Conclusion: Based on the research results, it is imperative that all chlorination facilities undergo redesigning to prevent corrosion, erosion, leakage, and rupture and to conduct risk-based inspections (RBI). Furthermore, regular chlorine leakage drills should be included to enhance emergency response and preparedness.

Keywords: Risk assessment, Water-treatment plant, HAZOP, Fuzzy HAZOP, PHAST.

Introduction

The high rate of water consumption, coupled with the rapid population growth and industrialization of communities, has made industrial water treatment a top priority.[1] Despite advances in water treatment technology such as membrane filtration, UV-ray, ozone and peroxide use, ion exchange, and biological filtering, the classic chlorination technique utilizing chlorine gas is still commonly used.[2] This is mainly due to the cost-effectiveness, antimicrobial properties, and relatively long-lasting effects of chlorine. In Iran, chlorine is commonly used as Cl_2 gas, calcium hypochlorite (OCL), Ca2, and/or sodium hypochlorite (NaOCL) for disinfection purposes.[3,4] Exposure to a concentration of 14–21 ppm of Cl_2 gas for a period of 30–60 minutes can be extremely dangerous for humans. Furthermore, if the concentration exceeds 100 ppm and lasts for more than one minute, it can lead to suffocation and even death.[5,6] Numerous studies have documented several incidents involving Cl_2 gas that have posed significant challenges.[7-9] It is crucial to visualize the potential consequences of a hazardous chemical material (HazMat) leak in the environment. Modeling catastrophic events allows us to identify zones with toxic vapor clouds, determine the time required for urgent evacuation, understand the diffusion pattern of these clouds, and ascertain the necessary emergency personal protective equipment (PPE) for survival.[10,11] Displaying the dangerous areas is crucial in order to estimate the potential mortality rate in case of emergency response failure or safety measures malfunction.[12] Additionally, the need for evaluating risks and predicting catastrophic outcomes has become extremely important when dealing with larger and more complex units that handle hazardous chemicals, such as toxic and flammable substances, under high temperature and pressure conditions.[13] Mathematical modeling can be a complex and time-consuming process. However, utilizing software to model the potential consequences is extremely important.[14] When it comes to the hazards of releasing substances into the environment, they can be categorized into three main types: toxicity, inflammation, and explosion. In chlorination facilities, one of the greatest dangers is leakage, which can occur from various sources such as washers, flanges, drain valves, and hoses.[11,15] Due to certain properties of chlorine, such as its high molecular weight, high concentration of aerosol particles, and low release temperature, a chlorine cloud created during a negative buoyancy situation tends to have a high density and remain close to the ground. This means that if Cl_2 gas is released, it can have devastating effects on the population living near the release site.[16,17]

Objectives

The primary objective focuses on modeling dispersion and estimating the concentration of released materials in the environment at a specific distance and time. The PHAST software, developed by the Norwegian consulting firm DNV, may generate simulated scenarios for hazardous compounds released into the environment. This software has been utilized to provide a comprehensive analysis of the consequences.[18,19] PHAST is a strong tool for investigating the whole chain of events in a potential incident, from the first release of dangerous substances and their dispersion radius to the modeling of evaporation and evaporation pools, as well as the assessment of flammable and toxic substances. It can simulate both continuous and catastrophic ruptures. Additionally, the software takes into account weather conditions as one of the input parameters that influence the diffusion pattern of toxic vapor clouds.[20]

Methods

The study conducted was descriptive and cross-sectional research. It consisted of five key stages: forming the HAZOP team, gathering relevant information from the chlorination unit for HAZOP studies, identifying deviations and operational nodes, assessing the risks associated with processing hazards using the fuzzy HAZOP method, and modeling the potential consequences of Cl_2 gas release using the PHAST software. The primary objective of this research was to initially utilize the HAZOP technique to identify deviations or processing hazards within the chlorination unit. The initial phase involved the formation of the HAZOP team, which comprised a team leader who was an HSE expert, the supervisor of the chlorination unit at the water treatment plant, an instrumentation expert, a fluid mechanics expert, and a chemical engineer. Each member was provided with their respective job descriptions. In the subsequent step, the team gathered all the necessary documents and information for the HAZOP studies from the chlorination unit of the urban water treatment plant. The layout, process, and facilities map (P and ID), process flow diagram (PFD), operational instruments, analytical reports on hazards and safety, incident reports related to the system under study, organizational principles, internal rules and regulations, operational parameters, special characteristics of the facilities (such as pressure and temperature), and the results of HAZOP analysis conducted on similar systems were all included.

In the third phase, the operational nodes were defined to detect any deviations. These nodes include chlorination cylinders (CY), regulators (RG), copper connector pipes (PI), flow control valves (VL), heaters (HT), pressure alleviators (PR), changeovers (CO), ejectors (EJ), and chlorinators (CL). The location of all these nodes can be seen in Figure 1. It is important to mention that occurrence probability, consequence severity, and risk rate values were estimated to identify each deviation individually. However, due to two different deviations having the same risk rate and a lack of precise ranking, a novel technique called fuzzy HAZOP was employed in the fourth step of the study.

In order to obtain more precise and reliable outcomes, the fuzzy HAZOP technique has effectively eliminated any quantitative uncertainties by utilizing a quality matrix.[21] In the present study, the fuzzification process in HAZOP involves converting linguistic descriptions into trapezoidal fuzzy numbers. As previously stated, the classical HAZOP method employs a quality matrix to assess the level of risk. The numerical value resulting from multiplying the probability and consequence parameters is assigned to each individual scenario, ranging from 1 to 25. The classical approach to risk categorization involves three levels: low, medium, and high. However, the Fuzzy HAZOP method utilizes a fuzzified matrix to design risk zoning based on seven levels, resulting in more precise results.[22] As part of the fifth step in the study, version 7.11 of the PHAST software was used to model critical scenarios derived from the results of fuzzy HAZOP studies. Initially, critical risks were extracted from fuzzy HAZOP worksheets and then matched with the scenarios defined in PHAST. The HAZOP team collected the necessary information to model the consequences. This included the wind rose map of the water-treatment region, meteorological data for both summer and winter (air temperature and relative humidity), and technical details of the chlorination unit (internal pressure, temperature of the cylinder, diameter of the hole, etc.). The desired concentration for mapping the consequences was set at 400 ppm for a duration of 30 minutes. Analytical diagrams were then created, including concentration-distance, concentration-time, cloud thickness of vapors-distance, and death rate-distance.

The project has been approved by the Ethics Committee of Kashan University of Medical Sciences and Health Services under the code number IR.KAUMS.NUHEPM.REC.1400.066.

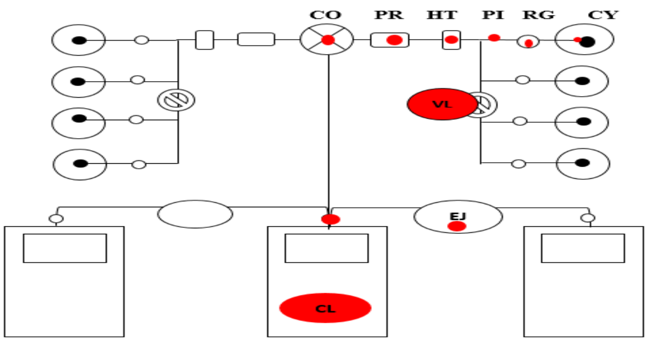

Figure 1. The determination of studying nodes on the P&ID map related to the chlorination unit of the urban water-treatment plant

Results

Following the establishment of the HAZOP team and the identification of the operational nodes, deviations pertaining to each node were identified. Specifically, a total of 41 deviations were detected in the chlorination process of the urban water treatment plant. Based on Figure 2, it can be observed that the node CY-01 exhibited the highest number of deviations in the processing line, specifically in relation to the chlorination cylinders.

The assessment of intensity and consequence was carried out for each operational node in the subsequent stage. The frequency of detected risks is illustrated in Figure 3. A total of 55 risks were identified in the chlorination unit of the urban water-treatment plant.

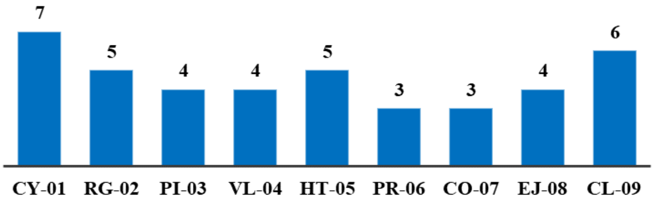

Figure 2. The frequency of detected deviations categorized by the operational nodes

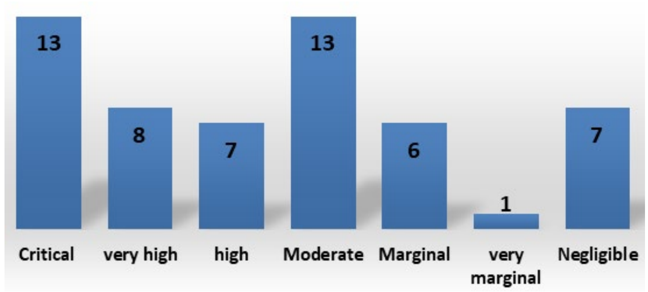

Figure 3. The frequency of detected risks in the operational nodes based on the fuzzy HAZOP method

Following the risk assessment, a total of 8 scenarios were chosen for the purpose of analyzing the release of Cl_2 gas and creating a consequence model. The study focused on the most critical scenarios, which involved the catastrophic rupture of chlorine gas cylinders, and utilized PHAST software to generate modeling graphs.

This article discusses the presentation limitations of consequence assessment results for various scenarios. One of the scenarios highlighted is chlorin gas leakage and catastrophic rupture, which are known for their high probability. Chlorin gas is highly oxidizing and corrosive, leading to erosion and common occurrences of spillage or leakage in connections over time. In this particular scenario, cylinders or chlorine reservoirs experience rupture or release of liquid chlorine due to factors like mechanical shocks or physical pressure. As a result, a cloud of highly concentrated chlorine vapors is produced at ambient temperature and dispersed by the prevailing wind. The Safety Data Sheet (SDS) for chlorine gas states that inhaling Cl_2 gas with a concentration of 400 ppm for 30 minutes can result in fatalities. To assess the potential consequences, two scenarios were considered: pressure vessel failure and catastrophic rupture. The characteristics of the chlorine cylinder, such as pressure, temperature, height from the ground, and material state in the chlorination room, were determined. The modeling calculation for fatality consequences resulting from a catastrophic rupture was performed using a 400 ppm concentration for 30 minutes. Two models, representing summer and winter climatic conditions, were defined with a wind angle of 240° (from southwest to northeast). Figure 2 displays the results of the modeling conducted using PHAST software for the consequences of a catastrophic rupture of liquid chlorine in the chlorination room of an urban water treatment plant.

Figure 4. The release profile of Cl2 gas from the catastrophic rupture scenario on PHAST software

The presence of blue and red circular lines serves as a visual representation of the release of chlorine gas. In summer, when the weather is relatively stable, the blue line indicates a concentration of 400 ppm. On the other hand, in winter, when the weather is relatively unstable, the red line represents the same concentration. Figure 4 provides valuable information about the expansion of chlorine vapors released during summer and winter, with durations of 263 s and 65 s, respectively. Moreover, the bold red lines at the center depict the expansion of chlorine in its liquid phase towards the northeast. Moving on to Figures 5 and 6, they showcase various diagrams, including concentration-distance, concentration-time, maximum concentration, death probability-distance, and the amount of produced vapors over time.

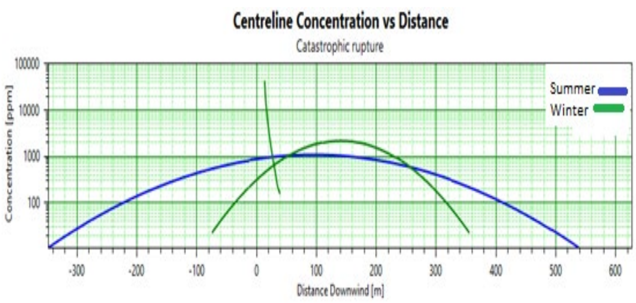

Figure 5. The concentration of chlorine vapors (ppm) in terms of the distance from the release focal on PHAST software

The diagram in Figure 5 displays the concentration of chlorine vapors released in relation to the distance from the release focal point. The concentration of chlorine vapors and distance are measured in ppm and meters, respectively. The blue line, representing summer, indicates that the concentration of chlorine vapors at the release focal point is 873 ppm, while the minimum concentration of 10 ppm is reached at a distance of 538 m (downwind) from the release focal point. The concentration also reaches 10 ppm in the crosswind direction. The maximum concentration of chlorine vapors is 1080 ppm at a distance of 100 m (downwind). The death probability within a 30-minute timeframe is equal to 302 meters downwind and 112 meters crosswind. During winter, as indicated by the green line, it is important to note that the highest concentration of chlorine vapors is found 142 meters downwind from the release point. Conversely, the lowest concentration of 22 ppm is achieved at distances of 74 meters downwind and 355 meters crosswind. At a distance of 270 meters downwind and 11 meters crosswind, the concentration reaches 400 ppm, which can result in death with a 30-minute exposure.

Discussion

The findings of the Fuzzy HAZOP studies in this research demonstrate that the leakage of chlorine gas at the connections of flanges, pumps, and pressure valves, as well as the catastrophic rupture of chlorine gas cylinders, are the most probable and significant events compared to other less frequent hazardous incidents. Furthermore, the consequence model for the catastrophic rupture of chlorine gas cylinders has revealed that a toxic vapor cloud is rapidly formed and dispersed in a southwest-to-northwest direction. This, in turn, leads to irritation of the lungs, skin, and eyes, severe difficulty breathing, suffocation, acute poisoning, and even fatal effects on individuals present in the affected area for more than a few minutes.

The article highlights the urgent need for emergency evacuation procedures to protect operators in hazardous areas. To enhance emergency response and recovery, it is crucial to conduct chlorine leakage drills. Additionally, the implementation of preventive measures like corrosion-proof coating and pressure control loops is essential, despite the associated costs and complexities involved in designing such measures for critical installations. In 2017, Rahimi et al. conducted a research project that utilized the HAZOP technique to identify deviations and hazards in an urban water-treatment plant.[23] The deviation identified by the keyword "more flow," which had the highest risk frequency, accounted for 55% of the risks. In contrast, the deviation associated with the keywords "vice versa" and "besides" had the lowest risk frequency at 5%.

The main objective of this research was to detect deviations and assess risks in the chlorination unit of the urban water-treatment plant using the HAZOP technique. Additionally, a risk matrix was employed to evaluate all the identified risks. The study titled "Risk Assessment and Prioritization of the Industrial Consumption Unit of the Ahvaz Water Treatment Plant Using the Comparative Multi-Criteria Decision-Making Method and HAZOP with TOPSIS Model and Providing Control and Improvement Solutions"[24] employed two methods, HAZOP and TOPSIS, to identify deviations, assess risks, and rank processing risks in the Ahvaz water treatment plant.

The findings revealed that the primary health and safety hazards in this industry are related to electric shock, exposure to deoxygenating chemicals, and noise. The current study found that Fuzzy HAZOP identified multiple factors contributing to critical risks in the cylinder room. These factors include leakage in cylinder connectors, such as regulators and cylinder valves; Cl_2 gas leakage from coupling screws and cylinder valves; damage to the liquid chlorine cylinder valve caused by human error; an increase in ambient temperature; failure of the cooling system; and inadvertent opening of the cylinder valve due to excessive heat during the summer. The common outcome of these factors is the release of Cl_2 gas into the surrounding area of the cylinder room and adjacent spaces, posing a significant threat of severe pulmonary poisoning and equipment corrosion. The study titled "Evaluating the Risk of Chemical Exposure in Wastewater Treatment Plants Through Multidisciplinary Decision-Making Methods"[25] presented findings highlighting the high risk of ammonia and chlorine gas exposure for technical and repair staff, as well as the risk of chlorine gas exposure for all employees. It is advisable to avoid using materials with a high or very high-risk factor and instead opt for suitable alternatives. In another study conducted by Paul et al., the impact of accidental chlorine gas release on the surrounding areas was investigated.[26]

The study utilized ALOHA software to identify hazardous spatial regions. Modeling was carried out to simulate the release of 1.6 tons of chlorine gas from a horizontal cylindrical tank over a duration of one hour. In a Bangladeshi summer climate, this simulated chlorine release resulted in a red zone spanning 1.1 km, an orange zone extending 3.6 km, and a yellow zone reaching 7 km downstream. In their study on the impact of chlorine leakage from the Rasht water treatment plant, Najmeh Setareshenas and her team utilized the PHAST software to define various scenarios under different climatic conditions.[18] By analyzing the data, they were able to identify high-risk areas in close proximity to the Rasht water treatment plant. According to the modeling results, the worst diffusion scenario, based on stability class F, was associated with a rupture in the chlorine vessel because it covered the most distance.

Conclusions

To avoid potential negative outcomes, various preventive measures can be implemented. Among these measures, risk-based inspection (RBI) is a crucial procedure for controlling risks. Inspection programs are developed based on risk assessment, particularly in relation to the corrosion of connectors in chlorination facilities. Additionally, an intrinsically safe design can significantly reduce the likelihood of leaks and releases in facilities. This approach involves reviewing all defects from a process safety and instrumentation perspective and strengthening vulnerable areas during the redesign process.

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Competing interests

The authors declare that they have no competing interests.

Abbreviations

personal protective equipment: PPE; process flow diagram: PFD; Safety Data Sheet: SDS; risk-based inspection: RBI.

Authors' contributions

All authors read and approved the final manuscript. All authors take responsibility for the integrity of the data and the accuracy of the data analysis.

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Role of the funding source

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Availability of data and materials

The data used in this study are available from the corresponding author on request.

Ethics approval and consent to participate

The study was conducted in accordance with the Declaration of Helsinki. Institutional Review Board approval (code: IR.KAUMS.NUHEPM.REC.1400.066) was obtained (April 2020).

Consent for publication

By submitting this document, the authors declare their consent for the final accepted version of the manuscript to be considered for publication.

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