Simulation and Analysis of Fire and Explosion Safety in Chemical Processing Plants

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Abstract: The handling of flammable, explosive and toxic materials under high pressure and high temperature operation conditions creates some of the most severe hazards in chemical processing plants, which can be fire and/or explosion accidents. The goal of this study is to simulate and analyze different fire and explosion scenarios in chemical processing plants, to determine the propagation of the hazard, and to assess the effectiveness of different engineering safety measures. The release, dispersion, ignition, combustion, and thermal radiation of hazardous materials under representative operating conditions are simulated using numerical simulation techniques such as computational fluid dynamics (CFD). The simulation results show that the application of both active and passive fire protection systems have a significant effect in reducing the fire spread, thermal radiation intensity and the risk of domino effect spread. Results show that simulation-based risk assessment has the potential to give a significant contribution to accident prevention, emergency preparedness and safety system optimisation.

Keywords: Fire Accident, Fire safety, Explosion safety, Chemical processing plants, **Simulation, Analysis**

INTRODUCTION

In the chemical, petrochemical and hydrocarbon industries, there are occasions when you may be exposed to a wide range of highly flammable and explosive chemicals. Their chemicals are used in countless ways in a variety of products. There are various kinds of environments that have potentially harmful substances. The term 'ignition' will be used throughout this protocol. The major focus of this regulation is to provide fire protection. With this Guideline's aims in mind, the following is an appropriate definition of fire prevention and fire protection: With the goal of reducing the damage that flames do to persons and property, this research focuses on fire control and extinguishment. Fire protection solutions include fire detection and prevention devices as well as control devices, and, of course, fire fighting. Fire prevention" in this context means any action that will help to lower the probability of fires. Prevention and protection against fire are related practices. Fire injury prevention is one of the main objectives of a fire safety program. For instance, control of potential ignition sources is important to reduce the fire hazards; however, this alone is not enough to ensure adequate fire protection, as indicated by the Guideline. The current safety laws are focused on one thing: preventing disaster incidents, such as fire and explosion. This can be done by separating substances that can cause harm from the processing system.

Based on the results of the investigation into the past domino accidents, explosion is the most frequent cause of domino effect, comprising 57% of all domino accidents. Flames, on the other hand, are responsible for 43% of all domino accidents.

The storage rooms are the most likely places to start a domino effect, according to a research that looked at 225 mishaps that included domino effects. The process plant was the second most likely place to start a domino effect (30%). Also, fire-explosion (27.5%), fire-explosion (27.6%) and fire-fire (18%) combination accidents are the most frequently occurring sequences of accidents. However, the issue encountered while assessing and/or analysing domino effects for industrial properties has led to the creation of a number of methods and software tools to solve this issue.

An analytical technique has been developed to conduct a quantitative analysis of the industrial risk caused by seismic occurrences which are the cause of accidents. This method utilizes available data, historical data, for the purposes of prediction of frequency and magnitude of seismic occurrences. Based on Monte Carlo simulation, a technique that can be used to assess domino effects has been developed by. The authors developed an algorithm that mimics the operation of a multi-unit system by simulating its reaction to a series of possible experiments. This algorithm has been developed by. Chemical processing plants are one of the most hazardous environments in which to work because they involve the handling of combustible dust, volatile liquids, flammable gases and reactive chemicals, all of which work under high pressure and high temperature. Although these industries are vital to the manufacturing of fuels, fertilisers, medicines, petrochemicals, plastics and industrial chemicals, they also possess a significant operational risk. Incidents involving fires and explosions that occurred at chemical factories have resulted in significant human casualties, damage of the environment, and economic losses all around the globe. This has led the management of the process sector to incorporate fire and explosion safety as an extremely significant element.

Many industrial accidents are caused by inadequate design, poor safety practices and lack of awareness of potential hazards that could become a reality during plant operation, as stated by

Kletz (2009) [1]. He stressed that good process safety management should focus on prevention of accidents rather than on accident control once it has happened. Likewise, Lees (2012) [2] explained that systematic hazard identification and risk assessment (HIR) should be implemented in the chemical industries to prevent catastrophic explosions and fires. This is because such devastating catastrophes may be caused by very little leakage or operational anomalies.

Several industrial tragedies brought to light the terrible results of hazardous industrial activities. The Texas City refinery explosion, Flixborough explosion in the United Kingdom and the Bhopal Gas Tragedy in India were among them. The devastating domino effect extended when a Texas City refinery went up in flames. These events highlighted the importance of implementing rigorous safety regulations, implementing effective emergency response protocols, and providing comprehensive training for workers. Current process safety engineering is an integrated approach of technical concepts and hazard management strategies to minimize the risk of accidental chemical spills and ignition, says Crowl and Louvar (2011) [3]. These were taken to ensure that there were no accidents. The implementation of legislation pertaining to fire and explosion safety has considerably improved the safety procedures of industrial facilities.

As a result of industrialization and fast technological advancements, chemical processing systems have become more complicated. This was brought about by the abrupt occurrence of these two factors. Consequently, the use of state-of-the-art safety equipment, such as gas detection systems, automatic shutdown systems, explosive venting devices, and computer-based risk assessment models has risen. In the context of accident prevention and sustainable development of industry, Mannan (2014) [4] states that it is important to have safety culture, discipline in operation, and a risk management system. This is because these are important basic controls for minimising the incidence and severity of accidents in the workplace.

Explosion and fire safety procedures should be considered as essential requirements in the process design, operation and maintenance for modern chemical processes. It is a principle that is followed by the chemical industry in general. In order to reduce the risk of causing injuries in their industrial operations, companies are increasingly investing in raising awareness about safety, educating workers, preparing for emergencies and adhering to international safety standards. We are doing this in order to save human beings and the earth.

Explosion is one of the many concerns that businesses that handle petroleum products, chemicals, and other types of chemicals may encounter. In fact, both big and small businesses suffer from fires and explosions annually that result in extensive environmental damage and economic losses [5, 6].

The National Fire Protection Association (NFPA) reports that a total of over 37,000 fires occur every year on industrial and manufacturing sites. It is much better to prevent explosions than to respond to them, because they cause 18 deaths, 279 civilian injuries, and $1 billion in property damage [7].The high temperatures and working pressures, combined with the flammability and reactivity of the materials and high volatility and evaporation of the liquids, are a risk of fire and explosion [8-12].

LITERATURE REVIEW

Qu, et al., (2023) [13] framework was proposed to assess and manage fire risk in chemical plants. Hazard and operability analyses were conducted to identify the deviations and contributing factors leading to fires in a chemical plant. For fire risk points, a hierarchical control structure model of the system production process was integrated with the internal production and external safety management interactive feedback unit to clarify the safety constraints and controls. Chemical plant operation scenarios were developed to focus on coordination and feedback between multiple organizations in the system. A decision-making trial and evaluation laboratory (DEMATEL) and interpretative structural modeling (ISM) were combined with an analysis of constraint defects. A case study of a fatty alcohol polyoxyethylene ether plant was conducted. The results show that the DEMATEL–ISM model describes the potential cross-level control process and can comprehensively analyze the relationship between contributing factors to improve the system's overall safety and prevent accidents.

Zhou, et al., (2020) [14] proposed framework consists of 5 steps: (i) establishment of hierarchical safe control structures (SCSs) of important chemical processing zones in the CIP, (ii) computational fluid dynamics (CFD) modeling for potential explosion evolutions in each zone by changing the examined parameters randomly, (iii) development of a convolutional neural network (CNN) prediction model through constant self-learning of CFD pressure field data, (iv) comprehensive assessment of blast damage by incorporating the outputs of the above numerical models into existing evaluation methods, (v) identification of unsafety control actions and causes, and safety constraints for the improvement of SCSs. Provided with monitoring data, the developed analysis architecture can predict explosion process hazards and recommend appropriate safety strategies in real time. This would service the multi-level requirements for explosion prevention and protection, supporting better-informed decision-making. The paper describes the concepts and implementation process of the method as a first step.

Alenezi, & Al-Qabandi, (2022) [15] purpose of this article is to provide an overview of the hazards and risks associated with the Petroleum/Chemical sector to students, scholars, governments, and non-governmental organizations. The evaluation concentrated on fire and explosion as the most evident risks that frequently occur in these facilities. It is critical to any country's economic prosperity. A discussion of the different casual features of such threats at various Petroleum/Chemical sites is offered. The most typical cause factors are combustible materials, static electricity, and lightning strikes, among others. The impact of risk mitigation and management studies based on various approaches and techniques, such as qualitative, quantitative, and dynamic changes in risk assessment, is clearly highlighted. According to most research publications, tank farms are the most dangerous region in the plant for sparking fires.The secondary effects of fire and explosions, such as the domino effect and air pollution, are investigated. To summarize, all efforts must be coordinated in order to successfully manage risks and crises in Petroleum/Chemical facilities and prevent their recurrence in the future.

Lu, et al., (2020) [16] excavate and analyze the underlying causes of accidents, this paper first integrates emergency elements in the frame of orbit intersection theory and proposes 14 nodes to represent the evolution path of the accident. Then, combined with historical data and expert experience, a Bayesian network (BN) model of CPEAs was established. Through scenario analysis and sensitivity analysis, the interaction between factors and the impact of the factors on accident consequences was evaluated. It is found that the direct factors have the most obvious influence on the accident consequences, and the unsafe conditions contribute more than the unsafe behaviors. Furthermore, considering the factor chain, the management factors, especially safety education and training, are the key link of the accident that affects unsafe behaviors and unsafe conditions. Moreover, effective government emergency response has played a more prominent role in controlling environmental pollution. In addition, the complex network relationship between elements is presented in a sensitivity index matrix, and we extracted three important risk transmission paths from it. The research provides support for enterprises to formulate comprehensive safety production management strategies and control key factors in the risk transmission path to reduce CPEA risks.

Saloua, et al., (2019) [17] aim of this study is to assess and model the fire and explosion hazards of liquefaction natural gas in Algeria as long as this later plays an important role in gas industry and global energy markets in the next several years. The first step used in this study is the hazard identification using HAZID tool. This step is completed by DOW's F&EI as a second step to predict and quantify mathematically the fire and explosion damages in the Scrub Column and the MCHE the most critical systems in the LNG unit. In order to better understand the hazards severity of these risks, PHAST software is used to model and simulate the accident scenarios. The results will reveal that the two principal equipments of liquefaction unit (Scrub Column–MCHE) present an important risk as per HAZID and they present a severe risk as per DOW's F&EI. The modelization of fire and explosion scenarios using PHAST software gives us a real image about these hazards which presented by Fireball, Flash Fire, Early and Late explosion. The combination of HAZID, DOW's F&EI and PHAST simulator leads to better risk assessment, and helps in creating preventive measures, and taking serious decisions to reduce and limit fire and explosion risks in order to save human life as a first goal, environment and installations as a second goal and to avoid the financial and economic loss of Algeria.

STATEMENT OF PROBLEM

Chemical processing plants process a lot of flammable, explosive and hazardous materials under high-pressure and high-temperature operating conditions, making them easy targets for fire and explosion accidents. These occurrences can have significant repercussions such as loss of life, pollution of the surroundings, damage to equipment, loss of production, and economic losses. Traditional risk assessment approaches can be limited in describing the dynamic behaviour of fire and explosion scenarios for a variety of operating and environmental conditions. A comprehensive simulation study is needed to accurately model fire and explosion behavior, assess the performance of active and passive fire protection features, and provide guidance for plant design to reduce risk, emergency response planning, and plant safety management.

OBJECTIVES

- To determine the major fire and explosion hazards in chemical processing plants.
- To simulate and analyse fire and explosion scenarios through the use of numerical simulation techniques.
- To test the ability of fire protection systems to enhance plant safety.

MATERIALS AND METHODS

This study primarily aims to mimic fires that originate from ignition sources situated on FLNGs, or floating LNG tanks. At the same time, the FLNG is evaluating how well the safety measures are working. This is accomplished by simulating the LNG's release and distribution in order to come up with a number of possible outcomes. To determine the impact of the fire on the FLNG, we run computational fluid dynamics (CFD) models for each possible outcome. Next, we find the worst possible situation. Installing safety measures like a firewall and automated fire suppression system may lessen the impact of a fire on nearby buildings, people, and assets.

The four main phases of the research framework are scenario development, fuel release and dispersion modelling, fire consequence analysis, and mitigation measure evaluation. The method quantifies the efficacy of both passive and active fire protection systems and makes it possible to identify worst-case fire scenarios.

The objective was to examine the effects of various ignition source distributions on the evolution of safety features. This strategy's users are free to select any extra criteria they choose, not only the ones used in this research.

In order to simulate the release and dispersion, inquiry makes use of the FDS model. The goal of these models is to find out where the gasoline concentration is distributed. In order to create plausible situations, it is essential to be able to calculate the magnitude of the fuel vapour cloud.

This study will proceed on the assumption that the majority of the gas is methane. Lagrangian particles are used as a symbol by FDS when problems cannot be addressed using the numerical grid. A sprinkler is used to depict the discharge of gasoline from a tank opening for the purpose of this study.

Studies calculate the most dangerous situations caused by different ignition source locations. The results of the distribution and release model lend themselves to several reasonable hypotheses. Through the use of the FDS code, we are able to model several scenarios. An example of a computational fluid dynamics (CFD) model developed by NIST is the FDS model of fluid flow driven by fire. The most recent validation of the FDS was by NIST, however it has been verified by other inspections and experiments.

Table 1: Assumed FLNG Parameters

Parameter	Value
FLNG Length	488 m
Width	74 m
LNG Storage Capacity	220,000 m^3
LNG Composition	95% Methane
Ambient Temperature	30°C
Wind Velocity	5 m/s
Relative Humidity	75%
Atmospheric Pressure	101.3 kPa

Table 2: Fire Scenarios Considered

Scenario	Leak Size	Ignition Source Location	Wind Speed
S1	Small Leak	Near Tank	5 m/s
S2	Medium Leak	Mid Deck	5 m/s
S3	Large Leak	Compressor Area	5 m/s
S4	Large Leak	Processing Module	5 m/s
S5	Catastrophic Leak	Adjacent Tank	5 m/s

Table 3: CFD Model Parameters

Parameter	Value
Grid Size	0.5 m
Time Step	0.01 s
Simulation Duration	600 s
Turbulence Model	LES
Solver	Fire Dynamics Simulator (FDS)

We compare the FDS simulation results to the control group's without safety measures after we incorporate them. Finding out how the fire safety measures could affect the situation is the goal.

Table 4: Consequence Severity Classification

Heat Flux (kW/m²)	Consequence
< 4.5	Minor
4.5 – 12.5	Moderate
12.5 – 37.5	Severe
> 37.5	Catastrophic

RESULTS

- **Scenario development**

The study made use of two meshes, one with 964800 cells and the other with 1878750 cells. A comparison of the simulation results of the time-varying temperatures of some slice files for different meshes is shown in figure 1, which indicates a good correlation. For each scenario, the 62nd simulation length is taken into account.

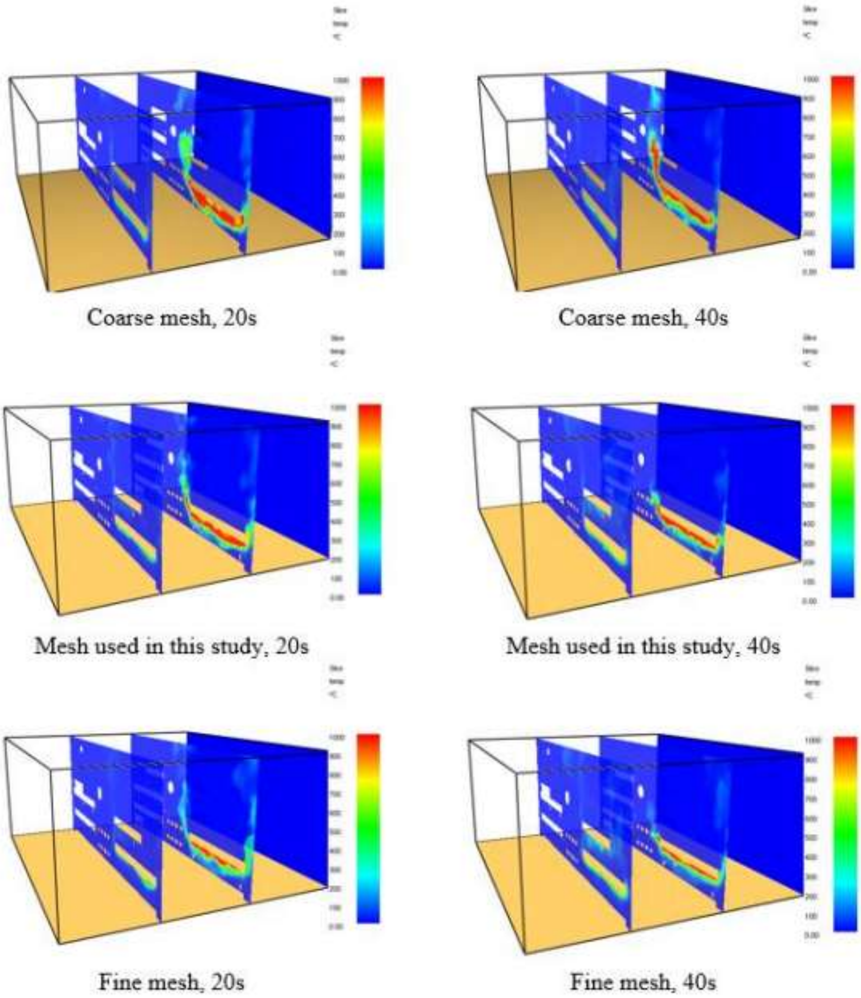

Figure 1: Study of Sensitivity

- **Release and dispersion simulation**

Offshore activities will produce emissions and locations of leaks may change in practice. Temperature and wind speed are two environmental factors that might hasten the pace of natural gas evaporation and distribution. Figure 2 shows an example of the FDS code's output.

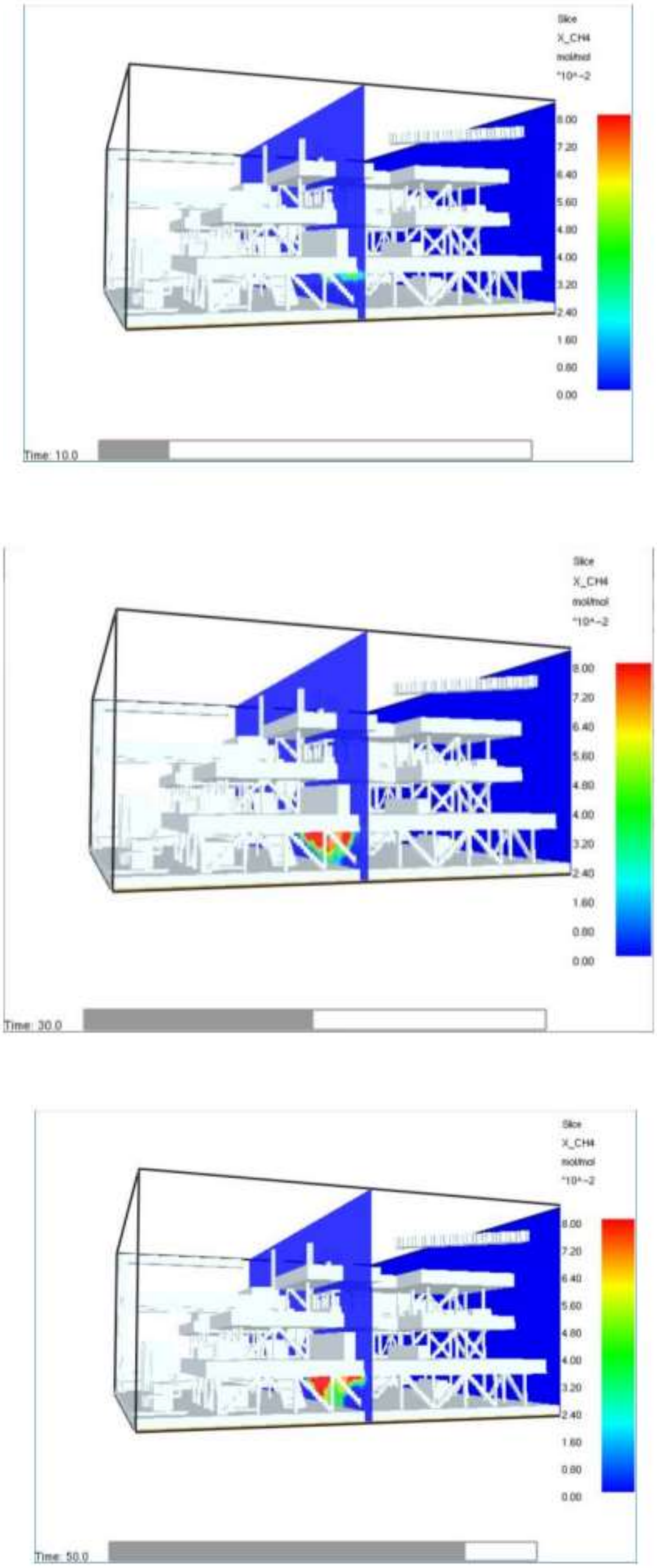

Figure 2: Different Times Slice File Concentration (a) 10s (b) 30s (c) 50s

- **Fire simulation and analysis**

The fourteen situations are displayed in Table 1. The ignition source is also depicted in figure 3.

Table 1: Ignition Sources Location

	X(m)	Y(m)	Z(m)
Scenario 1	11	10	4
Scenario 2	11	22	4
Scenario 3	11	34	4
Scenario 4	23	10	4
Scenario 5	23	22	4
Scenario 6	23	34	4
Scenario 7	35	10	4
Scenario 8	35	22	4
Scenario 9	35	34	4
Scenario 10	47	10	4
Scenario 11	47	22	4
Scenario 12	59	10	4
Scenario 13	59	22	4
Scenario 14	23	22	12

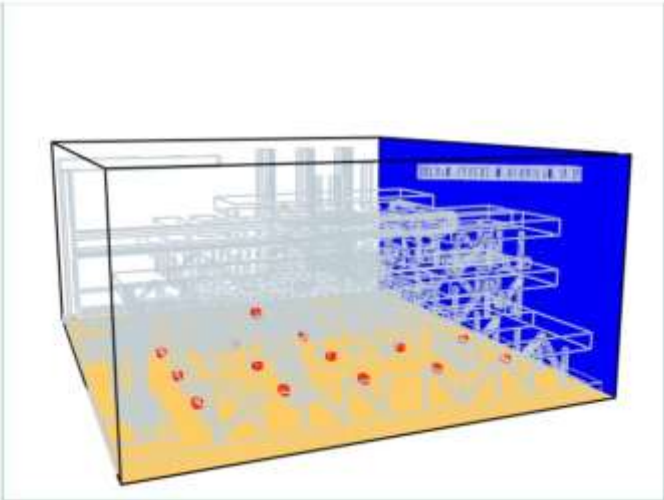

Figure 3: The Locations of the Ignition Source

The FLACS model is used here to show the dynamic pressure created by the explosion in Figure 4. The statistics say that it was about thirty seconds before the ignition. In this case, the overpressure of the explosion was not enough to cause damage to the assets; therefore, the thermal radiation is mainly considered as an effect in this study.

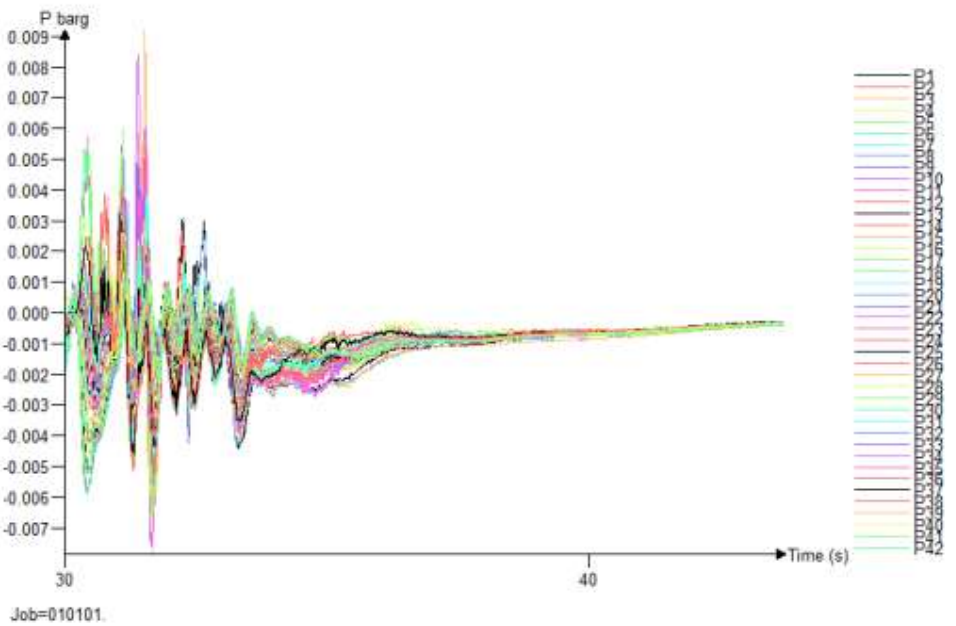

Figure 4: Pressure changes over time in FLACS simulation

- **Fire suppression simulation and analysis**

Failure to take these precautions makes the possibility of the target structure burning to the point where the temperature shown in Figure 5 becomes catastrophic. The worst case scenario for each of the three situations includes the maximum possible temperature a fire could attain in an enclosed area of the designated building, where a firewall and fire suppression system is in place.

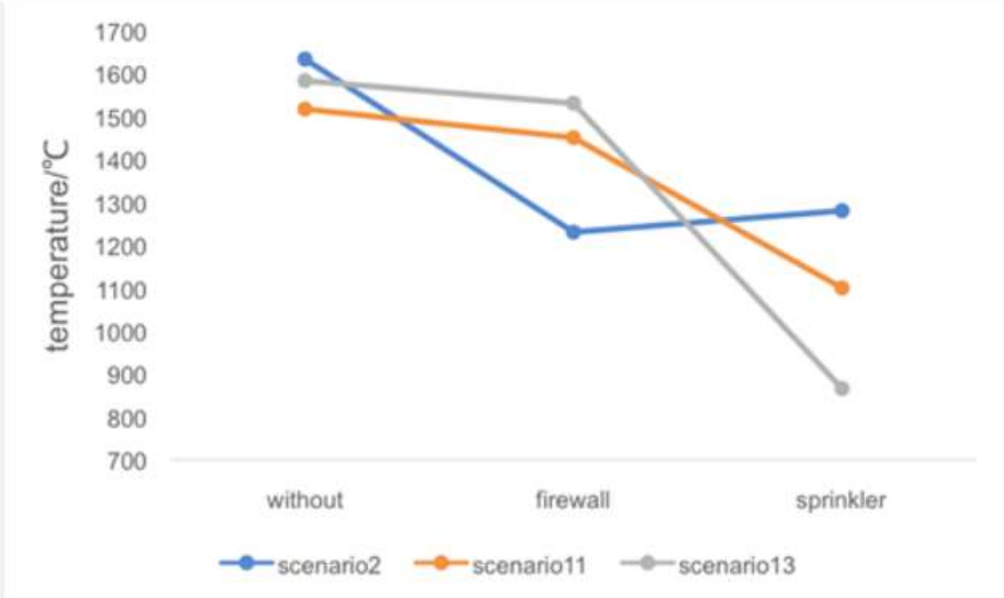

Figure 5: Maximum Temperature the Fire Caused Before and After Application of Safety Measures

DISCUSSION

The present study shows that simulation-based methods are effective in assessing fire and explosion risks in chemical processing facilities. The simulations of release and dispersion showed that the development of the fire is greatly affected by environmental conditions and the positions of the ignition sources. The size of the flammable gas cloud was influenced by variations in wind direction, ambient temperature and leak position which would influence the probability of ignition and fire propagation. These results are consistent with earlier studies that found one of the key factors for industrial fire risk and accident escalation to be the dispersion characteristics of the gases [5,6]. The fire suppression analysis showed that there is a need to combine both active and passive fire protection systems. The automatic fire suppression system helped control flames and prevented them from reaching maximum surface temperatures and the fire wall contained the spread of flames between structures. These synergistically applied safety measures contributed enormously to the decrease of thermal exposure, which also helped to minimize the risk of escalation through a domino effect. The results of this study corroborate the findings of Kletz [1], Lees [2], Crowl and Louvar [3] and Mannan [4] who recommended that the consequences of industrial accidents can only be minimized using engineering controls and systematic hazard management.

While the present study was conducted under representative FLNG fire scenarios involving a principal fuel component such as methane, there is a potential for industrial accidents to include multicomponent fuels, changing weather conditions, equipment failures and human operational mistakes. Future studies should therefore take into account the transient meteorological conditions, complex chemical reaction mechanisms, structural response analysis and probabilistic risk assessment to enhance the accuracy and applicability of fire and explosion simulations in large scale chemical processing facilities.

CONCLUSION

The simulation-based methods proved to be effective for chemical plant fire and explosion hazard analysis in this study. The findings indicated that Computational Fluid Dynamics (CFD), Fire Dynamics Simulator (FDS), and FLACS can be used to accurately predict hazard behaviour and used to evaluate the performance of active and passive fire protection systems. The results are in favor of using simulation-based risk assessment to enhance accident prevention, emergency preparation, and process safety in chemical industries.

FUTURE SCOPE

Real-time monitoring and artificial intelligence can be added for predicting fire and explosion occurance in the future. The simulation method can be adapted for other chemical factories and dangerous materials at different operating conditions. Further enhancement of the safety of industry can be evaluated by advanced fire protection technologies and emergency responses.

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