

Numerical Assessment of Passive Fire Protection in an Oil and Gas Storage Facility



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1 Introduction

Oil storage and processing facilities, such as refineries, are constantly handling large quantities of hydrocarbons and chemicals in both liquid and gas forms that are inherently flammable. If accidents or errors such as human mistakes, equipment failure or deficiency in management plan were to occur, there is a high risk that property loss, economic disruption and production interruption will occur (Baalisampang et al. 2018a). To tackle such issues, there are a variety of guidelines and standards for refinery construction, building material selection and layout design to prevent accidents from occurring and to reduce the impact of structural, economical and production accidents. However, although guidelines and standards are constantly being updated and implemented, it is observed that chance of fires, detonations and explosions occurring cannot be eliminated in the hydrocarbon processing industry as too much flammable hydrocarbon is being handled (Vervalin 1985), and there are countless modes of failure in this industry (Baalisampang et al. 2018b). According to Chang and Lin (2006), of the type of complex in which fire and explosion have occurred over the past 50 years, 116 of 242 accidents occurred in refineries which contribute to approximately 50% of the accidents. Among the 116 accidents in refineries, 60% of them are related to fire. In addition, Hu et al. (2013) concluded that 27% of major accidents over the past 30 years occurred in petroleum refineries and fire or explosion accounted for 96% of the total number of cases. Based on these researches, it is observed that fire protection systems that are commonly installed in hydrocarbon storage facilities must be considered and selected carefully. This has

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F. I. Khan et al. (eds.), *Advances in Industrial Safety*, Springer Transactions in Civil and Environmental Engineering, https://doi.org/10.1007/978-981-15-6852-7_1

not been extensively studied previously. Fire protection system (FPS) is designed to respond to fire if fire or smoke is detected, and it can be categorised into an active, passive, and inherent fire protection system (Baalisampang et al. 2016). Active fire protection (AFP) is a system or component that requires human action or some mechanisms to activate and is employed to suppress and mitigate the fire. On the other hand, passive fire protection (PFP) system is a defensive mechanism that requires no activation method to prevent the spread of fire and disintegration of structure (Roe 2000). Some examples of PFP are fire rated walls and doors, fire protection spray and self-expanding foam which are designed to limit the temperature rise and excessive heat absorption of equipment and structures. Another type of PFP system is intended to prevent the spread of hydrocarbon particularly liquid hydrocarbon which includes drainage sumps and bunds (Spitzenberger et al. 2016). With such a wide variety of fire protection systems, the choice of an FPS is mainly dependent on the targeted fire type, i.e. pool fire, jet fire or flash fire. A selection of an FPS must be considered carefully to maximise the effectiveness of the PFP applied. In addition, immoderate or excessive use of PFP can lead to problems such as increase in fabrication and building cost, risk of schedule delay (Friebe et al. 2014) and increased difficulty in performing corrosion testing (Tugnoli et al. 2012). Thus, selection of the PFP system and careful consideration of the combination of passive and active fire protection systems are of great importance.

2 Literature Review

Since the late nineteenth century, due to the high cost and time required to perform full-scale experiments in the laboratory, numerous mathematical models have been proposed to predict the thermal behaviour of fire. These mathematical models range from simple models such as algebraic correlations that can be solved with a calculator, to complex models such as field modelling which can only be solved with computer software (Carlsson 1999). With the rapid development of technology and computational power, field modelling is progressively becoming the more common model for fire researchers and fire safety engineers to perform fire safety researches and predict the behaviour of fire. Field models, particularly the computational fluid dynamics (CFD) model, is widely recognised as one of the most dominant method to predict the behaviour of hydrocarbon fire and explosion as it allows fire to be simulated even in complex geometries and different surrounding conditions (Baalisampang et al. 2017). To date, there are several CFD software packages designed for fire engineering application, which can precisely predict and estimate the heat and smoke transport during a fire. Fire Dynamics Simulator (FDS) is a CFD software developed by National Instrument of Science and Technology (NIST) which has the capability of modelling fire-driven fluid flow and with emphasis on smoke and heat transport from the fire. With the information on heat transport, thermal load and temperature rise on surrounding structures can be obtained and effect of thermal load can be investigated (McGrattan et al. 2013). Flame Accelerator Simulator (FLACS)

is another software for fire modelling that can perform full three-dimensional fire modelling with the input of original 3D drawings, and it has the capability to model jet fire, pool fire and flash fire. This software is suitable for high and low momentum flow fire, passive fire protection optimisation, vessel heat up modelling and heat radiation modelling (Gexcon 2017). In addition, SMARTFIRE is software developed by Fire Safety Engineering Group (FSEG) to perform fire field modelling. The advantage of this software is that it has two modes of operation which are novice mode, which embeds expert knowledge into the software to assist beginners, and expert mode in which users have full control over the configuration and settings (Taylor et al. 1997). Kameleon FireEx (KFX) is another type of CFD software developed by Computational Industry Technologies (ComputIT) which focuses on gas dispersion and fire simulation, mainly for industrial usage.

Although there are extensive applications of numerical simulation in fire impact modelling, as well as predicting performance of fire extinction using AFP system such as water mist or fire hydrants, by reproducing the heat release rate (HRR) decrease of fire in scenario, there is limited research on effectiveness and assessment of PFP system adequacy in specific scenario (Jenft et al. 2013). Currently, there are several research papers (Baalisampang et al. 2017a, b) which performed CFD modelling of fire impact and risk analysis. Rajendram et al. (2015) studied the fire risks and impact associated with jet fire and fireball in offshore facility using FDS. In addition, Ryder et al. (2004) performed consequence modelling using FDS to determine the impact of pool fire in both a small and a large room. Some researchers (Lim et al. 2019; Landucci et al. 2009) have studied the performance of PFP system and determined the adequacy using different methods. This includes Shirvill (1993), Mróz et al. (2016) and Suardin et al. (2009) performed full-scale experiments on various types of PFP material including cementitious material, intumescent coating, ablative building materials and high expansion foam under direct flame impingement or exposure. Dalzell and Melville (1993) presented a method for preliminary design of PFP based on maximum potential fire consequences. Friebe et al. (2014) applied finite element analysis (FEA) to determine the effect of PFP on collapse time of a Floating Production Storage and Offloading (FPSO)'s topside module. In addition, Landucci et al. (2009) adopted finite element analysis to determine the performance of an LPG tank coated with different PFP materials under fire engulfment. Li et al. (2016) used CURISK, which is a fire risk analysis software to determine the effect of fire barriers on a building. It is worth mentioning that Vianna et al. (2010) performed numerical simulations to determine the adequacy of PFP in an offshore facility using Kameleon Fire Modelling (KFX) and FAHTS. However, only the applied methodology were explained but the detailed information about type of PFP system installed was not stated and only one offshore fire scenario was considered in the paper.

Analysis of effectiveness and performance of PFP system in the oil and gas industry has not been performed extensively. Thus, this study presents the numerical assessment of PFP in an oil and gas storage facility, predominantly in refineries using CFD modelling to determine the effectiveness of various types of commercially available PFP materials. In addition, the study will also assist in determining the accuracy of numerical modelling in PFP system which will allow fire engineers

to have higher accuracy when utilising CFD software to determine the application and adequacy of PFP. FDS is used as the main tool in fire scenario modelling as it is a specialised tool for fire modelling which has been well validated and used by professionals.

3 Proposed Methodology

The study of PFP system effectiveness in an oil and gas storage facility can be broken down into different stages which form a proposed methodology. The methodology begins with the development of the fire scenario in the oil and gas storage facility, and an accident occurrence credibility score is assigned to each fire scenario to determine the most credible fire scenario. CFD simulation is performed on the most credible fire scenario. In addition, various types of PFP systems will be modelled for the fire scenario. The results of CFD simulation are adopted to determine the effectiveness of various PFP systems in preventing a rise in equipment temperature, fire propagation, structural collapse and impact reduction when exposed to hydrocarbon fire. An overview of the proposed methodology is presented in Fig. 1.

3.1 Fire Scenario Development

In the first step, the development of the fire scenario in oil and gas storage facility is performed. A fire scenario is a description of the major cause of the fire event which generally originates from hazards at the facility that have the potential of threatening the facility or personnel (Ahmad et al. 2013). In an oil and gas storage facility, hazardous products such as crude oil, or any crude oil by-products, are stored and once loss of containment occurs, fire or explosion may occur within a short period of time if they are in contact with an ignition source. The fire can spread at a high rate which leads to a high number of casualties and economic losses (Zhou et al. 2016). In this proposed methodology, fire scenarios are developed based on root causes that lead to the loss of containment from past oil and gas storage facility accidents. Through the generation of fire scenarios, potential fire types such as pool fire, jet fire or flash fire are determined. This is important as each type of fire has unique characteristics and a different mitigation technique (Spitzenberger et al. 2016). The fire scenarios generated are presented in Table 1.

3.2 Fire Scenario Credibility Assessment

In step 2, ranking of each fire scenario is performed based on credibility assessment. Among different types of assessing methods, the Maximum Credible Fire Scenario

Fig. 1 Proposed methodology

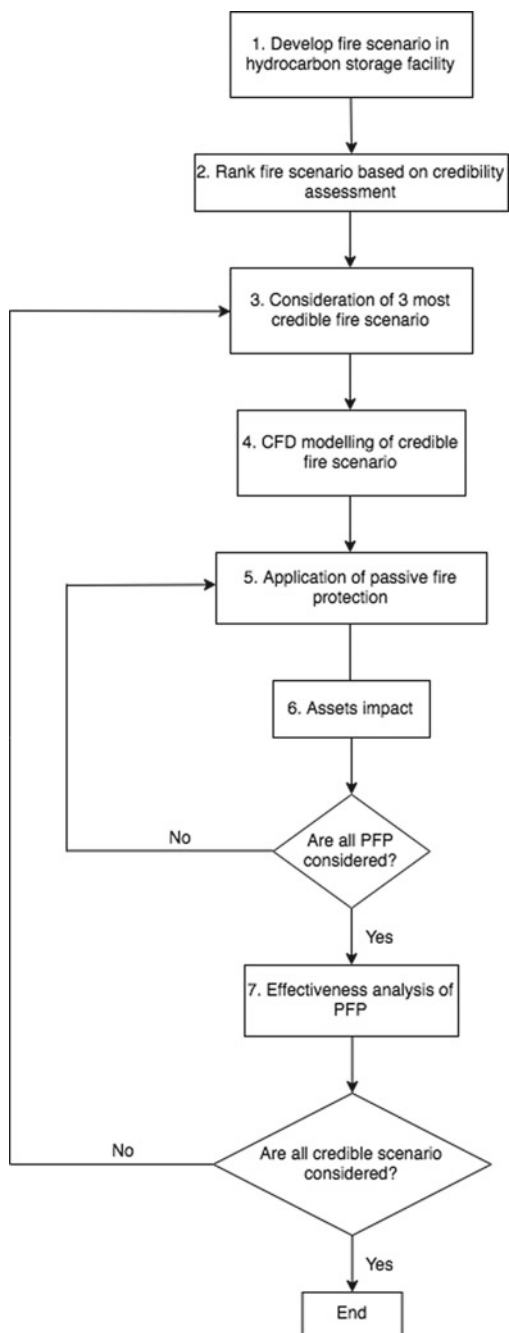


Table 1 Fire scenarios in oil and gas storage facility

No.	Fire scenario	Accident location	Year	References
<i>Loading and unloading area</i>				
1	Spark from an electric motor ignited leaked jet fuel	Stapleton International Airport	1990	Persson and Lönnermark (2004)
2	Leakage of LPG due to an earthquake caused fire and explosion	Cosmo Oil Chiba Refinery	2011	Krausmann and Cruz (2013)
3	A pool fire was formed during an unloading of crude oil to storage tank	Amuay Refinery	1982	Parraga (2013)
<i>Crude oil tank</i>				
4	Overfill of crude oil tank caused liquid pool and formed vapour cloud which ignited instantly	Philadelphia Gulf Refinery	1975	Persson and Lönnermark (2004)
5	Leakage of crude oil at rate of 0.006 kg/s due to crack at bottom plate of crude oil storage tank and caused a fire	Fawley Refinery	1999	Whitfield (2002)
6	Pool fire forming at tank roof after an explosion occur at the tank due to contact with ignition source	Tanzania Pipeline Company	1989	Persson and Lönnermark (2004)
7	Lightning strike caused tank roof to fail and ignited after contacting with ignition source resulting in pool fires	Czechowice-Dziedzice Refinery	1971	Persson and Lönnermark (2004)
8	Spark from man lift ignited gas oil vapour causing pool fire	Conoco Refinery	1999	Persson and Lönnermark (2004)
<i>Distillation tower</i>				
9	Spill of propane from distillation tower due to equipment failure caused liquid pool and vapour cloud ignited	BP America Refinery	2005	Holmstrom et al. (2010)
10	Failure of storm drainage system caused waste oil to wash out of drain and ignited at distillation tower	La Plata Refinery	2013	Parks (2013)

(continued)

Table 1 (continued)

No.	Fire scenario	Accident location	Year	References
11	Crude oil vapour released from main crude column pressure safety valve due to pumps and cooler malfunction	Texaco Refinery	1994	Kletz (1998)
12	Leak of crude oil from a branch in distillation column due to incorrect building material caused a fire	Mazeikiu Refinery	2006	Kramer (2006)
13	Diesel leak in a pipeline in the crude distillation unit caused a flash fire	Chevron Refinery	2012	CSB (2015)
<i>Refined oil processing unit</i>				
14	Leak of gasoline at rate of 15 kg/s due to failure of block valve to seal pump strainer properly at visbreaker unit	El Paso Refinery	2001	Shiva and Fung (2016)
15	Failure of valve bonnet in hydrocracker unit caused gasoline of 101 kPa pressure to release at a rate of 17 kg/s	Chevron Richmond Refinery	1999	Persson and Lönnermark (2004)
16	Heat exchanger failure caused release of gasoline at a rate of 14.5 kg/s in hydrosulphurisation unit causing explosion and fire	Sodegaura Refinery	1992	Persson and Lönnermark (2004)
17	Release of flammable liquid at a rate of 0.95 kg/s during the removal of malfunctioning pump when shut off valve was open	Ciniza Oil Refinery	2004	CSB (2005)
<i>Product storage tank</i>				
18	Overfill of 568 m ³ gasoline tank caused liquid pool and vapour cloud formation which was then ignited	Texaco Refinery	1983	McLennan (2013)
19	Lightning strike caused naphtha tank to fail and ignited causing a tank fire	Pulau Merlimau Refinery	1988	Rodante (2005)
20	Weld failure caused leakage of refrigerated propane tank and later resulted into a fire.	Umm Said NGL Plant	1977	McLennan (2013)

(continued)

Table 1 (continued)

No.	Fire scenario	Accident location	Year	References
21	LPG leakage at a rate of 2.35 kg/s due to drain valve frozen during drainage operation which was then ignited after contacting the ignition source	Feyzin Refinery	1966	McLennan (2013)
22	Failure of pump house used for blending refined product caused liquid pool to form which later ignited	Pulau Bukom Refinery	2011	Lin et al. (2017)
<i>Process pipeline</i>				
23	Rupture of expansion joint on transfer line caused release of hydrocarbon	Houston Fuel Oil Refinery	2002	Persson and Lönnermark (2004)
24	Leak of crude oil at rate of 4.35 kg/s from pipe supplying the refinery caused liquid pool to form and formation of vapour cloud which then ignited	ISAD Nord Refinery	2006	Garrone (2006)
25	Leak at bending elbow due to incorrect piping material caused liquid heavy oil pool at distillation unit which ignited causing a fire	Lemont Refinery	2001	McLennan (2013)
26	Weld failure of 2-inch hydrogen line cause hydrogen release at 10.5 kg/s and was ignited resulting into a fire	Chevron Richmond Refinery	1989	McLennan (2013)
27	Erosion failure of 10-in. recycle oil line caused release of liquid at 15.5 kg/s at coking unit and was ignited	Syncrude Oil Refinery	1984	Lees (2012)
28	Corrosion of pipe in catalytic cracker caused hydrocarbon gas with pressure of 1861 kPa release at 30.37 kg/s and ignited	Shell Oil Co. Refinery	1998	McLennan (2013)
29	Leak of propane from piping at propane deasphalting unit at a rate of 34.02 kg/s caused jet fire to occur and flame encroached onto nearby steel structures	McKee Refinery	2007	CSB (2008)

Table 2 Credibility score calculation for most credible fire scenarios

Parameters	Values
Damage radius (m)	649
Area inside damage radius (m ²)	1,325,022
Probability of occurrence	0.000945
Asset density (\$/m ²)	10,000
Unacceptable financial loss (\$/year)	10,000
Population density (persons/m ²)	0.0025
Population distribution factor	0.5
Unacceptable fatality rate (persons/year)	0.01
Importance factor	0.2
Unacceptable damage area (m ² /year)	1000
Financial loss factor (Factor A)	0.614
Fatalities factor (Factor B)	0.6138
Ecosystem damage (Factor C)	0.153
Credibility score (L)	0.67

(MCAS) method is adopted to assign a credibility score to each scenario. A credible fire scenario is defined as a fire scenario which has a high degree of occurrence probability and has the potential to cause significant consequence (Khan 2001). The benefits of MCAS method are that it accounts for both the damage it can cause and the probability of occurrence of an accident, which is the optimum method for assessing different fire scenario. With the information on fire scenario credibility, greater concern can be placed on the scenarios with high damage impact and occurrence likelihood. Before MCAS method can be applied, the expected damage of different fire scenarios needs to be quantified in terms of damage radius. The Multivariate Hazard Identification and Ranking System (HIRA) method proposed by Khan and Abbassi (1998) is employed to determine the approximate damage radius for each scenario due to the high sensitivity and accuracy of this method as it accounts for various factors such as leak size, vessel pressure, volume and temperature. An example of the credibility score calculation is shown in Table 2.

3.3 Credible Fire Scenario Selection

In step 3, the most credible fire scenario is selected for further analysis. According to Khan (2001), fire scenarios with a credibility score greater than 0.5 are credible and they are prone to catastrophic consequences. Based on various fire scenarios developed in Table 1 and MCAS ranking method, the most credible fire scenario is listed in Table 3.

Table 3 Most credible fire scenario

No.	Fire scenario	Credibility score
1	Leakage of propane from piping at propane deasphalting unit at a rate of 34.02 kg/s caused a jet fire to occur and flame encroached onto nearby steel structures	0.67

3.4 CFD Simulation of the Credible Fire Scenario

In step 4, a CFD simulation of credible fire scenario is performed. Due to the wide applications of FDS in fire modelling, numerical simulation is performed using FDS. FDS is a CFD model which focuses on smoke and heat transport from the fires (McGrattan et al. 2013). FDS has the capability to model the effect of thermal load and temperature on surrounding environment and can also be used for predicting sprinkler, heat detector and smoke detector activation. A mesh independent analysis is performed prior to the commencement of actual simulation. As the mesh size is decreased, the output result will be more accurate and the main objective of mesh independent analysis is to determine the optimum mesh size for the scenario with least percentage of error in output results. By using results from FDS simulation, thermal load distributions received on equipment are obtained. In addition, wall temperature and total heat radiation are obtained. To generate FDS code with higher accuracy, PyroSim, a software developed by Thunderhead Engineering is utilised. Computer-Assisted Drawings (CAD) geometry is imported into PyroSim as mesh generation; fire setup and simulation setup can be managed efficiently through PyroSim. The parameters used in the simulation setup for the fire scenario are given in Table 4. As the layout for the entire oil and gas storage facility is relatively large, the layout is divided into smaller sections. Figure 2 presents the full layout and the simulation layout for the scenario.

Table 4 PyroSim simulation setup

Parameters	Scenario
Scenario location	McKee refinery
Simulation volume	129 m × 104 m × 22 m
Simulation time (s)	300
Number of cells	900,000
Boundary condition	Open
Fuel type	Propane
Burn radius (m)	1.5
Burn area (m ²)	7.07
Heat release rate per unit area (kW/m ²)	4600
Output parameters	Net heat flux Wall temperature

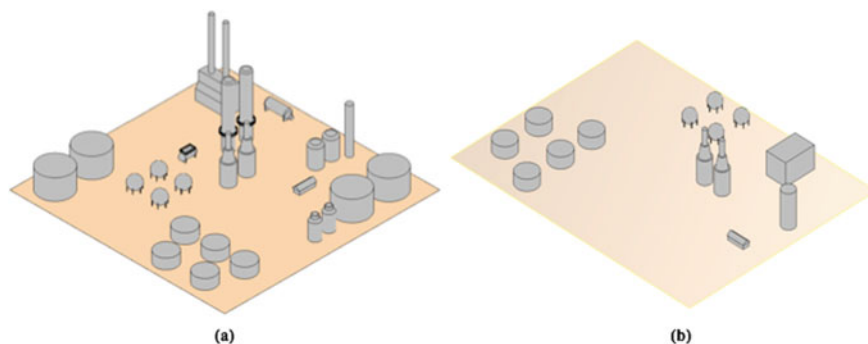


Fig. 2 **a** Full scenario layout, **b** simulation layout

Table 5 Structural steel thermal properties (Hurley et al. 2015)

Material	Structural steel
Density (kg/m^3)	7850
Specific heat (kJ/kg K)	0.46
Conductivity (W/(m K))	45.8
Emissivity	0.95
Absorption coefficient (1/m)	50,000

In the scenario, the simulation time is assumed to be 300 s which is based on the longest time required for a fire rescue team to arrive at the fire scenario and the commencement of fire rescue. In the scenario, the boundary condition is specified as open to indicate the infinite domain which is the representation of real fire scenario as only part of the layout is being modelled. The equipment surface material is assumed to be structural steel with thermal properties stated in Table 5.

3.5 Application of Passive Fire Protection

In step 5, various PFP coatings are applied to the equipment. The main objective of PFP is to avoid structural disintegration by keeping the temperature in the material below critical point, slowing down propagation of the fire and reducing escalation of the fire (Spitzenberger et al. 2016). Thus, by obtaining a credibility score for each fire scenario, the most vulnerable equipment or facility is identified and the higher level of PFP can be applied to that equipment. On the other hand, the least hazardous areas can have low level of PFP as immoderate use of PFP coating can lead to increase in fabrication cost and risk of schedule delay (Friebe et al. 2014). Depending on the type of fire, heat flux received, and duration and size of the fire, a different passive fire protection system can be applied. For jet fire, which is the releasing of gaseous jet or liquid jet through small openings and ignited by ignition

source, effective mitigation methods include fire wall, intumescent coating, mineral fibre coating and cementitious material coating. For a pool fire with little momentum, effective passive protection includes self-expanding foam, thermal insulation barrier, intumescent coating or endothermic building material which can withstand long periods of fire exposure. Flash fire, which is defined as the advancing flame front of an ignited vapour cloud, can be protected using thermal insulation barrier and intumescent coating to mitigate thermal impact on structure (Spitzenberger et al. 2016). In the current study, PFP systems in the form of fire proofing coating are applied to the equipment to determine the effectiveness of various PFP coatings in preventing equipment temperature rise and to reduce heat flux received by equipment. The selection of fire proofing coating materials is based on commercially available materials such as intumescent coating, vermiculite spray and gypsum board. The thermal properties of various selected fire proofing coating materials are given in Table 6.

An epoxy intumescent expands instantaneously up to final thickness when exposed to fire in a real-case scenario. However, in this study, the swelling effect of epoxy intumescent is neglected as the chemical and physical changes occurring within the material are too highly complex to be modelled by FDS. This assumption is similar to a statement made by Landucci et al. (2009) where increase in thermal properties due to swelling of the material was neglected. The selected PFP coating materials are specified in PyroSim as a new material. After specifying material properties, a surface of the selected material with specified thickness is applied to equipment thus forming a fire proofing barrier.

Table 6 Thermal properties of various PFP materials

	Density (kg/m ³)	Specific heat (kJ/kg K)	Conductivity (W/(m K))	Emissivity	Absorption coefficient (1/m)	References
Epoxy intumescent	1000	1.172	0.066	0.90	50,000	Landucci et al. (2009)
Vermiculite spray	680	0.970	0.100	0.90	50,000	Landucci et al. (2009)
Cementitious material	1200	1.000	0.400	0.92	50,000	Hurley et al. (2015)
Fibre glass	150	0.700	0.040	0.75	50,000	Hurley et al. (2015)
Gypsum board	930	1.090	0.170	0.90	50,000	Hurley et al. (2015)
Mineral wool	100	0.920	0.380	0.90	50,000	Landucci et al. (2009)
Cellular glass	115	0.770	0.078	0.20	50,000	Hurley et al. (2015)

3.6 Impact Analysis

In step 6, the impact analysis is performed by interpreting thermal load distribution and wall temperature of equipment. Impact analysis only takes thermal load or impact on surrounding facilities into account without considering the chemical or materials being released during the fire process. Impact analysis on assets includes determination of wall temperature measured at different distances away from fire source and assessing the percentage of temperature exceeding structural yield strength threshold (Krueger and Smith 2003). If the threshold is exceeded, there is a high chance of structural material failure. For the application of this study, S355J2H structural steel is assumed to be the equipment material. In general, when the strength factor drops below 60%, the steel structure is assumed to have failed (American Institute of Steel Construction 1978). According to experiment performed by Outinen (2007), the yield strength of structural steel begins to decrease significantly when the temperature is above 550 °C. When the temperature reaches 576 °C, a 60% reduction in yield strength is observed compared to yield strength at room temperature, which is assumed to be the failing point of structural steel. A comparison between yield strength of structural steel at elevated temperature is presented in Table 7. In addition, the impact analysis of fire on steel equipment is calculated based on thermal radiation received by equipment. The thermal radiation received by equipment is greatly dependent on the surface emissivity as well as convection heat transfer associated with it (Sjöström and Andersson 2013). The effect of thermal radiation can

Table 7 Yield strength versus temperature for structural steel S355J2H (Outinen 2007)

Temperature (°C)	Yield strength (MPa)	Reduction compared to 20 °C (%)
20	566	0
500	368	35
576	226	60
600	181	68
700	102	82
800	42	93

Table 8 Effects of thermal radiation (Sjöström and Andersson 2013)

Radiant heat flux (kW/m ²)	Observed effect
0.7	Normal sunshine
12.5	Volatiles from wood may be ignited
29.0	Wood may ignite spontaneously
37.5	Steel equipment damaged
52.0	Fibreboards ignite spontaneously in 5 s

be summarised in Table 8. Based on these values and criteria, the impacts of fire on steel equipment are being analysed.

3.7 Effectiveness Analysis

In step 7, the effectiveness analysis of PFP applied to equipment is performed. The effectiveness of PFP is determined based on its ability to protect a structure against temperature rise and reduce thermal load received by reducing heat transfer to the equipment being analysed (Tugnoli et al. 2012). This is done by assessing the wall temperature and thermal load on equipment after the fire and determining whether the applied PFP can succeed in preventing temperature escalation until the critical temperature of the building material is reached. By obtaining the effectiveness of PFP, the amount or level of PFP required in a certain area is determined.

4 Results and Discussion

In this section, the results obtained from CFD simulation are discussed and compared based on the maximum heat radiation and wall temperature obtained for bare or/ unprotected (without PFP) steel and PFP coated equipment.

4.1 Mesh Independent Analysis

A mesh independent analysis is performed to determine the optimum mesh size for the scenario. During mesh independent analysis, wall temperature is chosen as the responding variable as it will be the main factor in determining the effectiveness of PFP coating applied. Figure 3 presents the mesh independent analysis for the scenario. From Fig. 3, it is found that the wall temperature remains constant at 870 °C when the number of cells exceeds 900,000. Thus, mesh size of 0.79 m × 0.64 m × 0.65 m with 900,000 cells is utilised for further analysis.

4.2 Bare Steel Equipment

Based on the simulation results, it is found that the equipment adjacent to the fire source which is the propane deasphalting unit (PDA) has a maximum net heat flux of 55 kW/m² and a maximum wall temperature of 820 °C after 300 s of exposure. At this temperature, the yield strength of equipment has reduced by approximately 93%, which is well above the failure threshold stated in Table 1. Based on criteria stated

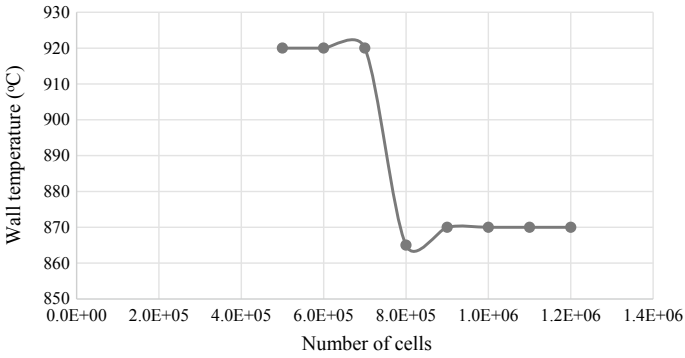


Fig. 3 Mesh independent study

in Table 2, it is assumed that the steel equipment receiving 55 kW/m^2 of thermal radiation will ignite spontaneously causing severe damage, which ultimately leads to loss of containment. Based on these values, various PFP coatings are applied to the equipment to investigate the temperature variation. The results from the simulation are presented in Figs. 4 and 5.

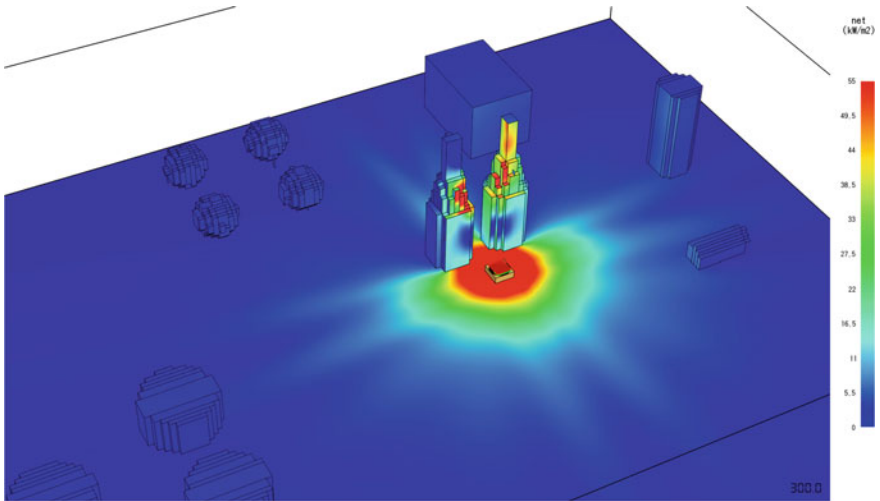


Fig. 4 Heat flux contour (kW/m^2)

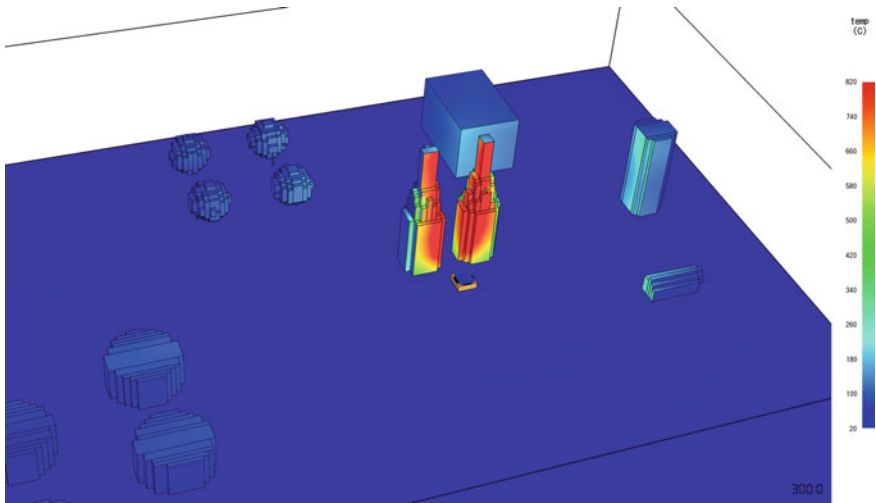


Fig. 5 Wall temperature contour (°C)

4.3 Heat Flux Comparison Between Bare and PFP Coated Equipment

According to simulation results of various types of PFP, comparisons between heat flux received by equipment after 300 s are obtained, as illustrated in Fig. 6. According to Fig. 6, as a comparison to heat flux of 55 kW/m² received by the bare steel, all PFP coatings show a decrease in heat flux received by equipment when 10 cm PFP thickness are applied on the equipment surface. Fibre glass and cellular glass coated equipment have 25 kW/m² of heat flux received which is equivalent to a decrease

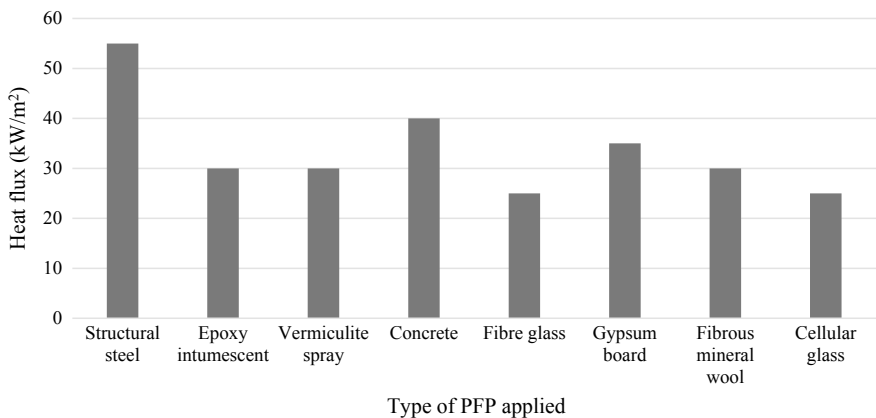


Fig. 6 Thermal radiation received by equipment at 300 s (kW/m²)

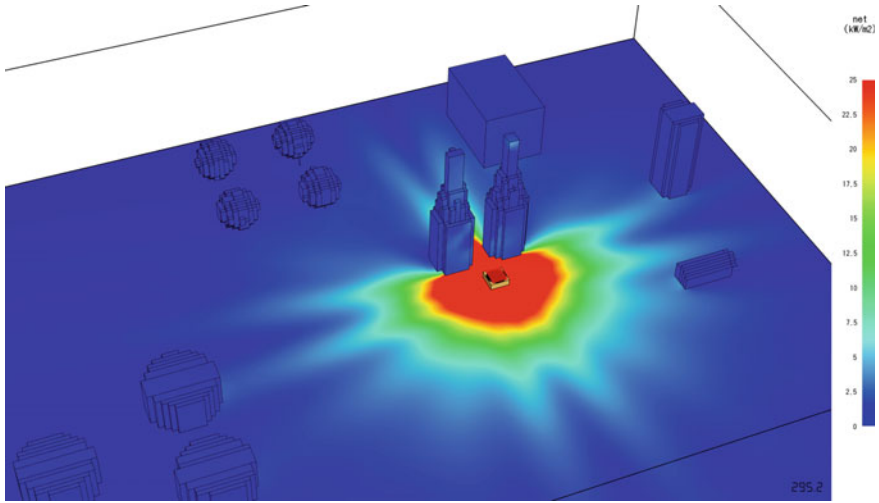


Fig. 7 Heat flux contour for cellular glass-coated equipment (kW/m²)

in 55% of heat flux received by equipment. With 25 kW/m² heat flux received by equipment, it is likely that the equipment will not fail according to criteria stated in Table 8. Heat flux contour of cellular glass-coated equipment is presented in Fig. 7.

4.4 Wall Temperature Comparison Between Bare and PFP Coated Equipment

Based on the results obtained from PFP coated equipment simulations, wall temperature of equipment is examined and determines the capability of various types of PFP coating in maintaining the wall temperature below critical point. Figure 8 presents the wall temperature of equipment at 300 s for equipment with a different coating applied. Based on this figure, it is shown that concrete and cellular glass have maintained the wall temperature of equipment at 670 °C after 300 s which is significantly lower compared to 820 °C after 300 s of uncoated steel. However, based on the result obtained, it is shown that a thickness of 10 cm coating applied is insufficient to maintain the wall temperature of equipment below critical point of 576 °C when exposed to fire of this scenario. Thus, further analysis is required to determine the required thickness to maintain the wall temperature of equipment below critical point. Figure 9 presents the wall temperature contour of equipment coated with cellular glass.

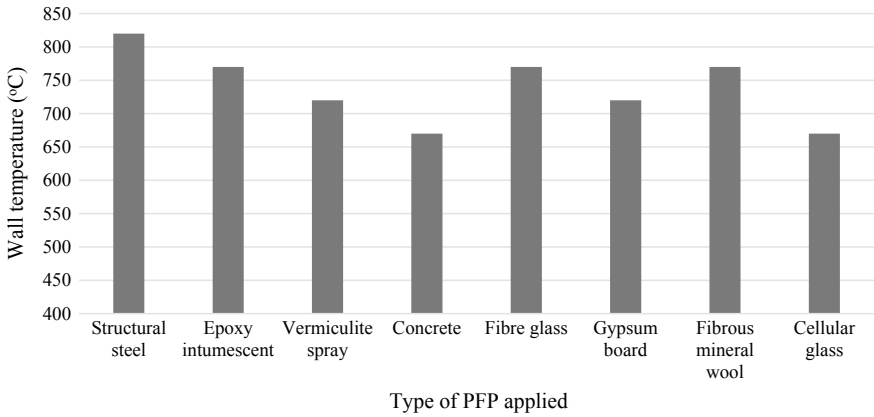


Fig. 8 Wall temperature of equipment at 300 s (°C)

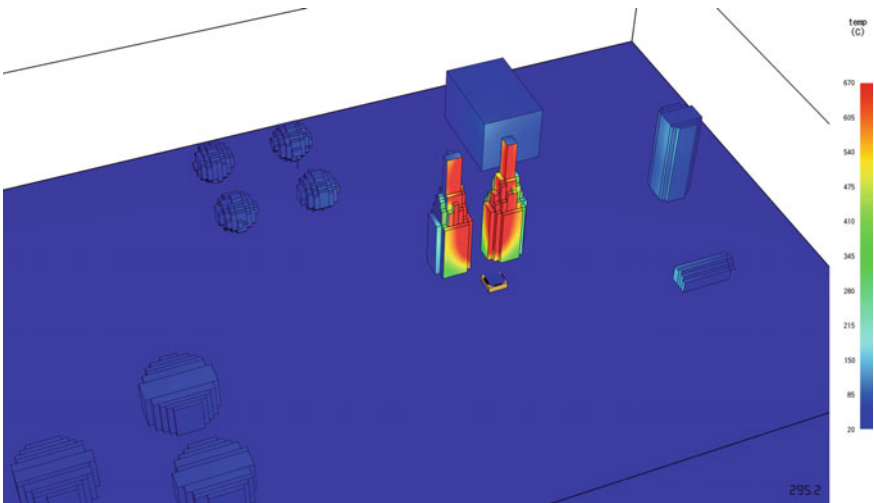


Fig. 9 Wall temperature of cellular glass-coated equipment (°C)

5 Conclusion

In this study, a methodology is proposed for assessing the effectiveness of passive fire protection. An effectiveness study of various passive fire protection (PFP) systems is performed considering a case study. A total of 29 real fire accidental scenarios are considered, and the most credible fire scenario was identified using the Maximum Credible Fire Scenario (MCAS) method. The scenario was simulated in Fire Dynamics Simulator, and the thermal radiation received by equipment was used to assess the failure potential of equipment based on its temperature rise. It is found

that without PFP, the equipment is subjected to failure risk having exceeded both radiation and temperature threshold limits. However, after applying PFP, thermal radiation on equipment was reduced below the threshold limit. From the simulation results, it is found that fibrous mineral wool is less effective for passive fire protection coating application as equipment coated with fibrous mineral wool has shown higher wall temperature than other PFP applications. On the other hand, it is revealed that cellular glass and concrete have prevented rise in thermal flux above the threshold value. However, further analysis and more scenarios are required to determine the required coating thickness to maintain wall temperatures below critical point in each case.

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