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Original Article

Simulation and Damage Analysis of an Accidental Jet Fire in a High-Pressure Compressed Pump Shelter

Chang Bong Jang, Sang-Won Choi*

Bureau of Occupational Safety Research, Occupational Safety and Health Research Institute, Korea Occupational Safety and Health Agency, Ulsan, Republic of Korea

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A B S T R A C T

Background: As one of the most frequently occurring accidents in a chemical plant, a fire accident may occur at any place where transfer or handling of combustible materials is routinely performed.
Methods: In particular, a jet fire incident in a chemical plant operated under high pressure may bring severe damage. To review this event numerically, Computational Fluid Dynamics methodology was used to simulate a jet fire at a pipe of a compressor under high pressure.
Results: For jet fire simulation, the Kemeleon FireEx Code was used, and results of this simulation showed that a structure and installations located within the shelter of a compressor received serious damage.
Conclusion: The results confirmed that a jet fire may create a domino effect that could cause an accident aside from the secondary chemical accident.

1. Introduction

Most chemical plants have and operate a significant number of compressors as installations to transfer raw materials, products, and waste gas from production. As the compressor is operated mainly under a high pressure, vibration generated from a pump operation may increase the time-dependent fatigue in a pump and nodes connected to surrounding devices, and thus an area with such issues is categorized as an area with a high risk of leakage of internal fluid.

Gómez-Mares et al [1] and Darbra et al [2] analyzed past cases of chemical accidents based on the MHIDAS (Major Hazard Incident Data Service) database, and their results showed that, for causes of major accidents in a chemical plant, fires accounted for 54% of events whereas explosions accounted for 30% [1–3]. This led to an evaluation that more interest and study are required to help reduce/eliminate fire hazards in chemical plants.

Moreover, recent studies involving numerical analysis of jet fires [4–7] only analyzed these fire incidents from the context of simple geometry, and there is not enough study about a simulation of jet fire in a complex structure such as a chemical plant [3].

Therefore, an analysis of a jet fire from a pipe connected to a compressor under high pressure with a simulation methodology was conducted with respect to a fire accident that frequently occur in a chemical plant, and various variables such as forms of installations and tools, positional density, turbulence, atmospheric condition, obstacles, and wind effect were assessed for an analysis of the thermal effect using Computational Fluid Dynamics (CFD), which generates the virtually estimated result to be very similar to the actual result [3,7,8].

In this study, a jet fire from a high-pressure compressed pump shelter in a chemical plant is described using the CFD method, and its damage effect on structure and devices is analyzed.

2. Materials and methods

2.1. KFX governing equation for analysis of gas combustion

To analyze the consequences of a jet fire, the Kemeleon FireEx (KFX) Simulator developed by ComputIT (Norway, Trondheim) was used. The KFX Simulator prepares a Cartesian grid in a three-

* Corresponding author. Bureau of Occupational Safety Research, Occupational Safety and Health Research Institute, Korea Occupational Safety and Health Agency, 400, Jongga-ro, Jung-gu, Ulsan 44429, Republic of Korea.
E-mail address: swchoi@kosha.or.kr (S.-W. Choi).

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dimensional space and applies a finite volume technique to analyze a fluid behavior under a direction of each axis [3,9].

The governing equations of the KFX Code applied to analyze a combustion generated from a place with complicated spatial features because of the structures and devices in a plant are a mass fraction budget equation of chemical species [Eq. (1)], continuity equation for mass conservation [Eq. (2)], momentum equation to compute a momentum in the coordinate direction with Navier–Stokes equation [Eq. (3)], and energy transmission equation for a flow of compressed gas [Eq. (4)] as follows [3,9]:

$$\frac{\partial\bar{\rho}\tilde{Y}_l}{\partial t}+\frac{\partial\bar{\rho}\tilde{u}_j\tilde{Y}_l}{\partial x_j} = -\frac{\partial}{\partial x_j}\left(\overline{\rho Y_l V_{lj}}\right)-\frac{\partial}{\partial x_j}\left(\overline{\rho u_j'' Y_l''}\right)+\bar{\rho}\tilde{R}_l+\bar{\rho}\tilde{R}_{liq,l} \tag{1}$$

$$\frac{\partial\bar{\rho}}{\partial t}+\frac{\partial\bar{\rho}\tilde{u}_j}{\partial x_j} = \bar{\rho}\tilde{R}_{liq} \tag{2}$$

$$\frac{\partial\bar{\rho}\tilde{u}_i}{\partial t}+\frac{\partial\bar{\rho}\tilde{u}_j\tilde{u}_i}{\partial x_j} = -\frac{\partial\bar{p}}{\partial x_i}+\frac{\partial}{\partial x_j}\left(\overline{\tau_{ij}}-\overline{\rho u_j'' u_i''}\right)+\overline{\rho f_i}+\bar{\rho}\tilde{F}_{liq,i} \tag{3}$$

$$\frac{\partial}{\partial t}\left(\bar{\rho}\tilde{e}_T\right)+\frac{\partial}{\partial x_j}\left(\bar{\rho}\tilde{u}_j\tilde{e}_T\right) = \frac{\partial}{\partial x_j}\left(\overline{(\tau_{ij}-P)u_j}\right)+\frac{\partial}{\partial x_j}\left(\overline{k_l\frac{\partial T}{\partial x_j}}-\bar{\rho}\tilde{u_j''\tilde{e}_T''}\right)+\overline{Q}_{gs}+\overline{Q}_{Rad}+\bar{\rho}\tilde{S}_{liq}, \tag{4}$$

where

$$R_{liq} = \sum_l R_{liq,\,l}$$

$$\overline{\tau_{ij}} = \mu\left(\frac{\partial\tilde{u_i}}{\partial x_j}+\frac{\partial\tilde{u_j}}{\partial x_i}\right)+\left(\kappa-\frac{2}{3}\mu\right)\left(\frac{\partial\tilde{u_\kappa}}{\partial x_\kappa}\right)\delta_{ij}$$

$$e_T = e+\frac{1}{2}u_iu_j$$

$$e = \sum_l Y_l e_l(T)$$

Comparing the KFX involves a CFD analytical methodology of the Reynolds averaged Navier–Stokes (RANS) technique with the equation of analytic methodology of Large Eddy Simulation and

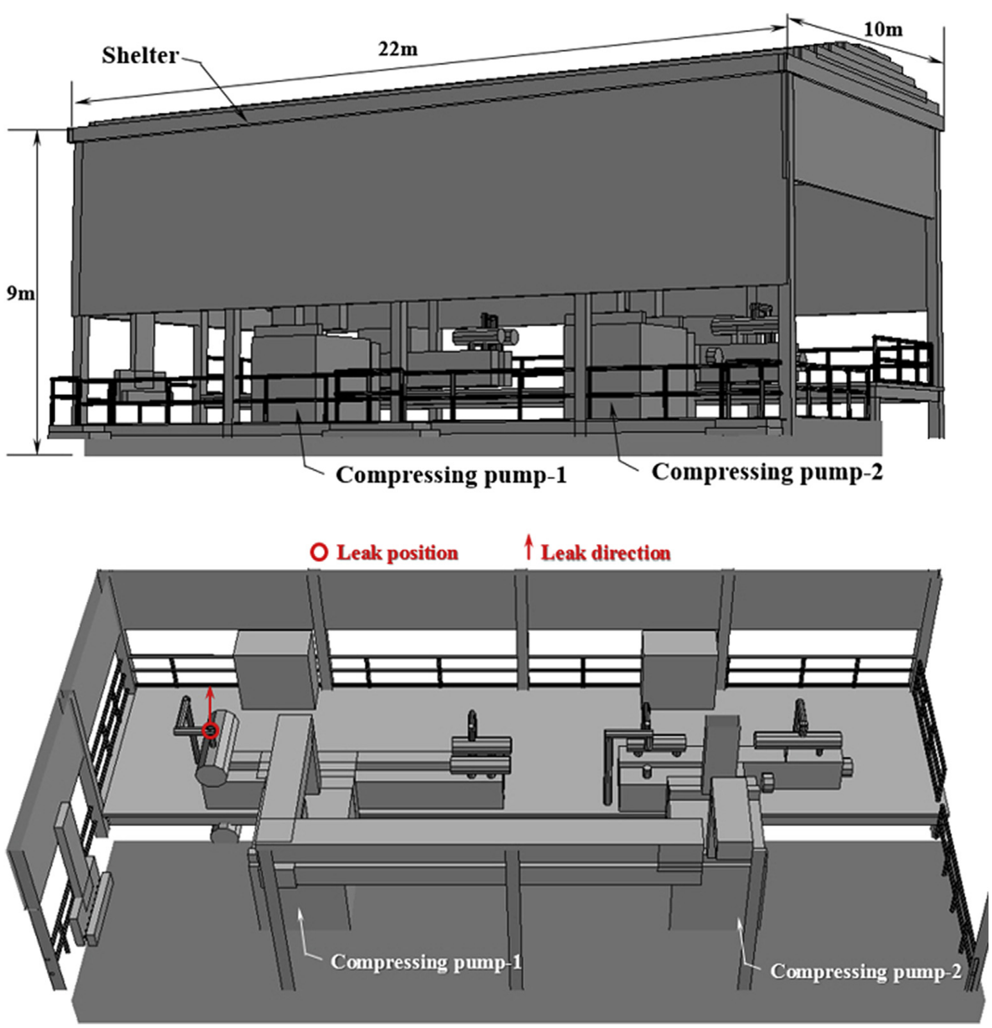

Fig. 1. 3-D geometry of the compressor pump shelter (top) and description for leak position and direction (down).

Direct Numerical Simulation. The extended equation concerning the buoyancy term and low Reynolds number effect on the conventional k–ε equation to compute turbulence with low accuracy is used to show a good numerical calculation result. Moreover, to compute the turbulent combustion, the Eddy Dissipation Concept model with extended eddy dissipation model is used, and the k–ε model used in the KFX Code is shown in Eq. (5), and ε for the dissipation ratio of turbulence kinetic energy is expressed in Eq. (6) [3,9].

$$\frac{\partial(\overline{\rho}k)}{\partial t}+\frac{\partial(\overline{\rho}\tilde{u}_i k)}{\partial x_i}=\frac{\partial}{\partial x_i}\left(\frac{\mu_{eff}}{\sigma_k}\frac{\partial k}{\partial x_i}\right)+P-\overline{\rho}\varepsilon+\mathrm{B} \tag{5}$$

$$\frac{\partial(\overline{\rho}\varepsilon)}{\partial t}+\frac{\partial(\overline{\rho}\tilde{u}_i\varepsilon)}{\partial x_i}=\frac{\partial}{\partial x_i}\left(\frac{\mu_{eff}}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_i}\right)+\mathrm{C}_1 f_1 P\frac{\varepsilon}{k}-\mathrm{C}_2 f_2\rho\frac{\varepsilon^2}{k}+\mathrm{C}_1\mathrm{C}_2\frac{\varepsilon}{k}B \tag{6}$$

where

$$\mathrm{P}=\overline{\rho}\nu_t\left(\frac{\partial\tilde{u}_i}{\partial x_j}+\frac{\partial\tilde{u}_j}{\partial x_i}\right)\frac{\partial\tilde{u}_j}{\partial x_i}$$

$$\mathrm{B}=\overline{\rho}\widetilde{u_i''\rho''}g_i=-\Gamma_{\rho t}\frac{\partial\overline{\rho}}{\partial x_i}\mathrm{g_i}$$

$$\mu_\mathrm{t}=\mathrm{C_D}f_\mu\rho\frac{k^2}{\varepsilon}$$

$$\mathrm{f_u}=\exp\left[\frac{-2.5}{1+R_t/50}\right]$$

$$\mathrm{R_t}=\frac{\rho k^2}{\mu\varepsilon}$$

$$\mu_\mathrm{eff}=\mu_l+\mu_r$$

Table 1
Input data for jet fire simulation

Itesm	Input data	Incident outcome	Input data
Fuel	H_2: 89%, CH_4: 11%	Wind	0.1 m/s
Leak area	0.000345 m^2	Surrounding temperature	20°C
Discharge rate	1.62 kg/s	Duration	30 s
Leak direction	+Z	Grid nodes	494,325 ea

As a turbulence model coefficient, $C_D = 0.09$, $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.3, C_1 = 1.44, C_2 = 1.92$.

So far, based on various tests and working-level projects, the accuracy and usability of KFX were verified, and the simulation result shows a very good result relative to the actual test [3,8–11].

2.2. Three-dimensional geometry for simulation

As part of the equipment industry, a chemical plant has many pipes that are operated for transport and return of materials for production. Fluid in these pipes is transferred by pump pressure, and because a length of pipe installed in a chemical pipe is very long, a very high pressure is required to transfer the fluid within a pipe. To generate such high pressures, a compressor is installed and operated in each plant, and it is generally located around other installations. A compressor is usually installed inside a structure, and this structure is called a "shelter."

In this study, to numerically analyze a leakage accident on a pipe within a shelter operated in a chemical plant, an arbitrary feature of a shelter operated in a general chemical plant was modeled (Fig. 1). Fig. 1 shows the internal and external feature of an arbitrarily modeled shelter in the virtual space; the shelter is 22 m long, 9 m high, and 10 m wide. This modeled shelter is composed of pumps inside, installation form, and positional density with surrounding devices.

2.3. Applied scenario

Because a chemical plant handling gas with hydrogen operates under high pressure, when there is a leakage accident on a pipe, it forms a jet leakage. Within this process of jet leakage, if the gas is ignited by friction of fluid or other surrounding sources of ignition, a jet fire is generated.

In this study, the scenario of a jet fire occurring from a leakage of mixed gas (89% hydrogen and 11% methane) on a pipe [97 bar(g) of pressure] connected to an outlet of high-pressure compressor was simulated.

The leakage point on the pipe connected to the compressor in Fig. 1 (down) is located 4.7 m high from the ground, and the area of the leakage hole is 0.000345 m^2. The wind speed of 0.1 m/s that is effective inside the shelter structure, atmospheric stability Pasqual class of F, and atmospheric temperature of 20°C were entered in as boundary conditions. The duration of the leak was set as 30 seconds considering the time it takes for an operating room to shut off under the pressure difference (ΔP) when there is a leakage on a

Table 2
Guidelines for assessing fire damage effects; description of the types of damage that may occur in the heat exposure zone categories

Temperature range (°C)	Heat/temperature effects	Observations and conclusions
426–730	• Long exposure to these temperatures may affect grain structure, properties and corrosion resistance of steels and stainless steels. • Steel starting to oxidize, the thicker the scale the hotter the temperature.	• Vessel, piping, and tankage components, and associated structural steel supports, that are warped or distorted may require repair or replacement. Regular carbon stainless steels are sensitized, may need replacing. • All gaskets and packing should be replaced. • Major equipment, including pressure vessels, heat exchangers and rotating equipment should be cleaned, inspected and pressure tested.
More than 730	• Heavily scaled steel may be distorted because of thermal stresses. • Steel that is water quenched may harden and lose ductility. • All heat-treated or cold-worked materials may have altered properties.	• Check piping and vessels in low temperature service for increase in grain size and loss of toughness. • Check bolting, vessels and piping components for metallurgical changes.

Note. From "API-579 Fitness-For-Service," by API, 2007. American Society of Mechanical Engineers. Copyright 2007. *Copyright Holder*. American Petroleum Institute.

Table 3
Guidelines for observing fire damage; thermal effects on materials

Temperature (°C)	Material of construction	Forms or usage	Thermal effects
595	Steel	Vessels and piping	Thermal distortion and creep, some heat scale
1,400	316 SS-cast	Pumps, valves	Melts
1,455	316 SS-wrought	Vessels, pipe	Melts
1,515	Steel	Various	Melts

Note. From “API-579 Fitness-For-Service,” by API, 2007. American Society of Mechanical Engineers. Copyright 2007. American Petroleum Institute.

Table 4
Consequences of thermal heat flux [13,14]

Heat flux (kW/m^2)	Observed effect
37.5	Damage to process equipment and collapse of mechanical structures
25.0	Thin steel (insulated) can lose mechanical integrity
12.5	Wood can ignite after a long exposure; 100% lethality
11.7	Thin steel (partly insulated) can lose mechanical integrity
10.0	Certain polymers can ignite

Note. From *Manual of industrial hazard assessment techniques*, edited by Kayes PJ, 1985. The World Bank. From *Guidelines for chemical process quantitative risk analysis*, by Center for Chemical Process Safety of AIChE, 2000. Wiley, New York. Copyright 2000. CCPS (center for chemical process safety).

pipe of the compressor. The input value for simulation is shown in detail in Table 1.

The grid is one of the most influential factors on the result of simulation. In the case of jet fire, the damage is relatively smaller than the damage induced by an explosion or a gas leak in general, and the domain selected for an analysis of fire is not wide. A grid for the analysis of jet fire is created to select a domain wider than a domain of a general fire, and the density of the grid is increased partially and intensively in a region expected to have flame propagation. In the case of KFX, a grid generator is used, and this grid generator divides the computed domain in horizontal and vertical directions to create grids and nodes [9]. In this study, the domains of x, y, and z axes applied for the jet fire analysis are 27, 60, and

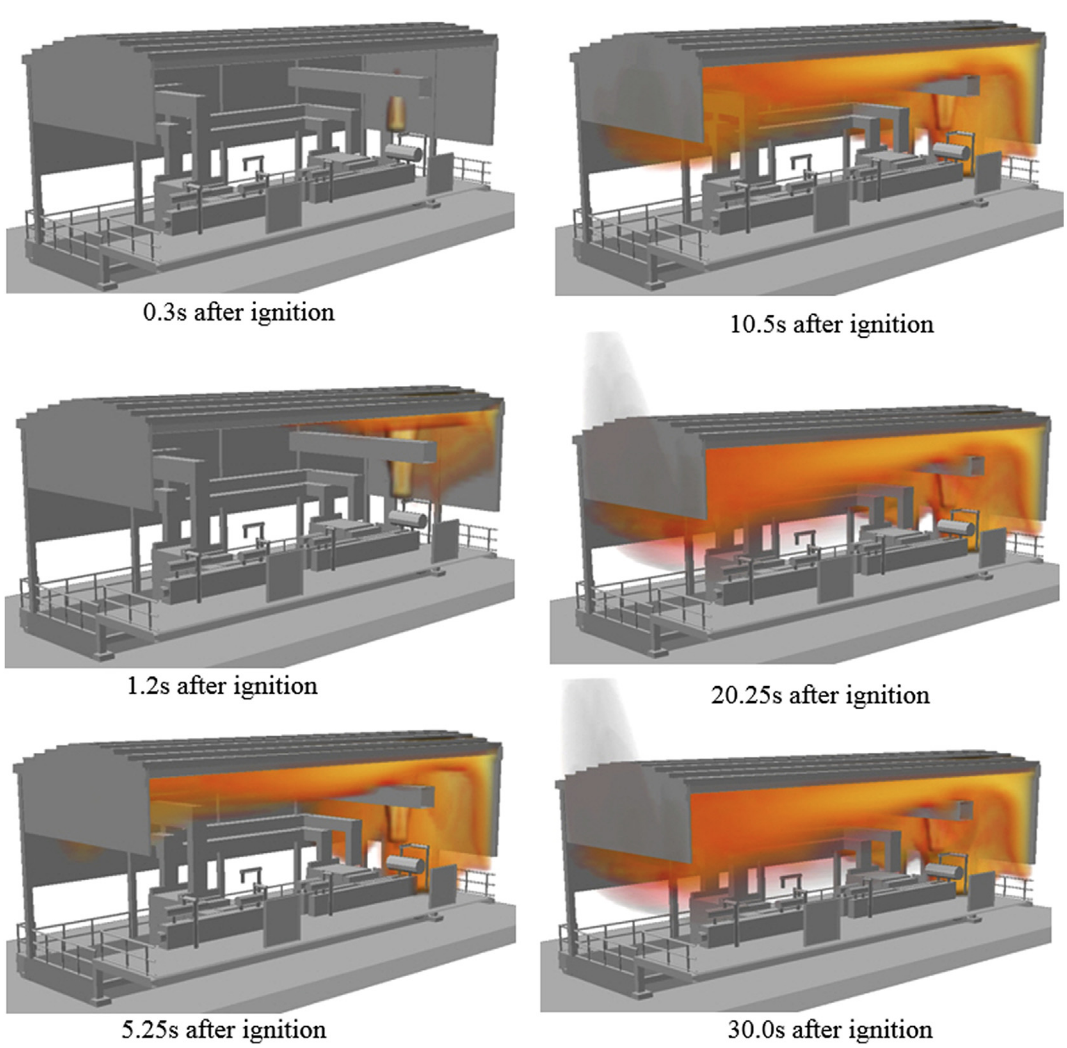

Fig. 2. Flame shape and propagation of jet fire as a function of time.

14 m, respectively, and there are 494,325 nodes from the grids generated within the domain.

3. Results

3.1. Fire damage criteria

In the case of jet fire from a leakage of mixed gas mainly composed of hydrogen in a pipe connected to a compressor, pumps, pipes, and other equipment installed in a shelter may receive thermal damage caused by flame. In particular, because a domain of flame is directly affected by high temperature and radiant heat, humans, structures, other installations, or equipment within this domain of effect receive greater damages. The American Petroleum Institute (API) 579 [12] and World Bank [13,14] have proposed the damage criteria by fire, which are shown in Tables 2–4.

Table 2 [12] indicates the form of damage in the region exposed to heat. When the temperature of the region exposed to heat reaches 426–730°C, all gaskets and packings will have to be replaced. Major equipment, heat exchanger, and spinning equipment including a pressurized vessel should be cleaned, inspected, and subjected to pressure tests.

Table 3 [12] shows the effects of temperature on different materials. When a container and a pipe made of steel are exposed to a high temperature of 595°C, thermal distortion, creep, and heat scale are generated. When exposed to the high temperature of 1,400°C, pumps and valves cast with 316SS may melt.

Table 4 [13,14] shows the consequences of thermal heat flux, specifically damage caused by radiant heat, i.e., when a region is affected by radiant heat of 37.5 kW/m^2. In such cases, certain devices within a plant may be damaged and structures may collapse.

This study has categorized the results of simulating a jet fire caused by mixed gas leakage (composed mainly of hydrogen) into temperature distribution and radiant heat distribution to illustrate the representative results of the resulting damage.

3.2. Flame propagation and shape

As a result of simulating jet fire caused by mixed gas leakage under high pressure in a compressor shelter, features of flame and expansion are computed as shown in Fig. 2. Fig. 2 shows that the flame impinges on the upper ceiling at the leakage point within a shelter, which then rapidly expands, and the size of directly influential flame reaches 22 m, in the opposite outlet from the leakage point.

3.3. Temperature distribution

Fig. 3 shows the impact of temperature as a result of the jet fire for 30 seconds, which may damage devices, inner installations, and shelter structures under the standard of API 579 [12]. Fig. 3A shows the domain where the temperature exceeds 426°C, whereas Fig. 3B shows the domain where the temperature exceeds 730°C. Fig. 3C shows the domain where the temperature is more than 1,400°C, whereas Fig. 3D shows the domain where the temperature exceeds 1,515°C. Applying Fig. 3 to the standard of Table 3, the installations and devices made of 316SS-cast may be melted down in the domain of Fig. 3C, and those in the domain of Fig. 3D may receive enough damage to melt materials made of steel.

3.4. Radiant heat distribution

Fig. 4 shows the distribution of radiant heat from a jet fire within a shelter structure. Fig. 4A shows the domain exposed to a radiant heat of 37.5 kW/m^2, and Fig. 4B shows the computed radiant heat on the surfaces of the shelter structure, internal equipment, and devices. Comparing the domain proposed in Fig. 4 with the damage effect criteria in Table 4, most of the internal space in a shelter is affected by a radiant heat of 37.5 kW/m^2, and plant equipment within this domain may be damaged, and the structure may collapse. Furthermore, Fig. 4B shows which installation is affected

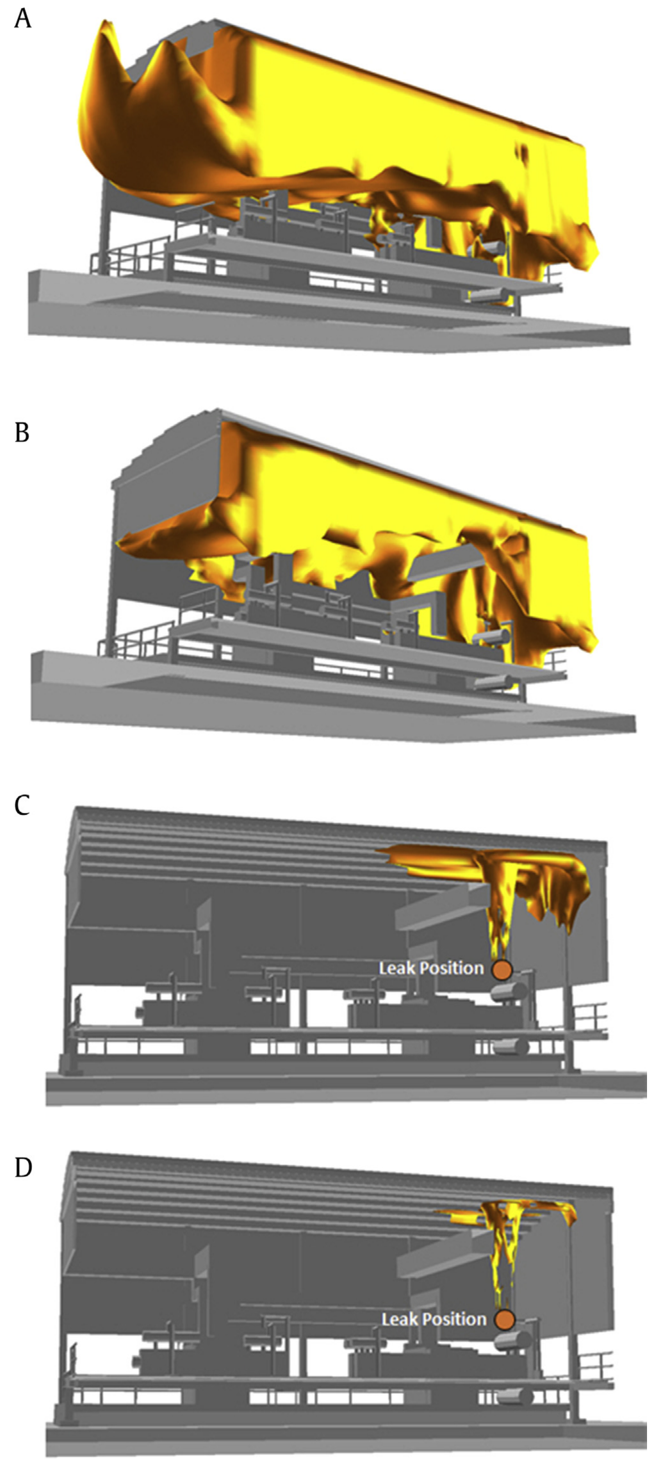

Fig. 3. Temperature isosurface for fire damage based on thermal effects on materials by jet fire. (A) Zone affected by temperature exceeding 426°C. (B) Zone affected by temperature exceeding 730°C. (C) Zone affected by temperature exceeding 1,400°C. (D) Zone affected by temperature exceeding 1,515°C.

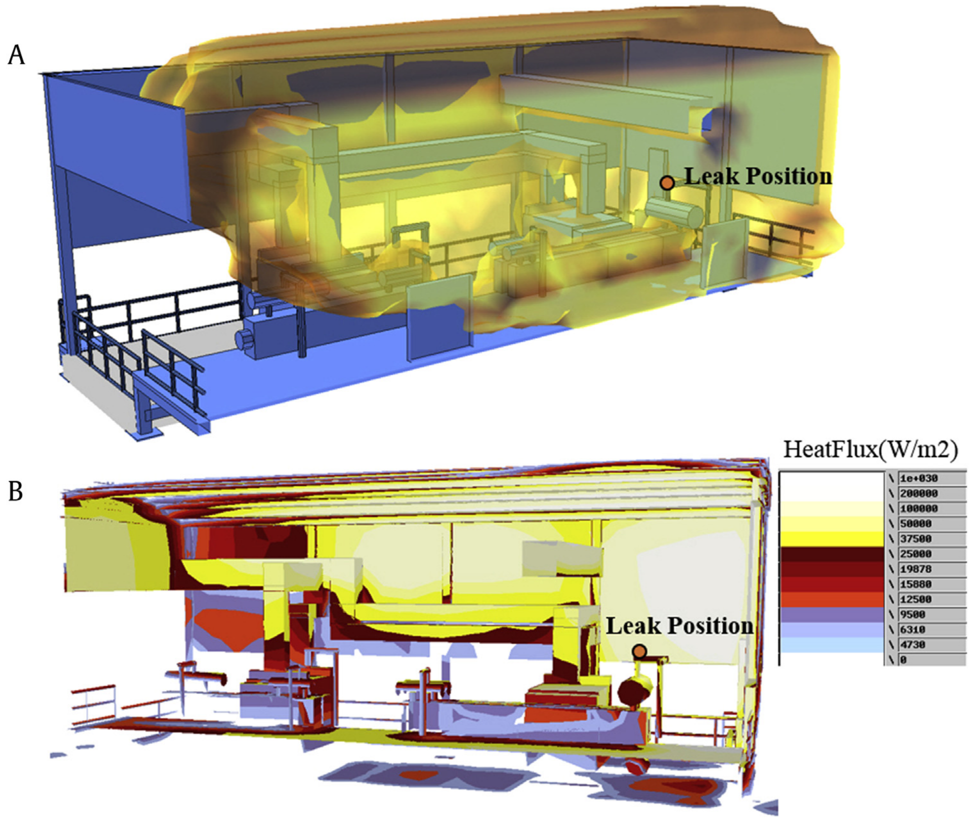

Fig. 4. Radiation heat flux and surface heat flux of compressor pump shelter by jet fire. (A) For radiation heat flux isosurface: >37.5 kW/m^2 affected zone. (B) For footprint of net heat flux with an assumed surface temperature

by a radiant heat of more than 37.5 kW/m^2 through the computed radiant heat on the surfaces of shelter structure, installations, and equipment.

According to the simulation results, the temperature effect would require repair or replacement of structures and devices within the domains of Figs. 3A and 3B, and the structure and devices within the domains of Figs. 3C and 3D may receive critical damage. In the case of radiant heat, the thermal heat flux of 37.5 kW/m^2 causing damage to devices and collapse of structure is described as shown in Fig. 4, and the overall structure itself may sustain critical damage.

4. Discussion

In the compressor shelter, a jet fire caused by the leakage of mixed gas composed mainly of hydrogen was simulated using the KFX Code, a CFD simulator of RANS methodology, to compute the impact of flame, temperature, and radiant heat. Furthermore, the predicted damage on the shelter was analyzed and proposed through the computation result. The API 579 [12] was applied as the damage criterion of temperature of damage by the jet fire, and the World Bank [13,14] criterion was applied for the radiant heat. As a result, the following conclusions were obtained.

(1) When a jet fire is generated from a pipe connected to a compressor under high pressure, it took 30 seconds for an operator in the room to detect and respond to a leakage; as a result, installations and equipment inside a shelter structure may receive severe damage. Moreover, owing to the effect of the flame, a domino effect [15,16] that may bring secondary and tertiary accidents of leakage in the surrounding installations and equipment may be predicted.

(2) Concerning the complex and various installations and equipment found in a chemical plant (a part of the equipment industry), it was confirmed that the KFX code was able to use the simulation method more effectively than the conventional empirical equation model to predict and analyze the damage result of a jet fire accident from a potential hazard.

(3) The methodology of simulation analyzes a possible fire accident in a chemical plant with many hazardous materials precisely similar to the actual accident, to assist plant owners and operators to be alert and responsive against the possibility of fires (during the design stage) so as to prevent human casualties and heavy damage to structures. This study was also conducted to help come up with a solution and design safety measures such as emergency plans in case of fires, and to effectively minimize the damages incurred during such accidents.

Conflicts of interest

The authors declare no conflicts of interest.

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