INTRODUCTION

The occurrence of various chemical accidents in the last 4 years has led the government of Korea to recognize the importance of chemical safety. The hydrogen fluoride release from Hube Global Co., Ltd. located in Gumi City on 27 September 2012 was the first critical chemical accident to bring such awareness. Owing to this accident, five employees died, and approximately 7000 people, including employees, local residents, and firefighters, were hospitalized. Furthermore, more than 36 billion KRW was required to compensate the damage to environment and properties caused by the accident. Because of this accident, the Korean government established a new organization to manage and supervise safety of chemical substances in January 2014, and on 20 January 2015, the Korean government enacted the related law called the Chemical Control Act.

Currently, the Korean government is performing various preventive and responsive activities to reduce chemical accidents. Relative to these activities, this paper will share the scientific analysis of the chemical accident and propose the technology to be used to improve safety.
This paper is a case study analyzing the explosion accident that occurred on 3 July 2015 at a chemical plant located in Ulsan, Korea based on the information from Korea Occupational Safety and Health Agency (KOSHA) and from media data. This accident was one of the major incidents in Korea, and related information can be obtained easily from the press.

The explosion occurred during cutting and welding of a pipe from the facility extension work to improve the odor disposal performance of the wastewater storage pond (WWSP) that treats the wastewater generated from the production process (the workers were connecting the wastewater transfer pipe at the WWSP roof). Because of the explosion, the entire structure of the concrete roof at the top of the WWSP was destroyed, and surrounding facilities were partially damaged as well. This accident resulted in six fatalities and one injury.

It is generally difficult to analyze an explosion accident because there are many factors which influence the phenomenon like flame instabilities and flame-turbulence interaction that should be considered in numerical simulations. In addition, the facility geometry, structure, and obstacles at the spot affect the explosion. Moreover, the fuel, oxygen, and ignition affecting the explosion need to be analyzed. Empirical approaches using simple, numerical, and analytical methodologies such as TNT equivalent or TNO multi-energy model may not be sufficiently accurate since they do not consider the aforementioned factors, while computational fluid dynamics (CFD) can be used to compute the overpressure impact considering these factors. By using CFD, although the facilities, devices, and obstacles affect the explosion phenomenon to calculate the turbulent combustion, the structural damages on the facilities or devices owing to the explosion pressure are usually estimated by simple comparison with the damage criteria from the reference overpressure. In order to resolve this limitation, the structural effect on facilities or devices owing to the explosion pressure should also be analyzed to obtain a more scientific and accurate result. This study analyzes the explosion accident focusing on the complex calculation of the spatial coordinate and time, calculated through CFD simulation for the explosion, by connecting them to nonlinear finite element analysis (FEA).

2 | DESCRIPTION OF THE ACCIDENT

The location of the explosion accident leading to six deaths and one injury was a WWSP with a concrete structure. The WWSP temporarily stores various mixtures of wastewater of high concentration from the S-PVC plant, which produces adhesives under atmospheric temperature and pressure and transfers the product to a biological wastewater disposal facility.

Figure 1 describes the inlet process of wastewater from the S-PVC process to the WWSP. In the figure, VCM refers to vinyl chloride, VCG refers to the gas state of vinyl chloride, and DW refers to demineralized water. Slurry is a mixture of PVC powder particle and water after reaction.

Figure 2 shows the picture of the WWSP before the explosion. It was constructed with concrete with majority of walls buried underground and some parts aboveground.

Before the explosion, the top (roof) of the WWSP was under construction to expand the capacity of the conventional environmental facility and solve the odor problem due to the wastewater. The main activity of construction was to replace the conventional pipes by cutting and welding.

For the construction, there were six workers at the top (roof) of WWSP, and one security guard was inside the guard house adjacent to the WWSP. As a result of the explosion, all six workers at the top died, and the security guard was injured.

Figure 3 shows the damage at the WWSP after the explosion. Figure 3 indicates that the walls of WWSP were relatively in good condition but the roof was completely destroyed; the reason for this is the underground construction, where the walls are supported by the mounting pressure of soil.

Figure 4 is a photograph taken from the black box of a vehicle passing around during the accident.

Figure 5 indicates the initial and final locations of the container and pump outlet header on top of the WWSP. Because of the explosion, the WWSP was completely destroyed beyond recognition except for the underground wall (Figures 3 and 5).

For the investigation, the WWSP was restored in 3D based on drawings and related data as shown in Figure 6. As shown in Figure 6B, the WWSP was composed of two storage ponds called C-1 and C-2, with agitators in the middle.

Based on the landing locations of the container and pump outlet header as well as the ceiling damage of C-1 and C-2 ponds in Figures 3-5, the pattern of explosion was analyzed as follows:

1. The explosion occurred almost simultaneously in C-1 and C-2 ponds with a small time gap, but the explosion overpressure of C-2 pond was greater.

2. The overpressures were uniformly distributed over the wall and ceiling connection of C-1 and C-2 pond momentarily; then, the concrete roof was ejected vertically and destroyed.

3. From the references, the explosion overpressure to destroy a 20-30 cm thick brick wall is 0.482-0.551 barg, and the overpressure to completely destroy the whole structure is approximately 0.689 barg. The actual explosion overpressure is estimated to be over 0.48 barg to cause similar consequences.
Computational fluid dynamics (CFD) and finite element analysis (FEA) were used to analyze the explosion accident. The CFD simulation was performed first to obtain numerical results to connecting with the FEA simulation. This method is a cutting-edge technique to categorize the overpressure from the grid cell within the explosion domain into the particular time-dependent coordinate to be connected to the FEA.

Once the numerical calculation is performed using the CFD code for the explosion phenomenon, the results of time-dependent 2D and 3D features and overpressures are generated. Using these values, the explosion pattern can be determined. By connecting these with nonlinear FEA, the damage of structure can be scientifically evaluated. The schematic of CFD-FEA connection is presented in Figure 7.

3.1 | Computational fluid dynamics modeling for explosion

To analyze the explosion phenomenon of the WWSP accident, the flame acceleration simulator, (FLACS), developed by Gexcon was used. Specialized in analysis of gas propagation and explosion analysis, the FLACS code is widely used to estimate the explosion intensity in oil and gas industries. FLACS uses the Reynolds-averaged Navier–Stokes to prepare Cartesian grids in 3D space and use the finite volumetric method; it has a logic structure to extract the result through Navier–Stokes equations. To calculate the

FIGURE 1 Description of S-PVC process and inlet of wastewater into the WWSP

FIGURE 2 Photograph of the WWSP before the accident
turbulence, it uses k-ε model. The main governing equations of the FLACS using the finite volumetric method are composed of conservation of mass, Navier–Stokes momentum, and transport equation for enthalpy and fuel mass fraction. FLACS can analyze the turbulent combustion under spatial properties and features of facilities.6,14

3.1.1 | Explosion model setup with the essential elements for combustion

For combustion to occur, there are three elements required: fuel, ignition, and oxidizer.5 Relative to this accident, the condition for generating explosion based on these three main elements of combustion was analyzed.

As shown in Figure 1, the WWSP temporarily collects various wastewater from S-PVC process for biological treatment, and while there are various mixed compounds, based on the analysis of plant data investigated by KOSHA, vinyl acetate (VA) was confirmed as the main element. The physical and chemical properties of VA are shown in Table 1.

Figure 8 shows the amount of wastewater estimated from the record and size of the WWSP. At the time of accident, the recorded amounts of wastewater stored in C-1 and C-2 were 146.6 tons and 126.5 tons, respectively. The atmospheric temperature was 21.5°C while the temperature 3 m below the ground was 17°C, and the inner temperature of C-1 and C-2 was 14°C. Based on the temperatures, the vapor pressure of VA is less than 0.13 bar so that it is possible to have the VA concentration less than its upper flammability limit 13.4%. In fact, there were other chemical compositions in the wastewater and it is difficult to exactly calculate the vapor concentration at the time. However, it is reasonable to assume that the concentration of VA inside was between its
lower flammability limit, 2.6% and upper flammability limit, 13.4% since the explosion occurred and the main composition was VA.

To generate the explosion under a mixture of VA vapor and oxygen within the WWSP, there had to be an ignition source. In this accident, it was evaluated that the ignition source came from outside the WWSP since cutting and welding of pipes were performed by workers on the top (roof) at the moment of explosion. Therefore, the path of ignition source from the top (roof) of WWSP to the inside was very evident. The ignition point was inside of the WWSP where the flammable vapor can exist. Figure 9 shows the possible four paths (IG-P-1–4) for welding sparks to get into the inside from the top. The small gaps (IG-P-1,2) for the agitators installed on the roof of C-1 and C-2 ponds and the gaps for the pump (IG-P-3, 4) were believed to be the inlet to inside. Two manholes had been closed during the welding so that they were excluded from this analysis.

Finally, a certain concentration of oxygen is required for combustion. To combust the gas mixture of air and VA vapor, a minimum amount of oxygen is required. A fire and explosion can be prevented by reducing the concentration of oxygen regardless of the concentration of fuel. Therefore, the minimum oxygen concentration (MOC) is very important, and the following equation can be used to calculate the MOC.\(^5\)

\[
\text{MOC} (\% \text{vol}) = \left( \frac{\text{moles of fuel}}{\text{total moles}} \right) \times \left( \frac{\text{moles of} \, O_2}{\text{moles of fuel}} \right) = \frac{\text{LFL of VA}}{\text{moles of} \, O_2} \times \left( \frac{\text{moles of} \, O_2}{\text{moles of fuel}} \right)
\]

The combustion reaction is in equation (2) to calculate the MOC of VA.

\[
\text{C}_4\text{H}_6\text{O}_2 + \frac{9}{2}\text{O}_2 \rightarrow 4\text{CO}_2 + 3\text{H}_2\text{O}
\]

Through equations (1) and (2), the MOC required to initiate the combustion of VA vapor in the WWSP is calculated to be 11.7 vol%. The oxygen concentration of 11.7 vol% possibly existed owing to the ventilation work 15 days before, in addition to the concrete manhole installed in the WWSP. The three elements of combustion mentioned above were analyzed. Based on this, for the explosion simulation, the geometry of the pond was designed in the FLACS as shown in Figure 10; the storage condition of wastewater at the moment of accident was taken into account. Since the VA (vinyl acetate) that caused the explosion in the sewage collecting tank is not a commonly used substance in FLACS, the simulator for explosion analysis does
not have it as default. However, this simulation was carried out by using the equivalent gas model to create a gas of the same nature as VA. VA was converted to a gas with compositions of CH$_4$ 15.6%, C$_3$H$_8$ 31.2%, and CO$_2$ 53.2% using equivalent gas model. In addition, the heat of combustion of the equivalent was 22.97 MJ/kg, which is almost similar to 22.69 MJ/kg of VA. In order to test the grid independency, we created lattice intervals of 0.05 m, 0.1 m, 0.2 m, 0.4 m, and 0.5 m, respectively, and performed preliminary simulations. Based on that, 364,585 grids were generated at intervals of 0.4 m for FLACS simulation. The grid with 0.2 m resolution was chosen consisting of 42,398 computational cells for FEA. The combustion model used in this simulation assumed one-step reaction kinetics with the laminar burning velocity being a measure of the reactivity of a give gas mixture. The flame model gives the flame a constant flame thickness of 3-5 grid cells to ensure the flame propagates into the reactant with the specified velocity. FLACS uses a standard k-ε model for turbulence.

Explosion overpressures can be uniformly discharged 360° from an ignition point in open area, but if the pressure front encounters an obstruction such as a structure, the overpressure can vary depending on the features of the structure.

**TABLE 1**  Physical and chemical characteristics of vinyl acetate (VA)

| CAS No. | Molecular formula | Molecular weight (g/mol) | Boiling point (°C) | Flammable limit (vol %) | Auto ignition temperature (°C) |
|---------|-------------------|--------------------------|-------------------|------------------------|-------------------------------|
| 108-05-4 | C$_4$H$_6$O$_2$   | 86.09                    | 72.7              | 2.6-13.4               | 427                           |
| Saturated vapor pressure at 21°C (bar) | Solubility at 20°C (g/mL) | Specific gravity (air = 1) | Appearance | Flash point (°C) | Density (g/cm$^3$) |
| 0.13 | 1.0/50 | 3 |

**FIGURE 8**  Size of C-1 and C-2 ponds within the WWSP, estimated ignition point, vapor cloud volume of VA, and stored mass of wastewater

**FIGURE 9**  Possible inlet of ignition source at the top (roof) of WWSP

**FIGURE 10**  Feature of the WWSP geometry modeled in FLACS
The advantage of CFD is the capability to take into account the details of the geometry predicting the spatial and temporal overpressure variations. For this case, the panels were installed in the program to monitor overpressures under the structural feature of the WWSP as shown in Figure 11. These monitor panels allow to measure average quantities on walls rather than point values.

3.1.2 Results and analysis

For each of the four ignition points (IG-P-1–IG-P-4) proposed in Figure 8, explosion simulations were performed. As a result, the simulated explosion was similar to the actual explosion in terms of destroying the roof of the WWSP. To perform this, two methods were followed. From the analysis of explosion patterns proposed above, the first method is to check whether the overpressure of at least 0.48 barg, which can destroy a concrete structure,\textsuperscript{5,12} is generated. Figure 12 shows the results of each simulation and maximum overpressures ($P_{\text{max}}$) generated within the WWSP among the center of 16 panels. As shown, the $P_{\text{max}}$ for the ignition points through IG-P-1, IG-P-2, IG-P-3, and IG-P-4 were determined to be 1.19 barg (1.55 s), 1.30 barg (1.50 s), 0.24 barg (2.55 s), and 0.33 barg (2.65 s), respectively. There are big differences of overpressure values between ignition point 1,2 and 3,4. And the reason seems a combination of the following:

1. locations of holes to outside
2. hole sizes
3. relative location of the possible ignition point and walls around

FIGURE 11 Panels for monitoring overpressures on structures caused by the explosion within the WWSP

FIGURE 12 Time-dependent maximum explosion pressure for each ignition point: (A) explosion of IG-P-1, (B) explosion of IG-P-2, (C) explosion of IG-P-3, and (D) explosion of IG-P-4

FIGURE 13 Pressure–impulse curves for the damage of 14” reinforced concrete roof\textsuperscript{16}
Out of these results, the simulations obtaining higher than 0.48 barg are those for IP through IG-P-1 Figure 12A and IP through IG-P-2 Figure 12B. The second method for impact analysis is using the pressure–impulse curve. Figure 13 shows the P–I curve graph proposed by the Department of Defense Explosives Safety Board in the U.S.\(^{16}\) It shows the criteria of 14” reinforced concrete roof rupture by the explosion pressure and impulse. Among the panels composed to determine the spatial explosion pressure under the WWSP, the explosion pressure values of 16 panels are shown as points on the P–I curve of Figure 13. As a result, the explosions to completely destroy the concrete roof were confirmed to be those for IG-P-1 and IG-P-2.

Subsequently, the results of explosion simulations for IG-P-1 and IG-P-2 were further analyzed. Figure 14 describes the proposed time-dependent development of flame and explosion pressure under the ignition spot inside the WWSP: (A) With ignition in C-1 pond, and (B) With ignition in C-2 pond.

In summary, although the explosion occurred because of the ignition within C-1 pond, the overpressure affecting the concrete structure of WWSP was higher for C-2 pond, primarily because the different storage height of wastewater and wall path between C-1 and C-2, as shown in Figure 10B, affect the behavior of explosion. Figure 16 describes the explosion caused by the ignition in C-2 pond, and although the explosion pressure inside C-2 pond is higher until 1.11 s, the overpressure of C-1 pond gets higher until the explosion pressure of C-1 pond reaches the maximum explosion pressure at 1.50 s thereafter. Although the explosions of IG-P-1 and IG-P-2 can be distinguished by the ignition spot, the development of explosion was similar but in reverse order, owing to the same feature of the ponds. Overpressures at each explosion simulation vary because the volumes of liberal activity of explosion flame vary with the difference of height of the wastewater stored. The results obtained via CFD analysis through IG-P-1 and IG-P-2 were further compared to the accident scene in Figure 5 to verify which one is more reasonable based on the dropping location of container and pump outlet header, the explosion pressure within C-2 pond was thought to be higher, because both container and pump which were located at the exact middle of C-1 and C-2 pond, flew across C-1 pond. Therefore, the simulation of IP through IG-P-1 can be considered the actual accident. However, it is not yet conclusive that the simulation results closely represent the actual accident. To scientifically resolve this, we used the explosion pressure calculated through the CFD numerical analysis into the FEA.

### 3.2 Nonlinear finite element modeling based on CFD modeling results

#### 3.2.1 Nonlinear finite element model setup

To measure the structure response caused by the explosion pressure, it is important to consider the following: the peak pressure during explosion, duration of explosion, and resistance and ductility of the structure.\(^{17}\) By applying these factors to the FEA, the response of the structure against the explosion pressure can be calculated. FEA is a numerical approximation method to solve a difficult problem of a structure with complex geometry. It is an approximate calculation for a difficult and complex model by dividing it into finite number of simple elements, calculating of each component and combining all.\(^{17,18}\)

In this study, to analyze the effect of the explosion on the structure using the result of FLACS simulation, the FEA tool called IMPETUS based on the LS-DYNA code was used. The feature of the WWSP for FEA was designed by using SolidWorks (Dassault Systems), and the mesh was preprocessed by using Hypermesh.
FIGURE 15  Development of time-dependent overpressure of C-1 & C-2 ponds under the ignition spot of C-1 pond
FIGURE 15  Continued
FIGURE 16  Development of time-dependent overpressure of C-1 & C-2 ponds under the ignition spot of C-2 pond
**FIGURE 16** Continued
13.0 (Altair) solver. Simulations involving blast effects were validated and it is known that IMPEUS can be handled as shown in tests. Taylor tests for different materials and different impact velocities were undertaken and compared with experimental results. In this paper, the materials and components of the object were applied as general concrete structures.21

The nonlinear stress distribution of the explosive load during explosion is focused on shattering the container by analyzing the explosion of the wastewater collection tank.

The boundary conditions of the time-dependent explosion pressure from the simulation with the ignition point location #1(IG-P-1) were entered into C-1 and C-2 ponds of the WWSP. Figure 17 describes the feature of these boundary conditions. The upper load collector is the location to collect the explosion load on the ceiling part and the lower load collector is for the lower part. The external constraint condition refers to the area that is fixed due to the surrounding earthen walls.

3.2.2 | The results of nonlinear finite element analysis

The explosion phenomenon generated from the ignition of IG-P-1 Figures 8 and 9 of the WWSP was analyzed with FLACS, and the result was connected with FEA for evaluation.

Figure 18A is a description of the time-dependent stress distribution generated from the inner ceiling of the WWSP. In the inner ceiling, the stress was estimated to be concentrated on the strut beam, partition wall, and corner of the ceiling at the initial moment of explosion, because the explosion overpressures may be different owing to the spatial feature inside C-1 and C-2 ponds. Figure 18B shows the time-dependent stress distribution at the roof of WWSP. The yellow arrows indicate the highest stress points affecting the container from the initial moment of explosion, the stress on the roof significantly affected the partition between C-1 and C-2; thus, the stress on the container on top of the partition was large.

Figure 19 shows the analysis of flying route of container located on the roof at the moment of explosion by using the above result. This route was analyzed by model connecting of the CFD with FEA. Comparing the flying route of the container on the analysis with the route in Figure 5, it was observed that the explosion by ignition at IG-P-1 was similar to the actual explosion. If the explosion occurred by the ignition at IG-P-2, with reference to Figure 16, the flying
route of container would be opposite. The observers at the scene said that the route was corrected as we indicated, and we assumed that the amount of overpressure only affected the route.

It is also predicted that the route of another flying object on the roof, that is, the pump outlet header has the same direction as the route of container considering the stress distribution in Figure 18.

**FIGURE 18** Nonlinear analytic result of inside and outside of the WWSP using the CFC (CFD and FEA connecting): (A) is the stress distribution for the inside of ceiling, and (B) is the stress distribution for the roof

4 | LOGICAL SEQUENCE OF THE ACCIDENT

It is difficult to represent the physical and chemical development mechanism of the actual explosion accident in a virtual space because such factors as composition and elements of the structure may not accurately correspond to those in the actual situation. In this accident, the main objects such as the
Concrete structure, facility, and device were severely damaged due to the explosion. Subsequently, most of the clues necessary to conduct an accurate analysis of the real cause of explosion were lost, resulting in a limited analysis and result. However, after sampling the fuel from C-1 and C-2 ponds, the simulation test using CFD and FEA techniques based on the review of container, pump outlet header, and concrete structure was used to analyze the explosion accident as follows:

1. The fuel that caused the explosion was mainly composed of VA (vinyl acetate) dissolved in wastewater. Since the WWSP had no ventilation for 15 days owing to the construction, the VA vapor from C-1 and C-2 created a sufficient condition for explosion.

2. The minimum oxygen concentration required for explosion is 11.7 vol%. It was evaluated that this concentration could be maintained through the manhole and inner connection of devices installed in the WWSP.

3. The ignition source is suspected to be the spark from the cutting and welding works at the top of the WWSP. To check the inlet path of ignition source, CFD and FEA methods were used. As a result of simulation, it was hypothesized that the explosion began at the lower region of C-1 agitator.

4. The intensity of explosion was large enough to completely destroy the concrete roof structure and to blow away the container as well as the pump outlet header simultaneously.

5 | CONCLUSION AND LESSON

The WWSP is installed and operated in many chemical plants to dispose wastewater. In general, the WWSP is operated focusing on the disposal of wastewater mostly for environmental compliances and underrate the safety effect; it is often excluded from the subject of risk management. This type of social concern is confirmed with the occurrence of the explosion accident, which was caused by inappropriate management of ignition source during work and improper ventilation before work, even if the factory was run by a large corporation. Based on this accident, the following measures shall be taken to ensure safety against explosion:

1. The vapor generated inside the WWSP shall be discharged through a disposal facility, such as a regenerative thermal oxidizer by installing a blower. In designing such facility, since the vapor inside the WWSP is mostly heavier than air, the vapor weight shall be considered to ensure that the vapor will be discharged properly.

2. A gas detector and alarm shall be installed in the WWSP to monitor and maintain the concentration of vapors below 25% of their lower flammable limit at all times.

3. In case of working around the WWSP, the elements of dangerous work shall be evaluated and dangerous items removed from the workspace. Furthermore, the path that may allow inward ignition shall be closed, and other safety measures shall be taken in advance.

4. Surveillance personnel assigned in the working area shall monitor any unsafe working condition or worker’s behavior, and if there is any danger, the work shall be stopped immediately, and measures shall be taken to improve the situation.

In addition, the cutting-edge method used to analyze the explosion accident in this study may be useful to implement a quantitative risk analysis. Furthermore, for sensitive facilities or
plants requiring accurate analysis, this method may be used to predict the consequences and damage of explosion in advance.

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REFERENCES

1. Bauwens CR, Chaffee J, Dorofeev SB. Vented explosion overpressures from combustion of hydrogen and hydrocarbon mixtures. Int J Hydrogen Energy. 2011;36(3):2329-2336.
2. Tolias IC, Venetsanos AG, Markatos N, Kiranoudis CT. CFD evaluation against a large scale unconfined hydrogen deflagration. Int J Hydrogen Energy. 2017;42(11):7731-7739.
3. Tolias IC, Stewart JR, Newton A, et al. Numerical simulations of vented hydrogen deflagration in a medium-scale enclosure. J Loss Prev in the Process Ind. 2018;52:125-139.
4. Li J, Abdel-Jawad M, Ma G. New correlation for vapor cloud explosion overpressure calculation at congested configurations. J Loss Prev in the Process Ind. 2014;31:16-25.
5. CROWL DA, Louvar JF. Chemical process safety: fundamentals with applications. Prentice Hall: Pearson Education; 2011
6. GEXCON AS; FLACS ver 10.4 user’s Manual. 2015.
7. Velikorodny A, Studer E, Kudriakov S, Beccantini A. Combustion modeling in large scale volumes using EUROPLEXUS code. J Loss Prev in the Process Ind. 2015;3:104-116.
8. van den Berg A, Lannoy A. Methods for vapor cloud explosion blast modelling. J Hazard Mater. 1993;34:151-171.
9. Skjold T, Hisken H, Lakshmipathy S, et al. Blind-prediction: Estimating the consequences of vented hydrogen deflagrations for homogeneous mixtures in 20-foot ISO containers. Int J Hydrogen Energy. 2018; In press.https://doi.org/10.1016/j.ijhydene.2018.06.191.
10. Lee J. An explosion accident at Hanwha Chemical Ulsan Campus. Republic of Korea: Ulsan Broadcasting Corporation; 2015.
11. Kim J. Explosion accident site at Hanwha chemical ulsan second campus. K: Ulsan Daily Newspaper; 2015
12. Clancy V. Diagnostic features of explosion damage. 6th International Meeting on Forensic Scientists; 1972.
13. Davis SG, Engel D, van Wingerden K. Complex explosion development in mines: case study—2010 upper big branch mine explosion. Process Saf Prog. 2015;34(3):286-303.
14. Pedersen H, Tomlin G, Middha P, Phylaktou H, Andrews G. Modelling large-scale vented gas explosions in a twin-compartment enclosure. J Loss Prev Process Ind. 2013;26:1604-1615.
15. Zhang Y, Cao Y, Ren L, Liu X. A new equivalent method to obtain the stoichiometric fuel-air cloud from the inhomogeneous cloud based on FLACS-dispersion. Theoret Appl Mech Lett. 2018;8(2):109-114.
16. Hardwick MJ, Hall J, Tatomi JW, Baker RG. Approved Methods and Algorithms for DoD Risk-Based Explosives Siting. 4th technical paper of Department of Defense; 2009.
17. Midas Information Technology. Midas Technical Paper; 2016.
18. Impetus Afea. IMPETUS ver 3.0 user’s Manual; 2015.
19. NIFDS. Vinyl Acetate. Chung-ju, Korea: NIFDS; 2015.
20. Vinyl Acetate. Wikipedia; 2016.
21. Grant WJM, Rinfret J. An evaluation of the finite element program IMPETUS. Scientific Report. Valcartier Research Centre; 2015.

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