Evaluation of Hydrocarbon Gas Dispersion and Explosion in a Gas Processing Plant

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Abstract. Gas leakage is one of hazard sources in a gas processing plant, where the released gas may form vapor cloud, which is dispersed or accumulated. At certain concentration, the vapor cloud may induce fire and explosion, which could harm people, equipment and environment. The effects of the incidents can be estimated to determine the consequences and to improve the plant design. Due to several complexities including congestion of plant equipment, 3D CFD model was developed to represent real configuration. In this study, the as-built 3D plant geometry and FLACS software were utilized to run the CFD model simulation to evaluate the quantity and placement of the existing gas detectors. The recommendation given according to evaluation results was to install two additional gas detectors. Thereby, in the case of gas leak, the gas detection system may alarm personnel and preventive action may be taken into consideration. The effects of explosion result from the selected scenario were predicted to not be able to cause steel frame distortion or eardrum rupture. These demonstrated that the evaluation of release consequence using 3D CFD model gave more advantage than 2D method by representing accurately physical characteristic of gas dispersion and explosion, which could eventually improve the plant safety strategy.

1. Introduction
The hydrocarbon-based industries face the risk of fire and explosion due to ignition of flammable vapors or gases released from its source. Process safety aspects shall be applied from the beginning of the project initiation to identify the hazards and consequences, and thus minimize the risk. Incident records provide lesson learned about the importance of inherently safer plant design and performance of Process Hazard Analysis (PHA) such as consequence analysis to minimize the risk and its consequences. Gas dispersion and explosion modeling is one method of consequence analysis due to gas release. Computational Fluid Dynamics (CFD) models have been developed and are appropriate to perform the 3D modeling of major events with all necessary details [1]. The 3D CFD modeling reports are expected to give more comprehensive results, better than the 2D method. It is agreed that this method is able to estimate the real configuration of the effects of gas release, explosion and fire. Modeling of releases impinging on structure killing the momentum of the release, air entrainment and subsequent dispersion are completely different compared to the cases where the geometry effects are neglected causing the release to remain as a high momentum jet before being diluted by the wind. FLACS has been widely used and approved as a solver to perform 3D CFD modeling of gas dispersion, explosion and fire [2].
In gas processing plant, Hazard Identification (HAZID) study is conducted to identify potential hazards such as flammable gas or toxic gas release caused by equipment rupture, pipe or valve leak and misaligned flange. The process and safety systems are designed and evaluated to ensure the plant safety. Gas detection system is commonly installed in the process facilities to alarm and in some cases may be designed to trigger safety measures in response to the hazardous leaks. The accumulation of flammable gas may lead to fire or explosion, while the accumulation of toxic gas to the threshold limit may cause health issues.

Failure in detection of gas leak may occur as a result of ineffective and poor design of the gas detection system; insufficient gas detectors quantity or incorrect positioning. The uncertainty to be considered when trying to determine the appropriate number and placement of gas detectors includes gas composition, process conditions, weather conditions, plant layout or geometry and leak location [3]. However, the quantity and placement of detectors that can be used are limited and should be optimized for maximum effectiveness.

The objective of this study was to investigate the implementation of gas dispersion model using CFD simulations to estimate the effects of gas dispersion and explosion caused by flammable gas release. In addition, the dispersion results were used to evaluate the quantity and location of existing gas detectors. Due to several complexities such as congestion of plant equipment, it is difficult to assess the vapor cloud characteristics correctly with 2D method where the main consideration is only wind speed and direction. As a result of improper estimation of vapor cloud, the volume of accumulated flammable gas is also imprecise [1]. Since the correct calculation is expected to give a more real configuration, 3D CFD model was used to give such outcomes. However, there are essentially infinite numbers of leak scenarios that may occur. Thus, the selection of appropriate leak scenarios is key to a successful CFD-based evaluation of gas detection system [4].

2. Mathematical Model and Simulation

Data sample was taken from one of hydrocarbon gas processing plant in Indonesia. Actual condition including wind speed, atmospheric condition, prevailing wind, process data, plant layout and 3D model layout were used in this study. FLACS software was used as a solver in the simulation and modeling.

2.1. Governing Equation

Dispersion and explosion models were solved with assumption of ideal gas. The continuity conservation is presented as follows [8].

\[
\frac{\partial}{\partial t} (\rho \phi) + \frac{\partial}{\partial x_j} (\rho u_j \phi) - \frac{\partial}{\partial x_j} \left( \rho \Gamma \frac{\partial}{\partial x_j} \phi \right) = S_\phi
\]  

(1)

Initial condition: at \( t = 0, \phi = 0 \)

Boundary condition: at leak source, \( S_\phi = \phi \)

at plant boundary, \( \frac{\partial \phi}{\partial x_j} = 0 \)

where

- \( \rho \): density
- \( \phi \): variable for mass, momentum or energy
- \( t \): time
- \( \Gamma \): diffusivity, viscosity or thermal conductivity
- \( S_\phi \): leak source
- \( x_j \): cartesian coordinate x, y, z
- \( u_j \): velocity at coordinate j

The conservation of mass was observed when the case was gas dispersion. The conservation of momentum was observed when the case is explosion, and the conservation of energy was observed when the case was fire. The dispersion, convection and accumulation occurred at all domains, yet the source was only specified at leak source where the gas release occurred.
2.2. Scenario Settings

The FLACS allows to define various initial and boundary conditions for simulation. In this study, scenarios were defined by varying wind speed, atmospheric condition and leak sizes. The model was made with approximately same dimensions as the actual facility without any scaling. The wind speed and the atmospheric condition were set based on actual condition at the facility; 1 m/s of wind speed with stable atmospheric, 2.7 m/s and 13.4 m/s of wind speed with neutral atmospheric condition. The leak sizes used in the simulation referred to Cox, Lees and Ang, Loss Prevention Handbook – Volume 2, 1990 and were set as 10 mm, 50 mm and 100 mm.

Delayed ignition of flammable vapor cloud was considered in this study as the type of explosion scenario. The explosion scenario was derived from the results of the dispersion simulations whose flammable cloud was not detected by any of existing gas detectors dissatisfying the plant safety. If the vapor cloud volume was relatively large, additional gas detectors were applied, or otherwise, the case was selected for explosion scenario.

The assumptions considered during study were jet pressure as the type of release, gas concentration at source leak was constant and modeled as step function. The wind speed and prevailing wind were assumed to be constant for each scenario. The gas compositions for each unit observed were based on respective process condition, but only methane gas was shown on the report considering the gas detector specification was detecting methane gas only, instead of mixed gas.

3. Results and Discussion

Referring to API RP 14C (2017), the gas detector system should alert personnel by audible and/or visual alarm to the presence of flammable gas or vapor as low as 25%-LFL, yet it does not mention about time detection. In this study, the acceptance criteria for gas detector placement is that the gas detectors located at the observed area should detect gas at minimum concentration of 25%-LFL during 60 seconds simulation at various wind speeds and leak sizes, the gas leak started at 1 second after the simulation started.

3.1. Dispersion

The Gas Turbine Generator (GTG) unit was defined as the medium congested area, where the equipment area was less dense yet located inside a turbine house that in case of gas release the gas accumulation at the top of room makes the cloud concentration higher. There were four GTGs equipped with two existing gas detectors installed in this unit, which named GD-1016B and GD-1017B, and several monitor points located for simulations named MP. The leak location and monitor points defined in this unit are shown in Figure 1. There were two leak locations in this GTG unit. The first one was between GTG A and GTG B facing -Y direction, and the second one was facing +X direction to observe semi-impinging effects on the GTG enclosure.

Figure 2 shows top view of gas dispersion result caused by Leak-1 was not in the same direction as the wind direction due to the presence of GTG geometry. It illustrates the concentration of methane gas at the range of 50%-LFL, denoted with blue color, to UFL, denoted with dark red color. At high wind speed, the gas dispersion followed the wind direction as it exited the turbine house. The vapor cloud with gas concentration of 25%-LFL due to 50 mm leak reached distance of 52 m and width of 7.8 m at 1 m/s of wind speed. With the same leak size, the vapor cloud reached distance of 51.9 m and width of 8.4 m at 2.7 m/s of wind speed. Meanwhile at 13.4 m/s of wind speed, the cloud reached 39.8 m distance with 7.21 m width. The distance between two facing GTG enclosure was 7.52 m with the width of GTG enclosure was 2.48 m, that the distance form one aisle to another was 10 m. From this measurement, it can be inferred that the maximum width of cloud formed was smaller than the width of the GTG. In the case of gas leak from one of GTG’s fuel source, the other GTG area was less likely to be affected.
Figure 1. Plant layout in gas turbine generator unit (top view).

Figure 2. Gas dispersion result due to 50 mm leak at 1 m/s wind speed (a) 2 seconds, (b) 10 seconds (c) 20 seconds; 2.7 m/s wind speed: (d) 2 seconds, (e) 10 seconds (f) 20 seconds; 13.4 m/s wind speed: (g) 2 seconds, (h) 10 seconds (i) 20 seconds.

Referring to API RP 14C (2017), in enclosed area containing natural gas-fuelled prime movers, the minimum number of flammable gas sensor is one per prime mover. Hence, in this study, two more additional sensors were placed in the area, giving a total of four sensors for four generators. The
recommendation as shown in Figure 3 was given to meet the standard, furthermore this has been proved to be required based on the evaluation result.

Figure 3. Recommended installation based on simulation result.

Figure 4. Dispersion result due to 50 mm leak from Leak-2 at 1 m/s (a) 2 seconds, (b) 6 seconds, (c) 15 seconds top view and (d) 15 seconds side view.

Figure 4 shows dispersion result due to 50 mm leak from Leak-2 point at wind speed of 1 m/s. The gas was released from the fuel gas supply to GTG B, and GD-1017B was expected to detect the gas leak. The top view observation at 15 seconds shows the gas dispersed to the other GTG, while the side view observation illustrates the gas cloud was accumulated on the top of engine room space under the effect of buoyancy of gas. The results from all scenarios showed that the existing detectors did not detect gas leak at minimum concentration of 25%-LFL that implies none of gas detector activates the high
alarm. On the other hand, 6 of 9 scenarios were detected by MP 9 (defined as GD-10YYB on the recommendation in Figure 3) except the scenarios with 10 mm leak size.

### 3.2. Explosion

The dispersion simulation results revealed that most scenarios with 10 mm leak size could not be detected by the existing gas detectors or predefined monitor points due to the distance reached by the gas cloud was short and not strong enough to form flammable vapor cloud. This brings the gas detectors should be installed as close as possible to the leak source. However, the leak source can be anywhere and in infinite number, yet the gas detectors are limited. In the case of the vapor cloud from these scenarios meet an ignition source, the vapor cloud explosion may occur.

This study only considered one explosion scenario from GTG unit where the largest volume of undetected gas dispersion was 9 m$^3$, derived from dispersion scenario with 10 mm leak size and 1 m/s wind speed. Ten monitor points were set near the critical location as shown in Figure 5. MP 1 and MP 3 were located at the front of GTG B enclosure facing the explosion source. MP 5 to MP 9 were located along the pipe rack above the cloud at every 2 m.

![Figure 5. Monitor points location for explosion scenario at GTG unit.](image)

Figure 6 illustrates the overpressure reading at each monitor point due to the explosion at GTG unit. The simulation results indicate that the GTG B surface (MP 1) was exposed to overpressure of 0.0104 barg (0.15 psig). As described by Crowl and Louvar (2002), a blast with an overpressure of 0.15 psig produces loud noise although having insufficient energy to cause eardrum rupture and steel frame distortion.

![Figure 6. Overpressure time plot due to explosion in GTG unit.](image)
4. Conclusion
The study of the evaluation of hydrocarbon gas dispersion and explosion in a gas processing plant using 3D CFD model of FLACS software has been performed. The 3D CFD modeling gave improvement on the gas detection system design, especially for the highly congested geometry. The results also demonstrate that the model might provide better safety design strategy compared to 2D model, where the geometry effect is not considered.

The recommendation given according to the standards and evaluation results was to install additional gas detectors. Thereby, in the case of gas leak, the gas detection system may alarm the personnel and preventive action may be taken. The undetected gas leak scenario, evaluated for explosion case, caused maximum overpressure of 0.15 psig that was predicted to not be able to cause steel frame distortion or eardrum rupture.

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Acknowledgments
This study was conducted as a research in the master program in Institut Teknologi Bandung and technically supported by Gexcon Indonesia. The authors would like to thank Rekayasa Industri for the opportunity of pursuing Master’s Program of Process Engineering in Chemical Engineering, Institut Teknologi Bandung.