Flexible alarming mechanism of a general GDS deployment for explosive accidents caused by gas leakage

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ABSTRACT

Gas detection system (GDS) is critical for identifying and suppressing the flammable or hazardous gas leaked by incidents. The spread of a flammable gas cloud is susceptible to external factors and highly uncertain, but the GDSs deployed today often raise alarms based on certainty. It means that the threshold value set in a GDS for triggering alarms is a constant. Such an approach sometimes cannot accurately determine the leakage location, and so it may result in a great delay of gas detection. To reduce the risk of gas leakage, this paper proposes a flexible triggering mechanism for GDSs, where an alarm is raised or not depending on the number of sensors whose reading are reaching or closing to the preset threshold. An equivalent gas cloud (EGC) model is introduced here to provide design inputs for such a flexible triggering GDS. The volume and location distribution of an EGC are estimated with the Gaussian dispersion model, based on the changes of wind speed and direction. A case study in a terminal station of LNG is conducted, to illustrate the effectiveness of the new approach. The findings show that the flexible triggering mechanism is able to make alarms of a GDS more accurate, and meanwhile avoiding unnecessary measures, which can effectively optimize alarming thresholds.

1. Introduction

When a flammable gas cloud encounters an ignition source, an accident of fires or explosions (Baalisampang et al., 2019) will occur. It is reported that accidents caused by flammable gas clouds account for about 50% of the total accidents in the petrochemical industries, and are often hazardous (Birk Michael, 2017). Gas leakage tends to lead to many serious accidents. For example, the Bhopal disaster in India, the liquid methyl isocyanate in the tank leaked as gas. And the leakage was about 30 t, resulting in 20,000 people died directly, 550,000 people died indirectly, and more than 20 million people were forced to move (Yang et al., 2015).

The consequence of an accident related with gas cloud is determined by the strength of ignition source, the ignition location and the context (Li et al., 2017; Han et al., 2016). A large number of experimental studies have been carried out since the 1940s in fields and laboratories, for gas dispersion and gas cloud explosion. Researchers have discovered the law of gas dispersion, the propagating rule of shock wave after an explosion, and the influence factors of the consequence of an explosion (Shebeko et al., 1988).

However, experiments of explosions are dangerous and always costly, and thus numerical simulation has gradually been widely used to study the effects of concentration and volume of a gas cloud on the consequence of an explosion (Hansen et al., 2013).

In the simulation of gas cloud spread and explosion, a general assumption is that the impacts of internal and external influencing factors keep same or only change regularly. The internal influencing factors include flammable gas density, reactivity, mixing uniformity of combustible gas and air, and volume of flammable gas cloud and so on, while the external influencing factors have ignition time, probability and location, the size and shape of obstacles, and changes in atmospheric environment, etc. In practices, the statuses of these factors change all the time, and their combined effects make gas clouds different, e.g. in concentrations and in shapes. Various leakage scenarios are thus generated. In addition, since gas cloud explosion is a kind of volume explosion, more uncertainties exist in combustion rate, explosion form, ignition probability, and severity of consequences. To simplify the simulation of dispersion and explosion of gas cloud with complexities, the model of equivalent gas cloud (EGC) has been proposed, in assumption of any gas cloud as an ideal homogeneous cubic (Fiates et al., 2016a). A complex gas cloud can then be simply equivalent to an EGC.

To prevent explosions or at least mitigate consequences, gas detection systems (GDSs) are widely installed in the petrochemical industries (Wang and Zhaoauthor, 2015). A GDS is a safety-instrumented system for detecting flammable and toxic gas leakages, so as raising alarm to protect personnel, equipment, facilities, pipelines and buildings. A GDS includes sensors in fixed positions, where the concentrations of the gas cloud can be detected.

The alarms shall be raised by the GDS, and alarm management is very important. Chang et al. Chag et al. (2011) have proposed a risk-based alarm prioritization method depending on the reliable alerts generated through redundancies of multi alert voting system, which can make the possibilities of alarm floods reduce. Hu et al. Hu et al. (2018) have studied the visualization of the alarm in industry domain to accommodate the development trends and the new research in alarming management and monitoring based on the big data. Wang et al. Wang et al. (2018) have proposed a Bayesian network-based method to analyze the alarm system performance, which can avoid and reduce alarm flooding efforts. It's based on the new scoring function to learn the dependence structure from a process alarm dataset. They are risk-based alarm management, which is helpful for the work of this paper. The purpose of the alarm management and the mechanism proposed by this paper are both to optimize the alarm, and the latter one can used to optimize the detecting threshold of the GDS. And the alarming mechanism proposed in this paper is mainly used to prevent the explosion accidents caused by gas leakage. However, the volume and location of a gas cloud keep changing, and thus the detection accuracy of sensor is in doubt. Therefore, the concept of EGC is proposed. And the flexible alarming mechanism can be proposed based on the assumption to detect the EGC.

In order to detect the leakage scenarios more efficiently, and avoid false alarms, the layout issue of sensors has been well considered in the existing studies. Relevant GDS specifications, such as API RP 14C API RP 14C (2001) and ISA RP 12.13.02 (ISA 12.13.02-2003, 03), provide a qualitative method of the geographical arrangement of sensors. API RP 14C API RP 14C (2001) recommends that largest distance between two sensors of a GDS with a grid structure should be no more than 6 m. ISA TR 84.00.07 (ANSI/ISA TR84.00.07, 2010) adopts risk assessment approaches in the layout of sensors, and proposes the concept of scenario coverage, the probability of a gas leakage scenario detected by sensors, in consideration of leakage frequency, the degree of leakage, and the voting mechanism of sensors. When it comes to the optimal layout of gas detectors in the petroleum industry, there are many studies. Marica S Araujo proposed that the CFD simulation can be applied to the layout of gas detectors in marine oil and gas environments (Araujo et al., 1999). Kelsey used the dispersion data from simulation obtained from experiment to evaluate the 5×5 gas detection network commonly in the marine environment and studied its sensitivity. It was found that the large and medium leakage can be successfully detected. But for small leaks, it is difficult to detect. Reasonable reduction of the sensor's detection threshold can effectively improve the detection rate of small leaks (Kelsey et al., 2002, 2005). Amirhosein quantifies the risk by comprehensively considering the possibility of leakage scenarios, personnel hazards, property damage and ignition possibility to establish risk-based optimization function model and solve it by greedy algorithm (Rad et al., 2017).

A well-deployed GDS should be able to cover most leakage scenarios as possible. For detection spacing of flammable gas, Stephen (Defriend et al., 2008) has proposed a sensor-spacing method based on wind direction and other impact factors of leakage, such as weather conditions, gas composition, and the size of leakage hole, operating pressure and so on, to assess the likelihood and severity of leakage consequence, including explosion shock waves, heat radiation, and fire. Wang Wang et al. (2016) has proposed that the efficiency of detection mainly depends on the whole detection network. The leakage scenarios generated by computational fluid dynamics (CFD) analysis are used as the input data for sensor layout. This study indicates that the shortest detection time does not necessarily bring the optimal solution, which cannot be obtained until taking geographic coverages and scenario coverages into account.

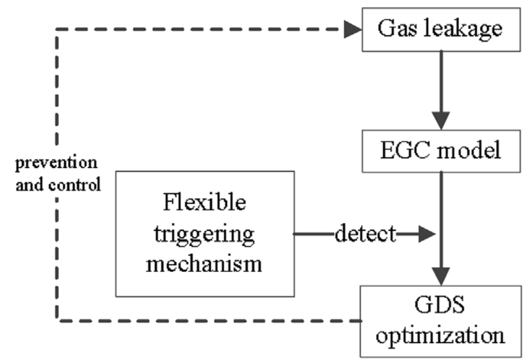

Fig. 1. Flow chart for gas leakage analysis.

The studies mentioned above focus on the layout optimizations, and they assume that sensors always can detect leakages and then send alarms. According to IEC 60079-29-2-2015 60079-29-2-2015 (6007), the alarms are sent, or sensors are triggered twice when they find the concentration of flammable gas reaches two levels, 20% of LEL (Lower explosion limit, the lowest concentration of the mixture of combustible gas and air that can explode in case of fire.), 40% of LEL. We can call this kind of mechanism as rigid triggering since these two thresholds have been determined. Such a mechanism is commonly used, but is challenged in some situations: (1) when a gas cloud spreads, the detected concentration at a certain point may be close to but does not reach the setting threshold. No alarming is raised, but the concentration and volume of gas cloud are actually high enough to cause explosion. For example, if more than 80% of sensors have reached 18% of LEL or even 19% of LEL (20% is the threshold), such a leakage may result in an explosion even though no alarm raises. (2) A gas cloud is unevenly distributed, and the concentration at some points is much higher than the average, so that a small leakage can cause the inputs to some sensors reaching the threshold and trigger alarms. Unnecessary following-up measures will affect the normal production in these cases. (3) Some sensors have faults on themselves, leading to false alarms or missing alarms.

To resolve these problems, it is reasonable to analyze the development of leakage scenarios, predict the triggering time of sensors, and then determine whether to raise an alarm. In this paper, we call such a kind of triggering mechanism as the flexible mechanism.

The main purpose of introducing flexibility is to improve the accuracy and effectiveness of alarming. Existing literature has studied the optimization of alarm thresholds, but the focuses are on the multiplicity of factors (Tian et al., 2018) and weight-based thresholds (Bernechea and Arnaldos, 2014; Wang et al., 2015). In order to reduce the risk (Tanjin Amin et al., 2019) and prevent explosion accidents caused by gas leakage, it's necessary to optimize the current alarming threshold. What we focus on here is to develop a new triggering mechanism of sensors to be adaptive to different scenarios. This study considers the uncertainty in gas cloud dispersion, and the movement and location changes of gas cloud. Since too many scenarios are possible when the gas spreads, it is difficult to analyze them one by one. Thus, the EGC model will be used to simplify the gas cloud dispersion process. The relative position of gas cloud and asset under protection (or equipment under control, EUC, e.g. center control room) will be visualized. Then, changes in volume and position changing can be obtained, and such information will be applied in the flexible alarming mechanism of a GDS.

The analysis process is shown in Fig. 1.

The reminder of this paper is organized as follows: Based on Gaussian model, the location of EGC is described in Section 2. The impact of external conditions on EGC is analyzed in Section 3. Then the flexible alarming mechanism is proposed based on the detection of EGC in Section 4. A case of LNG terminal station is studied in Section5. Finally, in Section 6, some conclusions are drawn, and further works are presented.

2. Model of EGC and the flexible alarming mechanism

2.1. Location of EGC

Using an ideal homogeneous cubic gas cloud instead of the heterogeneous ones with irregular shape and uneven concentration, EGC facilitates the calculation and analysis of gas cloud dispersion and explosion.

The gas dispersion models used for numerical simulation mainly include Gaussian model, 3D fluid dynamics model (CFD), similar model, shallow model, phenomenological model, etc. (Fiates et al., 2016b). Among them, Gaussian model and CFD model are widely used, while considering the more complexity of the latter (Toja-Silva et al., 2018), this study adopts Gaussian model in the rest.

According to the Gaussian model, the average concentration equation for a given location (x, y, z) is (Elperin et al., 2016):

$$C(x,y,z)=\frac{Q}{2\pi\sigma_y\sigma_z u}\exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]\times\left\{\exp\left[-\frac{1}{2}\left(\frac{z-H_r}{\sigma_z}\right)^2\right]+\exp\left[-\frac{1}{2}\left(\frac{z+H_r}{\sigma_z}\right)^2\right]\right\} \quad (1)$$

where Q is mass flow rate of gas leakage, kg/s, u is wind speed, m·s^{-1}; H_r is the height of leakage source. x, y, z are dispersion distances in downwind, lateral wind and vertical wind direction respectively, and σ_x, σ_y, σ_z are divergence coefficient at these three directions, changing with the atmospheric stability. Pasquill-Gifford-Turner classification is used here for atmospheric stability (Kahl and Chapman, 2018), as shown in Table 1, where class A is extremely unstable and Class F is the most stable.

To obtain the concentration contour distribution at a certain height, the gas dispersion distances on both x and y directions are needed, when that on the vertical wind z direction is constant. Covert the Gaussian model (1) to Eq. (2) and represent x as a variable of y (in the equation, σ_x, σ_y, σ_z are all the functions of x).

$$y=\pm\sqrt{-2\ln\frac{2\pi\sigma_y\sigma_z uc(x,y,z)}{Q}+2\ln\left\{\exp\left[-\frac{1}{2}\left(\frac{z-H_r}{\sigma_z}\right)^2\right]+\exp\left[-\frac{1}{2}\left(\frac{z+H_r}{\sigma_z}\right)^2\right]\right\}}\cdot\left|\sigma_y\right| \quad (2)$$

The coordinate system is established with the leakage source as the origin. Taking a certain step size (such as 1 m) along the x-axis and establishing the matrix $\boldsymbol{X}$, the value of corresponding y can be calculated by the Eq. (2) and be stored in the matrix $\boldsymbol{Y}$ under a certain concentration threshold (e.g. LEL). Then the maximum distances x^d_{max} and y^d_{max} of gas dispersion on the downwind and lateral wind direction can be obtained respectively. It is the range of concentration contour, and the region can be equivalent to an ellipse in this study. In calculation, if x is too large or too small, y will have no real solution. It can be explained as the concentration contour formed during gas dispersion is generally closed, and it keeps a certain distance from the leakage source, so that y is meaningful only in a certain range of x. Therefore x_{max} and y_{max}, as well as x_{min} and y_{min} of matrices $\boldsymbol{X}$ and $\boldsymbol{Y}$ can be obtained.

The gas cloud location is three-dimensional. Taking a certain length (such as 1 m) in the z direction, and establishing a matrix $\boldsymbol{Z}$, concentration contours can be obtained in different layers according to the certain length. When the vertical wind direction height is constant, the EGC is layered, and different concentration threshold are taken to obtain contours of different concentrations. Taking the center of the contours separately, the center coordinates $(x^{c_i}_{mid}, y^{c_i}_{mid})$ of the contour in each layer of gas cloud can be obtained. We have

$$\begin{aligned} x^c_{\text{mid}} &= \frac{1}{n}\sum_{i=1}^{n} x^{c_i}_{\text{mid}} = \frac{1}{n}\sum_{i=1}^{n}\left(x^{c_i}_{\max}-x^{c_i}_{\min}\right)/2 \\ y^c_{\text{mid}} &= \frac{1}{n}\sum_{i=1}^{n} y^{c_i}_{\text{mid}} = \frac{1}{n}\sum_{i=1}^{n}\left(y^{c_i}_{\max}-y^{c_i}_{\min}\right)/2 \end{aligned} \quad (3)$$

where x^c_{mid} and y^c_{mid} are central coordinate of the gas cloud when z is constant; $x^{c_i}_{mid}$ and $y^{c_i}_{mid}$ are the central coordinate of the concentration contour at the concentration threshold c_i, as the mean of matrix $\boldsymbol{X}$ and $\boldsymbol{Y}$, where $i = 1,2,3,\ldots,n$; n is the total number of concentration contours when z is constant. $x^{c_i}_{max}$ and $x^{c_i}_{min}$ are maximum and minimum of downwind direction distances at the concentration threshold c_i, and $y^{c_i}_{max}$ and $y^{c_i}_{min}$ are the maximum and minimum of lateral wind direction distances at the concentration threshold c_i.

The center coordinate of the EGC is

$$\begin{aligned} x^c_{mid_z} &= \frac{1}{m}\sum_{j=1}^{m}\left(x^c_{\text{mid-max}_{zj}} - x^c_{\text{mid-min}_{zj}}\right)/2 \\ y^c_{mid_z} &= \frac{1}{m}\sum_{j=1}^{m}\left(y^c_{\text{mid-max}_{zj}} - y^c_{\text{mid-min}_{zj}}\right)/2 \\ z_{mid} &= \frac{1}{m}\sum_{j=1}^{m}\left(z_{\max}-z_{\min}\right)/2 \end{aligned} \quad (4)$$

where $x^c_{mid\text{-}max_{zj}}$ and $x^c_{mid\text{-}min_{zj}}$ are the maximum and minimum of downwind direction distances of the single-layer gas cloud center, that is the maximum value of the matrix $\boldsymbol{X}^c$. $y^c_{mid\text{-}max_{zj}}$ and $y^c_{mid\text{-}min_{zj}}$ are the maximum and minimum of lateral wind direction distances of the single-layer gas cloud center, that is the maximum value of the matrix $\boldsymbol{Y}^c$, where $j = 1, 2, 3,\ldots, m$; m is the total number of vertical wind direction distances. z_{max} and z_{min} are maximum and minimum in vertical wind distance.

Through the analysis of the EGC location and the atmospheric conditions at a certain time, the leakage source could be tracked. So the movement of EGC should be studied.

2.2. Movement of EGC

2.2.1. Impacts of wind speed and direction

The Gaussian dispersion model is only used for the gas dispersion in fixed wind direction and a fixed speed, while wind is a decisive factor in the distribution of gas cloud location. The wind direction mainly affects the dispersion direction, and the wind speed impacts the moving distance of gas cloud and the mixing speed of combustible gas with air. Therefore, in the process of analyzing the location of EGC, it's necessary to establish a joint distribution of wind speed and direction.

Several probability models of wind speed have been developed (Mazzeo et al., 2017; Huang et al., 2019). With a general assumption that wind direction and wind speed are independent random variables. Wind direction has its own probability density function, and in a certain direction, wind speed follows another distribution.

Table 1
Pasquill-Gifford-Turner classification of atmospheric stability.

Atmospheric stability	σ_x/m orσ_y/m	σ_z/m	Atmospheric stability	σ_x/m orσ_y/m	σ_z/m
A	$0.18x^{0.92}$	$0.60x^{0.75}$	D	$0.06x^{0.92}$	$0.15x^{0.70}$
B	$0.14x^{0.92}$	$0.53x^{0.73}$	E	$0.04x^{0.92}$	$0.10x^{0.65}$
C	$0.10x^{0.92}$	$0.34x^{0.71}$	F	$0.02x^{0.89}$	$0.05x^{0.61}$

Their joint probability distribution model is the product of wind speed and direction.

Gumbel distribution has been found suitable for fitting the extreme value distribution of wind speed, and Weibull distribution is more suitable for average wind speed (Ozay and Celiktas, 2019). In this study, we adopt the Weibull distribution to analyze gas dispersion in different scenarios.

$$P_{u,\theta}\left(U,\theta\right)=P_\theta(\theta)\left\{1-\exp\left[-\left(\frac{U}{c\left(\theta\right)}\right)^{k(\theta)}\right]\right\}$$

$$=\iint f_\theta(\theta)f_{u,\theta}(U,k(\theta),c(\theta))dud\theta \tag{5}$$

$$f_{u,\theta}(U,k(\theta),c(\theta))=\frac{k(\theta)}{c(\theta)}\left(\frac{U}{c(\theta)}\right)^{k(\theta)-1}\cdot\exp\left[-\left(\frac{U}{c(\theta)}\right)^{k(\theta)}\right]P_\theta(\theta)$$

$$=\int_0^\theta f_\theta(\theta)d\theta \tag{6}$$

where $0\leq\theta\leq2\pi$. $P_\theta(\theta)$ is the probability for the wind in certain speed in the wind direction θ. $c(\theta)$ and $k(\theta)$ are scale parameters and shape parameters of Weibull distribution in a certain wind direction. $P_\theta(\theta)$ and $c(\theta)$, $k(\theta)$ are all according to the local statistics of wind speed and direction.

2.2.2. Conversion of global- and local-coordinate systems

We have used a local coordinate system (x, y, z, k), to mark the dispersion, volume, and location of an EGC, where k = 1, 2, 3,. . ., p, and p is the total number of wind direction sample. In the consequence analysis of gas cloud explosion, a global coordinate system is needed for evaluating all leakage scenarios. The conversion between global- and local- coordinate systems is according to the coordinate value of location and wind direction. For example, assume that there is a group of coordinate system. The origin of global coordinate system is (0.0.0), the east is x-axis, the south is y-axis, and the vertical direction is z-axis. Assume that wind is towards west and the leakage point is at (3.10.2). The local coordinate system takes the leakage point as the origin, the west as x-axis, the north as y-axis, and the vertical direction as z-axis. If the center of EGC is at (9.10.3), its corresponding coordinate in the global coordinate system is (−6.0.1), as is shown in Fig. 2.

2.2.3. Consequence analysis of gas cloud explosion

Shockwave overpressure is the main consequence of a gas cloud explosion. We adopt the TNT equivalent method, one of the typical empirical models (Casal, 2018), to convert the destructive effect of a gas cloud explosion into that of equivalent TNT heat. The advantages of this method lie in the simple calculation and easy-to-collect parameters.

The calculation process of the TNT equivalent method is as follow:

(1) The total energy of a gas cloud explosion:

$$E=\alpha W_f Q_f \tag{7}$$

where α is the proportion of flammable gas that participates in the explosion, generally taken as 0.04 (Sellami et al., 2018). W_f is combustible gas leakage quality, kg. Q_f is combustion heat of combustible gas, KJ/kg.

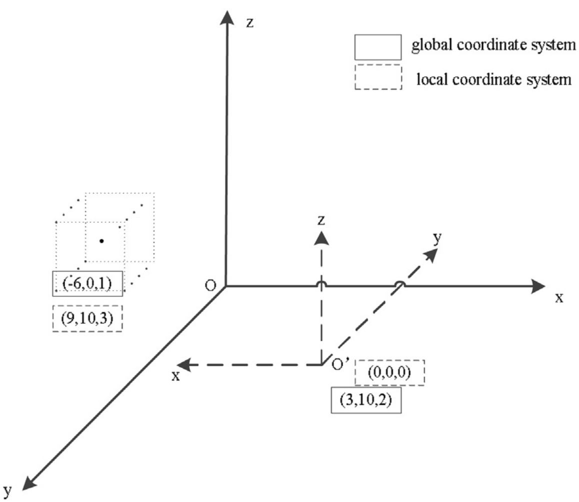

Fig. 2. The conversion between global- and local- coordinate systems.

(2) TNT equivalent of gas cloud:

$$W_{TNT}=E/Q_{TNT} \tag{8}$$

where Q_{TNT} is TNT explosion heat, KJ/kg.

(3) Shock wave overpressure:

$$\Delta P=0.084\frac{\sqrt[3]{W_{TNT}}}{r}+0.27\left(\frac{\sqrt[3]{W_{TNT}}}{r}\right)^2+0.7\left(\frac{\sqrt[3]{W_{TNT}}}{r}\right)^3 \tag{9}$$

where r is distance between EUC and center of explosion, m.

2.3. Flexible alarming mechanism

The initiative of the flexible alarming mechanism to detect basic status signals, compare them with the setting threshold or analyze the trend of the state change. Such a mechanism follows the principle of condition-based maintenance, which is an adaptive triggering mechanism that triggers based on the changes of detected values in different scenarios. If the value of variable exceeds the threshold, it needs immediate measures to control or interfere.

The flexible alarming mechanism based on the following assumptions.

(1) Sensors are evenly laid out in the leakage scenario, mainly based on the alarm threshold requirement of the current specification IEC 60079-29-2-2015.
(2) The main purpose of installing these sensors is to detect the equivalent gas cloud.

Sensors in a GDS can detect the concentration of the gas cloud at different time. The EGC volume will be calculated at different heights under a certain concentration value. 15% of LEL is selected as the detection reference value for flexible triggering. The prediction time T from 15% to 20% of LEL can be predicted by the curve which

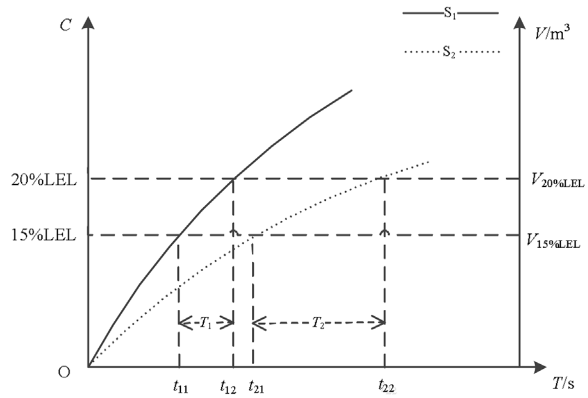

Fig. 3. Schematic diagram of flexible alarming mechanism.

can be fitted from the beginning of leakage to the concentration of 15% of LEL, as is shown in Fig. 3. If *T* is less than a certain time (tentatively 3 s), an alarm occurs. When the number of alarming sensors exceeds 50% of the total amount, the GDS is required to take measures.

As is shown in Fig. 3, S_1 and S_2 represent different sensors respectively. By t_{11} and t_{21}, the detection values of S_1 and S_2 reach 15% of LEL, s. $V_{15\%LEL}$ and $V_{20\%LEL}$ are the volume of EGC when the concentration reaches 15% of LEL and 20% of LEL, m^3. In addition, T_1 and T_2 are the periods required from 15% of LEL to 20% of LEL for S_1 and S_2.

Similarly, the sensor numbered *i*, corresponding to the prediction time is T_i. In the flexible alarming mechanism, if $T_i \le 10$ s, the sensor should raise an alarm. If more than 50% of sensors in the GDS have alarmed, the GDS should take prevention and control measures.

$$P_{N_{T_i \le 10s}} \ge 50\% \tag{10}$$

where P is the ratio of sensors, and N is the number of sensors which alarm occurs.

3. Case studies and results

LNG leakages can occur in terminal stations during reception, storage and external transmission. A LNG terminal station includes the unloading system, storage system, regasification/external transmission system, recovery system for evaporation gas, and other working areas. The work-flow in a LNG terminal station is shown in Fig. 4. Gas leakage from pipelines, tanks, valves or other equipment can form flammable gas cloud, which explodes when encountering the ignition source.

Table 2
Dispersion distance comparison of ALOHA simulation and EGC model.

Wind speed (m/s)	Simulation results		
	ALOHA(m)	EGC model (m)	Error (%)
1	149	148	0.67
2	104	97	6.73
3	85	76	10.59
4	41	42	2.44
5	36	37	2.78
6	19	21	10.53
7	18	19	5.56
8	17	18	5.88
9	16	17	6.25
10	15	16	6.67

3.1. Verification model of EGC

We use EGC to model the gas cloud from a leakage. In order to verify the accuracy of EGC model, we compare the clouds generated with EGC and those by a commonly used simulation software for assessment of leakage of hazardous chemicals, ALOHA (Shao and Duan, 2012). The software includes the database of thousands of chemicals, and is strong in simulating the heat radiation and shock waves generated by gas dispersion, fire, and explosion.

Fig. 4(a)–(c) shows the simulation results of a discharge arm by ALOHA software. The diameter of the leakage hole is 3 cm, leakage speed is about 0.43 m/s, and leakage time is 1 h. Simulation results of dispersion distance of gas cloud are selected when the LEL of LNG (5%) is as the concentration threshold and the wind speed is 1–3 m/s. The results are shown in Fig. 4(d)–(f) are from the EGC model in this paper, with the same leakage parameters. Table 2 compares the results of the two methods. The gas cloud dispersion range is too small if the wind speed is higher than 3 m/s, so the image results are not displayed when using the ALOHA software to simulate the scenario. It can be seen that the difference between the results with same settings is always blow 15%. Therefore, we can have sufficient confidence on the EGC model in the analysis of the gas cloud dispersion (Fig. 5).

3.2. The effect of EGC locations

In comparison with the ALOHA simulation results, for the consistency of expression, the local coordinate system is used, with the leakage point as the origin, the downwind direction is the *x*-axis, the lateral wind direction is the *y*-axis, and the vertical wind direction is the *z*-axis to establish the coordinate system. When analyzing the EGC location, for more intuitive comparison, the global coordinate system should be established with the northwest corner as the origin, east direction as the *x*-axis and west direction as the *y*-axis, and coordinate range is (260.260.22). These two coordinate systems can be converted according to the situation of leakage scenario.

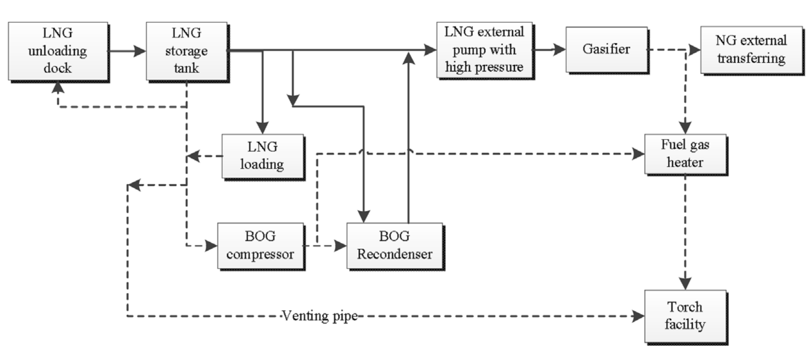

Fig. 4. Flow chart of LNG terminal station.

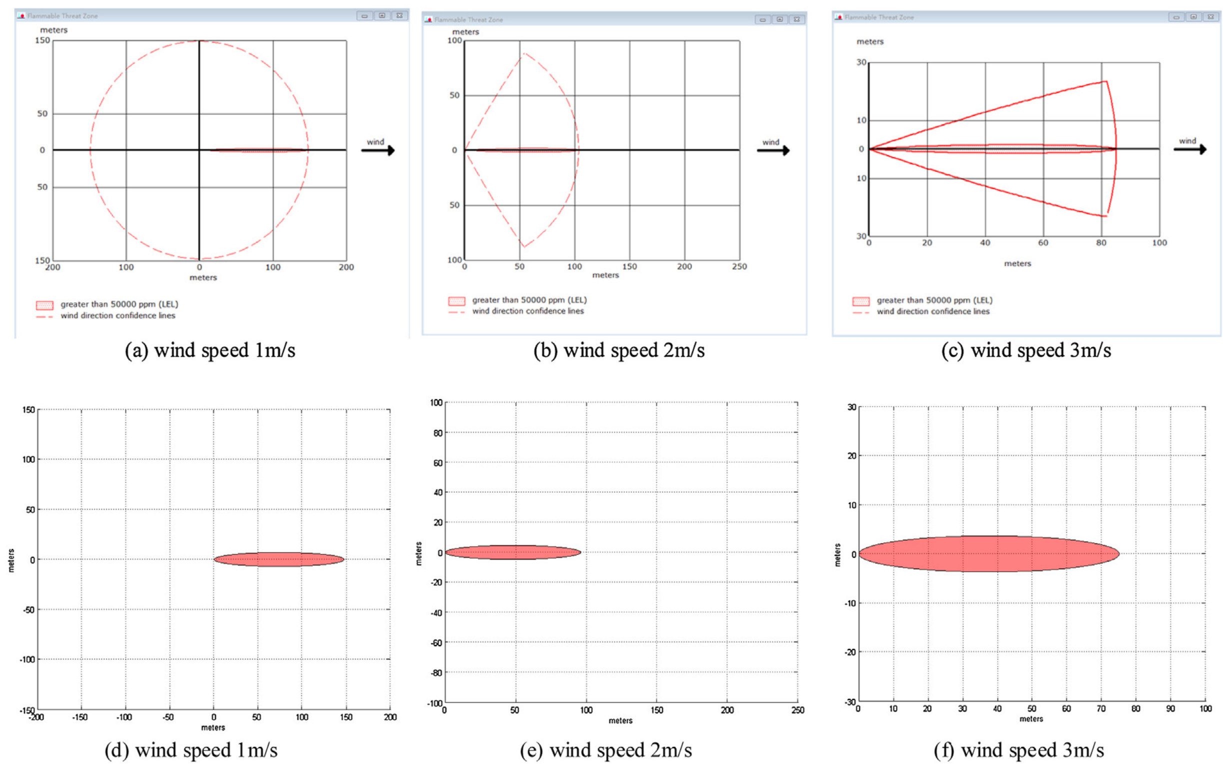

Fig. 5. Dispersion distance comparison of ALOHA simulation and EGC model.

Table 3
EGC location changing and explosion at different wind speeds.

Wind speed(m/s)	EGC location(m,m,m)	EGC volume(m^3)	The distance of EGC center and EUC(m)	Shock wave overpressure(kPa)
1	(156,91,15)	16970.3	98.3	2.57
2	(153,121,12)	5903.4	93.2	1.82
3	(152,131,11)	2513.6	93.6	1.40
4	(151,143,8)	507.3	95.4	0.79
5	(151,145,8)	393.7	95.7	0.72
6	(150,148,6)	94.9	96.5	0.44
7	(150,148,6)	71.1	96.6	0.39
8	(150,148,6)	61.0	96.7	0.37
9	(150,148,6)	46.0	96.7	0.34
10	(150,148,6)	43.9	96.7	0.33

According to the EGC location and volume formulas Eqs. (1)–(4), and the TNT equivalent method Eqs. (7)–(9), the dispersion process of gas cloud dispersion under different wind speeds is analyzed, where the coordinate of leak points is (150.150.1), and the EUC's (center control room) coordinate is (245.130.2).

Table 3 shows the influence of the change of wind speed between 1–10 m/s on the volume and location of gas cloud, where the wind direction is constant. The simulation shows that slower wind speed brings with lower the gas flow rate, and results in larger flammable gas cloud, and higher shock wave overpressure generated. When the wind speed is higher than 5 m/s, the volume of gas cloud is small, and the wind speed has little effect on the location of EGC. Therefore, consequence analysis of gas cloud explosion can focus on the cases when the wind speed is 1–5 m/s.

According to the joint distribution functions Eqs. (5) and (6), the local wind speed has a high probability of 3 m/s. Wind speed is taken as an example to analyze the distribution of EGC location and the impact of shock wave overpressure on EUC in different wind directions. The simulation results are shown in Table 4. It can be seen that the wind direction has a great influence on the position of EGC, which in turn affects the distance between the EGC center and EUC, resulting in different effects of gas cloud explosion on the EUC. Therefore, when being detected by GDS, the local meteorological conditions should be fully considered, so as to protect the EUC.

3.3. *Make triggering flexible*

The gas cloud at different location has different impacts on the EUC, but the triggering mechanism of the GDS is same so far. Here we can check the effects of triggering mechanism.

The sensors in this GDS are laid on a general evenly deployed sensor networks according to the standard IEC 60079-29-2-2015 with a spacing of 15 m. With x = 0, y = 0 as the initial point, one sensor is set every 15 m, and the height of deployment is set to be 15 m, so that the equipment can be completely covered. So the total number of sensors arranged in the scenario is 324. Two sensors are chosen without losing generality, as S_1 and S_2 respectively. The fit curve from the start of leakage to a concentration 15% of LEL is shown in Fig. 7. According to the curve, the time when the concentration reaches 20% of LEL and the corresponding volume of EGC can be predicted.

As shown in Fig. 6, the time required for S_1 and S_2 from 15% of LEL to 20% of LEL is 18 s and 10 s respectively. According to the Eq. (10), it is considered that S_1 will not alarm, but S_2 will do.

Table 4
EGC location changing and overpressure at different wind directions.

Wind direction	EGC location(m,m,m)	EGC volume(m^3)	The distance of EGC center and EUC(m)	Shock wave overpressure(kPa)
N	(152,131,11)	2513.6	93.6	1.40
S	(151,169,11)	2513.6	101.3	1.29
E	(131,148,11)	2513.6	115.7	1.12
W	(169,152,11)	2513.6	79.6	1.65
NE	(137,149,11)	2513.6	110.3	1.18
NW	(151,137,11)	2513.6	94.3	1.39
SE	(149,163,11)	2513.6	102.3	1.27
SW	(163,151,11)	2513.6	84.8	1.55

Table 5
The alarm situation at the same wind direction but different speeds.

No.	When the wind speed is 1 m/s				When the wind speed is 3 m/s			
	Flexible alarming mechanism			Rigid	Flexible alarming mechanism			Rigid
	Predicted time(s)	Proportion(≤10 s)	AlarmYes or no	Detection time(s)	Predicted time(s)	Proportion(≤10 s)	Alarm or not	Detection time(s)
1	12	65%	Yes	14	15	47%	No	18
2	8			9	13			15
3	6			7	7			8
4	9			10	9			11
5	15			18	10			12
6	5			5	12			15
......	......			......	......			......
99	2			3	8			9
100	11			12	13			16

Table 6
The alarm situation at the same wind speed but different directions.

No.	When the wind direction is N				When the wind direction is S			
	Flexible alarming mechanism			Rigid	Flexible alarming mechanism			Rigid
	Predicted time(s)	Proportion(≤10 s)	AlarmYes or no	Detection time(s)	Predicted time(s)	Proportion(≤10 s)	Alarm or not	Detection time(s)
1	9	60%	Yes	11	11	62%	Yes	13
2	8			10	6			7
3	5			5	9			10
4	10			11	8			9
5	12			12	12			13
6	15			15	13			15
......	......			......	......			......
99	8			9	7			9
100	6			8	8			11

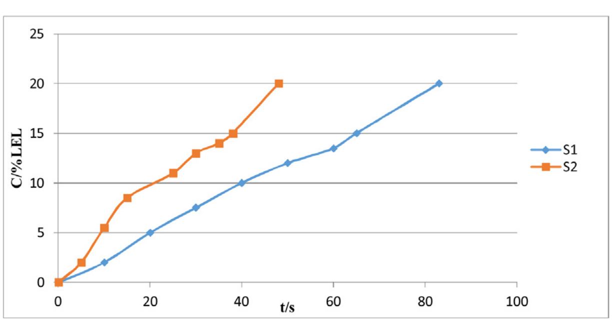

Fig. 6. Fitting curve of detection value of sensors.

100 sensors can be selected from all by using uniform sampling, to analyze the required time to alarm for flexible and rigid triggering mechanism in different wind speeds and directions, as shown in Tables 5 and 6.

Table 5 shows the alarm situation of flexible alarming mechanism at different wind speeds, and the comparison with the rigid triggering mechanism when the wind direction is same. Table 6 shows the situations at the same wind speed and different directions. It can be seen that the wind speed has a greater impact on the alarm situation, while the wind direction has less influence on the alarm situation, but the influence of the gas cloud formed in different wind directions on the EUCs is quite different. The flexible alarming mechanism is more conservative than the rigid one and can avoid redundant measures. The leakage scenario can be regarded as a whole for alarm analysis.

The flexible alarming mechanism can detect the dispersion trend of gas cloud after leakage and realize the control for leakage scenario at a higher level. With the rigid triggering mechanism, there is a possibility that even though each sensor has not reached the preset threshold, the volume of gas cloud may be large enough to have a destructive effect on the EUC. With the flexible alarming mechanism, this problem can be avoided. In addition, the flexible mechanism is more effective in detecting the volume and location of EGC. The center position of EGC is an approximate result by considering the gas cloud concentration distribution and dispersion speed.

In practices, there are many obstacles and different wind directions when the gas disperses. In this paper, the gas dispersion model, EGC, is mainly used to illustrate the flexible alarming mechanism. The flexible alarming mechanism is an adaptive trigger mechanism based on the detection result. According to the detection of GDS, if the alarm occurs, the location of leakage source can be determined by the changing path of EGC, and the atmospheric condition (such as wind speed and direction) at that time. In the future research, more focuses can be on the influence of obstacles.

4. Conclusions and research perspectives

The EGC model is proposed in this paper to capture flammable gas dispersion in view of its complexity and variability. Such a model has certain accuracy compared with the existing ALOHA software simulation results. The volume and location distribution of EGC are obtained under the influence of wind speed and direction. Based on the TNT equivalent method, the effects of EGC volume and locations on the EUCs are obtained.

GDS is used to detect the gas cloud formed by gas leakage, and a flexible trigger mechanism is proposed to optimize the operations of sensors. The volume and location of EGC is as the theoretical basis for the flexible triggering of GDS. Compared with the rigid trigger mechanism, the flexible detection mechanism requires shorter detection time and lower gas concentration, so it has the advantage of flexibility, more timely and accurate detection to optimize the alarm threshold. According to the current standard, the threshold concentration of the flexible trigger is formulated as the design input of the sensor. The flexible trigger mechanism is as an alarming threshold optimization scheme, which can reduce the risk of gas leakage and explosion, and optimize the alarming threshold as part of GDS detection optimization.

The contribution of this methodology is proposing the flexible alarming mechanism based on the EGC to optimize the current one. There is no fixed detection threshold, it can adapt to different scenarios. The detection time can be reduced and the invalid alarms and feedback can be avoided. The prediction time of gas concentration changing is required, and whether to alarm or not can be determined based on the prediction result.

Explosions of various gas clouds have very different effects on the EUCs, and the location of EGC is greatly affected by external influences, and thus the future studies should pay more attention to the influences of factors on the EGC model. Uncertainty in gas cloud should be analyzed quantitatively, to enhance the accuracy of EGC, so that it can represent as many scenarios as possible.

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