REVIEW ARTICLE

A Critical Review of a Computational Fluid Dynamics (CFD)-Based Explosion Numerical Analysis of Offshore Facilities

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Abstract

In oil and gas industries, the explosive hazards receive lots of attention to achieve a safety design of relevant facilities. As a part of the robust design for offshore structures, an explosion risk analysis is normally conducted to examine the potential hazards and the influence of them on structural members in a real explosion situation. Explosion accidents in the oil and gas industries are related to lots of parameters through complex interaction. Hence, lots of research and industrial projects have been carried out to understand physical mechanism of explosion accidents. Computational fluid dynamics-based explosion risk analysis method is frequently used to identify contributing factors and their interactions to understand such accidents. It is an effective method when modelled explosion phenomena including detailed geometrical features. This study presents a detailed review and analysis of Computational Fluid Dynamics-based explosion risk analysis that used in the offshore industries. The underlying issues of this method and current limitation are identified and analysed. This study also reviewed potential preventative measures to eliminate such limitation. Additionally, this study proposes the prospective research topic regarding computational fluid dynamics-based explosion risk analysis.

1 Introduction

There are lots of accidental scenarios in the oil and gas industry, but the most devasting accidents are fires and explosions that occur on offshore facilities. The injuries and property damage from an incident of this nature are extreme and can have long-term consequences [1]. The most severe recorded offshore incidents are the Piper Alpha accident, which occurred on 6 July 1988, and the Deepwater Horizon accident which occurred on 20 April 2010. Piper Alpha was an oil production facility in the North Sea, which consists of four separated modules. Some malfunctioning parts and a small gas leak which ignited under pressure caused an

explosion and the resulting oil and gas fires killed 167 people and caused damage of US$3.4 billion. At the time of the disaster, Piper Alpha provided about 10% of North Sea oil and gas production, and the accident was the worst offshore oil disaster in terms of loss of lives and economic damage [2–5]. In addition, Deepwater Horizon is the most recent explosion accident in the offshore industries. The accident not only caused an explosion in the topside area but also resulted in oil release for several months. The oil spill reportedly continued for 3 months after the explosion, and over 4.9 million barrels of oil were released [6–8]. Therefore, the extensive research regarding the evolution of major disasters and hazard evaluation is required for the safety of such facilities.

The purpose of risk assessment is to offer required information for the safety design and let operators recognize the significance of potential risks which consist of issues such as structural damage, failure, financial loss and injury. To understand such risks and reduce those possibilities, systematic investigation for managing risks effectively is required throughout the life cycle of the target structure. For successful explosion risk management, at first, the most possible explosion risk scenarios during a project's life cycle should be assumed based on the statistical data or historical cases, and then the consequence of potential hazard is calculated. The computational fluid

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dynamics (CFD) simulation is one of the most frequent and reliable approach for predicting specific explosion circumstances since its numerical models can be applied specifically considering detailed geometries and environmental conditions like turbulence effect by obstacles on the consequence of explosion incidents [9, 10]. A lot of oil and gas projects have been used the CFD method to predict the explosion scenarios and the extent of damage by them [11–13]. However, there is large variability due to the uncertainties which are normally related to lots of parameters including randomness and probabilistic feature. Therefore, it is the most important task to select the reliable scenarios which can represent the real situation.

In general, a few unfavourable cases or a single scenario is used in current oil and gas industries. There are several reasons for assuming such a scenario, it could be to get more efficiency in time and cost aspects, or to pursue more conservative design by reflecting the most unfavourable case. Although such an approach could be more proper in some projects, it is required to establish a set of realistic explosion cases that can represent most possible incidents but with limitative cases to prevent overlooked cases and overestimated design [14, 15]. When considered the explosion cases, many parameters should be used, such as leak profile, wind information, gaseous materials, and the geometries, so the suitable model involving such conditions is required.

There are several substitutes for that, but the Floating Production Storage and Offloading (FPSO) facility is one of the best target models when considering its structural functionality, vulnerability and properties all against possible explosion events. FPSO structures are equipped with many installations and systems for oil and gas production in limited space, and even generate lots of flammable gaseous material during operation. Because of such a complexity, more variables and correlation between them must be considered than onshore plant generally employing the simplified gas dispersion and explosion models [16–21].

Since the modelling process have an effect on the Explosion Risk Assessment (ERA) results, explosion risk information must be handled by considering the nature of relevant parameters and all condition regarding the target structure. Common sense in ERA is to assess the performance criteria and corresponding explosion design loads based on the overpressure or drag pressure which can be generated by explosion ignition [22, 23]. This is because explosion wave pressure is the most detrimental threat to structural stability. It can be characterised by a time-varying pressure and its duration, and the interaction of explosion waves and the structure is the main cause of partial or global structural failure. The explosion wave is a time-dependent load, so its influence on the physical behaviour of structures is totally different from static problems. Therefore, the influence of several factors associated with explosion load-time profiles

on the structural response should be extensively investigated considering not only static and dynamic analysis, but also linear and nonlinear analysis [24].

The typical methods for measuring explosion loads could be divided into two approach, correlation model based on experimental results (TNT and multi-energy theory) and numerical model based on Computational Fluid Dynamics (CFD) simulations. CFD methods can not only reflect lots of parameters and information regarding explosion phenomenon, but also do numerous analyses with little efforts, so it is normally regarded as preferable and practical in ERAs, rather than correlation model-based approach when analysing potential explosion events with a great number of scenarios [25].

CFD approaches can provide the potential to develop a comprehensive and accurate interpretation of an explosion load, but it is impossible to consider all possible scenarios due to the relatively high associated computational cost. Thus, it has simplified assumption and approximations based on probabilistic approaches to keep the number of possible scenarios manageable [26]. Although there are many guidelines or rules for structural design against explosion loads, very limited design codes are only available. That means current methods regarding ERAs include lots of uncertainties [27–29]. The objective of the present paper, therefore, is to review comprehensively from the phenomenological analysis of an offshore explosion to the current application/limitation and future study direction.

2 Background

2.1 Explosion Risk Analysis of Offshore Facilities

An explosion accident is a potential hazard that can lead to very destructive damage of the total system. Particularly in the oil and gas industry, explosion risk analysis (ERA) is compulsory in the design stage since the entire system in an offshore facility is exposed to hazardous and flammable hydrocarbon materials. The main purpose of ERA is to identify and mitigate vulnerable members in the target system that could lead to fatal damage if exposed to an unexpected situation. An explosion event occurs through accidental release of gaseous materials into the area followed by an ignition source. Therefore, ERA for such a target should take into account a series of events associated with the explosion like gas leak, dispersion and ignition. Based on the principle of quantitative risk assessment, it is possible to systematically identify events for that issue [30]. But the ERA is usually performed in a probabilistic manner since there are a great number of scenarios together with geometries or operational conditions.

The basic concept of the probabilistic ERA is to use the computational fluid dynamics (CFD) methodology. By using

CFD, it is possible to consider relevant factors involving their probability or frequency distribution with possible scenarios. Although there are almost infinite scenarios in the real world, fewer practical scenarios are used in the CFD. But reasonable scenarios can be used by dividing the possibility of real values into several intervals, and then selecting representative data at each interval. In this way, gas dispersion or explosion scenarios including hazard elements can be established, and then potential explosion wave pressure data caused by explosion ignition can be derived.

Figure 1 shows the schematic overview for ERA using CFD methodology. As described in the figure, it is divided into two categories according to the distribution of the gas cloud. The first section focuses on deriving the probabilistic distribution by considering the combination effect of gas dispersion analysis and its probability investigation. Leakage cases as the initial event should be studied based on the probabilistic approach, and then the frequency of established leak scenarios should be computed considering any relevant factors like wind direction, leak rate and distribution [31–33]. Ventilation analysis should be carried out prior to gas dispersion simulation to get the flow geometries influenced by wind conditions [34]. In the second part, explosion overpressure is assessed using the exceedance curve which consists of frequency distribution and the pressure range. It is normally used in the explosion-resistant design stage to determine the explosion design load.

2.2 Hazard of Offshore Explosion: Learnt from Accidents

Oil and gas industries and offshore facilities workers must take extreme precaution during all process of the drilling operation to prevent undesired situation. Even trivial design errors or mistakes can lead to a catastrophic blowout. Especially, explosion accidents that occur on offshore facilities are some of the most devastating cases that can occur [36]. The most severe recorded offshore incidents are the Piper Alpha accident, which occurred on 6 July 1988, and the Deepwater Horizon accident which occurred on 20 April 2010. Figures 2 and 3 show the aftermath from the accidents [37]. Other than that, there have been several explosion accidents in the history of offshore industries. The following sections describe the details of representative explosion related accidents, and Table 1 summarizes the explosion accidents that occurred in offshore platforms.

Fig. 1 Schematic overview of typical ERA based on CFD method [35]
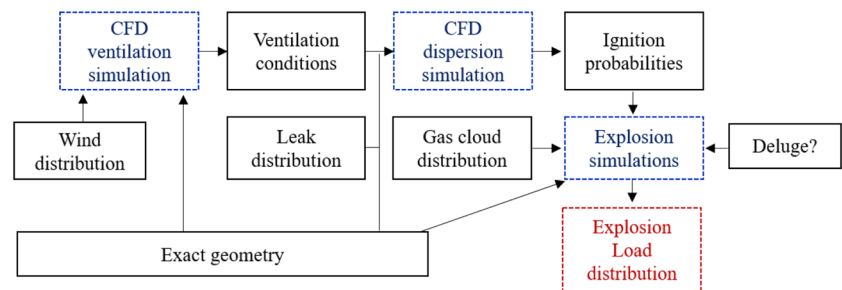
Fig. 2 Major explosion accidents in the oil and gas industries **a** Piper Alpha **b** Deepwater Horizon

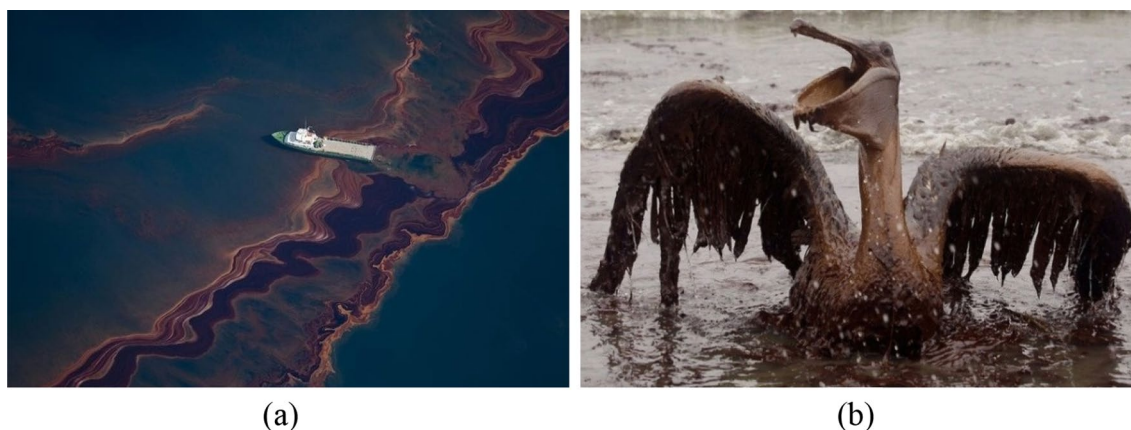(a)   (b)

Fig. 3 Aftermath from the disaster **a** marine pollution by oil spill **b** seabird losses from oil spill

2.2.1 Piper Alpha

Piper Alpha was an oil production facility in the North Sea, which consists of four separated modules. It was situated on the Piper oilfield, approximately 193 km northeast of Aberdeen, Scotland. It began production in 1976, operated by Occidental Petroleum Limited [38]. At first, it was an oil-only platform but later changed to add gas production module. For worker health and safety, the most dangerous operations were distant from the residence district. However, the process of converting the facility from oil to gas broke this safety doctrine, considering the other concept that sensitive areas should be located together. As a result, the gas compression caused this tragic accident.

On 6 July 1988, some malfunctioning parts and a small gas leak which ignited under pressure caused an explosion and the resulting oil and gas fires killed 167 people and caused damage of US$3.4 billion. At the time of the disaster, Piper Alpha provided about 10% of North Sea oil and gas production, and the accident was the worst offshore oil disaster in terms of loss of lives and economic damage. There are several reasons for the catastrophic outcomes. Most manager who had the authority to order evacuation were killed by the first explosion, and the platforms continued to pump oil and gas to Piper Alpha until the second explosion happened. The worker who saw that Piper Alpha was burning could not do anything because the worker thought they did not have authority to shut off production, even in such an urgent situation [39, 40].

2.2.2 Deepwater Horizon

Deepwater Horizon is the most recent explosion accident in the offshore industries. The accident not only caused an explosion in the topside area but also resulted in oil release for several months. It was wrapping up the well and was in the final stages of completion. An explosion of seawater from the drilling riser was occurred and the erupted seawater was followed by a combination of mud, flammable gas and water. As a result, several explosions took place on the platform. At the time of the explosion, there were 126 crew on board. Eleven workers were presumed to have died during the initial explosion. The rig was evacuated, with many workers airlifted to receive an emergency medical treatment. The burning continued for about 36 h after the first explosion, and then Deepwater Horizon sank two days later, on 22 April 2010. The remains of the rig came to rest on the seafloor at a location approximately 1500 m deep, and about 400 m from the northwest of the well. The oil spill reportedly continued for 3 months after the explosion, and over 4.9 million barrels of oil were released [41]. On 15 July 2010, the wellhead was finally capped. As well as the deaths and injuries of the crew, the released oil had an extremely negative effect on surrounding area, wildlife and coastal ecosystem. During the clean-up work, the coastline was closed, and a range of ships, barriers and many other methods were used to stop the spill from spreading. However, despite concerted efforts, it was estimated that over 450 km of the Louisiana coastline had ultimately been affected [42].

In January 2011, the oil spill commission team in the US White House released their report on the causes of the Deepwater Horizon accident. The report stated that the companies involved in the Deepwater horizon project had not taken measure to provide safeguards against an incident of this nature happening. The report also showed a chart on the correlation of decisions which possibly saved time and money but increased the risk to the crew aboard Deepwater Horizon [43].

Table 1 Representative offshore oil and gas fire/explosion accidents

Year	Location	Description	Consequence	References
1969 (The Santa Barbara Oil Spill)	The coast of Santa Barbara, CA, USA	the well blew out, spewing oil and gas. The explosion cracked the sea floor in 5 places and released 1000 gallons of oil an hour	Killed 3500 sea birds and marine animals	[44]
1980 (The Alexander L. Kielland Disaster)	The Ekofisk field, 235 miles east of Dundee, Scotland	The platform capsized after the failure of one of the bracings attached to one leg of the five-legged platform structure after strong winds created waves of up to 12 m-high on the day of the accident	Killed 123 people	[45]
1984 (Enchova Central Platform Disaster)	The Campos Basin near Rio de Janeiro, Brazil	The accident occurred due to a blowout, which caused a fire and explosion at the central platform of the Enchova field operated by Petrobras Another disaster struck the Enchova platform on 24 April 1988 as one of its 21 wells blew out and eventually ignited	Killed 42 people	[46]
1988 (Piper Alpha Explosion)	The North Sea, UK	Malfunctioning parts and a small gas leak which ignited under pressure caused an explosion and the resulting oil and gas fires and serial explosions were occurred on the platform	Killed 167 people, loss of US$3.4 billion	[38–40]
1989 (Seacrest Drillship disaster)	The South China Sea, 430 km south of Bangkok, Thailand	The drillship was capsized by the Typhoon Gay, which produced 40ft-high waves on the day of the accident The ship also had 12,500ft of drill-pipe in its derrick, which was believed to have resulted in an unstable high centre of gravity	Killed 91 people	[47]
2005 (Mumbai High North explosion)	The Arabian Sea, around 160 km west of the Mumbai coast	Mumbai High North, one of the producing platforms of the Mumbai High field owned and operated by India's state-owned Oil and Natural Gas Corporation (ONGC), caught fire after a collision with the multipurpose support vessel (MSV) Samudra Suraksha. The resultant gas leakage led to ignition that set the platform on fire. Heat radiation also caused damage to the MSV and the Noble Charlie Yester jack-up rig engaged in drilling operation near the platform	Killed 22 people Significant oil spill and a production loss of 120,000 barrels of oil and 4.4 million cubic metres of gas a day	[48]

Table 1 (continued)

Year	Location	Description	Consequence	References
2010 (Deepwater Horizon explosion)	The Gulf of Mexico, 64 km southeast off the Louisiana coast	An explosion of seawater from the drilling riser was occurred and the erupted seawater was followed by a combination of mud, flammable gas and water. As a result, several explosions took place on the platform. The oil spill reportedly continued for 3 months after the explosion, and over 4.9 million barrels of oil were released. As a result, about 450 km of the Louisiana coastline had been contaminate	Killed 11 workers; injured 17 others	[41]
2012 (Chevron Nigeria Oil rig fire)	10 km off the coast of the African nation	A major buildup of gas pressure from drilling have resulted in an explosion, and a fire was burning for 3 days	Killed 2 people	[49]
2015 (Petrobras oil rig explosion)	120 km off the coast of the state of Espirito Santo	The explosion was caused by a gas leak on board the Cidade de São Mateus, a floating oil production, storage and offloading ship (FPSO)	Killed 5 people; injured 25 others	[50]

3 Current Applications of Explosion Risk Analysis

Hydrocarbon explosions and relevant hazards like fires, blasts and heat are the most frequent accidents that could be occurred in offshore structures. The purpose of explosion risk analysis is to offer required information for safety design and let operators recognize the significance of potential risks. To understand the explosion risk, the systematic investigation of the risk factors from such a hazardous phenomenon is needed to be performed. This section describes the mechanism of an explosive ignition and the influence of explosion risk parameters on structural elements through the literature.

3.1 Explosion Phenomena

A gas explosion is regarded as an action in which the burning of gaseous materials, that is, combustible substances, cause a dramatic increase of pressure. It is a very complex phenomenon with several spatial and time issues as well as powerful gradients of field variables such as fluid density, velocity, temperature, and pressure. Gas explosions can occur almost anywhere if combustible substances are present, which could be inside process equipment, buildings, or offshore platform as well as open and unconfined process area. The level of explosion impact is related to the flame speed and the quantity of released waves from the ignition source [51]. Once an explosion occurs in a certain location, explosion pressure waves are produced, and the pressure build-up can damage not only personnel and facilities but also the environment and ecosystems.

When ignition is occurred, two types of the blaze, deflagration and detonation are generated. The difference between them is the speed of the blaze. The deflagration occurs at subsonic speed (1–1000 m/s), and pressure can be increased, up to 5 times higher than the initial value, while the detonation mode propagates at supersonic speed (1000–3500 m/s), and its peak pressure can increase to more over 20 times higher than the earlier pressure [52]. Therefore, detonation can create a much more dangerous situation.

Gas explosions are also classified as either confined or unconfined. If the gas cloud is located in an unconfined area, the explosion pressure can be negligible. However, in a confined situation, there is no venting and heat loss or very little relief of the explosion wave propagation, and the overpressure can be high. The detonation mode in a confined area is clearly the most dangerous situation. A gas explosion is very sensitive, its severity is dependent on many factors, making it difficult to estimate the consequences of each explosion case.

3.2 The Amplitude–Frequency Relation of Explosion Loading

In an explosion, a great amount of energy is released in several forms like high temperature, fire, shock wave and gaseous materials. All of them are harmful for structures, but the explosion shock wave accompanying high pressure and large impulse is regarded as the most dangerous in an explosion [53]. The explosion pressure, commonly called overpressure, is expressed relative to ambient pressure rather than an absolute value. In an offshore facility, structural failure may lead to environmental destruction, like the aftermath of the Deepwater Horizon accident. Therefore, a firm understanding of explosion wave load is required. Figure 4 shows the typical pressure–time history which can appear in an explosion event with the distribution of amplitude and frequency for several load cases. As described in the Fig. 4, the explosion pressure–time curve indicates a step rise in pressure from barometric pressure P_0 to the maximum, P_m, followed by a dramatic decrease in value during a duration time of positive pressure phase (t_p). The second peak is related to the negative pressure wave from the obstacle. The pressure then reduces to below atmospheric point over a period t_n, which is called the negative phase duration. Finally, pressure returns back to usual as the shock wave passes by. This type of pressure–time curve can be measured in detonation mode, where the maximum overpressure can be high as 15–18 bar [54, 55].

The explosion wave clearly has a much higher amplitude than the other cases. Although wind load is also included in high amplitude in some cases, its frequency range is very small. Generally, higher amplitude has a more severe effect on structural damage or deformation. However, frequency is also an important factor in damage and deformation aspects. Resonance is a good example related to frequency. Resonance is a phenomenon caused by an external force which can drive another structural system to oscillate with bigger amplitude at specific frequencies. This phenomenon normally occurs when the natural frequency of a structure is in accord with the external force duration. Under this condition, large amplitude oscillations can be generated despite small periodic forces. As described in Fig. 4, explosion wave load has a large frequency range from low to very high frequency. Therefore, structural response analysis based on the extensive scope of the amplitude–frequency relation is required. The relevant analyses considering the effect of explosion loads on structural damage would be reviewed in the next section.

3.3 Structural Damage Analysis Under Explosion Loading

An explosion wave profile is characterized by a time-varying pressure and its duration, and the interaction of explosion pressure wave and structural elements is the main cause of partial or global structural failure [56, 57]. Therefore, the input properties for an explosion wave profile are the deterministic factors which can directly influence on how the structure would be deformed. Basically, a number of parameters could be influenced on the feature of explosion wave properties, like explosion source, standoff distance, geometrical condition, as so on [58–60]. Therefore, the amplitudes and the frequencies of explosion load are varied, a series of analyses considering such variables are required to investigate the structural responses under explosion loads. Table 2 summarises the relevant research found in the literature for using methods, studied parameters, and main findings.

Experimental research has been conducted to investigate the explosion resistance for composite materials with a different laminate condition by Refs. [61, 62]. These studies reported the effectiveness of laminate on blast resistance, and also describes the optimal location of the laminate against such a loading condition. Cai et al. [61] found the influence of UHMWPE layer location on the interaction of the stress waves between the faces of multi-layered core. This paper described the mechanism of penetration of blast waves and fragments through the multi faces, thereby analysing the level of local bending deformation on each side.
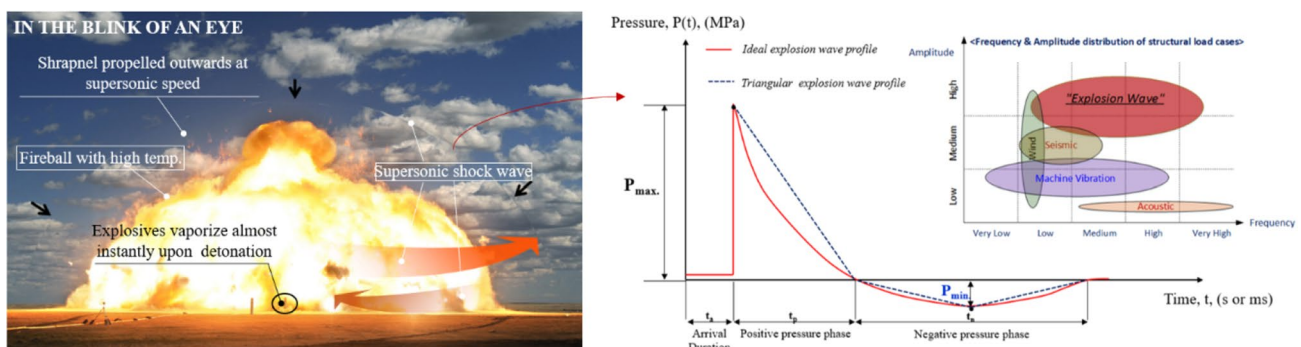

Fig. 4 Typical explosion pressure–time history characteristics produced by an explosion

Table 2 Structural damage analysis considering blast loads in literature

References	Method	Studied parameters	Main findings
Cai et al. [61]	Experimental	The effect of combined blast and fragments loading, laminate location, foam core gradation, ceramic fiber felt, and refractory interlayer	■ The dominant failure modes of the front faces and foam layers ■ The better position of the laminate against combined loads ■ The trivial effect of foam core gradation in failure modes ■ Weakened blast performance by ceramic fiber felt ■ The effectiveness of UHMWPE laminate on blast resistance
Chen et al. [62]	Experimental	The effect of PVB-laminated glass, TNT charge, standoff distance	■ Typical failure modes and structural dynamic response characteristics ■ The influence of negative blast loading and recovery force on displacement ■ The overestimation of current blast resistant design approaches
Zhao et al. [65]	Numerical/theoretical	The effect of concrete type, TNT charge, slab thickness, compressive strength, and dynamic increase factor	■ The relationship between damage modes and TNT charges ■ The feature of crack distribution and damage mode with thickness changing
Yang et al. [66]	Numerical	The effect of the CFRP strengthening schemes, the CFRP cloth thickness, stand-off distance, and TNT weight	■ Damage prediction of an RC tunnel by non-contact underwater explosions ■ The influence of the CFRP cloth on the blast resistance of the underwater tunnel ■ The mitigation effects by geometry conditions of the bonded CFRP cloth ■ The optimal thickness of the CFRP cloth
Choi et al. [67]	Experimental/numerical	The effect of pre-stress, concrete rebar, strain rate, acceleration behavior, standoff distance and crack patterns	■ Better shear resistance of prestressed concrete specimens. ■ The effect of rebar for blast-resistance ■ The pattern of flexural and shear macro cracks of target specimens ■ The results of damage assessment depending on blast load types, structural condition, material types, etc.
Kang et al. [68]	Numerical/theoretical	The effect of blast loading application methods, geometrical characteristics, strain rate, simplified pressure–time curve	■ The features of blast wave in congested geometry condition ■ The comparison results of structural response and plastic strain according to loading condition ■ The conservativeness of conventional blast design load assumption
Shi et al. [63]	Numerical/theoretical	The effect of geometry regarding corrugation, load types, strain rate, overpressure, and impulse	■ Pressure-impulse diagram combining shear rupture, bending and buckling failure ■ The influence of corrugated panel on structural damage ■ The effectiveness of SDOF model application
Syed et al. [64]	Numerical/theoretical	The effect of stainless steel blast wall, scale distance, TNT charge, SDOF model, peak pressure and impulse	■ Pressure-Impulse diagram regarding blast load parameters with structural responses ■ The damage patterns for the blast wall under considered loading conditions

The damage analysis using P–I diagram has been studied by Refs. [63, 64]. Shi et al. [63] found an analytical equation for the P–I diagram which combines shear rupture, bending rupture and buckling failure, and a series of analyses were conducted to assess the effect of the configuration of corrugated panels on the P–I diagram. As a result, they provided a parametric design guidance of corrugations in early design phase against potential explosion cases. Syed et al. [64] presented the P–I curves as a rapid assessment tool which can be used instead of nonlinear structural analyses for typical blast walls consisting of stainless-steel material, so that those curves can be effective on designing or

damage assessment of offshore blast walls considering possible explosion loadings.

Other literatures [65–68] have been focused on analysing the characteristics of structural dynamic responses like failure pattern, deformation, or crack criteria by using numerical model and then comparing with theoretical model. As an example, single degree of freedom (SDOF) model is normally used in such studies to verify the suitability of developed numerical models.

4 Methodologies for Explosion Modelling

Four different analysis methods are introduced in this section. Correlation models generally use the results obtained by experiments. Two representative methods (TNT and multi-energy theory) commonly used in the industry are discussed. Furthermore, experimental model and CFD numerical model are also described in detailed.

4.1 Correlation Model

4.1.1 TNT Equivalent Method

TNT equivalence is generally used to express the energy released by an explosion. The relationship between the weight of TNT charge and the distance from the ignition is considered. The diagram for TNT detonation has been used to estimate the gas explosion magnitude, even though there are differences between them [69]. The pressure generated by gas explosion is much lower than TNT detonations, and even the pressure decay from TNT is much more rapid compared to a gas explosion [70]. Nevertheless, the reason for using this method is to predict peak pressure from a gas explosion. The TNT model uses a pressure-distance diagram to transform the maximum overpressure of gas explosions, and the equivalence of TNT charge is calculated from the energy content in the ignited gas cloud volume [71]. To find the mass of TNT equivalent to the mass of hydrocarbon in the cloud, the following equation can be used:

$$W_{TNT} \approx 10 \cdot \gamma \cdot W_{HC}, [kg] \tag{1}$$

where W_{TNT} is the mass of TNT, γ is a yield factor ($\gamma = 3 - 5\%$), and W_{HC} is the actual mass of hydrocarbons in the gas cloud. The number 10 indicates that most hydrocarbons have ten times higher combustion heat than TNT. For military purpose, ample tests of TNT have been performed by many researchers. As a result, a great amount of data was obtained, explosion wave properties like overpressure, phase duration time and impulse can be described by using the scaled factors. These factors are for an explosion of ground level, and negative pressure influence on

the total overpressure. The scaled factors are described in Table 3. For convenience of calculation, the scaled factors are described using the below equation developed by Brasie and Simpson [72]:

$$log_{10}(z) = 0.082(log_{10}P_0)^2 - 0.529log_{10}P_0 + 1.526 \tag{2}$$

where P_0 is the maximum pressure in bars. This formula is only used when the maximum value is included in the range of 0.01 to 1 bar. In the original TNT equivalency model, however, the geometry was not considered. Therefore, in order to reflect the geometrical effects in the TNT model, another equation was proposed by Harries and Wickens [73]. The yield factor was increased to 0.2 and the weight of hydrocarbon was to accord with the weight of gas in the severely congested area. In case of natural gas, the equivalent TNT mass can be calculated using the following equation:

$$W_{TNT} \approx 0.16V_{eff}, [kg] \tag{3}$$

where $V_{eff} = min(V_{con}, V_{cloud})$ indicates the smaller of either the total volume of the congested part or gas cloud volume.

4.1.2 Multi-energy Method

The multi-energy method proposed by van den Berg [74] is normally used to predict the level of gas explosion with variable strength. It estimates that only part of the gas cloud would contribute to the blast. The reason for this assumption is that an unconfined gas cloud only has a small effect on increasing pressure, and the level of confinement is regarded as the most important factor for increasing the overpressure. In the numerical analysis for this technique, the generation condition of explosion wave is regarded as formulaic type. It is only ignited at the central position in the spherical cloud with constant flame speed. There are two variables in the formula: a combustion-energy scaled distance and the strength of the explosion. The scaled distance, R_{ce}, can be defined as:

Table 3 The scaled factors in TNT method

Scaled factors	Equation
Scaled overpressure	$P_s = P_o/P_a$, (P_o: Peak over pressure, P_a: Ambient pressure)
Scaled positive phase duration	$T_d = \frac{t_p}{W^{1/3}}$ (t_p: Positive phase duration)
Scaled arrival time	$T_a = \frac{t_a}{W^{1/3}}$ (t_a: Arrival time)
Scaled impulse	$i_s = \frac{i_p}{W^{1/3}}$ (i_p: Positive phase impulse)

$$R_{ce} = R_0/(E/P_0)^{1/3}, \text{[m]} \tag{4}$$

where R_0 is the distance from the ignition centre, E is the total combustion energy and P_0 is the barometric pressure. Most hydrocarbon type materials have similar total amount of energy, therefore the total combustion energy can be calculated by the following equation.

$$E \approx 3.5 V_{cloud}, \text{[MJ]} \tag{5}$$

The extent of the explosion impact is considerably different according to the position of ignition source. The charge strength is expressed using a number from 1 to 10, where 10 denotes a detonation mode.

A correlation for the charge strength has also been proposed, based on the three factors of the volume blockage ratio (B_r), the flame length (L_f) and the average obstacle size (O_s) [75]. This approach also considered not only the scale of the situation but also the fuel type by using the laminar combusting velocity (V_l) and a scale factor (D). The correlation is:

$$P_{CS} = a\left[\frac{B_r \cdot L_f}{O_s}\right]^b V_l^{2.7} D^{0.7} \tag{6}$$

When it comes to offshore structures, another researcher [76] has proposed a method for determining the charge strength using three variables:

- Congestion: If congestion level is over the 30% of the limitation, it can be regarded as "High".
- Ignition source: Low in spark and hot surfaces, High in naked flames and welding.
- Parallel confinement: Low for granted decks, High for plated decks.

4.2 Experimental Model

The test method is the most accurate method for generating an explosion consequence database if all the variations in environmental conditions and operational systems in target structures can be reflected. However, explosion tests have many constraints such as space limitations, safety issues and excessive cost. Therefore, laboratory scale tests are normally performed to compare to computational simulation results. Some experimental studies for gas explosion are introduced as follows. Gieras et al. [77] carried out a lab-scale experiment on methane gas explosions. Figure 5 shows the test apparatus of this study. A chamber which has a 40-dm³ volume with 140 mm in diameter and 441 mm in height was used and the initial gas temperature inside the explosion chamber was varied, at 297, 373 and 473 K. A pressure gauge and temperature sensor were attached to the chamber's outer surface.

Jingde et al. [78] tested vented gas explosion with different separation gaps between tanks. Explosion-proof fans were used to mix the methane and air. The pressure measuring range is from zero to 150 kPa. Several pressure sensors were installed on the tank wall in order to measure internal pressure, while two other sensors were mounted on the neighbouring tanks for external pressure. The ignition system was remotely controlled, and only the ignition scenario in the central area was considered. Figure 6 shows the explosion testing equipment.

4.3 CFD Numerical Model

Computational fluid dynamics (CFD) analysis is a useful and effective method, which can describe the circumstance related to engineering phenomena including detailed
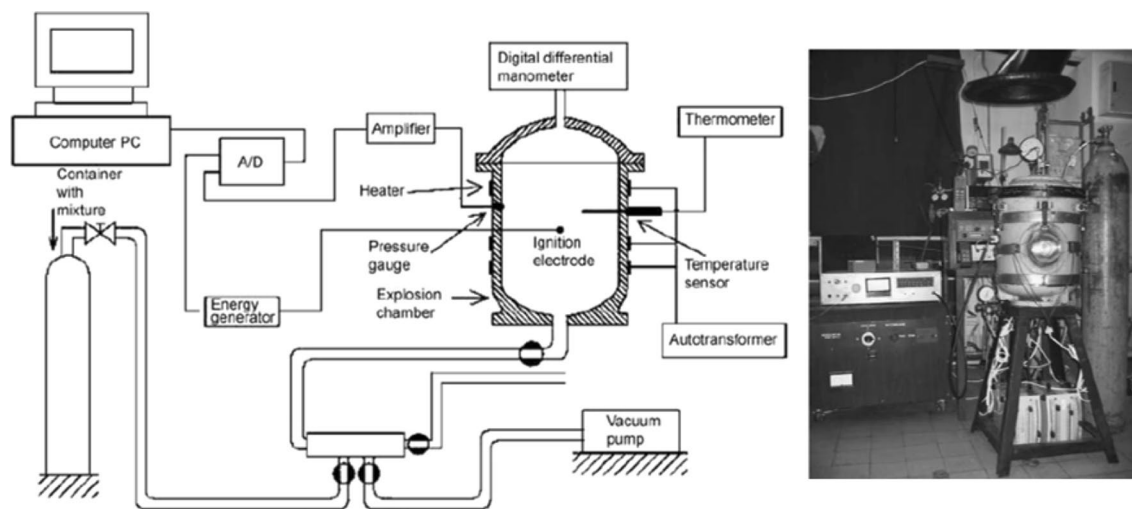

Fig. 5 General view of 40 dm³ explosion chamber and layout of the test facility [77]
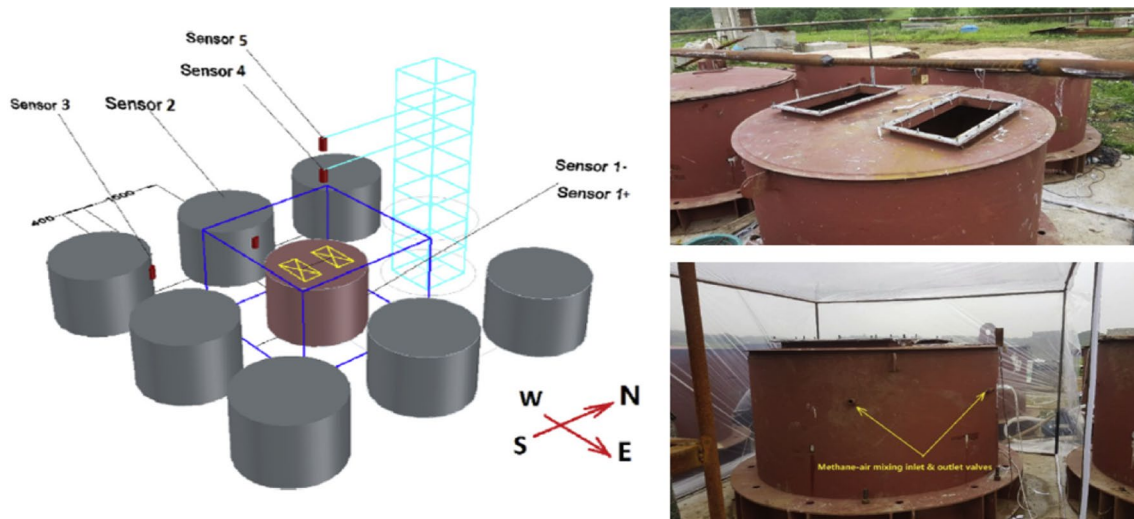
Fig. 6 The explosion test set using a series of tank groups [78]

geometrical condition. The main objective of such an analysis is to compute the numerical solutions using relevant governing equations for the phenomenon. To obtain the computation results, a series of mathematic techniques are required taking into account space and time domains. Through the discretisation process, several coupled algebraic equations are generated, and then they are applied to each sub-domain. Therefore, the outputs obtained by CFD model mean a great deal of information about the phenomenon.

In general, CFD analysis is widely used to model an explosion event and calculate the explosion wave loads. It can not only investigate many different scenarios but can also repeat the same analysis with little extra effort. The consequence of a gas explosion depends on many variables, but explosion simulation using a CFD model can reflect this complexity with more realistic and accurate input data. In addition, the complex geometries can be designed by importing the 3D-objective model. Table 4 describes the features of the representative CFD codes. While there are a variety of CFD codes developed for different purposes, the FLame Acceleration Simulator (FLACS) software developed by Global Explosion Consultants (GexCon) is the most

Table 4 The comparison for the representative CFD codes

List of models	Type	Developer	Features	Accuracy
FLACS	3D CFD Finite Volume	CMR-GEXCON in Norway	- A structured Cartesian grid - Finite volume code - PDR method of sub-grid obstacle	- First order - Reaction progress variable second order
EXSIM	3D CFD Finite Volume	Tel-Tek R&D in Norway	- A structured Cartesian grid - Semi-implicit - Finite volume code - PDR method of sub-grid obstacle	- First order temporal - Second order spatial
AUTOREAGAS	3D CFD Finite Volume	PML in Netherlands	- A structured Cartesian grid - Finite volume code - Integration of REGAS and Blast code - PDR method of sub-grid obstacle	- First order temporal and spatial
COBRA	2D and 3D CFD Finite Volume	Mantis Numerics Ltd.	- Unstructured Cartesian grid - Cylindrical Polar or Hexahedral Adaptive - PDR method of sub-grid obstacle	- Second order temporal and spatial

frequently used for the gas dispersion and explosion simulation. It is generally used to model the dispersion and combustion of flammable materials considering the geometries of the target and to generate explosion pressure responses by counting possible scenarios [79].

The validation of the model and the accuracy of simulation results has been confirmed by many studies [80–82]. Wang et al. [83] applied the FLACS model to analyse the shock wave propagation process in a building and to compare the blast-wave curve at different locations. Li et al. [84] used the FLACS model to assess the effect of safety gab in gas dispersion as well as the explosion risk for heavily congested offshore facilities. Hansen et al. [85] studied the explosion loading on different types of equipment with various shapes by using the FLACS explosion model. Dadashzadeh et al. [86] applied FLACS to investigate the dispersion of flammable hydrocarbon release and the explosion consequence of BP's Deepwater Horizon accident. Das and Weinberg [87] used the FLACS code to present a project result for improving the application of correlation models in quantitative risk assessment (QRA) considering vapour cloud explosion (VCE) events in offshore platforms. There are many previous research studies based on CFD analysis, but they have drawbacks. The main flaw is caused by the limitations imposed by the available computing hardware.

5 CFD-Based ERAs

ERAs are conducted in a design process of offshore facilities in order to determine the level of design accidental loads required for evaluating the explosion resistance of the objective structure. Following the major offshore explosion accidents, it was revealed that explosion models underestimated or overestimated the accidental loads [88]. Both industry and academia have since concentrated on increasing the accuracy of predicted overpressure for a reliable design against possible explosion hazards. A lot of efforts have been put into the relevant research, but CFD based approach is still regarded as one of the most reasonable method.

The typical approach of CFD-based ERAs is shown as Fig. 7. It requires complicated and sequent processes including lots of variables, which should handle the entire chain of scenarios regarding a gas release, dispersion, ignition, and explosion. First of all, the size of the release is subdivided into the spectrum of possibilities, and then the consequences of each scenario are calculated to determine the size of gas cloud. The following is to establish the gas cloud distribution considering combining results of the leak properties, wind information, and gas valve option (blowdown/emergency shutdown). The next process is related to predict the overpressure based on established scenarios. Herein, gas cloud distribution is important in evaluating explosion loads

since the number of scenarios for that influences on the total number of the explosion scenarios. Based on the predicted overpressure, the explosion-resistant design would be carried out. Since the nature of variables regarding an explosion indicates strong randomness, probabilistic approach is on the trend for obtaining more reasonable results in the current ERA study [89].

A great number of scenarios are required to validate the probabilistic approach for overpressures, especially, in case of complicated structures including numerous variables like offshore facilities, potentially thousands of scenarios are normally considered. Table 5 summarizes the previous CFD-based ERA studies, and relevant variables and assumptions considered in CFD models. All target models in Table 5 are offshore facilities which have a complicated geometry condition. The probabilistic sampling method or possible cases assumption is used to reflect the nature of strong randomness of wind/leak profiles. As for gas cloud properties, most studies used the constant release rates leading to steady state results [88, 92–96], but the effect of time-varying leakage has been studied by Refs. [90, 91]. In particular, Gupta and Chan [90] carried out a dispersion analysis with time-varying gas clouds and then compared with the results obtained by equivalent gas cloud assumption. The study found that constant release assumption may be more reasonable when considering the systems with slow depressurization rates, but in the case of rapid depressurization systems, such an assumption may lead to unreliable results. Yang et al. [91] considered both the constant release rate and the time-varying release according to the accident scenarios, and toxic gas profiles and flammable gas profiles were considered separately to investigate the effect of toxic gas-containing flammable gas leakage. The fundamental assumption for constant release rates is the flammable gas cloud volume acquired by such an approach could be alternative of actual transient gas cloud volume from varying release rates over time. The simulation results based on the constant release rate assumption, however, cannot be the same with the results by real release rate at any moment, so that the total mass of gas released in a given time is also different. In addition, the selection of variables can also raise questions that related to why that variable should be considered and how many categories should be required.

6 Future Possibility of CFD-Based ERA

Neutral Network can robustly determine the complex nonlinear relationship between the input and output data without the full understanding of the physical mechanism of the gas dispersion and explosion. As mentioned above, one of the simplifications in CFD-based ERA is to use equivalent cloud metrics, namely Q9, which is the most commonly used
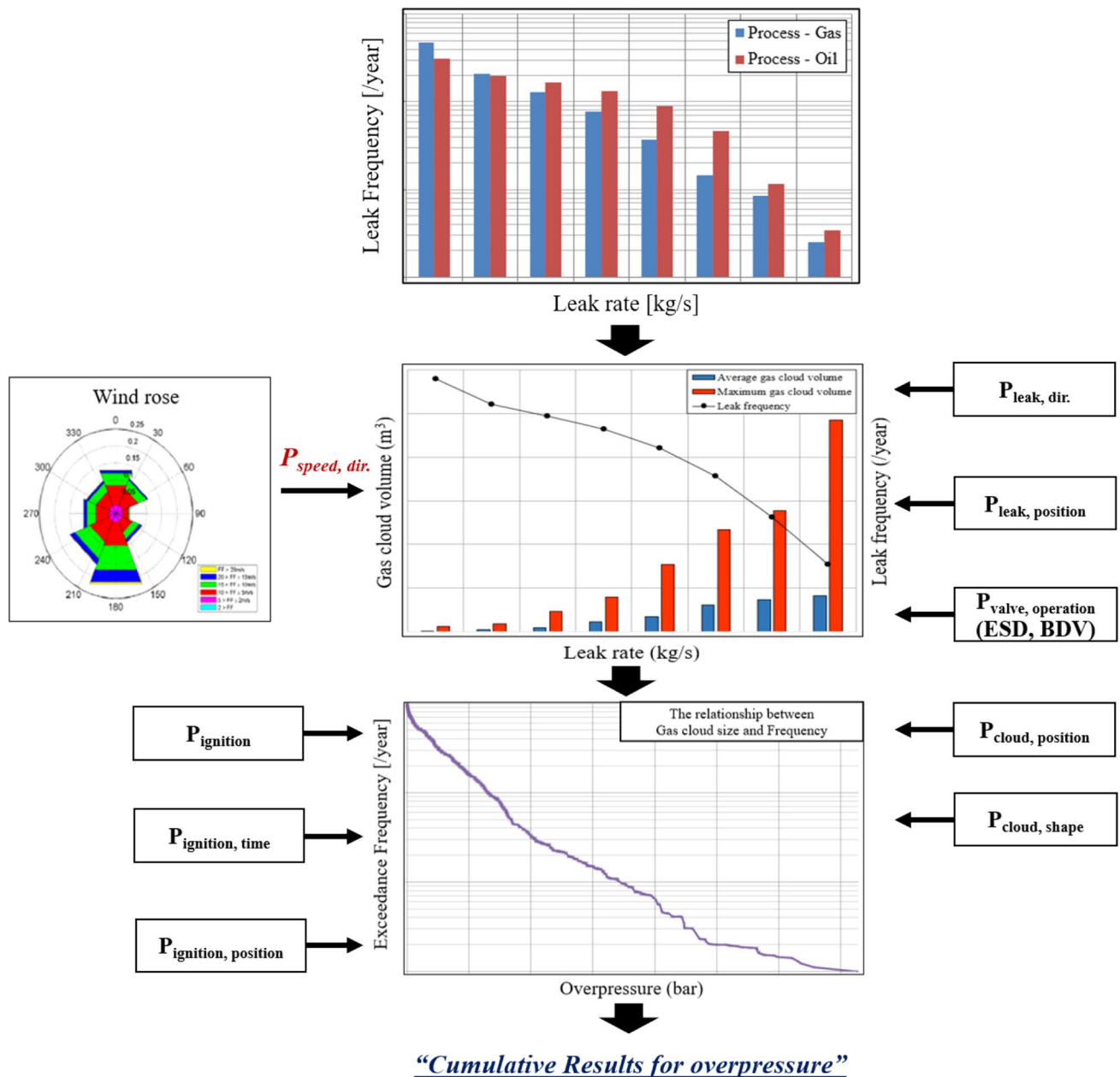
Fig. 7 Framework of typical CFD-based ERAs

in gas dispersion simulation using FLACS software. While inhomogeneous cloud is generated from realistic release, Q9 is to assume the equivalent stoichiometric gas volume as indicated in Fig. 8 and thereby reduces the number of potential explosion scenarios [97].

To provide a more accurate approach, this chapter covers such a limitation of CFD-based ERAs currently and provides future research trends that can increase the accuracy of CFD-based ERA by using ANN models. In addition, data visualization technologies for effectively managing a great amount of CFD results are proposed.

6.1 Limitation of CFD-Based ERA

CFD can be an effective tool to analyse the nonlinear engineering issues since detailed input parameters are used, and the output graphics are very persuasive and seductive. However the results could be totally different according to the skilfulness of the person setting up the model and interpreting the results. Moreover, idealized assumptions and simplification for saving computational costs and time can raise doubts on the accuracy of the results. Especially, complicated nonlinear problems like an explosion require the

Table 5 CFD-based ERAs in literature

References	Geometry details	Leak profiles	Wind condition	Gas cloud properties	Ignition condition	The number of scenarios
Xu et al. [92]	Topside module of FPSO	Stochastic sampling	Probabilistic assumption	Equivalent cloud	Immediate ignition & delayed ignition	60
Yang et al. [91]	Offshore platform module	Worst-case assumption	Worst-case assumption	Time-varying gas cloud	Delayed ignition	A specific-hypothetical accident scenario
Yang et al. [93]	Offshore drilling platform	Worst-case assumption	Worst-case assumption	Equivalent gas cloud	N/A	6
Shi et al. [94]	Offshore platform	Stochastic sampling	Sampling method	Equivalent gas cloud	N/A	384
Li et al. [95]	FLNG platform	Worst-case assumption	Worst-case assumption	Equivalent gas cloud	Center of the gas cloud	N/A
Jin and Jang [88]	Topside module of FPSO	Time-varying leak rate	Sampling method	Equivalent gas cloud	Time dependant ignition model	50
Gupta and Chan [90]	FPSO process area	Time-varying leak rate	Sampling method	Time-varying gas cloud	Time dependant ignition model	240
Hansen et al. [96]	Two confinement configurations	Worst-case assumption	Statistical assumption	Equivalent gas cloud	Pre-ignition turbulence	20
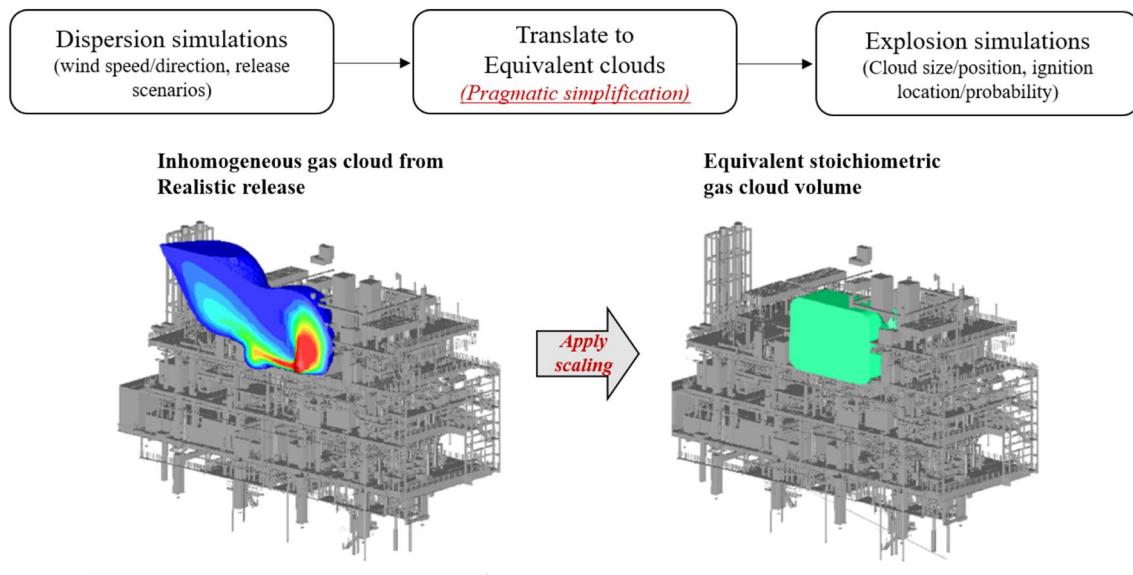
Fig. 8 Concept of equivalent gas cloud volume in the FLACS code

deeply understanding for mathematical model and physical theories, but it is impossible to reflect all variables without simplification in a CFD simulation.

At the present stage, CFD-based explosion models are useful to analyse the physics of such extreme loads, but simplified assumption and approximations in numerical process based on the probabilistic approach are unwillingly accompanied in constructing a model to keep the number of simulations manageable [98, 99]. For example, assumption of constant release rate and frozen cloud approach are normally assumed for simplification in gas dispersion modelling of CFD-based explosion analysis procedure [100]. The fundamental assumption for constant release rates is the flammable gas cloud volume acquired by such an approach could be alternative of actual transient gas cloud volume from varying release rates over time. The aim of this assumption is to minimize the number of scenarios as possible by giving similar level of explosion load as a realistic gas release.

6.2 Application of Artificial Neural Networks to CFD-Based ERA

ANNs can solve the complex nonlinear relationship between the input and output parameters by applying data mapping, regression, classification, and image processing. A variety types of ANNs have been applied in numerous fields, but the multi-layer perception (MLP) with back-propagation (BP) algorithm are most commonly used [101]. The BP algorithm performs learning on a multilayer feed-forward neural network as shown in Fig. 9. It consists of three main parts, namely input network, one or more hidden layers, and an output layer. The input variables are modelled through the pre-connected paths by using a series of numerical weights and combined together into an activation function in the hidden layer which outputs transient values. The outputs of the hidden layer can be input to another hidden layer, and so on. As a result, those processed input variables are conveyed by using another series of weights and eventually combined to be the output [102].

The transient output value of the network is then compared to the expected value, and an error signal is calculated for each of the output neurons. Since all the hidden layers can contribute to the level of errors in the output layers to some degree, the output error signals are delivered backwards from the output layer to previous neurons in the hidden layer directly connected to the transient outputs. Once the error for each neuron has been calculated, the errors are then used by the neurons to update the weight of each connection until the network meets the condition that allows all the training patterns to be encoded [103].

The purpose of ANNs application is to develop the efficient data management and to reduce the computational cost reasonably. Recently, a lot of researcher have tried to apply such technologies in gas dispersion or explosion analysis

regarding typical ERA procedure as described in Table 6. Dennis et al. [103] used ANN consisting of two hidden layers to predict the blast impulse based on validated numerical modelling data. Shi et al. [104] presented Bayesian regularization ANN-based simplification for gas dispersion and explosion part in CFD-based explosion risk analysis. This study used ANN model to capture real gas release state, and then the effectiveness and accuracy of the develop model for the CFD-based ERA was validated through a series of comparative studies.

The common purpose of such studies is to increase the accuracy of transient gas dispersion by incorporating ANN technologies into the CFD-based ERA. Although it requires further testing and validation with various geometries and operation condition of offshore facilities, such multidisciplinary studies are necessary to develop a more accurate gas explosion model.

6.3 Application of Data Visualization into CFD-Based ERA

In an explosion simulation using a CFD method, a series of mathematical calculation process are required to solve the problematic issue and then a set of physical quantities such as pressure, temperature, and velocity would be captured in the range of simulation domain [108]. The simulator cannot capture target information at an infinite area, so discretization process for simulation domain is initially required to define a finite set of geometric regions.

In an explosion simulation, the porosity monitoring tools like points and panels are distributed in such a finite region to capture the information of explosion wave propagation over a period of time. Since a range of variables with hundreds of scenarios are normally used in explosion analysis, the size, complexity, and dimensionality of the CFD result
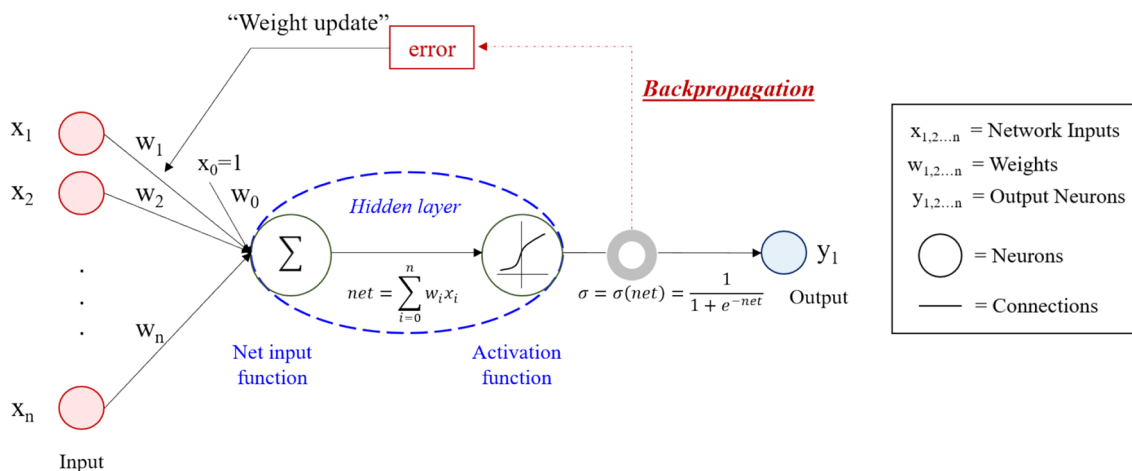

Fig. 9 Example of artificial neural network consisting of key parameters

Table 6 ANNs application in gas dispersion and explosion modelling

References	Network type	Training algorithm	Identification objective	Features	Limitation
Dennis et al. [103]	Back-propagation	Adaptive sub-gradient descent algorithm	To predict blast loading in a confined geometry	High accuracy for low impulse data	Unsuitable for high impulse dataset
Shi et al. [104]	Back-propagation	Error back-propagation and Levenberg-Marquardt algorithm	To apply the simplification to gas dispersion and explosion part of CFD-based ERA	Development of Transient-BRANN model for transient flammable cloud volume	Need to do further tests and validation for other geometry conditions
Zaranezhad et al. [105]	Feed-forward & Back-propagation	Error back-propagation and least squares algorithm	Prediction of accidents regarding repair and maintenance issues	Integrating Anns, fuzzy sets, and metaheuristic algorithms	
Wang et al. [106]	Back-propagation & Support vector regressions	Error back-propagation and least squares algorithm	To predict hazardous gas emissions and accidental leaks	Comparing the performance of two machine learning models in predicting undesired gas release	The accuracy is not enough in complicated area
He et al. [107]	Bayesian network	Bayesian ball algorithm	To predict the most likely undesirable events in a system	Transforming linguistic data into probabilities based on fuzzy sets and evidence theory	No specific risk probability index describing if a system is safe or not

data are immensely large [109]. Therefore, data visualization technologies are required to acquire quick and effective insight into those huge datasets. Figure 10 shows a schematic diagram of visualization system process for CFD explosion analysis results.

The input is the explosion pressure wave histories measured by porosity monitoring points in CFD simulation. The porosity monitoring manager is used to compute and investigate the explosion wave information. It is characterised by the high-dimensional data which includes position, velocity, and various simulation attributes such as pressure, viscosity, turbulent kinetic energy, etc. Drawing graphs provide an intuitive overview of explosion pressure variation with time at each position in a simulation domain. After gaining a basic understanding of the explosion pressure–time curve, the user can analyse input data specifically focusing on the dominant variables in details by using the polar histogram and parallel coordinates plot simultaneously. The polar histogram presents an intuitive visual summary of the explosion pressure distribution, while parallel coordinates plot compares the features between simulation variables to support exploration and analysis. Interactive glyph visualization could be also employed to enrich the user-defined data visualization. Direct visualization, vector clustering with pressure contour and geometrical images can provide insightful information. Finally, the user can compare and analyse the different data visualization, so that more intuitive CFD-based ERA and damage analysis could be conducted.

7 Conclusions

This paper presented a comprehensive review on the methodologies of explosion risk assessment, especially focused on offshore industries. The explosion phenomenon and mechanisms of interaction with structures, damage pattern, explosion model approach, and the limitation of current methods were extensively investigated through the findings of previous works. In addition, lots of relevant skills and theories for analysing explosion risks quantitatively such as probabilistic approximation, simplified assumption in FE analysis, and experimental methods were examined. As one of the most frequent analytical tools for explosion modelling, CFD method was especially thoroughly analysed by studying previous application, common limitation, and future possibilities.

In conclusion, this study summarized the future possibilities and requirements of CFD-based ERA by proposing the specific application method of ANNs into the CFD-based ERA to provide more accurate design reference values for industrial facilities having potential explosion possibilities and recommended to employ visualization system design
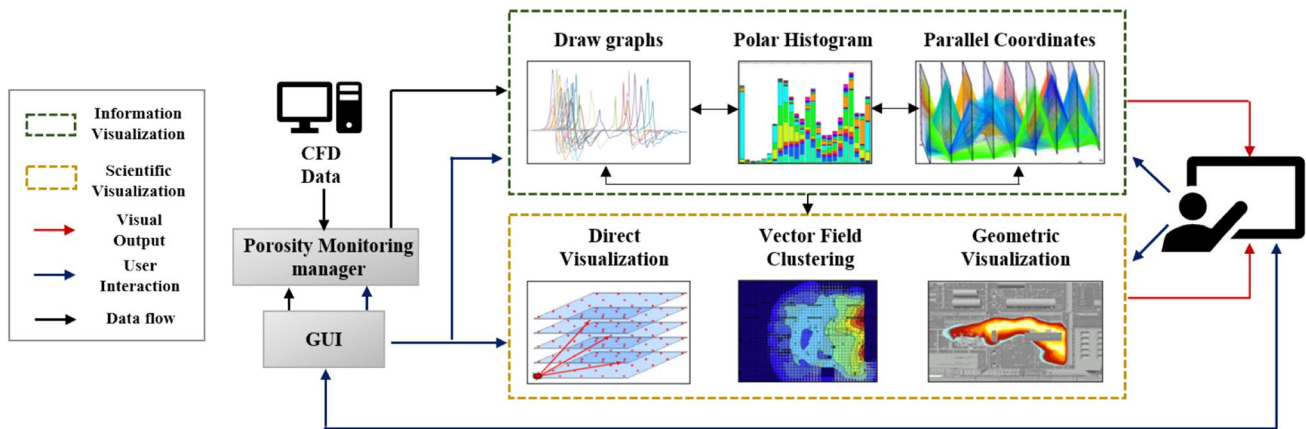
Fig. 10 A schematic diagram of visualization system process for CFD explosion analysis results

tool into the CFD-based ERA for effectively analysing a great amount of data acquired through CFD simulations.

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