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Risk assessment of offshore fire accidents caused by subsea gas release

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ABSTRACT

Subsea gas release is an industrial hazard that can impose fire hazards on offshore facilities near the gas surfacing area. However, risk assessment of the fire caused by subsea gas release is challenged due to inadequate recognition of the knowledge of subsea gas release mechanism and resulting hazards. At present, minimal researches involving risk assessment of offshore fire resulting from a subsea gas release were reported, and this paper is an extension of the previous works on subsea gas behavior. This paper focuses on modeling fire risk on offshore facilities due to subsea gas release. A numerical simulation is carried out using the Computational Fluid Dynamic technique of Fire Dynamics Simulator (FDS) to analyze fire propagation characteristics and assess the impact of fire on personnel and assets. A probit model is adopted to calculate the probabilities of injury or death caused by fire hazards. This study also investigates the effect of wind speed, gas release rate and the distance between gas pool and platform on fire impacts and casualty probabilities. The present study can support safety measure design to mitigate or avoid the impacts of offshore fire events from subsea gas release.

1. Introduction

The underwater gas release is a typical industrial accident that may be induced by a subsea pipeline leak or subsea blowout (Rew et al., 1995). The released gas moves from the seafloor to the surface and generates quite a large gas surfacing area/boiling zone on the sea surface. Subsequently, the released gas will also move from the surfacing area into the atmosphere and disperse above sea under the wind. It may generate a very adverse impact on the offshore facilities near the surfacing area (Yapa et al., 2010; Premathilake et al., 2016). Many offshore facilities are located above the sea to extract, process, and store hydrocarbons. Offshore fire accidents may occur when a flammable gas cloud encounters potential ignition sources on offshore facilities (Loes and Fannelop, 1987). A vivid case is the Pemex accident happened in 3 July, 2021. A rupture in an undersea gas pipeline in the Gulf of Mexico, sending flames boiling to the surface in the Gulf waters. Fig. 1 presents an offshore fire accident from subsea gas release, in which the left picture describes the surfacing zone and the adjacent platform, while the right picture depicts the fire scenario due to the ignition of surfacing gas. In light of the severe consequences, modeling accident scenarios and their consequences are necessary to assess and manage the risk of fire in such situations.

Recent years have seen considerable efforts on modeling and risk assessment of offshore fire. Vinnem et al., (2014) presented the fundamental theory and a method for offshore fire risk modeling. Offshore fire accident scenarios can be divided into two types: fire on the topside of an offshore facility, and fire on the sea surface. The first type of fire usually occurs in the case of blowout accident on offshore drilling platform or process module leak event in offshore oil and gas production facilities. Many studies were devoted to the topside fire risk modeling (Paik et al., 2011; Jin and Jang, 2015; Sun et al., 2017; Wu et al., 2018). The second type of fire is usually caused by the ignition of hydrocarbons released into seawater. For example, an accidental collision may cause the leak or rupture of the oil tanker or FLNG (floating liquefied natural gas), leading to oil or LNG fire on the sea surface. A series of experiments and CFD models were developed to simulate pool fire on water and assess its impact on offshore assets (Yi et al., 2019; Ahmadi et al., 2019; Vasanth et al., 2015; Betteridge, 2018; Luketa and Blanchat, 2015). Overall, past studies mainly concentrated on modeling and risk assessment of topside fire and liquid pool fire on water. The fire on the sea surface is also possible due to the ignition of flammable gas released from subsea sources. However, risk models of sea surface fire caused by subsea gas

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release were seldom reported in the literature.

The consequences of sea surface fire can be catastrophic since the influencing area of fire may be very large due to the large release size on the sea surface caused by the subsea gas plume. Thus, sea surface fire caused by subsea gas release is different from the topside fire caused by process modules leak. However, most available studies on subsea gas release mainly focused on modeling subsea gas plume and the corresponding physicochemical process (Olsen and Skjetne, 2016; Premathilake et al., 2016; Hissong et al., 2014; Wu et al., 2017; Li et al., 2019a). Recently, increasing attention has been paid to modeling the impact above sea surface when subsea gas moves into the atmosphere. Huser et al. (2013) executed preliminary research on gas dispersion above the sea due to a subsea release and established some simplified look-up tables for flammable gas clouds in different scenarios. Li et al. (2019b) presented a CFD model to simulate the flammable gas dispersion behavior above the sea from a subsea release and assessed the impact range on the nearby offshore facility. In a nutshell, only a few studies on offshore fire above sea due to subsea gas release can be found in the literature. The improved understanding of sea surface fire due to subsea gas release is helpful for safety-related activities. The risk of sea surface fire depends on a series of factors such as environmental conditions and release source parameters. Therefore, a detailed study of sea surface fire risk due to subsea gas release is urgent for developing safety measures.

To model and assess sea surface fire risk due to subsea gas release, a framework comprising of CFD simulation and Probit model is developed in this study. Rengel et al., (2018) recognized the FDS code as one of the most powerful tools to predict fire behavior. A 3D FDS model is developed to assess fire loads, which is used as a part of risk analysis and accident modeling. A Probit model is used to estimate the casualty probabilities. The present work is helpful for offshore fire risk assessment and accordingly designing the safety measures.

The rest of this paper is organized as follows: Section 2 presents the proposed methodology and flowchart for fire impact assessment. A case study is provided in Section 3 to illustrate the application of the proposed methodology. Section 4 summarizes the present work and summarizes the conclusions.

2. Methodology

This study focuses on assessing offshore fire risk resulting from a subsea gas release by combining fire scenarios simulation and probabilistic assessment. The steps of the proposed methodology incorporate scenario identification, fire modeling of gas breaking through the sea, the effect of wind speed and gas release rate, probability assessment, and fire impact assessment. The credible fire scenario is identified by a qualitative comparison based on hazardous characteristics. Then CFD simulation is employed to predict the fire evolution process and determine the impact range. The results from CFD simulations are adopted to assess the damage to personnel and adjacent assets. A Probit model is utilized to determine the probability of fire damage to personnel. The results can support decision-making on the implementation of safety measures. Fig. 2 presents the flowchart of modeling and assessment, which is discussed in detail in the following subsections.

2.1. Accident scenario analysis

Subsea gas release events include a series of possible scenarios caused by subsea pipeline or riser break and shallow gas blowout. Previous studies indicate that an underwater gas plume rising from the seafloor to the sea surface is generated, and a circular surfacing area is formed when the gas breaks through the sea surface and mitigates into the atmosphere. The gas is released from the sea surface and dispersed above the sea with wind. Fire and explosion accidents will occur when the flammable gas above sea encounters the potential ignition sources. Although an explosion may occur if a delayed ignition occurs in a congested area with offshore facilities, it is not considered since this study focuses on sea surface fire accidents. Offshore fire risk is subjected to several factors including environmental conditions, e.g., wind speed and direction, and the relative location between the surfacing area and offshore facilities.

The present work considers the case that an offshore platform carrying out workover treatment encounters a shallow gas blowout. The causes for the shallow gas blowout may include the low density of drilling fluid, the presence of abnormal pressure, lost circulation, pulling a piston, or too long-time for stopping the pump. Although several factors contribute to offshore fire risk, the relative location between surfacing area and platform plays a dominant role in consequence severity. Accident scenario analysis is conducted to identify the most dangerous accident scenario. Accounting for the impacts of the case with different relative locations, the scenario that the offshore platform is located in the downwind direction of the surface area is the most dangerous scenario, in which the flammable gas will migrate on the offshore platform directly. This scenario is used for further analysis.

2.2. Modeling offshore fire from subsea release

CFD simulation can support safety analysis and assessment and help to validate the effectiveness of safety measures. Fire is triggered when flammable gas released from the surfacing area encounters the potential ignition sources on the offshore platform. A flash fire on the platform that migrated back to the gas plume on gas surfacing area results in

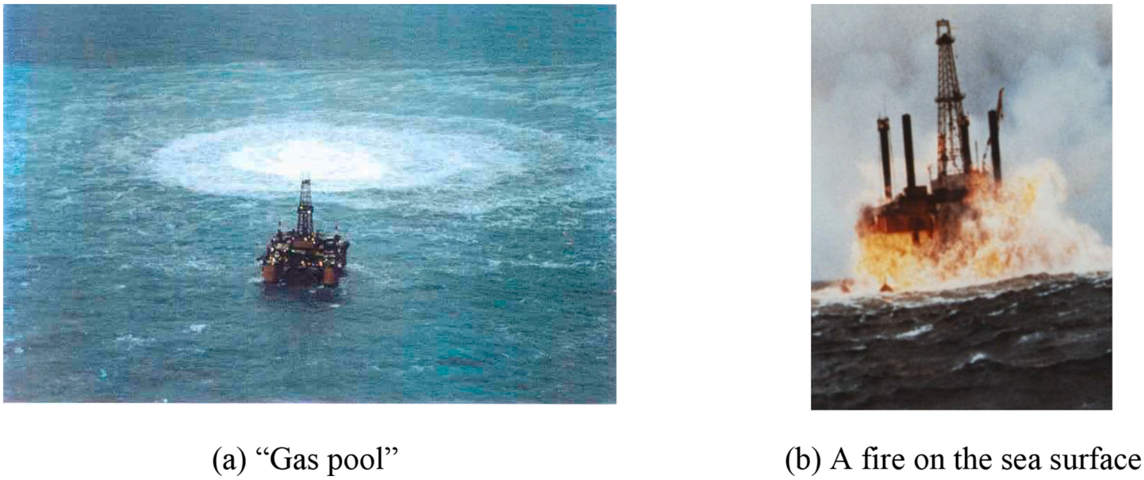

(a) “Gas pool”   (b) A fire on the sea surface

Fig. 1. A fire on the sea surface due to shallow gas blowout.

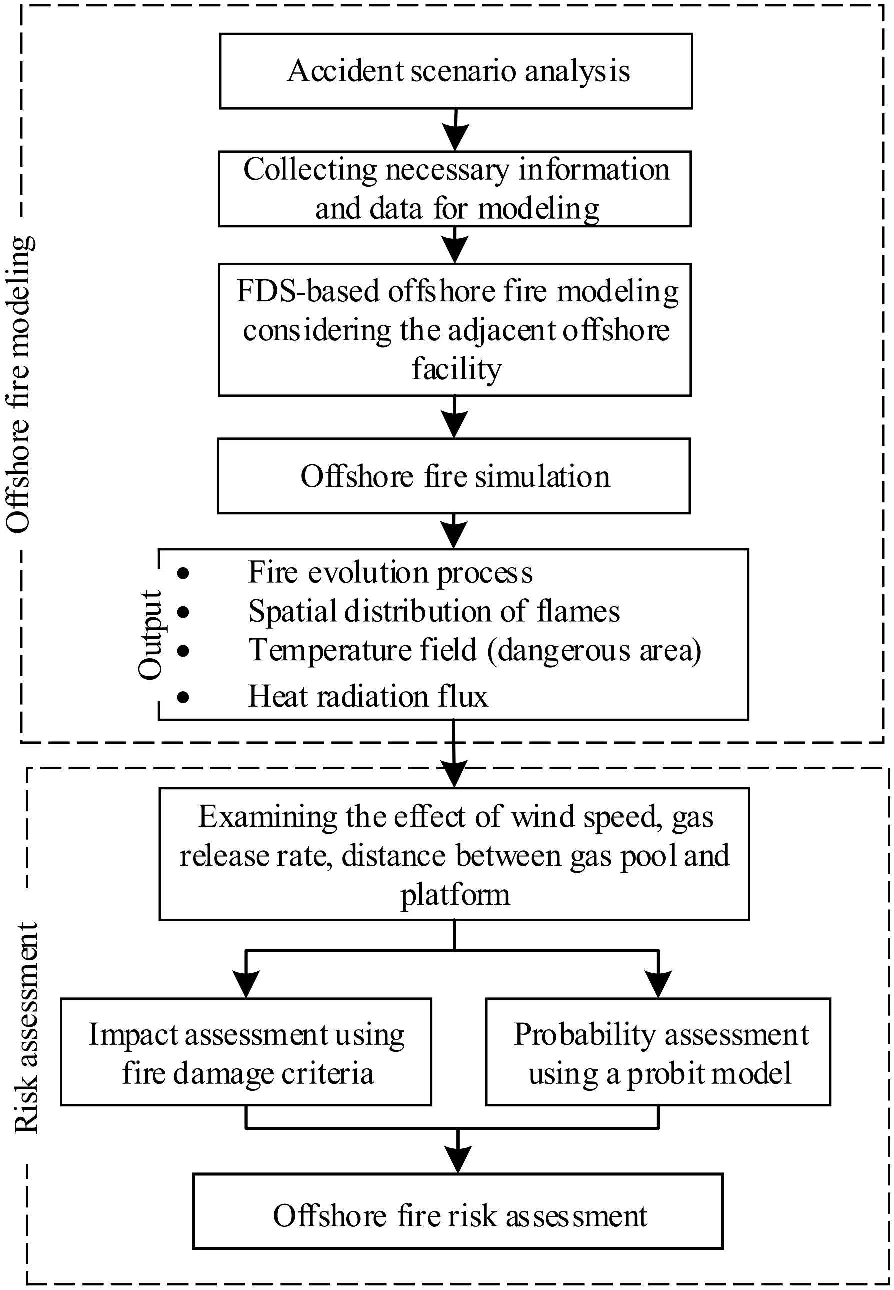


Fig. 2. Flowchart of risk assessment of offshore fire from subsea gas release.

sustained combustion of the sea gas fire. This study focuses on modeling offshore pool fire from subsea gas release. Previous accidents indicate that a pool fire on the sea surface can occur when the released gas is ignited and the fire may engulf the whole offshore platform since the release surface area can be about a few dozen meters in radius. Explosion is not included in the present study. The sea surface is an open area, which makes the overpressure from a flammable gas explosion may not be significant. As a result, fire is the main safety concern of offshore risk induced by subsea gas release events.

The procedure for CFD simulation includes geometric modeling, mesh generation, and parameters definition. The sizes of the surface area and offshore platform are essential for geometric modeling. Nowadays, various CFD techniques or tools are available for fire modeling. FDS is a CFD model of fire-driven fluid flow and has been verified to be a reliable and robust tool that is widely applied in the field of offshore fire risk analysis. FDS simulates the low-speed thermally driven flow with emphasis on smoke and heat transport from fire by solving a form of the Navier-Stokes equations, in which the turbulence is considered by the Large Eddy Simulation (LES). FDS is capable of simulating fire and resulting smoke development, thermal flow, and concentration of toxic substances released during combustion. The radiation from fire is calculated using the following equations (McGrattan et al., 2013).

$$\dot{q}_r'''(x) \equiv -\nabla\cdot\dot{q}''(x) = k(x)[U(x) - 4\pi I_b(x)] \tag{1}$$

$$U(x) = \int_{4\pi} I(x, s')\mathrm{d}s' \tag{2}$$

where $\nabla\cdot\dot{q}''(x)$ is the radiative loss term; *k(x)* is the absorption coefficient; U(x) is the total intensity integrated over the unit sphere; $I_b(x)$ is the source term; $I(x, s)$ is the solution of the radiation transport equation (RTE) for a non-scattering gray gas; x is position vector; s is a unit vector in direction of radiation intensity.

FDS is validated and verified by various fire scenarios at the National Institute of Standards and Technology (NIST), and is recommended for fire accident modeling (McGrattan et al., 2000; Wen et al., 2007; Wahlqvist and Van, 2013; Mun et al., 2013). Compared to other fire modeling tools (e.g., FAST, FDS), FDS can achieve three-dimensional models and obtain detailed results since it is solved based on Computational Dynamics, while FAST is an empirical fire simulation tool used for two-dimensional fire modeling. Thus, FDS is used to simulate the identified scenarios in this study. After geometric modeling, mesh generation is performed in the preprocessor of FDS. A grid independence test is essential since grid size may affect simulation accuracy. The boundary conditions with the initial parameters are defined based on the simulation scenarios. Eventually, a numerical model for offshore gas fire using FDS code is built, which can be employed to simulate the identified accident scenarios.

2.3. *Examining the effect of critical factors*

Considering the scenario that offshore platform is located at the downwind of surfacing area, wind speed, surface gas release rate, and the distance between the gas pool and offshore platform are considered as three crucial factors which may affect the fire damage level (including the spatial-temporal distribution and coverage area) in the risk analysis of offshore fire accidents. The control variable method is employed to examine the effect of wind speed and gas release rate on offshore fire consequences. Offshore gas fires under different wind speeds and surfacing gas release rates are simulated. When one parameter is examined, all other parameters remain unchanged to analyze the effect on fire consequences. Through a comparison of the influenced areas of the offshore gas fire in different scenarios, the highest risk scenario is determined considering the most dangerous fire consequence.

2.4. *Probability assessment*

The impact of fire accidents on personnel is mainly determined by the integrated thermal intensity. Fire impact on humans includes first-degree burn, second-degree burn, and death. The probability of injury or death for personnel in various scenarios can be calculated using the Probit model shown in Eqs. (3) and (4) (Assael and Kakosimos, 2010), when the heat load caused by the flame is determined.

$$P = F_k \frac{1}{2}\left[1 + erf\left(\frac{Pr - 5}{\sqrt{2}}\right)\right] \tag{3}$$

$$Pr = c_1 + c_2 \ln D \tag{4}$$

$$D = t_{eff}\left(q'\right)^{4/3} \tag{5}$$

where P is the probability of injury or death; F_k is clothes correction factor; D is the thermal dose which is a function of thermal radiation and time, and it can be calculated by Eq. (5), q' is thermal radiation flux, t_{eff} represents the person^{\prime}s exposure time to heat flux; c_1 and c_2 are probit coefficients depending on the degree of burn, as shown in Table 1. By determining different probit coefficients, the probit function can be used in various scenarios to calculate probabilities of injury and death.

Table 1
Coefficient c_1 and c_2 (TNO Green Book, 1989).

Impact to personnel	C_1	C_2
First-degree burn	-39.83	3.0186
Second-degree burn	-43.14	3.0186
Death	-36.38	2.56

2.5. *Impact assessment*

Temperature and heat flux generated during fire combustion are extracted from simulations. The real-time fire parameters at critical positions of the offshore facility are monitored to analyze the evolution process and reveal the fire characteristics. The impact of temperature and thermal loads on personnel and adjacent assets on the offshore platform is assessed based on numerical results and fire damage criteria. Human impact criteria and asset impact criteria are used to measure the consequence of fire accidents.

The fire impact on adjacent assets and personnel depends on the thermal loads and the surface temperature. Typical thermal radiation intensity limits can be found in Assael and Kakosimos (2010). For example, equipment damage occurs when the heat flux is larger than 37.5 kW/m^2, and the minimum intensity for ignition is 12.5 kW/m^2. These limits are directly related to specific radiation effects on people and materials. Facility materials are susceptible to thermal loads. The fire can cause the failure of the steel structure since the strength of the steel structure will decrease under the sustained action of fire. The yield strength of steel structure drops 40% at the temperature of 538 °C while that decreases by 80-90% at the temperature higher than 600 °C (Reniers and Cozzani, 2013). The temperature thresholds for slight injury and serious injury are 118 °C and 180 °C (Wei et al., 2014). The thermal loads on the structure surface and human skin during a fire are considered to assess the fire impact. Based on fire damage criteria, the damage level of the facility and humans can be assessed. Safety measures and strategies can be developed to mitigate the impacts of fire resulting from subsea gas release.

3. Results and discussion

3.1. *Scenario description*

As stated in Section 2.1, an offshore fire accident due to a shallow gas blowout is considered to illustrate the modeling and assessment of the impact of offshore fire on the offshore facilities adjacent to the surfacing zone. The fire impact on the offshore platform is assessed using the modeling and assessment flowchart presented in Section 2. This study is conducted as an extension of the previous simulation of underwater gas behavior from a shallow gas blowout. An offshore platform is located in the downwind direction of the surfacing area, and the primary safety concern is the impact of fire on this offshore platform near the surfacing area. The pool fire size is considered as the surfacing area generated when underwater gas reaching the sea surface. The distance between the surfacing area and the offshore platform is 10 m, and the size of the surfacing area is 30 m in diameter. In reality, the distance and pool fire size can be determined through the simulation of underwater gas plumes, which are assumed in the present study for illustration. The environmental conditions in the South China Sea are used in this study. The ambient temperature is 21.4 °C, and the relative humidity is 60%. The gas release rate of a shallow gas blowout can be calculated through the theoretical model (Buaprommart et al., 2019). This study uses the assumed gas flow rate based on previous publications and accident reports and takes multiple gas release rates to explore its effect on offshore fires. The size of the surfacing area and gas flowrate provided by Huser et al., (2013) are used in this study.

3.2. *Offshore fire modeling*

FDS code is employed to simulate the offshore pool fire scenarios and assess their impacts on the adjacent offshore platform. It is a well-validated tool in fire dynamics modeling, and is widely applied in the field of fire risk assessment with relatively high credibility (McGrattan et al., 2000). In this paper, an offshore platform shown in Fig. 3 is used to illustrate the fire impacts. The dimension of the offshore platform is 140 m (length) × 118 m (height) × 84 m (width). To reduce the calculation

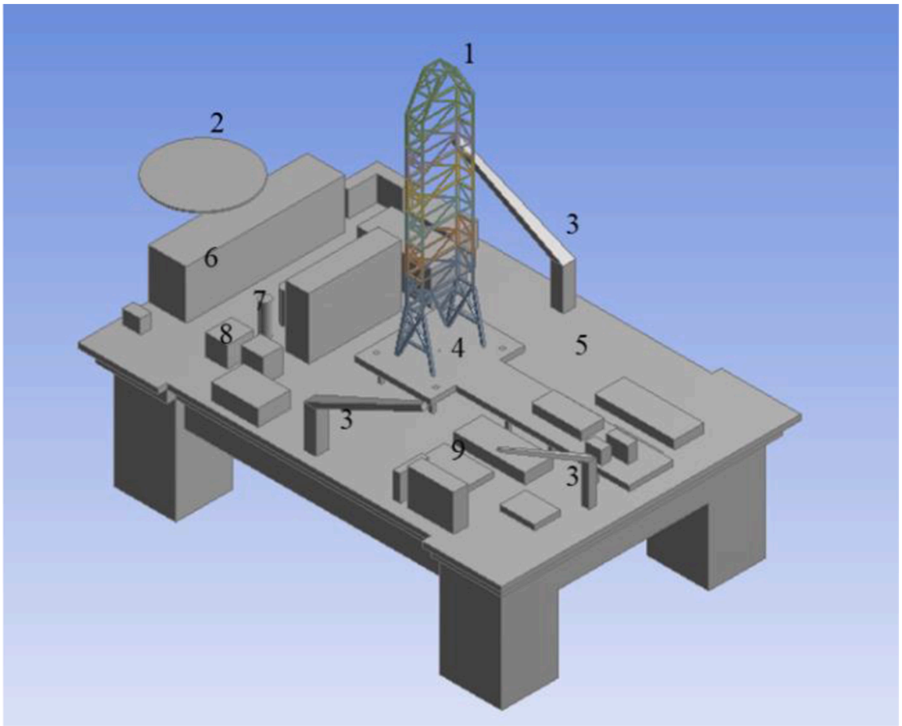


Fig. 3. Offshore platform model.

cost, the partial structures on the offshore platform are simplified. The topside modules of the offshore platform considered in this paper include (1) rig, (2) helicopter platform, (3) crane, (4) drilling floor, (5) main deck, (6) living building, (7) riser storage, (8) mud mixing room, (9) engine room, etc. The average draught of the offshore platform in operational condition is 19 m, and the distance between the sea surface and the main deck is 20 m. This study focuses on the total impact of offshore fire on offshore facilities excluding possible explosions, and the detailed structure has a negligible effect on the results. As a result, the offshore platform with a simplified structure is reasonable to illustrate the impact of sea surface fire on the offshore facility adjacent to the surfacing area.

The dimension of the computational domain is set as 240 m (Length) × 125 m (Height) × 150 m (width). The border of the computational domain depends on flame size, which is determined by several tentative calculations. The proper domain size is selected to present the full size of the flame and its influencing area. The required calculation grids are generated by dividing the entire computational domain into several blocks. Many simulations are conducted to find out a proper grid number to ensure the calculated results are independent of the number of grids. The grid number of 4.16×10^6 is used in the subsequent simulations considering both computational cost and accuracy. Finally, the total number of grid cells in each scenario is 4161260. The simulation period is set as 60 s since the tentative calculations indicate that the

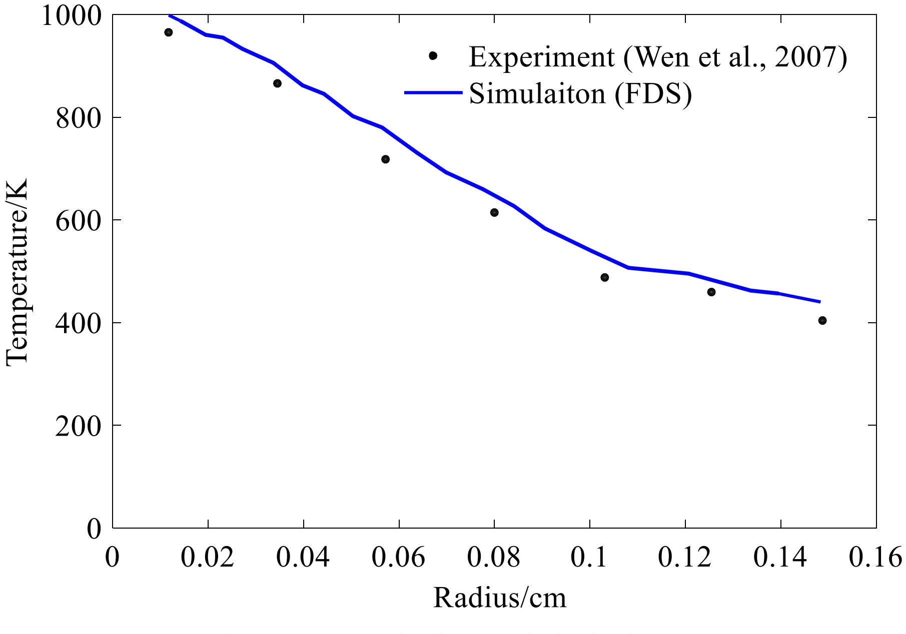


Fig. 4. Temperature distribution at the height of 30 cm.

offshore fire can become a steady state given the simulation time.

This study attempts to validate the FDS-based fire model by reproducing the experiment reported in the literature.Wen et al., (2007) conducted a small-scale experiment. In the open space at room temperature, the methanol was discharged in a pool with a diameter of 30.5 cm. The heat release rate is 24.6 KW. The pool fire in the experiment is simulated using the FDS code to obtain the temperature distribution above the pool 30 cm. Fig. 4 presents the temperature comparison between experiment and simulation. It is observed that the temperatures from the FDS simulation are a little higher, but they are almost consistent with the experiments. Thereby, FDS based pool fire model is validated to be a credible tool in the simulation of a pool fire and to predict its consequences.

It is assumed that the released gas combusts completely. A burner surface is created to simulate the surfacing gas pool in the burning state, and the released gas is spread uniformly over the surface area. Offshore wind speed follows the atmospheric profile. The left side of the computational domain is set as the wind inlet. The bottom side is treated without air exchanging. The types of other sides except for left and bottom is set as open surface, allowing the air to flow through. A series of monitoring points and planes are created in the simulation to record fire loads on the offshore platform.

A total of 14 scenarios is simulated to examine the effect of critical parameters on offshore fire, as shown in Table 2. Wind speed, gas release rate, and the distance between gas pool and platform are considered in this work. The control variable method is employed to analyze the effect of the single factor on offshore fire. The scenario with wind speed 13 m/s and gas release rate 630 kg/s is used as a standard case, and the simulation results of other scenarios are compared with the standard case to illustrate the effect of these studied parameters.

3.3. Results and discussion

3.3.1. Offshore fire evolution and impact assessment

This study considers wind speed and gas release rate as two important factors affecting offshore gas fire. For illustrative purposes, the fire scenario with a wind speed of 13 m/s and a gas release rate of 630 kg/s, is utilized as the standard case to illustrate the development process of offshore fire from subsea gas release. Fig. 5 presents the offshore gas fire development process. Flammable gas rapidly involves the combustion reaction when it is ignited. The geometric size of the flame gradually increases. The flame flows along the downwind and migrates from bow to space above the main deck with the wind. The fire covers the whole bow at 5 s after combustion beginning. The flame length reaches 85 m, and the flame height reaches 58 m. The flame reaches the rig at 10 s and covers the whole drilling floor, which may pose a severe threat to operators and the steel structure of the rig. The flame flows toward the stern with the wind, and the influencing range of fire continues to increase. The flame nearly covers 67% of the offshore platform, and the height of the flame reaches about 80 m. Note that the partial flame migrates along with the air space and spills from the stern, which may generate an adverse impact on the helicopter deck. Besides, the position of the lifeboat is also affected by the flame, and it is difficult for the operators to evacuate from the platform in this scenario. The flame reaches the heyday at approximately 40 s with a maximum flame height of about 96 m. At this moment, the flame covers the whole topsides of the offshore platform, and operators and steel structures of the offshore platform will suffer severe damage caused by fire. During the fire development, the outline of the flame is in dynamic change due to the effect of offshore wind and air pulsation.

Table 2
Scenarios used for simulations.

Scenario. No	Wind speed/ (m/s)	Distance of release from platform (m)	Gas release rate/ (kg/s)
1	5.28	10	630
2	7	10	630
3	9	10	630
4	11	10	630
5	13	10	630 (standard case)
6	15	10	630
7	13	10	210
8	13	10	420
9	13	10	840
10	13	10	1050
11	13	10	1260
12	13	20	630
13	13	30	630
14	13	40	630

Fig. 6 presents the temperature field of the computational domain during a steady fire. Temperature is the main index to measure the fire consequences. The temperature of the area that flame flows increases rapidly when the fire occurs, which may pose severe damage to operators and the steel structure of the offshore platform. It can be found that the maximum temperature in the area affected by the fire is about 1500 °C. As shown in the temperature field in the horizontal section and vertical section, the central area of high temperature distributes along with the bow, main deck, and stern. The temperature in this area reaches 1000 °C. Due to the obstruction of the rig, riser storage, and mud mixing room, the temperature in the living area is relatively low, about 150 °C. According to the damage criteria of flame temperature on humans, most operators that are outdoors may suffer severe damage caused by the high temperature of the fire. High-temperature detection and alarm devices should be placed in the living area to conduct an effective emergency evacuation. In addition, fire suppression measures, e.g., carbon dioxide fire suppression system and water deluge system should be installed to mitigate fire consequences.

A continuous fire could reduce the structural strength of the offshore platform. The yield strength of the steel structure when the temperature on the steel structure surface reaches 538 °C is approximately 60% of that at the normal room temperature. The complete failure of the steel structure will occur when the temperature on the steel structure surface reaches 600 °C (Reniers and Cozzani, 2013). As seen in Fig. 6, the temperature on most areas on the offshore platform exceeds 538°C, indicating that the steel structure of the entire offshore platform is subject to the effect of high temperature. The yield strength of the steel structure decreases significantly due to the continuous fire. The steel structure of the offshore platform will lose its original supportability and collapse, possibly resulting in deformation. The rig is the core equipment of the offshore platform, and the collapse of the rig will be caused by continuous fire. Furthermore, the complete failure of topsides distributing on the bow and stern will be induced. Thus, offshore fire from the subsea gas release can lead to a catastrophic consequence and cause the collapse of the entire offshore platform.

Heat radiation and convection generated by fire damage nearby assets and equipment. Heat radiation is an important index to measure fire consequences. To record the dynamic change of heat radiation flux, three representative positions at the offshore platform are set as monitor points: one at the rig (GAS10), one at 50 m from the rig in upwind (GAS03), and the other one at 50 m from the rig in downwind (GAS12), as shown in Fig. 6(a). Fig. 7 presents the time-dependent profile of the heat radiation flux in three monitor positions. It can be found that the radiation flux changes over time. The heat radiation flux in GAS03 starts to increase after a fire happens and reaches 437 KW/m^2 at 4 s. Then, the radiation flux in GAS03 appears high-frequency fluctuation and reaches the maximum value of about 539 KW/m^2. The maximum heat radiation flux in GAS03 is about 40 KW/m^2. The flame flows towards the stern with the wind, and the heat radiation flux in GAS10 starts to increase at 4 s and appears low-frequency fluctuation. The maximum radiation flux in GAS10 of 544 KW/m^2 is reached at 17 s. The minimum radiation flux in GAS10 is about 85 KW/m^2 when the fire is in a steady state. The heat radiation flux in GAS12 starts to increase rapidly at 23 s and reaches the

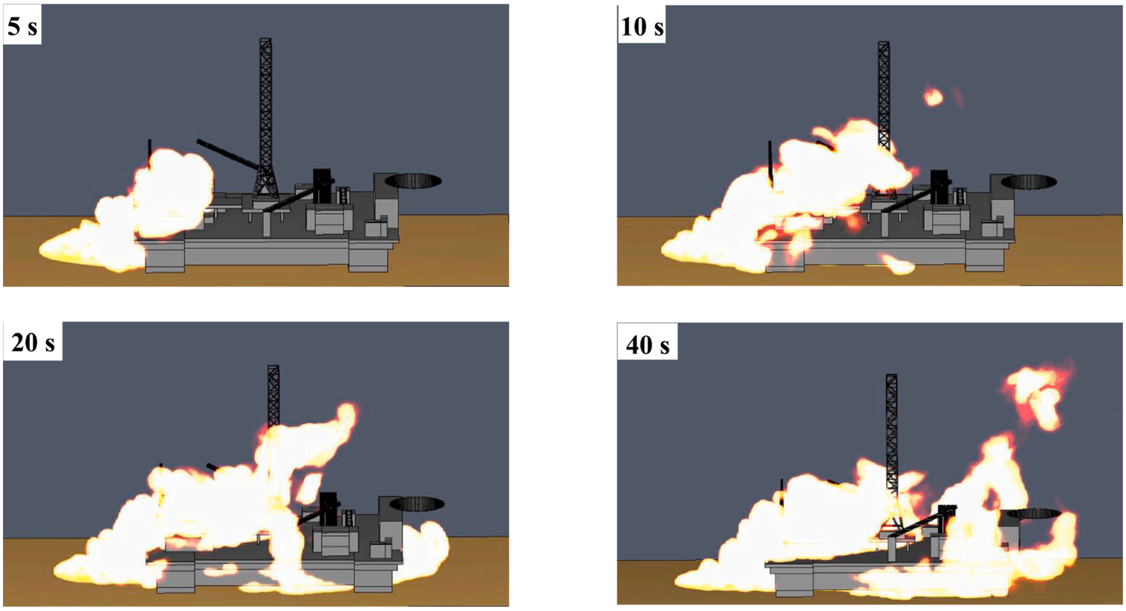
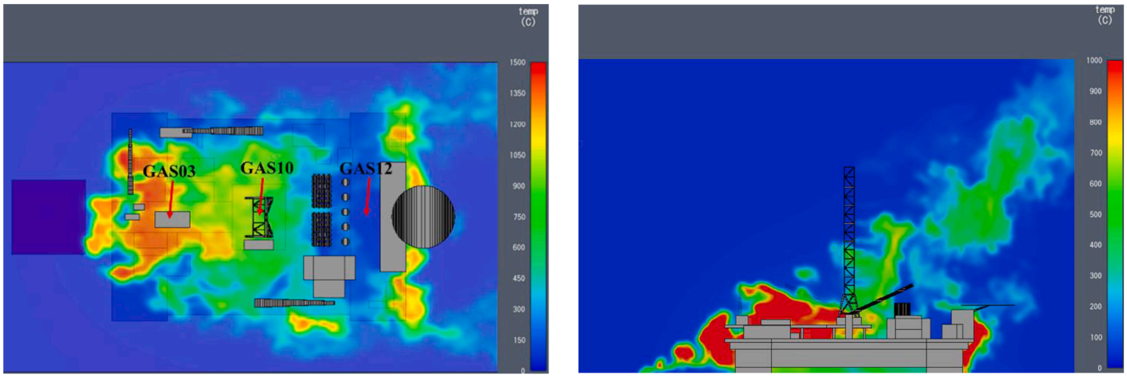


Fig. 5. Development process of offshore gas fire.



(a) horizontal section

(b) vertical section

Fig. 6. Temperature field of the cross-section of the computational domain during a steady fire.

maximum value of 468 KW/m^2 at 26 s. Then it reduces to the steady value of 9 KW/m^2. GAS12 is at the stern of the platform, and flames reaching this point requires more time compared to others. The increase of the heat radiation flux at this point is later than other monitoring points. It is observed that the heat radiation flux at GAS12 is quite low with little fluctuation and has two isolated peaks. The fire development process indicates that there is nearly no flame distribution due to the obstruction of upwind topsides. The rig indeed affects the spatial distribution of flames, leading to the variation of heat radiation flux. Besides, the fluctuation due to fire turbulence leads to the presence of few flames at two observed moments. Thus, the fire turbulence and the obstruction of upwind topsides contribute to the observed phenomena.

3.3.2. *Effect of wind speed*

Wind speed is a critical environmental factor influencing offshore gas fire. The fire scenarios with different wind speeds are simulated and assessed to examine the effect of wind speeds on offshore pool fire damage levels. A total of six typical wind speeds in the South China Sea are used, as shown in Fig. 8. It is assumed that the surface gas release rate is 630 kg/s, fire scenarios under different wind speeds are simulated. Fig. 5 presents the spatial distribution of fire flame at 60 s. It can be found that wind speed has an apparent impact on the spatial distribution of offshore gas fire. Flame mainly flows upward in the scenario with a wind speed of 5.28 m/s since buoyancy is the driving force. The height of steady fire is about 110 m, and the main influencing area distributes around the bow and the upper space of the main deck. The action of wind on fire flow increases with the increase of wind speed. In the case of the scenario with a larger wind speed, the fire mainly flows along with the downwind direction. The fire height decreases gradually, and the distance between the flame and the topsides of the offshore platform decreases, which causes the coverage area of the fire to increase gradually with the increase of wind speed. In terms of the scenario with a wind speed of 7 m/s, the flame covers the rig, and the height of the steady flame is about 95 m. When wind speed increases to 11 m/s, the steady flame covers most of the topsides on the offshore platform except for the living area. Note that the helicopter deck is also covered by the flame flowing from the bottom of the offshore platform, which may pose a challenge for the evacuation of operators. In the fire scenarios with wind speeds of 13 m/s and 15 m/s, nearly the whole offshore platform is covered by the flame, which may cause a catastrophic consequence. It can be concluded that wind is the main driving force for flame flow along with the offshore platform, and wind speed has a dominant effect on the spatial distribution of offshore gas fire from subsea gas release.

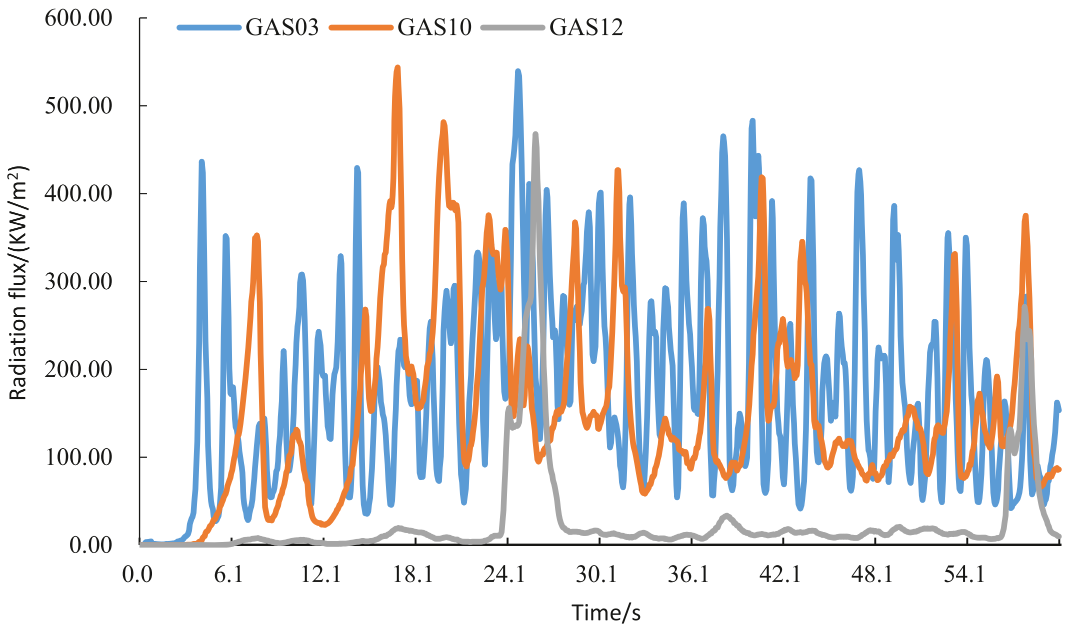
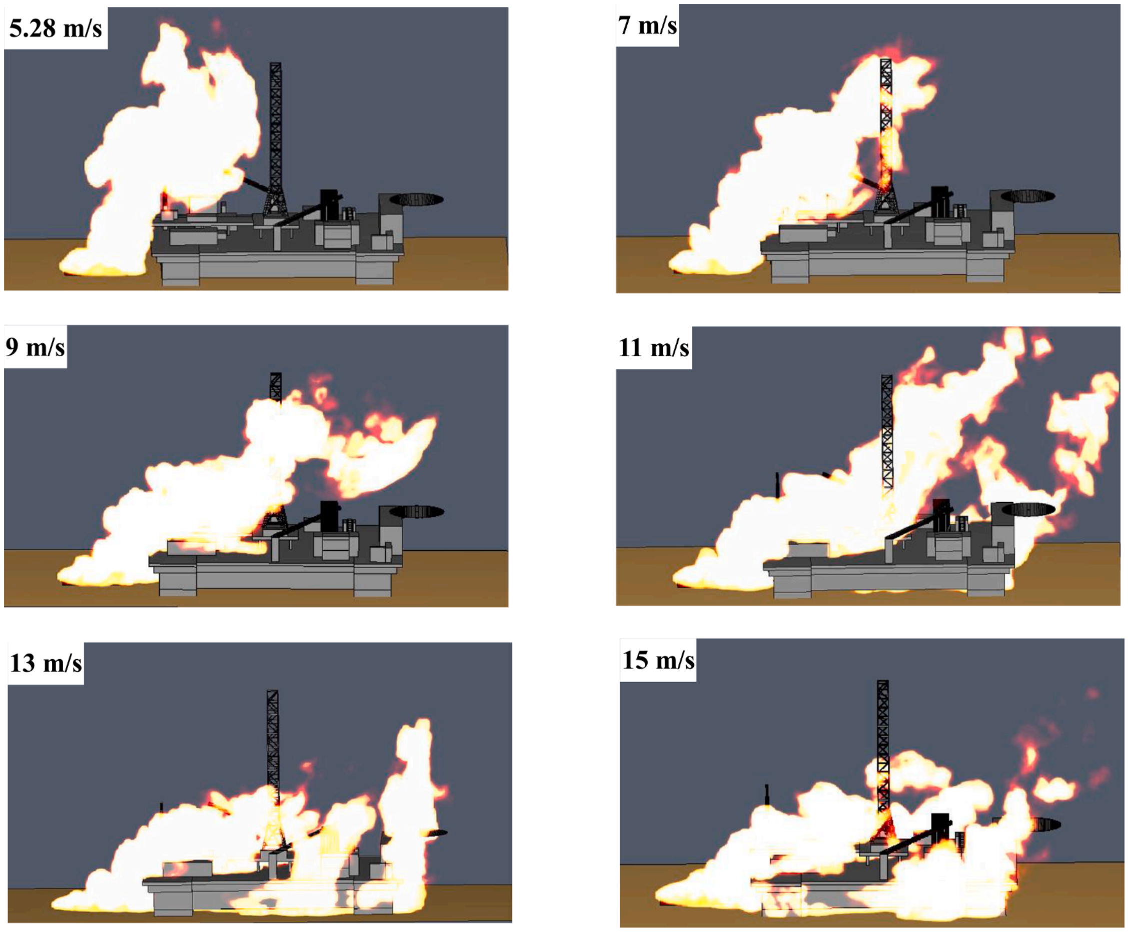


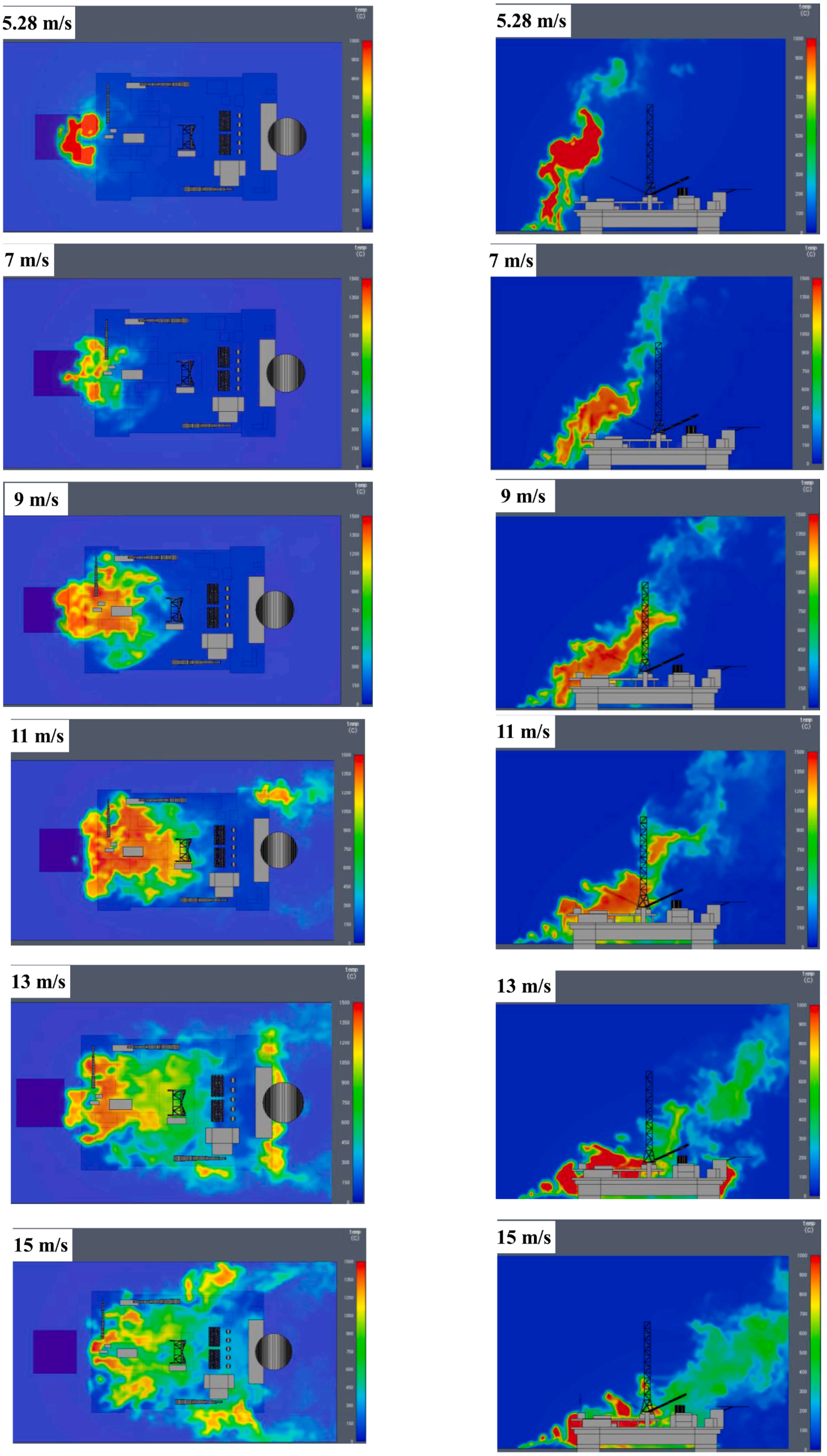
Fig. 7. Time-dependent profile of heat radiation intensity of sea surface gas fire.



(e) 13 m/s

(f) 15 m/s

Fig. 8. Spatial distribution of steady fire under different wind speeds.



(*a*) Horizontal section (*b*) Vertical section

Fig. 9. Temperature field of steady fire under different wind speeds.

Fig. 9 presents the temperature field of the steady fire under different wind speeds, including horizontal and vertical sections. It is clear to see the influencing area of the offshore gas fire. The maximum flame temperature is about 1000°C for the scenario with a wind speed of 5.28 m/s, and the area with high temperature nearly does not cover the offshore platform. The area with the high temperature on the offshore platform increases with increasing wind speed. In the scenarios with a wind speed of 7 m/s and 9 m/s, the flame moves on the offshore platform, and the bow and the main deck is included in the area with high temperature. Also, the partial area of the rig is affected by the high temperature of the fire. In the scenario with a wind speed of 11 m/s, about 2/3 area of the offshore platform's topsides (except for the living area) is affected by the high temperature. The temperature in the mentioned area reaches the critical damage value of the steel structure. The main deck and rig of the offshore platform will be subject to severe damage. In the scenarios with wind speeds of 13 m/s and 15 m/s, the high temperature distributes on the whole topsides of the offshore platform including the bottom of the platform. The temperature on the whole platform exceeds the critical damage value, and the collapse of the whole offshore platform may be caused by continuous fire.

Fig. 10 depicts the time-dependent profile of heat radiation flux at GAS 10 under different wind speeds. Wind speed has an apparent effect on the profile of heat radiation flux. The change of heat radiation flux depends on the spatial distribution of flame. In the scenarios with wind speeds of 9 m/s, 11 m/s and 13 m/s, the lower part of the rig is covered by the flame. The monitor point is located at the bottom of the rig, and the overall radiation flux of the above three scenarios is larger than other scenarios. By comparison, the scenario with a wind speed of 11 m/s has the maximum radiation flux, which is consistent with the flame distribution in Fig. 10. For the scenarios with lower wind speeds, the flame is mainly driven by buoyancy and flows towards the upper space. The distance between the flame and the bottom of the rig is relatively longer than that in other scenarios, resulting in a lower heat radiation flux. The wind has a dominant effect on the flame flow in the scenarios with a wind speed of 15 m/s. Most flames flow along the bottom of the offshore platform, and the flame distributes on the topsides is less than the bottom. Therefore, the radiation flux of the monitored position is lower than that in other scenarios. The minimum radiation flux is about 10 KW/m^2 at 28 s. Expect for the partial period in the scenario with a wind speed of 15 m/s, the overall radiation flux under different scenarios exceeds the critical value of damage on personnel and steel structure, i.e., 25 and 37.5 KW/m^2. The continuous impact of the fire will cause the death of operators, the fracture, or the collapse of the rig structure.

Table 3
Average probabilities of injury or death under different wind speeds over 60 s.

Probabilities of injury or death	Wind speed/(m/s) 5.25	7	9	11	13	15
The first-degree burn	0.88	0.89	0.91	0.90	0.88	0.69
The second-degree burn	0.35	0.76	0.87	0.85	0.77	0.19
Death	0.21	0.65	0.84	0.83	0.70	0.13

Table 3 presents the average probabilities of first-degree burn, second-degree burn, and death in the scenario under different wind speeds over 60 s. The probability of injuries mainly depends on the radiation intensity. Thus, the trend depends on the monitored radiation intensity. It is observed that wind speed has an important influence on the probability of casualties. The probabilities of injury and death first increases and then drops with the increase of wind speed. By comparison, the probability of the first-degree burn is the largest compared to second-degree burn and death, while the probability of death is minimum.

3.3.3. *Effect of gas release rate*

The gas release rate is an important factor affecting the offshore fire consequences. Given the wind speed of 13 m/s, the fires under different gas release rates are simulated. Fig. 11 depicts the steady flame under different gas release rates. It can be found that the gas release rate has a significant effect on the spatial distribution of fire. The influencing range increases with increasing the gas release rate. For the scenario with the gas release rate of 210 kg/s, the steady flame height is about 55 m, and the flame length above the topside is about 90 m. Wind plays a leading role in flame migration since the gas release rate is relatively low. The steady flame above the offshore platform does not reach the rig while the flame under the offshore platform flows to the stern. More gas involves in the combustion reaction when the gas release rate increases. Therefore, the influencing range of flame increases with increasing the gas release rate. In the scenario with a gas release rate of 420 kg/s, the flame flows to the rig and the influencing range in the stern also increases significantly. However, there is no flame in the riser storage area and living area. When the gas release rate increases to 840 kg/s, the steady flame nearly covers the whole offshore platform except for the living area. The flame height is about 100 m, and the flame length is about 175 m. In the scenarios with gas release rates of 1050 kg/s and 1260 kg/s, the whole offshore platform is filled with flame, and the flame volume grows significantly compared to other scenarios. These results demonstrate that the gas release rate plays a dominant role in offshore fire consequences.

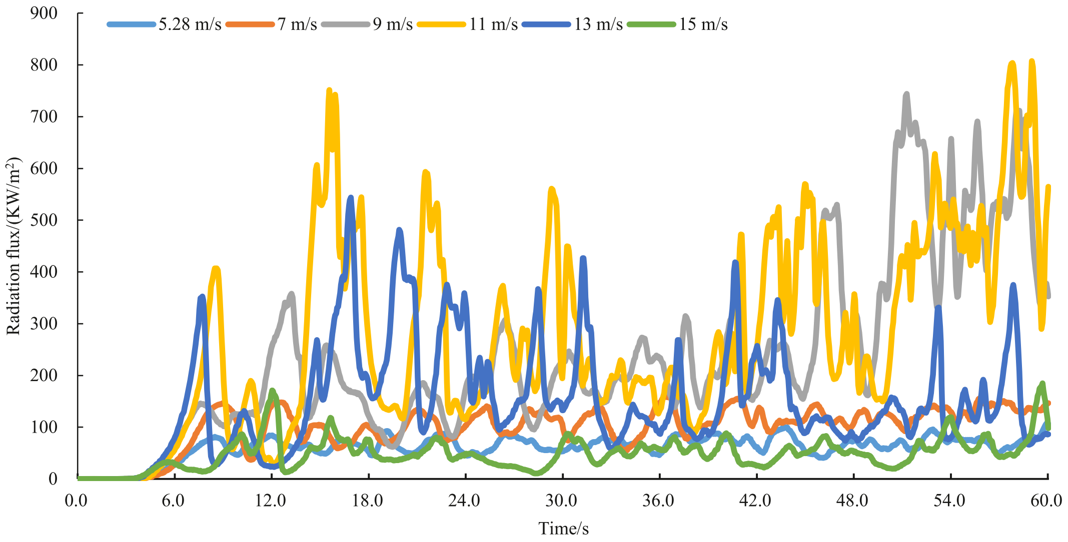


Fig. 10. Time-dependent profile of heat radiation flux with different wind speeds.

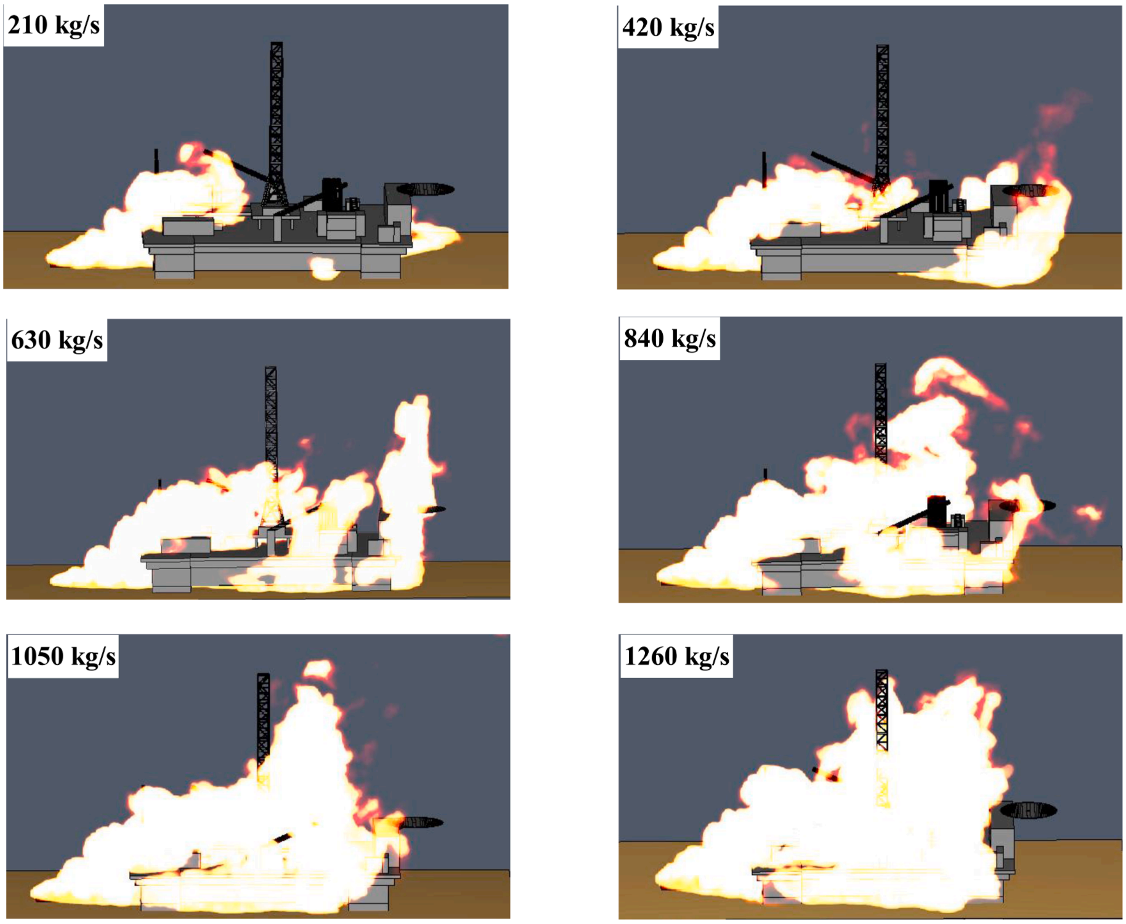
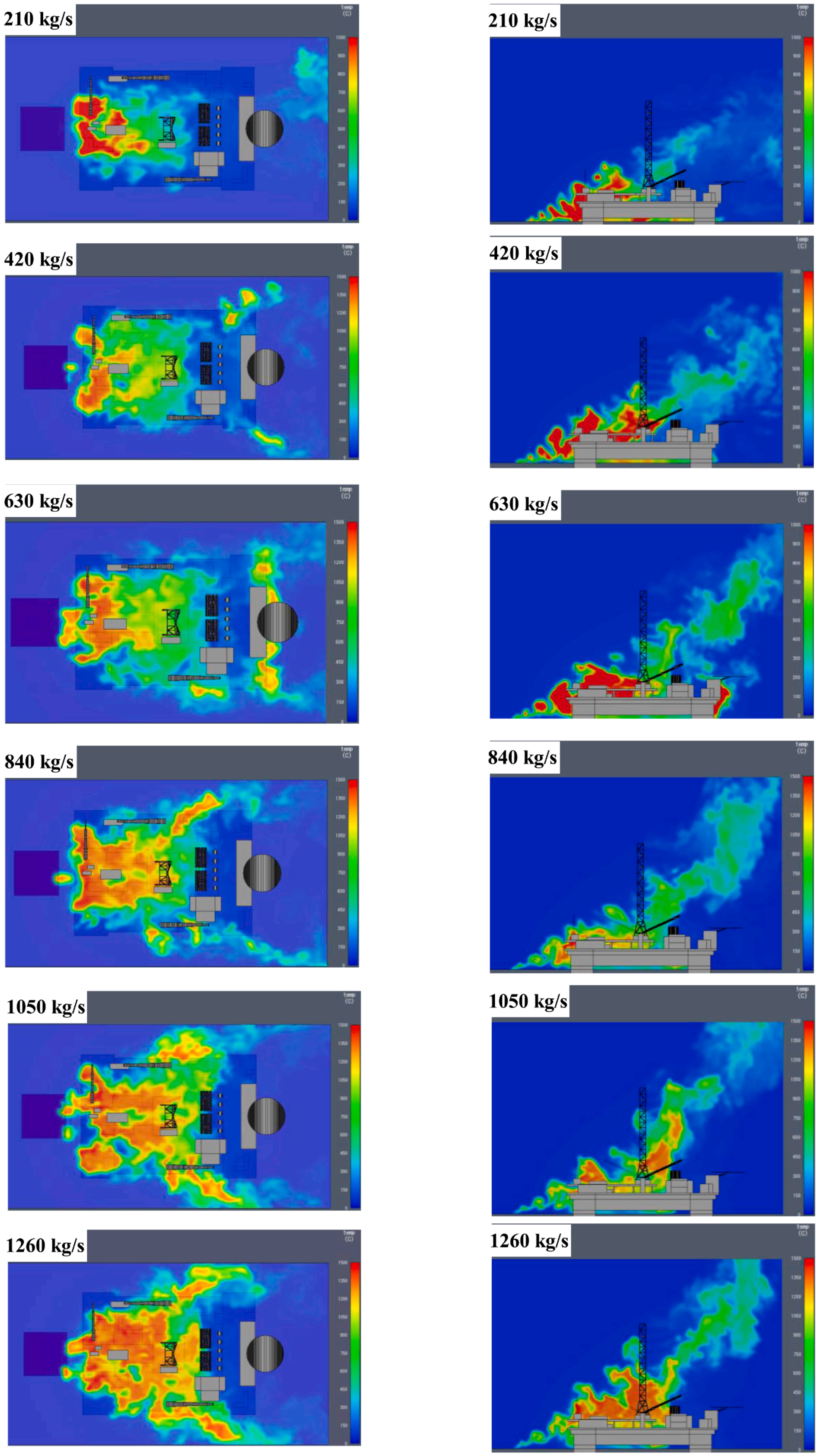


Fig. 11. Spatial distribution of steady fire under different gas release rates.

Fig. 12 presents the temperature field of steady fire under different gas release rates, which reflects that the gas release rate has a significant effect on the temperature field of fire. For the scenario with a gas release rate of 210 kg/s, high temperature generated by fire mainly distributes around the bow and the main deck. The maximum temperature around the bow is about 1000°C and the temperature around the rig ranges from 350°C to 500°C, which may cause the partial failure of the rig while not collapse or fracture. For the scenarios with a bigger gas release rate, more heat quantity is released during the fire since more gas involves in the combustion reaction. As a result, the coverage area of high temperature increases with the increase of the gas release rate. The high-temperature area covers the rig and reaches the front of the riser storage area. The temperature around the bottom of the rig is about 1000°C, exceeding the critical damage temperature that can cause the collapse of the steel structure. Overall, the range of the influencing area increases with the increase of the gas release rate. The length of the high-temperature area is confined to the front of the riser storage area due to the obstruction of the riser storage area. The temperature in the living area is relatively low; thus, the operators can be evacuated to the living area. The width of the high-temperature area increases significantly with the increase of the gas release rate. The high-temperature area covers the port and the starboard. Note that the horizontal migration of fire is mainly driven by wind. Therefore, the longitudinal high-temperature area only reaches the riser storage area since the fire in all scenarios is driven by the same wind speed. It can be concluded that the longitudinal influencing range of high temperature mainly depends on wind speed, and the gas release rate has an essential effect on the temperature value of the influencing area.

Fig. 13 depicts the time-dependent profile of heat radiation flux at GAS10 under different gas release rates. It can be found that the heat radiation flux increases with the increase of the gas release rate. It can be explained that more heat quantity is released because more gas involves in the combustion reaction in the scenario with a larger release rate. Heat radiation flux varies with little fluctuation for the scenario with a gas release rate of 210 kg/s. The maximum radiation flux is 53 KW/m^2 at 36 s, while the steady radiation flux is in the range of 11-30 KW/m^2. The radiation flux increases significantly when the gas release rate increases to 420 kg/s. The maximum radiation flux is about 410 KW/m^2 at 33 s, and the steady radiation flux ranges from 18 KW/m^2 to 50 KW/m^2. The minimum radiation flux in the scenario with a gas release rate of 620 kg/s is 85 KW/m^2. For scenarios with a larger gas release rate, all the radiation fluxes range from 100 KW/m^2 to 770 KW/m^2, which are much greater than the critical damage value for steel structure and personnel. The heat radiation in these scenarios can cause the death of operators and rig collapse. Overall, the gas release rate has a dominant effect on heat radiation flux on the offshore platform, and a larger gas release rate contributes to a higher heat radiation intensity.

Table 4 shows the average probabilities of injury or death in the scenarios with different gas release rates over 60 s. Overall, the probability of casualty increases with the increase of the gas release rate. For the scenario with a release rate of 420 kg/s, the probability of first-degree is estimated to be 0.66, and the probabilities of second-degree and death are estimated to be 0.283 and 0.23, respectively. For the scenario with a release rate of 840 kg/s, the probabilities of first-degree, second-degree and death are estimated to be 0.91, 0.85 and 0.82, respectively. Therefore, the gas release rate a strong impact on the casualty probability of operators under offshore fire from subsea gas release, and the probabilities of injury or death increase with the increase of gas release rate. The probability of first-degree burn is largest, while the probability of death is smallest.



(*a*) Horizontal section (*b*) Vertical section

Fig. 12. Temperature field of steady fire under different gas release rates.

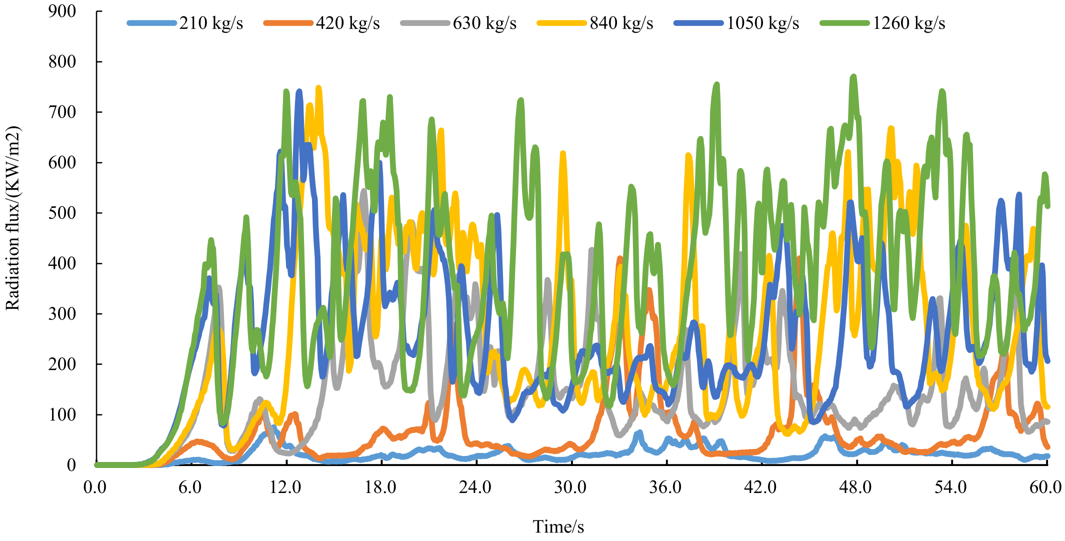


Fig. 13. Time-dependent profile of heat radiation flux with of different gas release rates.

Table 4
Average probabilities of injury or death with different gas release rates over 60 s.

Probabilities of injury or death	Gas release rates/(kg/s) 210	 420	 630	 840	 1050	 1260
The first-degree burn	0.22	0.66	0.89	0.91	0.93	0.93
The second-degree burn	0.012	0.283	0.78	0.85	0.91	0.92
Death	0.0066	0.23	0.71	0.82	0.89	0.90

3.3.4. *Effect of distance between gas pool and platform*

This study considers the effect of distance between the gas pool and offshore platform on offshore fire risk. Given a wind speed of 13 m/s and a release rate of 630 kg/s, a total of four scenarios with distances of 10 m, 20 m, 30 m, and 40 m are simulated. Fig. 14 depicts the spatial distribution of a steady flame under different distances between gas pool and platform. It seems that the distance has little effect on the spatial distribution of a steady flame given wind speed and gas release rate. The flame can develop completely and has enough length in the downwind direction. The steady fire covers the entire offshore platform. This may be the reason why little difference can be found from the simulations of offshore flames under different distances between the gas pool and the platform.

Fig. 15 gives the temperature field of the steady fire under different distances between the gas pool and platform. It reflects similar observations in the simulations of fire distribution. The distance seems to have little effect on the temperature field. The area with high temperature mainly distributes on the bow and main deck, and the temperature ranges from 800 °C to 1350 °C. But it should be noticed that the temperature on the main deck in the scenario with a distance of 40 m decreases significantly compared to other scenarios, which indicates that the temperature on the main deck may decrease with increasing the distance between the gas pool and platform. This can be explained that the impact of temperature will descend with the increase of the distance away from the gas pool. However, the serious structural damage of the offshore platform can be caused by the high temperature in all scenarios.

Fig. 16 presents the time-dependent heat radiation flux at GAS10

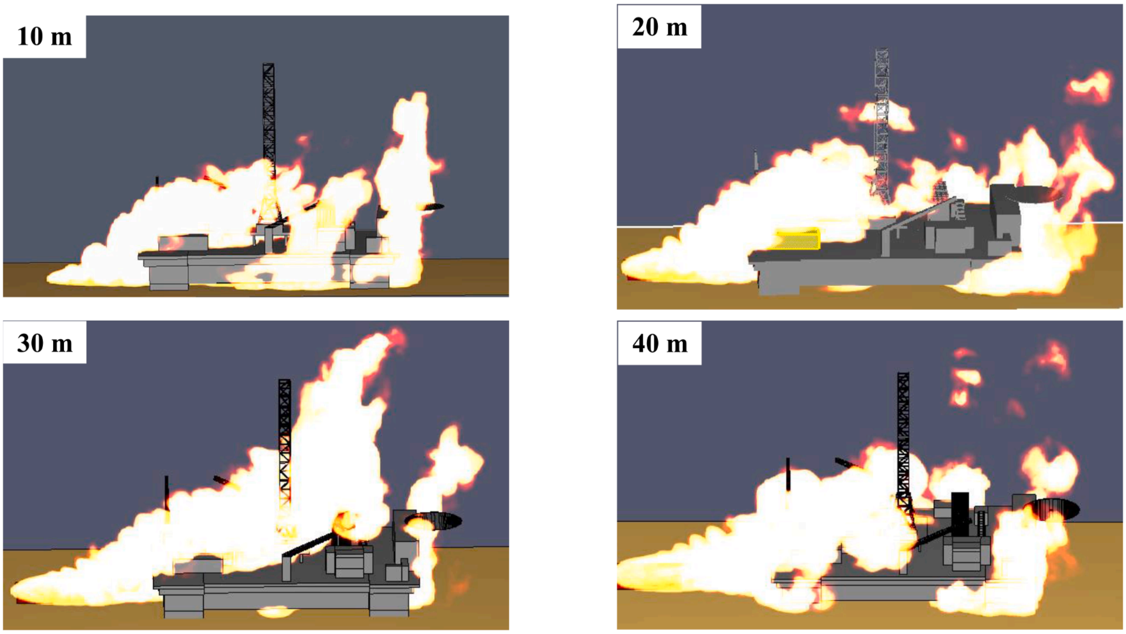
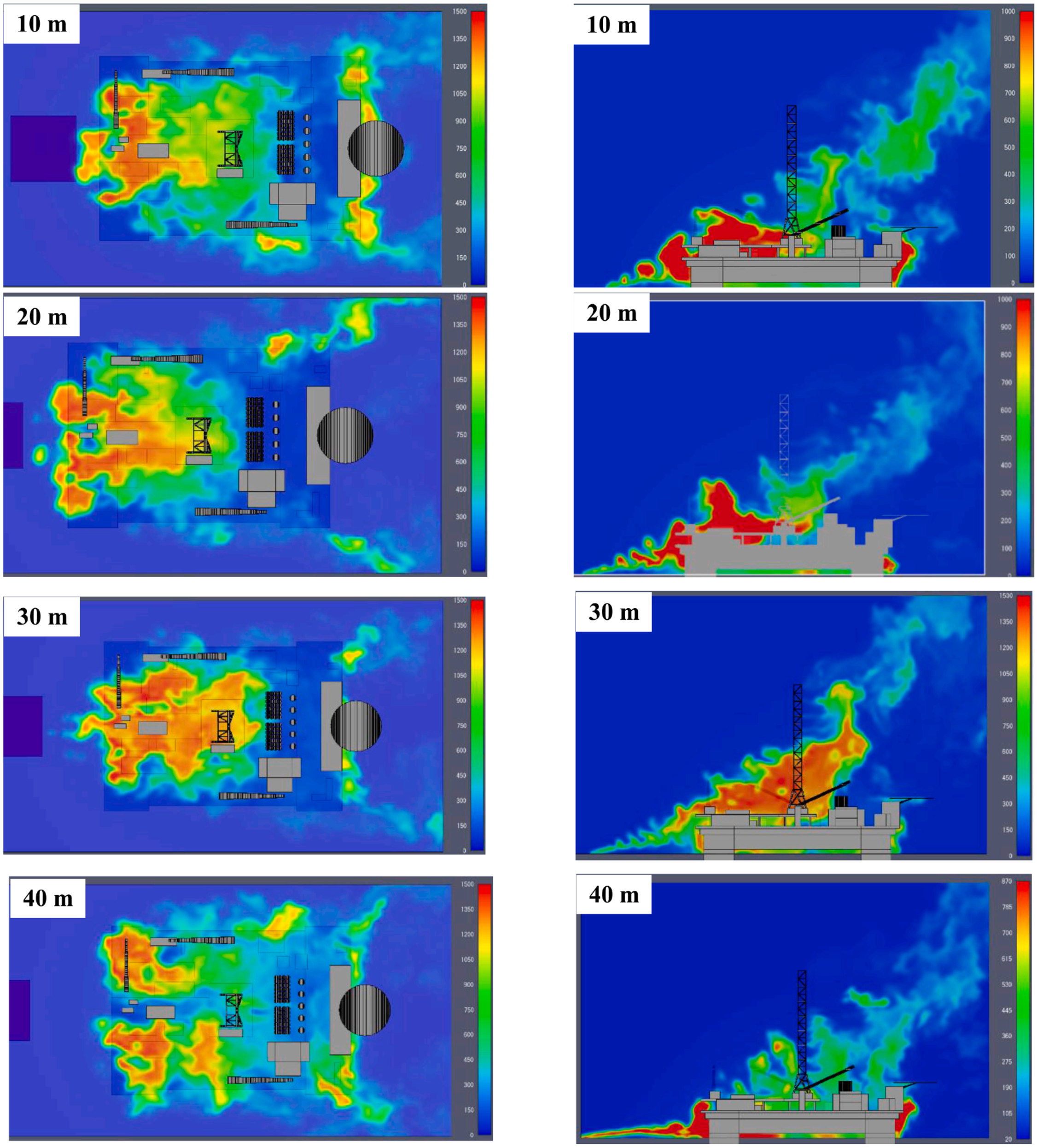


Fig. 14. Spatial distribution of steady fire under different distances between gas pool and platform.



(*a*) Horizontal section

(*b*) Vertical section

Fig. 15. Temperature field of steady fire different distances between gas pool and platform.

under different distances between gas pool and platform. It can be found that the heat radiation flux from 10 s to 60 s in the scenario with a distance of 40 m is lower than that in other scenarios. The lowest heat radiation flux is 10 KW/m^2. The reason may be the increase in the distance between the offshore platform and the gas pool. It is consistent with results reflected in the temperature distribution. It also should be noticed that the heat radiation flux in the scenario with the distance of 30 increases significantly from 36 s, and the maximum heat radiation flux is 711 KW/m^2. But except for the scenario with the distance of 30 m, the heat radiation flux almost decreases with the increase of the distance between the gas pool and the platform.

Table 5 presents the average probability of casualty at GAS10 in the scenarios with different distances. The probability of casualty gradually decreases with increasing distance. The reason may be that the heat radiation intensity decreases with the increase of distance between gas pool and platform, and the impact of fire hazard may be reduced. In the scenario with a distance of 10 m, the average probabilities of first-degree burn, second-degree burn, and fatality are 0.89, 0.77, and 0.71, whereas the average probabilities of first-degree burns, second-degree burns, and death decrease to 0.79, 0.40 and 0.31 in the scenario with the distance of 40 m. It can be concluded that the increase of distance between the gas pool and platform can effectively reduce the probability of casualty due to sea surface fire.

4. Summary and Conclusion

This paper assesses the offshore fire risk caused by subsea gas releases. The sea surface fire due to shallow gas blowout is used to illustrate the offshore fire risk considering the offshore platform operating adjacent to the gas surfacing area. The fire simulation is carried out using the FDS code. The damage probability is estimated using a Probit model. The effect of wind speed, gas release rate, and the distance

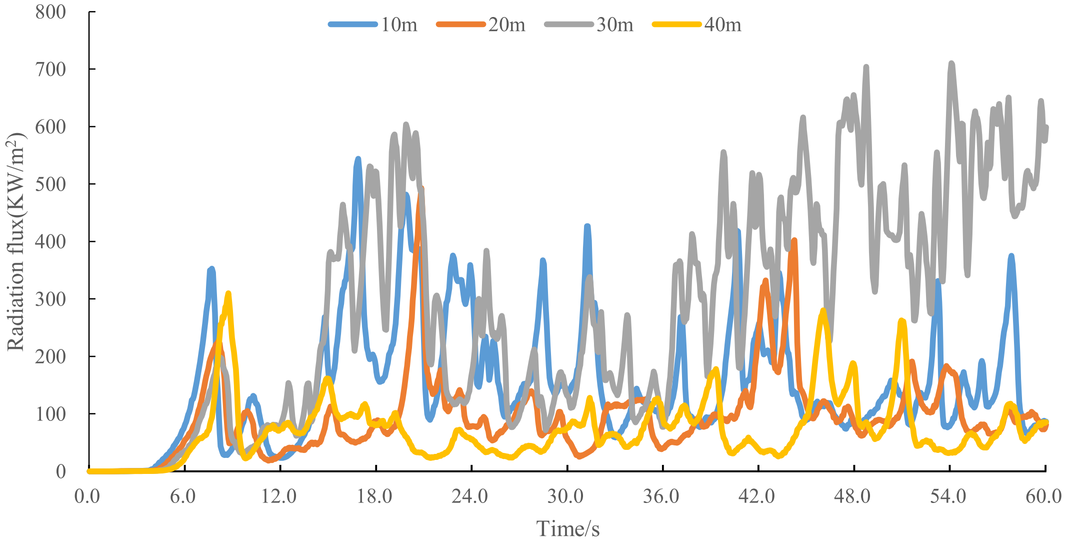


Fig. 16. Time-dependent profile of heat radiation flux with of distance between release and platform.

Table 5

Average probabilities of injury or death under different distances over 60 s.

Probabilities of injury or death	Distances between release and platform/m			
	10	20	30	40
The first-degree burn	0.89	0.87	0.84	0.79
The second-degree burn	0.77	0.59	0.52	0.40
Death	0.71	0.48	0.41	0.31

between gas pool and platform on offshore fire risk is investigated. By these simulations, this study is to illustrate the offshore fire risk from subsea gas release and support safety decision-making and emergency planning of similar accident scenarios.

The geometric size of the fire flame increases rapidly when the flammable gas is ignited. Then the flame flows along the downwind and migrates from the bow to the space above the main deck under the wind. The flame front migrates along with the air space and spills from the stern. In the standard case, the flame is in a steady-state at about 40 s, which covers most of the topsides of the offshore platform. The main high-temperature area distributes around the bow, the main deck, the rig, and the stern. The temperature in these areas is about 1000°C, exceeding the critical damage value for personnel and steel structure, which may cause a catastrophic consequence. Heat radiation flux on the offshore platform fluctuates with time since the flame changes over time due to the effect of offshore wind and air pulsation. Wind speed, gas release rate and the distance between the gas pool and platform, have a dominant effect on spatial flame distribution, high-temperature range, and heat radiation intensity. Wind speed affects the flame migration in the horizontal direction, while the gas release rate determines the combustion heat quantity.

This work is an illustration of offshore fire risk from a subsea gas release event. It could help to improve the knowledge and understanding of subsea gas release-induced offshore fire risk. Remarkably, explosion is also a possible hazard that can be caused by subsea gas release, while it is not in the scope of the present study. Besides, this paper only presents a model for simulating the offshore pool fire, neglecting the subsea gas plume. Future work can attempt to model subsea gas plumes. The other limitation is that this work uses a simplified offshore platform to illustrate the impact of offshore fire on offshore facilities. Future work may study the impact of subsea gas release-induced flammable gas explosion on offshore facilities with detailed structures.

Declaration of Competing Interest

None.

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