Developing a fire model for offshore QRA

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Abstract

The complex and densely packed nature of offshore facilities presents a series of challenges in terms of the potential for fire hazards to develop as well as the ability to model them. In the former, the key issue is the increased potential for escalation, i.e. hazards originating in one area could pose a risk on equipment and people in other areas, and the difficulties to evacuate workers. With the later, the challenge is being able to understand the extent to which the geometry impacts on the development of the hazard and account for this in the modeling. Modfire, a new empirical fire model, has been developed specifically for fires in offshore modules for offshore QRA. It extends the application of simple fire models developed for pool fires and jet fires for onshore QRA to the offshore environment. Using discharge results as the input, Modfire predicts flame shapes with consideration of the interaction between a fire and surrounding boundaries, without the need of huge computing power. The predicted fire characteristics are dependent on release conditions, boundary geometries and ventilation. This paper presents the modeling approach of Modfire and validation work undertaken against CFD predictions.

1. Introduction

An offshore installation normally houses complex facilities for a range of production processes. Space limitation leads to closely packed equipment and pipework and, subsequently, the likelihood of escalation from a relatively small fire is much higher compared to onshore installations and it is far more difficult to evacuate workers when an accident occurs. For instance a fire escalated to riser failure during the Piper Alpha incident in 1988 and caused major loss of life and loss of the platform.

CFD models are the most sophisticated tool available to predict fire dynamics in offshore installations. They solve the fundamental equations of combustion with explicit account for the influence of geometry (e.g. walls, decks, large equipment items) on the development of a fire. However, due to the high demand on resources (e.g. cost, manpower and time) and the large number of scenarios to be considered in a QRA, CFD based analysis becomes impractical for Quantitative Risk Assessment (QRA). Instead, simple fire models developed for onshore scenarios, such as the jet fire model by Chamberlain① and the pool fire models reviewed by Mudan②, are normally used. Whilst the simple models offer quick solutions to very practical problems, they have the obvious drawback that they cannot take account of the platform geometry.

Modfire is a new empirical fire model developed specifically for offshore QRA. It extends the application of simple fire models to the offshore environment. Using discharge results as the input, Modfire predicts flame shapes with consideration of the interaction between fires and boundaries, without the disadvantages which have prevented CFD models for being used routinely for QRA. Modfire predicts the spread of the initial fire into wider areas. Fire characteristics predicted are dependent on release conditions, material properties, boundary geometries and ventilation. The model also considers escalation of fires through boundaries or by causing further process leaks. This paper presents the modeling approach of Modfire and validation work undertaken.

2. Modeling approach

2.1 Background

The flames of hydrocarbon fire consist of high-temperature combustion products with temperatures up to 1600K. Heat is transferred between hot gases of the flame to objects in the surrounding area through convection, conduction and radiation. Heat convection and conduction are important for calculating heat load on facilities engulfed by fire. At some meters away from the fire, heat radiation is normally predominant in heat transfer③. Very near to the flame, radiation is usually high and close to fatality levels for personnel risk. The objectives of this fire model are to predict:

- flame shape of fires to assess whether equipment or walls and decks are engulfed by fires and to enable the prediction of subsequent escalation by fire.
- radiation away from fires for the assessment of flammable risk to workers, process equipment and boundaries

Temperature of the hot gases from a fire fluctuates due to turbulence caused by jet momentum, thermal buoyancy and wind. The radiated heat depends on a wide range of parameters, such as fuel property, release and environmental conditions, and it is difficult to make accurate predictions. In models for QRA, the concept of ‘solid-flame’ is normally used. Heat from the combustion process of a fire is considered to be emitted from the visible flame surface with constant surface emissive power. So once the flame shape is known, the radiation at targets can be estimated as:

$$q = VF * SEP * \tau \quad (1)$$

Where q is the radiation flux at a target (kW/m^2), VF is the view factor of the target to the flame, SEP is surface emissive power of the flame (kW/m^2) and τ is the atmospheric transmissivity.

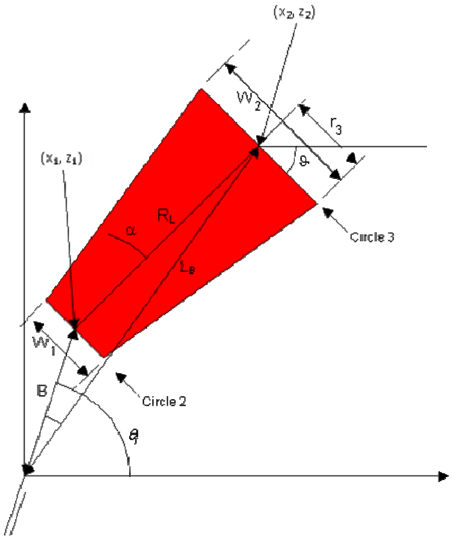


Figure 1 'Solid-flame' model for jet fires

Even though simple, models based on the concept of 'solid-flame' have proved to produce satisfactory results for risk assessment, e.g. the jet fire model by Chamberlain① and tilted cylinder flames for pool fires②. These models are implemented in Phast & Safeti, software tools for risk assessment. Figure 1 illustrates the flame shape for jet fires of the Chamberlain model. The flame has a cone shape with its dimensions correlated to the discharge and weather conditions. The flames of pool fires are represented by tilted cylinders.

Surface emissive power (SEP) of the flame surface is assumed to be constant and can be calculated as:

$$SEP = \frac{F_s m H_{COMB}}{A} \quad (2)$$

Where F_s is the fraction of heat radiated from the surface of the flame, m is the fuel burning rate [kg/s], H_{COMB} is the heat of combustion of the fuel mixture [kJ/kg] and A is the total visible surface area of the flame.

Simple 'solid-flame' models for jet fires and pool fires are primarily developed for fire hazards in relatively open spaces with good ventilation. They have no consideration of the interaction between fires and the surrounding obstacles, and this interaction is an important characteristic of offshore or dense onshore installations because of the closely packed equipment and pipework. Therefore for Offshore QRA, the fire model needs to reasonably predict the interaction between flames and the surrounding boundaries, and subsequent spreading of fire into wider areas through openings and connections. Modfire is a new fire model developed specifically for offshore QRA with these capabilities.

2.2 The Modfire approach

In Modfire, the concept of ‘solid-flame’ has been extended to allow a flame to change shape when interacting with boundaries and to spread into other areas when reaching openings. Depending on complexity of the offshore installation concerned and the release conditions, the flame of a fire could spread into wider areas so that the fire cannot be accurately represented using a single cone, cylinder or sphere. In Modfire, this kind of fire is represented a combination of sub-flames of various shapes, i.e. cone, cylinder & cuboid.

Without considering the wind effect, Figure 2 illustrates the flame shapes of a pool fire on a deck of four scenarios:

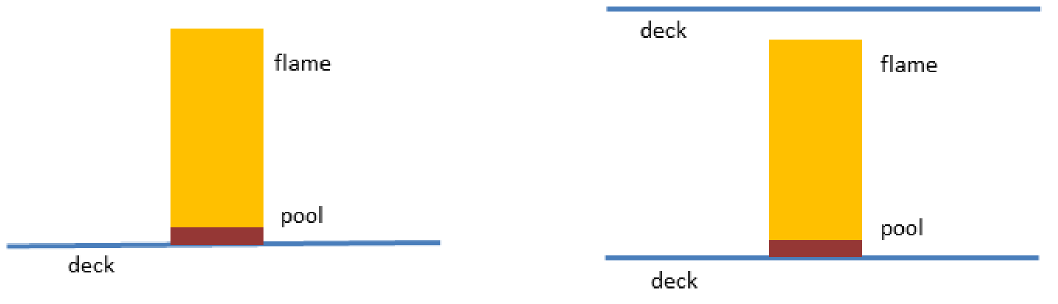
- Scenario (a): there is no upper deck so the flame shape remains like a cylinder, which tilts when wind is blowing.
- Scenario (b): there is an upper deck, but it is not reached by the flame, so the fire still has a cylinder shape as for Scenario (a).
- Scenario (c): the pool fire impinges the upper deck and spreads outwards beneath it. The top section of the flame is represented by a cone and the low part by a cylinder in Modfire.
- Scenario (d): the flame has spread to the edge of the upper deck and goes upwards after the edge. Apart from the cone and cylinder flames as shown in Scenario (c), a cuboid flame may be needed to represent the hot layer near the upper deck depending on shape of the upper deck and position of the fire, the escaped flame above the upper deck is represented by cylinder flames which tilt according to wind..

The following algorithm is followed to determine the flame shape due to the interaction with boundaries and spreading into openings:

- Flame shape of a fire is determined in an iterative searching process starting at a relatively small volume. Sub-flames are gradually introduced when a fire gets into new spaces when the volume is increased in the searching process.

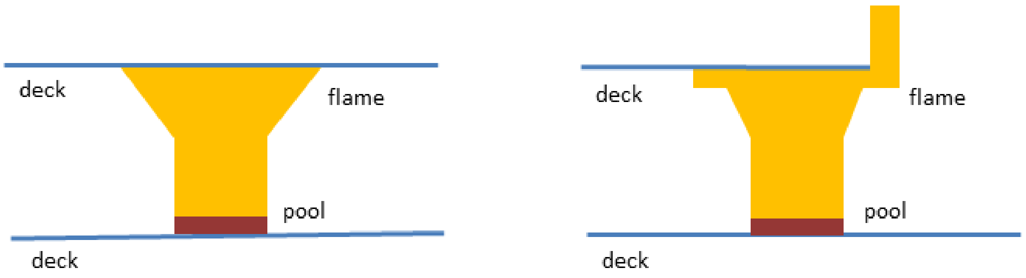
- Volume of the fire is defined by the fire of the same release rate in the open at a wind speed of 3m/s, i.e. volume of the undisturbed fire of the same release conditions. This wind speed is selected by taking into consideration of generally slow air movement inside offshore installation. For an area to be classified as ‘open area’ according to IP15 of Institute of Petroleum④, air velocity inside is defined as rarely below 0.5 m/s and frequently above 2m/s. Air movements in sheltered areas are less than that in open areas.

  Volumes of the undisturbed fire are estimated using the Chamberlain model for jet releases and the model by Cook et al⑤ for pool fires, which uses the correlations overview by Mudan.



(a) Pool fire in the open

(b) Pool fire has no interaction with the upper deck



(c) Pool fire interacts with the upper deck

(d) Pool fire interacts with the upper deck and goes up

Figure 2 Flame representation for pool fires of four scenarios

- When ventilation in a module is limited, the flame volume inside is capped to the volume of the undisturbed fire at a transitional fuel rate as given by Lowesmith et al⑥ as

  $$m_{tr} = m_{vent} / r \qquad (3)$$

  Where r is the mass ratio of air to fuel required for stoichiometric burning, m_{vent} is the mass flowrate of air available for the fire and m_{tran} is the transitional rate at which the fire is controlled by ventilation available, instead of the release rate.

- The fraction of emitted radiation is estimated using the correlations by Chamberlain for jet fires and by Mudan for pool fires.

- Surface emissive power (SEP) of a fire is calculated using the visible surface area of the predicted flames and equation (2). Overlapped flame surfaces between sub-flames are excluded to prevent over-estimation of flame surface area. When there is no interaction between a fire and any boundary, the surface emissive power predicted by Modfire would be the same as that of undisturbed fires.

- Radiation at targets is the sum of all sub-flames which are visible to them, i.e. no boundary in between.

3 Model validation

Even though the ‘solid-flame’ concept has been used with success to predict radiation from pool fires and jet fires, Modfire is an extension of the concept and needs to be validated to be used with confidence. Validation was carried out by comparing Modfire predictions against the results of CFD codes. The validation includes qualitative comparison of the predicted flame shapes and quantitative comparison of radiation predicted for pool fires and jet fires, i.e. against the results of FDS for cases with a two-deck setup as shown in Figure 3 and the results of KFX on a medium-size offshore platform shown later.

FDS is a computational fluid dynamics CFD) model developed by National Institute of Standard and Technology (NIST) of USA for fire-driven fluid flows⑦. It is an open-source CFD code and has been widely used all over the world and validated by the developer and the users. Kameleon FireEx KFX® 2010 is a CFD code from ComputIT for fire simulations and has been used widely to model fires for risk assessments.

For the simple test cases shown in **Figure 3**, a fire is initiated between two decks from a pool or a jet release in the middle of the domain. All sides of the computation domain are open. When the fire is large, it would impinge on the upper deck, spread outwards in all directions and go upwards after reaching the edge of the upper deck. The central vertical plane is assumed to be symmetric to reduce computing time using the mirror option available in FDS.

The pool fire is located on the lower deck and is modeled with a given heat release rate equivalent to the pool burning rate calculated by Modfire. Vertical jet releases are positioned upwards at the center with the required mass release rate. No wind speed is specified for the cases, heat transfer between flame and upper deck has been ignored.

Temperature contours on the symmetry plane are used to qualitatively assess the flame shapes predicted by Modfire. Temperature contours by FDS are representative snapshots selected from the animated results over a period of 180s. For quantitative validation, predicted radiations are compared on six transects as shown by the red lines in Figure 3. The radiation values predicted by FDS are the averaged values at positions over the last 120s of the 180s period simulated. Location of these transects and observer orientations used to calculate the radiation are given in Table 1. Radiations predicted by FDS are the values as measured by radiometers with the specified orientations. Planar observers are placed at the same orientations in Modfire predictions for a direct comparison against the FDS results.

Table 1 Location and observer orientation at transects for radiation predictions

Transect Name	*Location*	*Observer orientation*
Y2	Y=2 & Z=0	Facing the upper deck
Y3	Y=3 & Z=0	Facing the upper deck
Y5	Y=5 & Z=0	Facing the upper deck
X3	X=3 & Y=8	Facing into the direction of -Y
X8	X=8 & Y =8	Facing the flame central line
Z2	Y=5 & Z=2	Facing into the direction of -Y

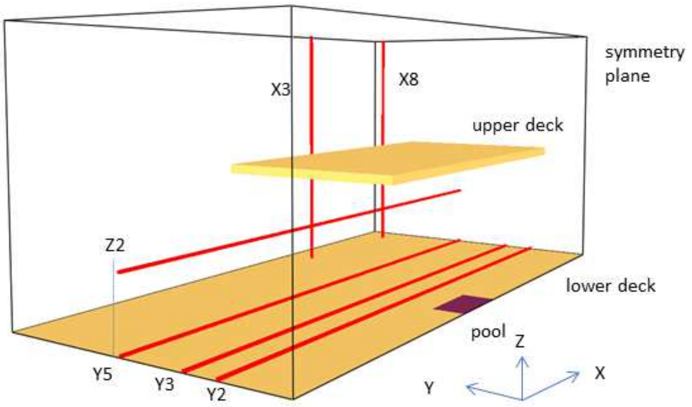


Figure 3 Setup of simple test cases to validate Modfire

3.1 Simple test cases: pool fires

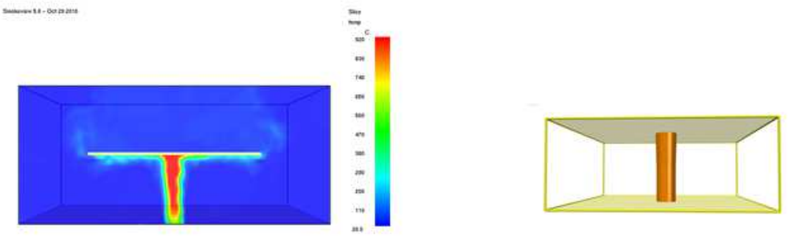
Table 2 gives the input data of the pool fire test cases. The pool has a square shape in FDS models with a specified HRRPUA (heat release rate per unit area) calculated using the pool burning rates.

Table 2 Input data for the test cases of pool fire

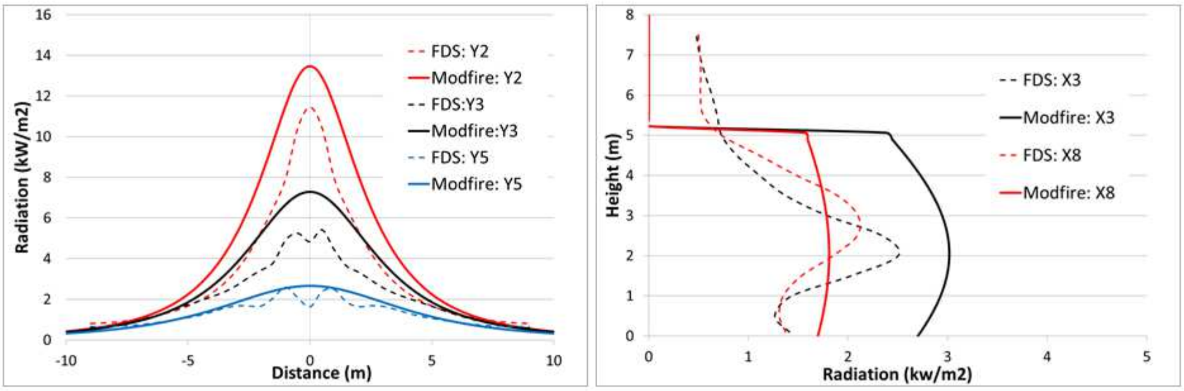
Case name	Material	Pool area (m^2)	Pool burning rate (kg/s m^2)	HRRPUA (kW/ m^2)
P1	n-Pentane	1	0.106	4812
P2	n-Pentane	4	0.106	4812
P3	n-Pentane	9	0.106	4812
P4	n-Pentane	16	0.106	4812

Figure 4 shows the predicted results for the pool fire with a pool area of 1m^2. In this case, the fire is quite small and the flame has just reach the upper deck without much spreading. Therefore the flame by Modfire is close to a cylinder confined between the decks and this is confirmed by FDS as shown by the temperature contours. Modfire does not predict the hot layer under the upper deck, but temperature of the layer is still relatively low as shown by the FDS results. Results of the two models agree well in trends and Modfire has slight over-predictions on all transects.

When the pool size has been increased to 9 m^2, the fire has spread beneath the upper deck to the edge as indicated by both FDS and Modfire as shown in **Figure 5**. At this point, radiation predictions by Modfire are still in good agreement with FDS results with slight over-predictions along transects on the lower deck, i.e. Y2, Y3 & Y5. However, a region of under-prediction appears on the vertical transects at the height about 2m above the lower deck.



(a) Temperature contours by FDS (b) Flame shape by Modfire



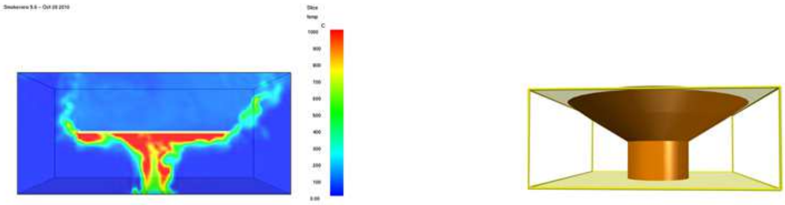
(c) Radiations on horizontal transects (d) Radiations on vertical transects

Figure 4 Modeling results of tset case P1 for pool fire, i.e. a pool area of 1 m^2

When the pool size is increased to 16 m^2, fire is escaping the region between the two decks and going upwards as predicted by both models as shown in **Figure 6**. In Modfire the flame of the escaped fire is represented by two cylinders at each side. Modfire starts to under-predict in the region very close to the flame on transect X2, i.e. near to the centre. Despite the under-prediction seems large, but the radiations predicted in the region are higher than 60 kW/m^2, which would have caused 100% fatality if the Probit method is used for flammable risk⑧. So under-predictions at this level on the lower deck are unlikely to cause problems in risk calculation.

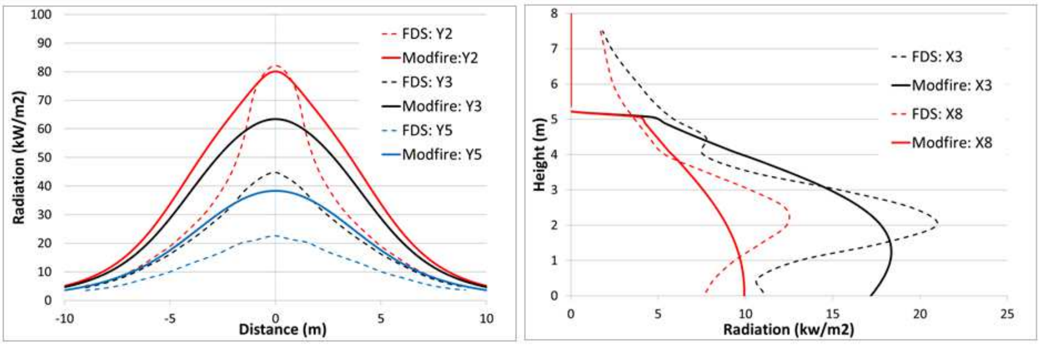
There are also under-predictions on the vertical transects. Flames predicted by FDS can reach low positions occasionally due to turbulence and unsteadiness of the burning process, as illustrated in Figure 7 for the pool fire case P4. Modfire is too simple to predict these fluctuations and this should have contributed to the under-predictions. On the other hand, as shown in the validation for the Chamberlain model⑨, the discrepancy between predicted and measured radiations can be ± 40% at some locations, and this is consistent with results by Modfire.

In QRA, radiation is usually calculated using optimised observer orientation, i.e. the orientation that gives the highest radiation for planer observers, to represent the worst case by radiation. Figure 7 compares the predicted radiations with optimised observer orientation on transect Z2, which locates at the height where Modfire produces the highest under-predictions as shown in **Figure 5** and **Figure 6**. The under-predictions are almost eliminated if optimised observer orientation is used in the case.



(a) Temperature contours by FDS

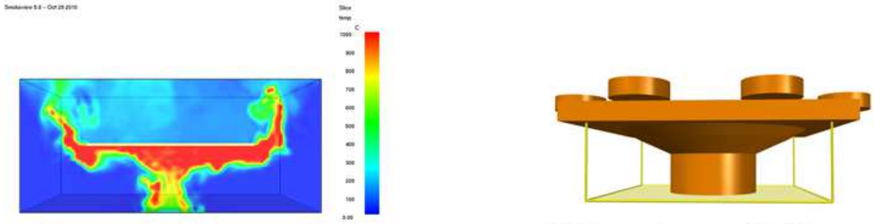
(b) Flame shape by Modfire



(c) Radiations on horizontal transects

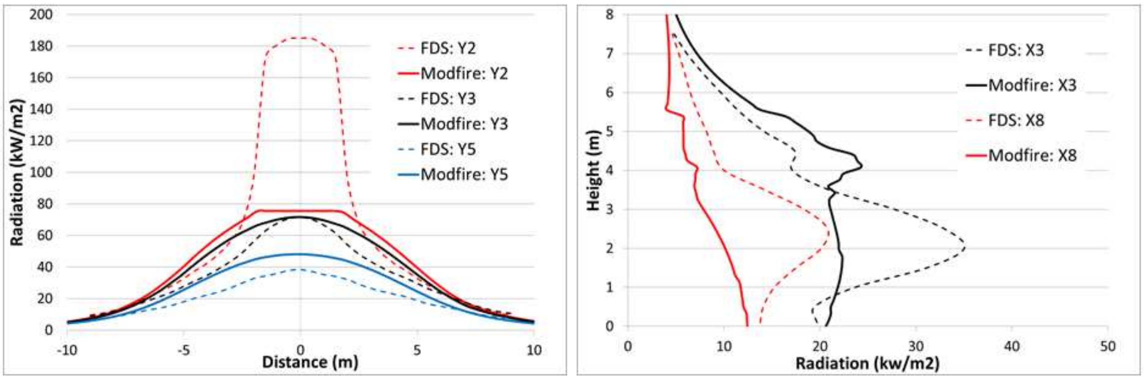
(d) Radiations on vertical transects

Figure 5 Modeling results of the test case P3 of pool fire, i.e. a pool area of 9 m^2



(a) Temperature contours by FDS

(b) Flame shape by Modfire



(c) Radiations on horizontal transects

(d) Radiations on vertical transects

Figure 6 Modeling results of test case P4 of pool fire, i.e. a pool area of 16 m^2

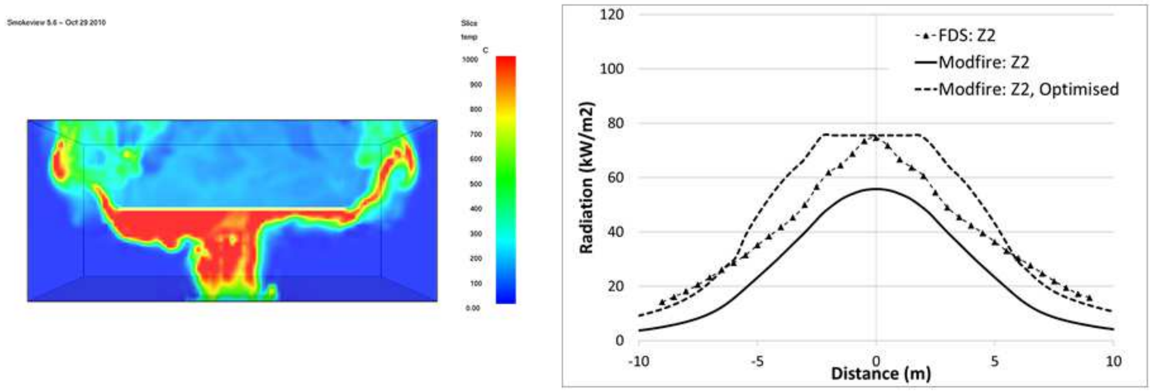


Figure 7 Predicted radiations on the horizontal transect Z2 for the pool fire of 16m^2.

3.2 Simple test cases: Jet fires

Table 3 gives the input data of the jet fire test cases. The jet release is positioned upwards in the middle of the computational domain with a square shape in the FDS model. The jet release conditions are the identified release scenarios of an offshore QRA.

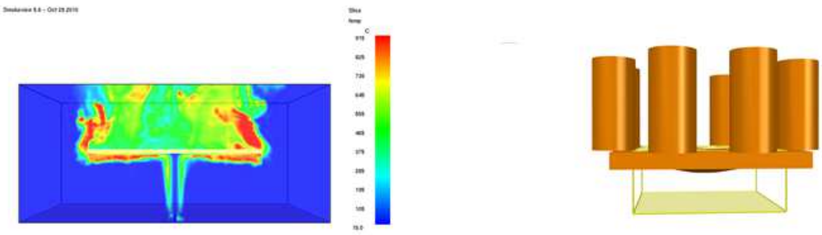
Table 3 Input data for test cases of jetfires

Case	Material	Release rate (kg/s)	Jet velocity (m/s)
J1	methane	1	400
J2	methane	2	400
J3	methane	4	400

Because of the momentum of jet releases, there is usually an uplift of the jet fire away from the release point. The lift-off distance is calculated as in the Chamberlain model. In Modfire, the lift-off distance is capped to the half distance between the release point and the upper deck to reflect the restriction of upper boundaries on fires. **Figure 8** shows the predictions of a jet fire at a release rate of 4 kg/s. At this rate, the fire has spread outwards beyond the edge of the upper deck, which is confirmed by FDS simulations. The flame predicted by Modfire is represented by a cone sub-flame and a cuboid sub-flame below the upper deck as a hot layer and cylinder sub-flames for the escaped fire around the upper deck.

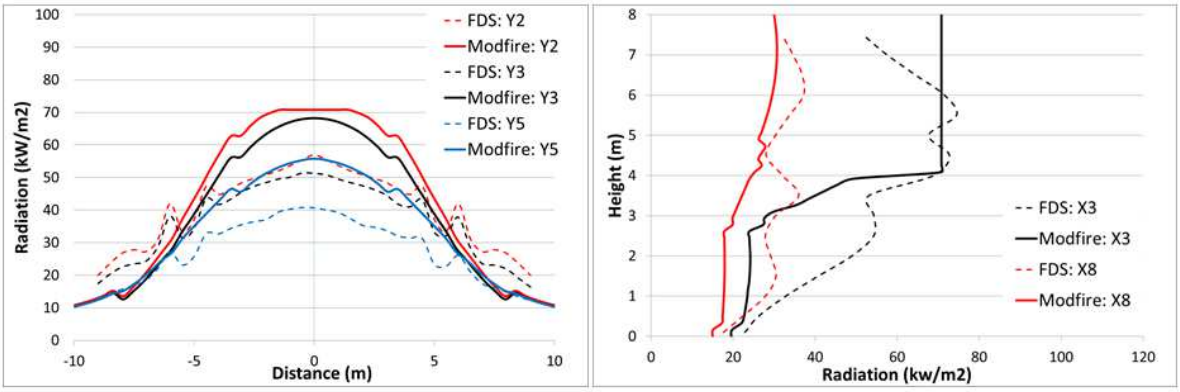
The predicted radiation on the lower deck is satisfactory with slight under-predictions in the far regions from the centre. That indicates the hot gas may have travelled further in the horizontal direction after reaching the edge of the upper deck, instead of going upwards immediately as assumed in Modfire. The lift-off of the jet flame in Modfire has produced no fire between the lower deck and the lift-off point as shown in **Figure 8**(b), this should have contributed to the under-prediction of radiations between the decks on the vertical transects X3 & X8. The under-predictions can be addressed using optimised observer orientation as demonstrated in Figure 7 for a pool fire.

For the jet fire shown in **Figure 8**, FDS has predicted large entrainment of high-temperature combustion products into the region behind the upper deck. Modfire has not included this kind of phenomena. Instead, Modfire has predicted larger flames with increased heights. Even so, radiation values predicted on the transects are still very reasonable.



(a) Temperature contours by FDS

(b) Flame shape by Modfire



(c) Radiations on horizontal transects

(d) Radiations on vertical transects

Figure 8 Modelling results of test case J3 of jet fire, i.e. at a release rate of 4kg/s.

3.3 An offshore platform

Offshore installations are usually complex and packed with facilities. **Figure 9** shows a medium-size platform for oil production. Modfire has been used to model several release scenarios in the production area, i.e. the left section of the platform shown **Figure 9**. In a complex situation as this, a network of cuboids has been created to represent the platform in Modfire. Boundaries, i.e. walls & decks, are defined as a property of the cuboids. A fire starting inside the production area will spread into connected cuboids if there is no boundary to stop it. **Figure 10** shows the cuboids generated to represent the platform and the flames of a pool fire.

The predictions of Modfire are compared against the results of KFX. As the results shown above against FDS predictions, Modfire is predicting the spreading of fire within the platform with good accuracy. **Figure 11** shows the predicted radiations on two horizontal transects at the south side of the platform of a pool fire case. The flat section of Modfire results indicates the locations are on fire.

In a simulation for QRA with Modfire, properties of the cuboids are updated according to the consequences they have experienced. Boundaries are being impaired due to explosion and fires, and the fire development history is predicted using the updated geometry as it changes with time.

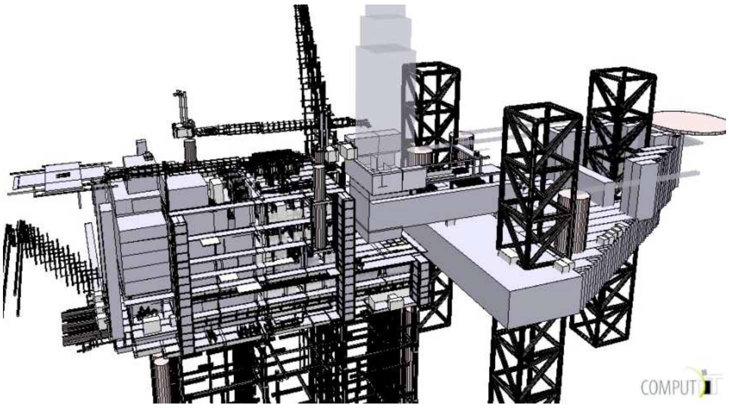


Figure 9 A medium-size offshore platform for oil production

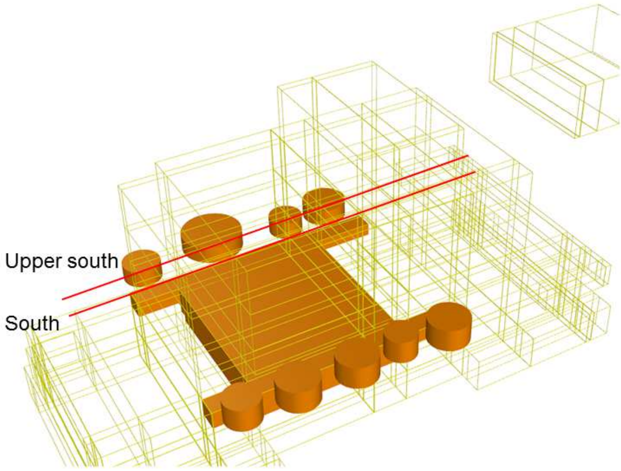


Figure 10 Cuboids for Modfire predictions and the predicted flames

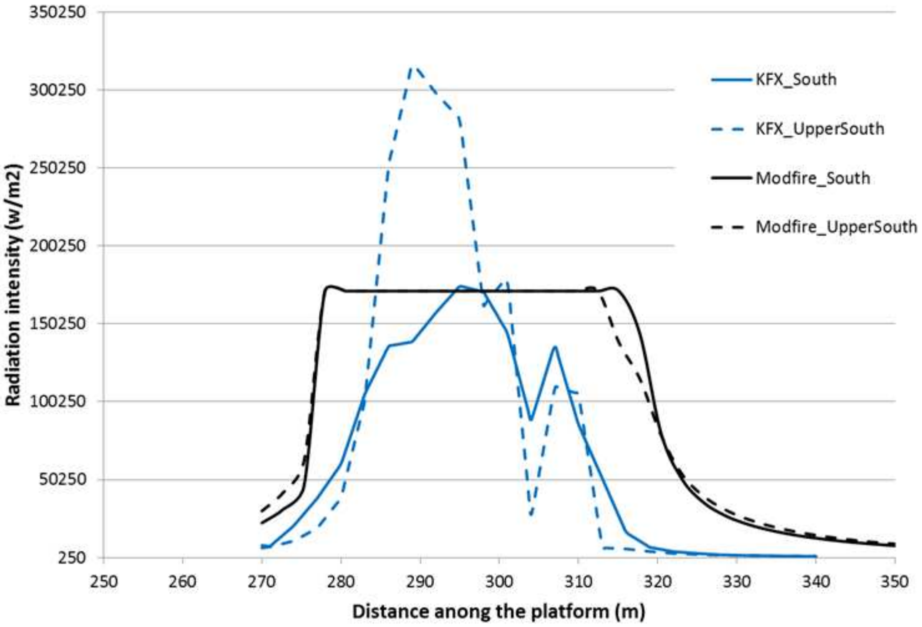


Figure 11 Comparing the predicted radiations on two transects along the platform

4 Conclusions

A new method has been developed to model fire hazards and risk in the offshore environments. This method is an extension of the ‘solid-flame’ concept which has been used successfully for the QRA of onshore installations. Predictions of this new method have been compared against well validated CFD fire models using results for a range of test cases:

- Pool fires with four pool diameters within a two-deck setup
- Jet fires at three release rates within a two-deck setup
- Pool fires and jet fires on a medium-size platform.

In all of these test cases, predictions of Modfire have been compared against the CFD results qualitatively for the predicted flame shapes and quantitatively for radiation predictions. The predicted radiation is generally in good agreement with CFD results. However, there are under-predictions at some locations when using a fixed plane orientation. This is a weakness of the solid flame approach in that the flame geometry is idealized and does not fluctuate with time. In QRA, radiations are usually calculated with optimised observer orientation to detect the worse-case scenarios. With this option, the under-predictions by Modfire using fixed orientations are largely addressed and overcome this limitation of the solid flame approach.

In practice, offshore hydrocarbon fires can vary widely in characteristics due to the variations in production process and in design of the installations. Further validation is needed to test the model for more scenarios, such as multiphase and multi-component releases, wind effects and horizontal fires.

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