Numerical Investigation on the Effectiveness of Water Spray Deluge in Providing Cooling, Smoke Dilution and Radiation Attenuation in Fires

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ABSTRACT

The effectiveness of water spray is influenced by nozzle type, spray momentum and orientation as well as water droplet size. It is also subject to the influence of environment conditions, most notably wind condition in open fires and ventilation in enclosures. The present study is focused on the effect of such external parameters on the effectiveness of water spray systems when used as water curtains to provide cooling and smoke dilution; and create an “escape” corridor for crews on offshore oil and gas production facilities. In such applications, water spray is more frequently referred to as “water deluge”. A related study has also been carried out to investigate the attenuation of thermal radiation by water deluge on an oil tank fire. Overall the present study has led to some useful conclusions and demonstrated the potential of numerical modeling techniques as an effective means to aid the design of water curtains and surface water deluge systems.

KEYWORDS: water spray, water deluge, suppression, radiation attenuation, CFD

INTRODUCTION

The basic mechanisms of fire extinguishment by water sprays were investigated by Rasbash et al. [1] in the early sixties. Oxygen dilution by the water vapour resulting from droplets evaporation was identified as a key extinguishment factor [1]. In a more recent study, Mawhinney et al. [2] have identified the primary and secondary extinguishment mechanisms of water mist in fire suppression. The primary mechanisms include (i) heat extraction by cooling of the fire plume or wetting/cooling of the fuel surface and (ii) displacement of oxygen and dilution of fuel vapour. The secondary mechanisms are (i) radiation attenuation and (ii) kinetic effects. A significant number of experimental and theoretical studies have been undertaken in the last decades to investigate the interaction between fire and water sprays [3-4]. Among the experimental works, the extinction in open space of methane and heptanes pool fires by water sprays was studied by Heskestad [5]. The effect of water mist on methanol and hexane pool fires in a compartment was investigated by Kim and Ryou [6]. The theoretical approaches presented in the literature to model fire and water spray interaction have different levels of complexity and computational demands. A computationally less demanding CFD approach was developed by Jackman et al. [7] based on detailed modeling of heat and mass transfer between droplets and hot gases by a particle tracking algorithm. The most complex and time consuming CFD approaches for spray-fire interaction solve the complete set of governing equations for heat and mass transfer and include the effects of thermal radiation, turbulence and combustion [8-11].

Most previous studies were concerned with obtaining the combination of engineering design parameters (e.g. nozzle type and size, spray momentum and orientation) necessary to extinguish a given fire. Relatively little attention has been given to the effect of environment conditions such as wind in open fires and ventilation in enclosure fires.

The present study is focused on fire protection and thermal radiation attenuation on offshore oil and gas production facilities, where water spray deluge is used extensively to control fires and mitigate their impact, and also could be used as water curtains to provide protection to the designated escape route thus providing an “escape” corridor for crews in the event of fire. There is a general consensus supported by tests that water deluge is effective as a protective measure. This is achieved by controlling the development and severity of pool fires, reducing the heat load on equipment and structures and reducing radiation and smoke to personnel sheltering on or near the facility. McCaffrey [12] carried out a feasibility study on using water sprays for the control of offshore oil/gas well blowout fires. He found that the effect of flame

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temperature reduction due to water deluge could correlate with a single spray parameter - the median drop diameter.

The design of deluge systems is usually by codes and standards. The effect of the environment such as ambient wind, or changes of environment such as a change in ventilation conditions are not explicitly accounted for in the design by additional evaluation. Typically, deluge or sprays are composed of a multitude of liquid droplets of different sizes and velocities. The suppression or mitigation of pool fires by water deluge is achieved through thermal cooling, oxygen displacement, fuel surface cooling and attenuation of radiant energy. The performance of a water deluge system is affected by factors such as the droplets size, velocity, spray pattern, geometry, momentum, fire properties and ventilation conditions. In an effort to understand the effectiveness of the water deluge technique in mitigating potential offshore jet and pool fires, a large scale study, sponsored by a joint industry project involving several oil companies, was undertaken recently [13]. It was found that liquid pool fires of diesel and condensate can be rapidly controlled by area water deluge applied at an area deluge application rate of 12 $l/min/m^2$. The deluge progressively reduces the size of the fire and its coverage of the pool surface. Also, levels of smoke evolving from the fire are significantly reduced. The main mechanism for the control of this type of fire in unconfined or partially confined conditions is the cooling of the liquid surface by water entering the pool. It was also found that wind speed can significantly affect the rate of control of pool fires. The complexity of fire control or suppression by water deluge due to the variety of factors involved was highlighted through these studies, which suggested that it would be prudent to take these factors into account in the design of such systems for particular installations.

The authors recently reported on numerical study of the interaction between water deluge and fires for a range of applications [14]. Through numerical simulations of four representative scenarios, the application of advanced CFD tools to quantify the behaviour and performance of water deluge on fire control was illustrated. The work also demonstrated that the effectiveness of water deluge strongly depends on the ventilation conditions, the droplet size and spray momentum, as well as the wind speed for open fires. In the present study, numerical investigations have been carried out to investigate the effect of water curtains to provide cooling and smoke dilution and create an escape corridor for crews on offshore oil and gas production facilities. A related study has also been carried out to investigate the attenuation of thermal radiation by water deluge on an oil tank fire. Particular consideration is given to the effect of droplet size, deluge rate and wind conditions. Further comparison is also carried out to investigate fire protection through the attenuation of thermal radiation from oil tank fires by water deluge. In such applications, fire is not extinguished but the application of water deluge provides protection for facility and personnel through radiation attenuation.

NUMERICAL MODEL

The CFD code used for the simulations is the Version 4.0.7 of FDS (Fire Dynamics Simulator) developed by the National Institute of Standards and Technology (NIST) in the USA [15]. The code solves the Navier-Stokes equations for low Mach number ($Ma<0.3$), which covers most thermally-driven flows that occur on onshore and offshore oil/gas production facilities. The numerical algorithm employed is an explicit predictor/corrector scheme, second order accurate in space and time, using a direct Poisson solver. Turbulence is treated by means of Large Eddy Simulation with the Smagorinski sub-grid scale model. For combustion, a mixture fraction model is used. It assumes “infinitely fast reaction”, the mass fraction of oxygen is calculated from the so-called “ideal state relation”, which is generated from the definition of mixture fraction. The corresponding mass fraction of fuel and products are obtained from the oxygen mass fraction. The two-phase flow of water droplets and gas is modeled by the Eulerian-Lagrangian method. For radiation, FDS solves the radiative transport equation using the finite volume method (FVM). However this method could be computationally expensive for real fire scenarios in particular if fine meshing is needed. The alternative method to account for radiation in FDS is to prescribe the radiative fraction (fraction of combustion energy emitted as thermal radiation) and in each computational cell the radiated energy is approximated as 35% of the total energy released by the flame. This approximation although less accurate is CPU saving compared to solving the radiative transport equation.

The code accounts for the contribution of soot using a simple approach through some band-mean absorption coefficients. The built-in sub-models in FDS for water spray simulation was used. In this relatively simple model, the initial size of each droplet is described in terms of random distribution. The force term in the momentum equation representing the momentum transferred from the water droplets to the gas is obtained by summing the force transferred from each droplet in a grid cell and dividing by the cell volume. The trajectory of an individual droplet is governed by an equation which tracks a sampled set of the droplets. The evaporation of water droplets is handled semi-empirically. Further details of the underlying methodology and sub-models can be found in the FDS technical reference guide [15].

SCENARIOS STUDIED AND COMPUTATIONAL DETAILS

The first scenario (Scenario 1) considered in the study is based on the experimental work of Kim and Ryou [6] and shown in Fig. 1. It investigates the interaction of water sprays with medium scale pool fires in a under ventilated compartment. The experiments were carried out in a steel-walled enclosure of dimensions 4 m × 4 m × 2.3 m. The methanol fuel was burning in a rectangular steel pan of dimensions 30 cm × 30 cm × 5 cm which was positioned at the centre of the floor. The water spray nozzles were installed on the ceiling, 1.8 m above the floor. The mean burning rate of the fuel was 0.0148 kg/m^2s and the heat release rate 26.64 kW. The orifice diameter of the nozzle was 3 mm. Under an operating pressure of 13 bar, it delivered water spray at a rate of 6 l/min with a K-Factor of 1.66. The Sauter mean diameter for this operating condition is 121 µm at nozzle exit. The spray envelope covers the whole fuel pan area when there is no fire. The temperature distributions in the compartment were measured by thermocouples [6]. For FDS simulations, the boundary condition at the wall is based on the heat transfer coefficient, which depends on the flow conditions next to the wall. The temperature in the cell closest to the wall is considered as the fluid temperature and the heat loss through the wall calculated from the temperature difference between the wall surface temperatures. This scenario is a good test case for a comparative analysis between the CFD predictions and the experimental data.

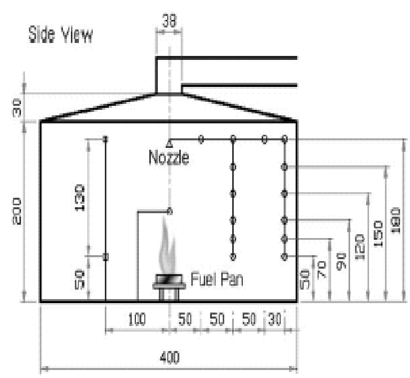


Fig. 1. Schematic view of the experimental set-up for Scenario 1(reproduced from Kim and Ryou [6]). Location of sensors shown in circles, dimensions in cm.

The second scenario (Scenario 2) investigates the application of partial water deluge on a crude oil pool fire (Fig. 2). Such water spray curtains arrangements are employed on offshore oil and gas installations as a mean to provide cooling and smoke dilution; and create an "escape" corridor for safe evacuation of crews. A vertical blast wall of dimensions 15 m × 15 m is installed on a 35 m × 35 m simplified offshore platform deck. A crude oil pool fire of dimensions 10 m ×10 m is located in front of the blast wall, the center of the pool is at coordinates x=17.5 m and y= 7.5 m. The mass burning rate of the fuel is 4 kg/s and the crude oil heat of combustion is specified as 46.1 MJ/kg. The total rate of heat output of the fire is 184 MW. The water spray deluge system consists of a total of 93 nozzles arranged on three rows (31 nozzles per row) at a height of 4.5 m above the pool surface. The length of each row is 12.75 m and the spacing between the first and third row is 1 m. The coordinates of the central nozzle of the deluge system is x=11 m, y=8.4 m and z=4.5m. The partial water deluge system is only applied to the left hand side of the blast wall referred to as "wet side". No deluge is applied to the right side of the blast wall referred to as "dry side". Scenario 2 represents the deployment of deluge to form a curtain between the fire and the escape route which would be on the wet side. The computation domain is extended to ensure that the free pressure boundaries are of sufficient distance to the interested region to avoid numerical instability.

The multi-block option of FDS is employed to save computational time and memory. The total computation domain is 35 m × 35 m × 20 m. A grid sensitivity analysis carried out showed that a grid size of 0.2 m offers a good compromise between accuracy of calculated temperatures and computing time. Finer grids do not significantly improve the accuracy of results whereas computing time could become prohibitive (threefold increase if a grid size of 0.15 m is selected instead of 0.2 m).

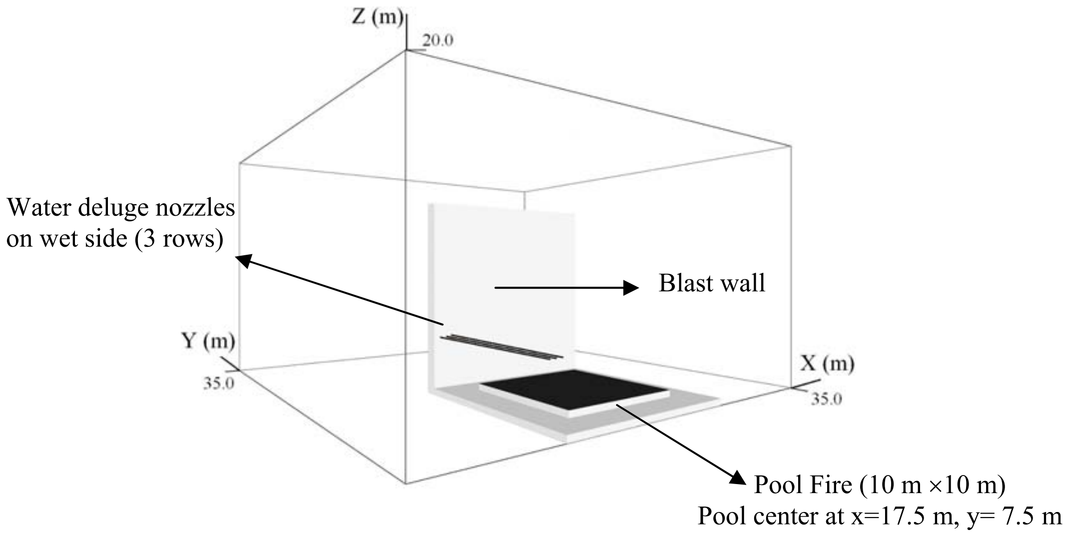


Fig. 2. Schematic diagram of Scenario 2.

Table 1 shows the different simulations cases considered in scenario 2, which could be grouped into four simulations sets. Simulation set 2-1 investigates the effectiveness of water deluge on pool fire suppression under different deluge flow rates for the same mean droplet size at nozzle exit (1000 μm) in a quiescent environment (no wind). In case 2-1-1 the water deluge is not activated, cases 2-1-2, 2-1-3, and 2-1-4 correspond to deluge rates of 10, 20, and 40 l/min/nozzle respectively. The corresponding application rates for these three flow rates are 2.2, 4.4 and 8.8 l/min/m^2. Simulations set 2 analyze the effect of the droplet size on the water deluge effectiveness for a constant flow rate of 20 l/min/nozzle in a quiescent environment. Cases 2-2-1 (300 μm), 2-2-2 (600 μm) and 2-2-3 (1000 μm) are considered in set 2-2. In simulations set 2-3 a moderate wind blowing towards the blast wall at a low speed of 2m/s is taken into account. The deluge rate is constant (40 l/min/nozzle) and two cases are investigated - case 2-3-1 (droplet size 300 μm) and case 2-3-2 (droplet size 600 μm). The effect of a moderate wind speed (5m/s) is considered in simulations set 2-4 with different droplets size (1000 μm and 1800 μm) and deluge rates (20 and 40 l/min/nozzle). In cases 2-4-1, 2-4-2 and 2-4-3 the droplets initial velocity at nozzle exit is 8 m/s, in case 2-4-4 a higher velocity of 16m/s is investigated.

For all of the simulations sets and cases, the spray has a cone angle of 140^0 and the deluge covers on average 30% of the pool area in a no-wind, no-fire situation. The offset distance is 0.1 m, and the droplets are uniformly distributed within the spray belt. The deluge was activated 2 s after the start of the fire. Flame length variations in pool fires are oscillatory and could be characterized by a flame pulsation period related to air entrainment. In previous tests on crude oil pool fires, the pulsation period was found to be from 3.2 to 3.5 s [16]. The mean values in simulations were obtained by averaging over 10 pulsation periods.

Radiation calculations in scenarios 1 and 2 are carried out with the radiative fraction approach in FDS discussed above. A radiative fraction of 20 % typically found in experiments is assumed for simulations [17]. Although less accurate than solving the full radiation transport equations, preliminary simulations in [14] for scenario 1 showed that the radiative fraction approach in FDS predicts temperatures close to experimental data in the fire plume region. One possible explanation to this relatively good predictions with the radiative fraction approach is that for this particular scenario, radiation is a secondary mechanism as identified in [2] and its accurate modeling does not have a significant impact on temperatures predictions in the fire plume region. However care must be taken not to extrapolate this finding to any scenario.

Table 1. Details of simulations cases for Scenario 2.

Simulations Set	Case	Water spray characteristics				Wind velocity (m/s)
		Flow rate/nozzle (l/min)	Mean droplet diameter (μm)	Spray angle	Initial velocity (m/s	
2-1	2-1-1	-	-	-		-
	2-1-2	10	1000			
	2-1-3	20	1000			
	2-1-4	40	1000			
2-2	2-2-1		300			-
	2-2-2	20	600	140^o	8	
	2-2-3		1000			
2-3	2-3-1		300			
	2-3-2	40	600			2
2-4	2-4-1	20	1000			
	2-4-2	40	1000			
	2-4-3	20	1800			5
	2-4-4	20	1000		16	

The third scenario (Scenario 3) shown in Fig. 3 investigates the application of water deluge curtains in mitigating thermal radiation from an oil tank fire. Unlike scenarios 1 where the aim is to extinguish or control the fire, the objective in scenario 3 is to mitigate the radiation heat from the fire in order to protect surrounding targets and prevent fire escalation and domino effect. The water deluge curtain system consists of 34 × 2 nozzles arranged at two different heights: 6 m and 10 m, delivering water at 40 l/min/nozzle. The location of nozzles is given in Fig. 3. Each curtain has a length of 8 m and is 0.5 m wide. The distance between the deluge system and the tank's edge is 1.75 m. The computation domain size is 27 m × 14 m × 20 m. Two meshes, 90 × 90 × 125 and 64 × 70 × 100 are used for the two simulation cases 3-1 (no water deluge) and 3-2 (water deluge activated). The mass burning rate of the fuel in Scenario 3 is 0.602 kg/s with the heat of combustion specified as 41.2 MJ/kg. The radiation transport equation is solved by FDS with the finite volume method for this scenario.

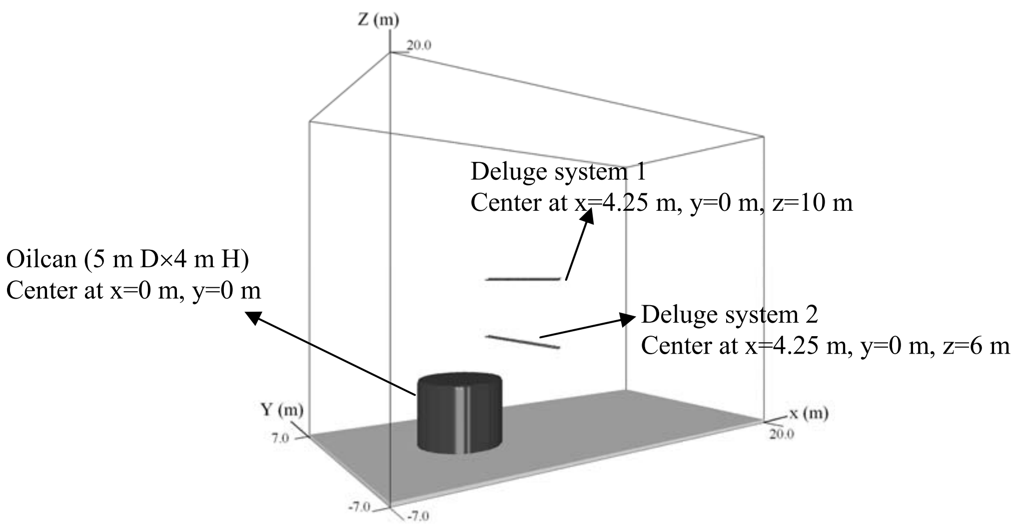


Fig. 3. Schematic diagram of Scenario 3.

RESULTS AND DISCUSSION

Scenario 1

Scenario 1 is concerned with the application of water deluge on a methanol pool fire in a compartment. FDS predictions are compared to the experimental temperature data. Figure 4 shows the mean temperature distributions at a radial distance R=0.5 m from the centerline along the ceiling when the water spray is not activated. There is relatively good agreement between the predictions and the experimental data. The water deluge was activated 300 s after the start of the pool fire, at which time, a near steady state was reached [6]. Fig. 5 presents the effect of the water deluge on the average temperature at the ceiling. The water droplets that vaporized after heat absorption became part of the hot combustion gases layer under the ceiling. The predictions are slightly higher than the experimental data after 350 s in Fig. 5. For the methanol pool fire investigated, there are two cooling regimes: sudden and gradual. In the sudden cooling regime, the temperature of the smoke layer decreases rapidly as a result of rapid droplets vaporization [6]. In the gradual regime, the temperature difference between the droplets and smoke layers is relatively lower than in the sudden regime, resulting in gradual temperature drop. However care must be taken not to extrapolate this behavior to other fuels since oxygen consumption and heat release rates of hydrocarbon fuels for example are larger than those of alcoholic fuels such as methanol. The water deluge flux of 67 $l/min/m^2$ was relatively high compared with the 12 $l/min/m^2$ recommended by NFPA, but was not sufficient to extinguish the fire. This is mainly due to the definition of the extinguishment criterion in FDS which is based on the lowest oxygen concentration in the whole compartment rather than on the local value near the flame zone. The study has nevertheless demonstrated the cooling effect of water deluge on compartment fires.

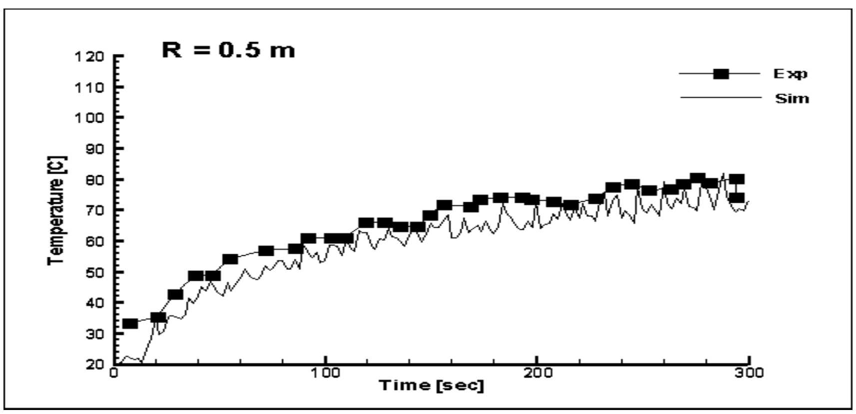


Fig. 4. Experimental and predicted temperature along the ceiling at R=0.5 m (Scenario 1, no water deluge).

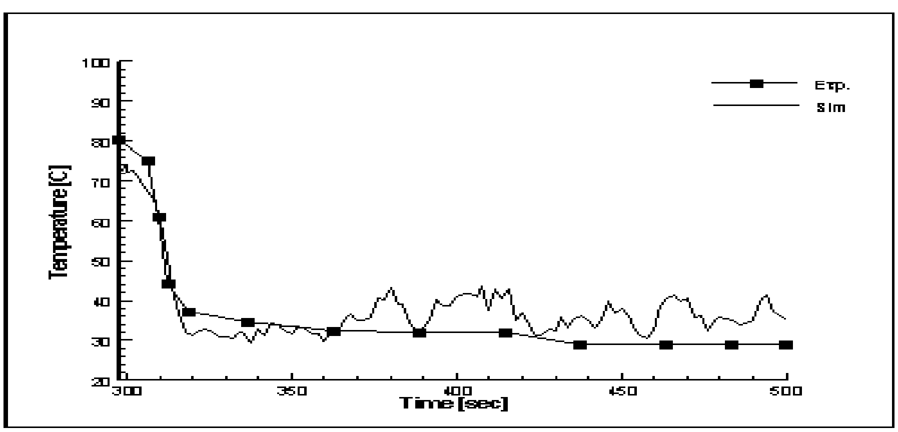


Fig. 5. Variation of mean ceiling temperature after water deluge activation (Scenario 1).

Scenario 2

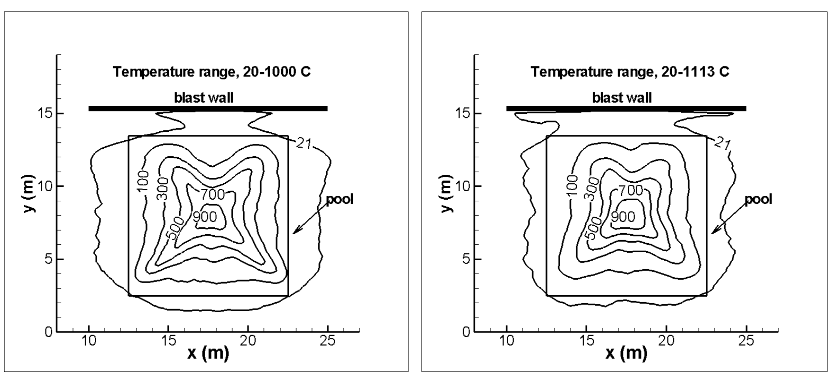
Simulations are firstly performed for case 2-1-1 (no deluge) and the time-averaged temperature distributions are shown in Fig. 6 on two horizontal planes at Z=3 m and Z=5 m above the pool surface. The water deluge nozzles is located at Z=4.5 m.

Figs. 7a, b & c. present the temperature distributions at two locations, one on the wet side (X=15 m, Y=8 m, Z=3 m) and the other on the dry side (X=20 m, Y=8 m, Z=3 m. As the flow rate is increased from 10 l/min/nozzle (case 2-1-2) to 40 l/min/nozzle (case 2-1-4) the local temperature on the wet side is reduced from an average value of about 300^0C to near ambient temperature. The beneficial effect of the flow rate on cooling for the droplet size of 1000 μm is demonstrated.

Soot laden smoke is important is assessing safety hazards. Figs. 8a, b & c show that the smoke concentration on the wet side decreases with the increase of the deluge rate. The simulations demonstrate that higher flow rates provide better cooling and smoke dilution, shifting the fire envelope further from the "escape" corridor.

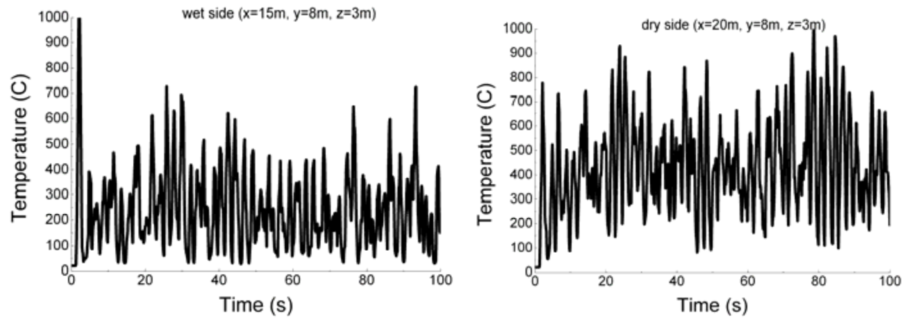
Figures 9a, b & c present the average temperature distribution for different droplet diameters (Case 2-2-1: 300 μm, Case 2-2-2: 600 μm, Case 2-2-3: 1000 μm) and a deluge rate of 20 l/min/nozzle. As the water droplets become finer, the fire plume shifts from the centre to the dry side and the temperature decreases on the wet side. More cooling is obtained for 40 l/min/nozzle with similar trends (results not shown here). It is clear from simulation results that finer droplets provide better cooling than larger droplets in non windy environments as consistently reported in the literature [2-4]. One possible explanation is that smaller water droplet has larger ratio of surface to volume which can increase available surface area for heat absorption and accelerates evaporation. The water vapour then generated is entrained into the fire enhancing the cooling and dilution processes in the fire.

As stated earlier the purpose of the water deluge curtain is not to extinguish the fire but instead to provide cooling and smoke dilution for evacuation in safety corridors on the wet side. Although the deluge rate of 40 l/min/nozzle was found to provide cooling and smoke dilution, in practice, there is still optional difficulty to physically provide this flow rate on an offshore installation. On the other hand the 20 l/min/nozzle rate was found to be reasonably effective and operational viable. Hence in the subsequently investigations, this deluge rate was mainly chosen with the view to identify the favourable operating conditions (droplet sizes) in certain environment (wind) conditions.

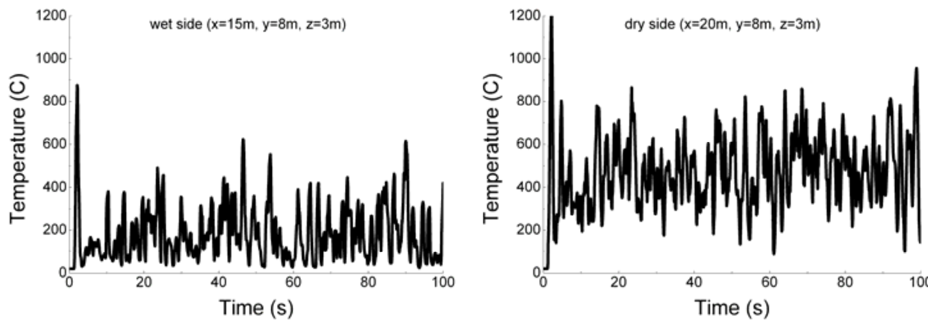


Z=3 m Z=5 m

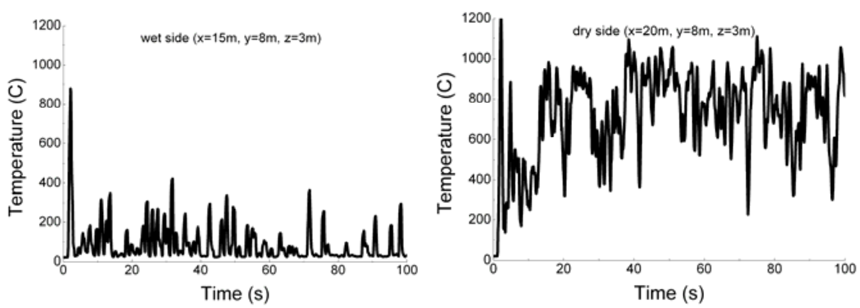
Fig. 6. Time-average temperature distributions at Z=3 m and Z=5 m above pool surface (Scenario 2, case 2-1-1, no deluge).



(7a) Case 2-1-2 (10 l/min/nozzle)

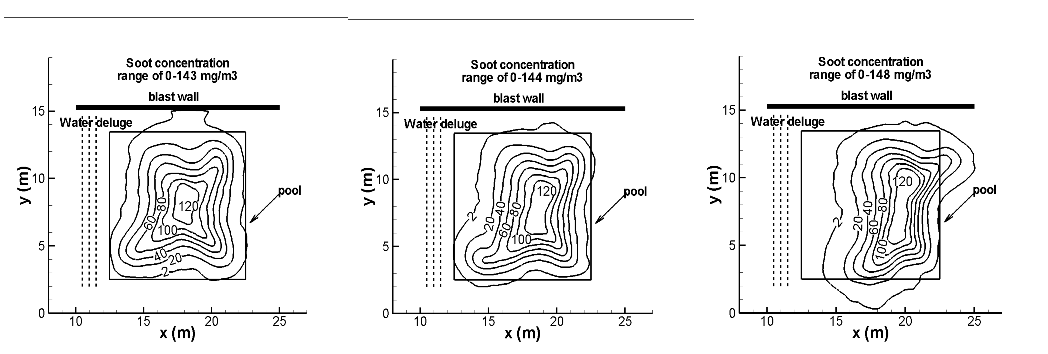


(7b) Case 2-1-3 (20 l/min/nozzle)



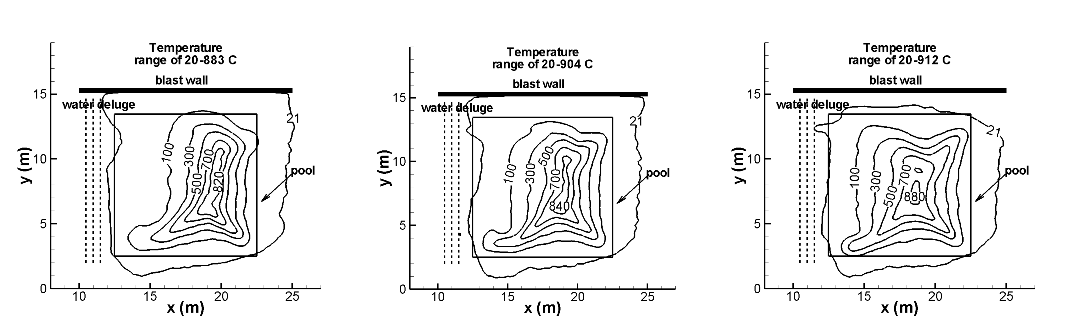
(7c) Case 2-1-4 (40 l/min/nozzle)

Fig. 7. Temperature distributions at two locations on wet and dry sides (Scenario 2, Set 2-1, droplet size 1000 μm).



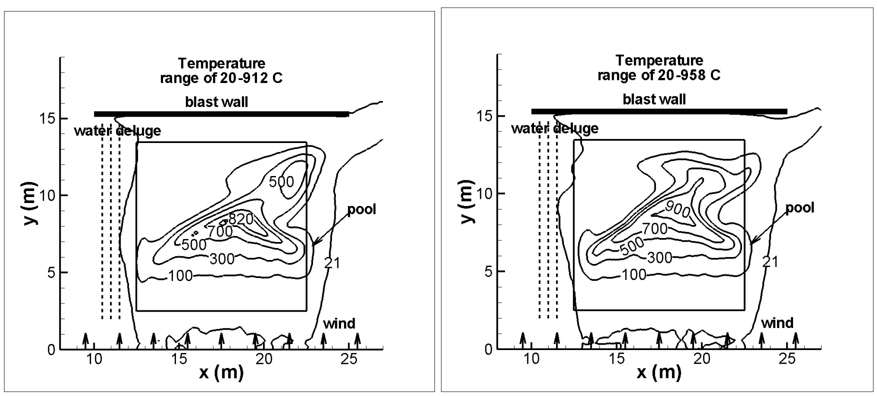
(8a) Case 2-1-2 (10 l/min/nozzle) (8b) Case 2-1-3 (20 l/min/nozzle) (8c) Case 2-1-4 (40 l/min/nozzle)

Fig. 8. Time-average soot concentration distribution at Z= 5 m above pool surface (Scenario 2, Set 2-1, droplet size 1000 μm).



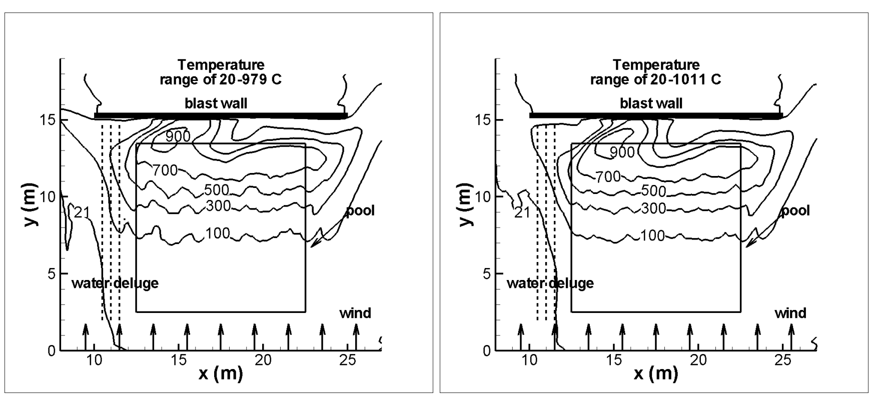
(9a) Case 2-2-1 (300 μm) (9b) Case 2-2-2 (600 μm) (9c) Case 2-2-3 (1000 μm)

Fig. 9. Time-average temperature distribution at Z=3 m above pool surface (Scenario 2, Set 2-2, 20 l/min/nozzle, no wind).



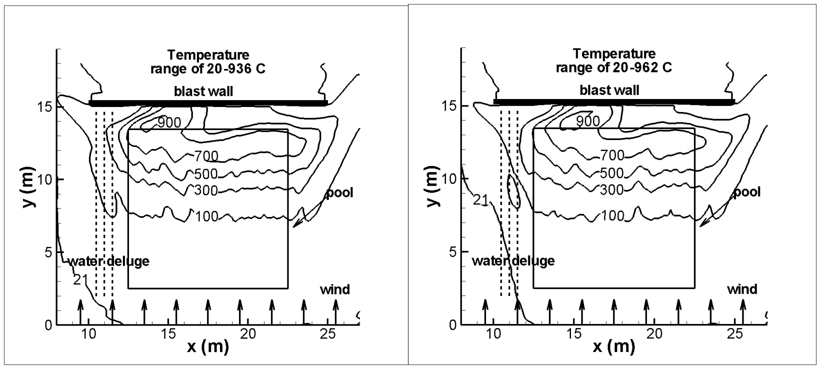
(10a) Case 2-3-1 (300μm) (10b) Case 2-3-2 (600μm)

Fig. 10. Time-average temperature distribution at Z=3 m above pool surface (Scenario 2, Set 2-3, 40 l/min/nozzle, wind speed 2 m/s).



(11a) Case 2-4-1 (20 l/min/nozzle) (11b) Case 2-4-1 (20 l/min/nozzle)

Fig. 11. Time-average temperature distribution at Z=3 m above pool surface (Scenario 2, Set 2-4, droplet size 1000 μm, wind speed 5 m/s).



(12a) Case 2-4-3 (1800 μm) (12b) Case 2-4-4 (1000 μm), 16 m/s

Fig. 12. Time-average temperature distribution at Z=3 m above pool surface (Scenario 2, Set 2-4, 20 l/min/nozzle, wind speed 5 m/s).

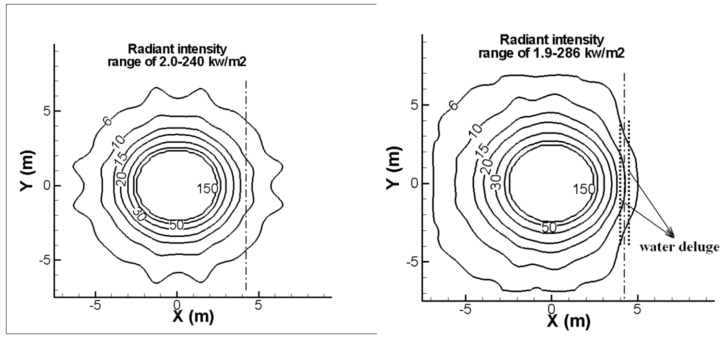
Simulations set 2-2 shows that finer droplets provide better fire mitigation than larger droplets in quiescent environments. However, this conclusion may not be applicable in windy conditions. Figs. 10-12 present the temperature distribution in light (2 m/s) and moderate (5 m/s) wind conditions. When the wind speed is relatively large compared to the droplet exit velocity, the droplets trajectories are strongly influenced by the wind. As shown in Fig.11, an almost symmetric distribution in temperature can be observed. Water droplets are carried away by the wind, and the fire plume is blown toward the blast wall. On the south side, the air temperature is low, about 100 ^{0}C. Finer droplets (300, 600 μm) are easily carried away by the wind and therefore play a minor role in fire attenuation as shown in Fig. 10. In contrast, larger droplets (1000, 1800 μm) have higher momentum, and provide slightly enhanced fire mitigation in windy conditions (Fig. 12). Using the nozzle with larger droplets is therefore considered as both economical and effective in windy conditions.

Scenario 3

Radiation heat transfer plays an important role in sooty flames such as oil fires. On hydrocarbon facilities, fire radiation impinging on neighboring vessels could lead to a domino effect and escalation of the fire damages. Scenario 3, as shown in Fig. 3, was conducted to study the effectiveness of water deluge system in absorbing and mitigating the radiant heat from the fire. For this kind of scenario, the aim is not to extinguish or suppress the fire, but to protect surrounding potential targets (personnel, hazardous vessels etc…)

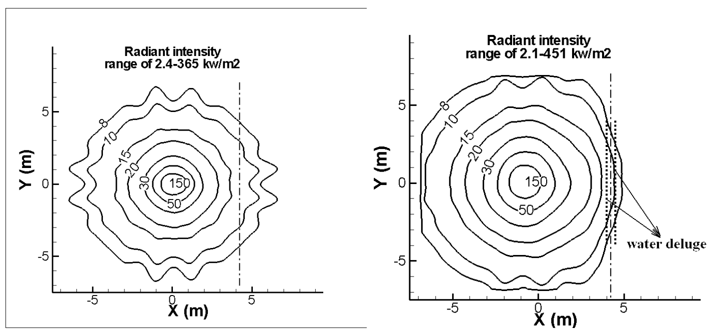
Figs. 13-14 show the distribution of radiation heat flux for cases 3-1 and 3-2 at two different heights, 4 and 8 m. In both figures the activation of the water deluge (case 3-2) significantly lowers the radiant energy on the protected side (right side).The mitigation at Z=4 m is better than at Z=8 m due to the increased droplets flux at the lower location. The water deluge attenuation is mainly the result of radiant heat absorption by the water droplets and also the water vapor formed after the vaporization process. The other important factors are the reflection and refraction properties of the water droplets. The study clearly demonstrates the potential of water deluge to mitigate radiant energy and effectively improve the safety of the protected regions.

In a recent review paper, Lowesmith et al. [18] summarised some unpublished tests results carried out by Advantica in the late 1990s on water deluge of jet fires. It was found that at 12 L/min/m^2, incident radiation levels could be reduced by about 20% for a single row of nozzles, 30-40% for two rows and 40-60% for more than two rows (general area deluge). Increased deluge rate was found to further reduce incident radiation levels: 60-70% at 18 l/min/m^2; 24 l/min/m^2 for general area deluge. Smaller droplets were also found to have an enhanced mitigation effect. The present predictions are in line with these earlier experimental findings.



(13a) Case 3-1 (13b) Case 3-2

Fig. 13. Comparison of radiation heat flux distribution at Z=4.0m (Scenario 3).



(14a) Case 3-1 (14b) Case 3-2

Fig. 14. Comparison of radiation heat flux distribution at Z=8 m (Scenario 3).

CONCLUSIONS

The effect of water deluge system on pool fire suppression may be influenced by many factors, such as deluge flow rate, droplet size and wind conditions. The simulations showed that the water deluge curtains have increased cooling and smoke dilution effect with increased deluge flow rate, pushing the fire envelope further from the "escape" corridor. Furthermore, in quiescent environments finer droplets were found to be more effective than larger droplets due to larger overall surface area. However, in light wind conditions of 2 m/s, the finer droplets were found to be carried away by the wind while the larger droplets with higher momentum were found to be more effective. In moderate wind conditions (5 m/s) though, even the largest droplets of 1000μm were found to be carried away by the wind and unable to play any role in fire suppression. The investigation also revealed that the water curtains can effectively protect personnel and facility by provide cooling and smoke dilution. The study on oil tank fires have shown that water deluge can effectively attenuate thermal radiation from fires.

While the current design of the deluge systems is normally by codes and standards, present study has highlighted the potential to choose economical and effective deluge systems for given applications by explicitly accounting for the above key parameters in the design and examining their effect on fire suppression or protection. Suitably validated CFD code can serve as a useful tool for parametric studies in risk assessment and practical design to optimize nozzle arrangement, spray size, momentum and orientation appropriate for the expected operating and environment conditions. It is also possible in this process to consider design modifications which can mitigate the wind effect or alternative means of fire and smoke control in severe environment conditions.

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