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Fire Hazard Calculations for Hydrocarbon Pool Fires – Application of "Fire Dynamics Simulator – FDS" to the Risk Assessment of an Oil Extraction Platform

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A major area for fire protection in the industrial sector deals with controlling the impact from hydrocarbon fires. The primary mechanism for injury or damage from such fires is thermal radiation, that can be evaluated with the aid of different software. Analytical models are those most widely used for this purpose.
Other aspects of great importance to assess the possibility for an individual to survive a fire, like smoke emission, toxic combustion products dispersion and visibility, and the temperature profile reached by each component involved in the pool fire (necessary for a better understanding of the structure fire resistance) are however not easily assessed or not assessed at all by analytical models. These information can be obtained by means of computational fluid dynamics software like the "Fire Dynamics Simulator" (FDS), developed by the National Institute of Standards and Technology of the United States Department of Commerce, that allows the 3-dimensional analysis of fires both in enclosed spaces and in the open. This model has been applied for the analysis of fires in enclosed structures (buildings, underground stations, tunnel fires). It has been recently applied in D'Appolonia to the assessment of pool fires for different Offshore Oil Platforms. The paper will discuss the results achieved and the comparison with the results obtained by analytical modeling.

1. Introduction

When a large hydrocarbon fire occurs in a plant, especially if in an offshore platform, the first thought usually is: "Can the personnel reach a safe location?". This concern becomes for the risk analysts: "How can we establish if the people involved will have enough time and sufficient good conditions to arrive at the muster area or the temporary refuge present on the platform?"
Analytical models normally employed during risk assessment and consequences evaluation are not aimed at giving adequate information about the smoke generated from the pool fire, the toxic combustion products concentrations, the visibility, the time interval at which each structural element exposed to that particular fire load in that specific environmental condition could resist. These elements are necessary to evaluate the potential impairment of the escape routes, strictly related to the possibility of the personnel to survive. When this evaluation becomes the priority, as in case of an

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offshore platform, where the impossibility to reach the muster area or the temporary refuge can almost surely lead to fatality, more sophisticated models, like computational fluid dynamics (CFD) ones, are needed to provide a detailed understanding of the fire-related phenomena, from which time and space evolution of the main parameters can be inferred, allowing a complete evaluation of the damages of the considered scenario.

2. Methods

The software employed in this work are briefly described in the next two subparagraphs.

2.1 Fire Dynamics Simulator

“Fire Dynamic Simulator” has been developed by the National Institute of Standards and Technology of the United States Department of Commerce for fire-driven fluid flow, given particular emphasis to smoke and heat transport from fires.

As for all the CFD models, the starting point is the system of coupled partial differential equations that describe the balance between the competing influences on the transport of mass, chemical species, momentum and energy within the fire and throughout the space around it. However, rigorous solution of the system of equations, resolving fully the length and time scales that occur in the flows associated with the turbulent combustion characteristic of fire, is still beyond the capabilities of even the largest computers currently available. As a consequence, it is necessary to simplify the system of equations by some forms of modeling. FDS exploits the large-eddy simulation (LES) technique, where the larger turbulent vortices are simulated rigorously by means of the Smagorinsky method. The model solve a form of the Navier-Stokes equations appropriate for low-speed and thermally driven flow, approximating the partial derivatives of the conservation equations as finite differences and updating the solution in time on a three-dimensional, rectilinear grid. Thermal radiation is computed using a finite volume technique on the same grid as the flow solver. Lagrangian particles are used to simulate smoke movement. (For major details, see “NIST-1018-5” or “NUREG-1824”.)

FDS requires a fast CPU and a substantial amount of random-access memory (RAM) to run efficiently. The CPU speed determines how long the computation will take to run, while the amount of RAM determines how many mesh cells can be held in memory. In addition, a large hard drive is required to store the output of the calculations: it is not unusual for the output of a single calculation to consume more than 1 GB of storage space. With a 64-bit hardware and operating system, nevertheless, the 64 bit version of the software allows to create fire models with many more cells than with a 32 bit system, permitting access to memory beyond the traditional 3 GB limit in Windows operating system. Many more cells can be translated into smaller cells, and, consequently, in more accurate results. FDS results are, in fact, very dependent by the mesh dimension: the error associated with the discretization of the partial derivatives is proportional to the square of the grid cell size (NUREG-1824).

2.2 Phast

Phast (Process Hazard Analysis Software Tools) is a Window-based toolkit, which determines the consequences of accidental releases of hazardous material. It examines the progress of a potential incident from initial release, through formation of a cloud, and eventually a pool, to its dispersion. The program uses DNV's unique Unified Dispersion Model (UDM) to apply the appropriate entrainment and dispersion models as the conditions change and to integrate the relevant individual models such that the transition from one behavior pattern to another is smooth, continuous and automatic. It may be used to identify situations which present potential hazards to life, property or the environment. It is to point out that Phast isn't a CFD model and the results are available in few seconds, unlike FDS.

2.3 Input setup

The comparison of the analyses obtainable with a CFD and an analytical model is done with reference to two case studies: an offshore oil platform and an onshore kerosene storage tank.

2.3.1. Offshore Oil Platform

The application of FDS to Offshore Oil Platforms consisted in the assessment of the possible impairment of muster areas and evacuation means due to smoke and toxic combustion products, following a 12 m-diameter pool fire on the sea surface, just within the platform legs, due to an accidental liquid release from an equipment located on the lower deck (mainly grated). The size of the pool fire has been evaluated with the aid of Phast software. The wind velocities have been assumed equal to 2 m/s and 5 m/s towards the points of interest. The heavy hydrocarbon liquid fuel has been approximated to the $C_{14}H_{30}$. The Heat release Rate Per Unit Area of Fire has been considered to be 1500 kW/m^2.

2.3.2. Kerosene Storage Tank

In the second part of the article the comparison between the output thermal radiations of Phast and FDS are discussed for a large hydrocarbon pool fire, due to a catastrophic rupture with immediate ignition of a 1250 m^3 kerosene vessel, due e.g. to a major earthquake. The pool fire size in this case will be limited by the existing bund around the storage vessel itself, having dimensions of 41 m width, 66 m length. The basin contains other five storage tanks and it is located upwind respective of an other smaller basin with other five fuel storage tanks. The wind velocity is equal to 5 m/s. Heat radiation is calculated at points positioned every 10 m all along the domain at two different heights from the ground level: 1.5 m and 5 m. Their values are registered in the outputs database every 5 sec.

3. Results

The results, in terms of smoke emission, visibility and toxic combustion products will be shown for the considered offshore oil platform, while the thermal radiation results will be discussed for the kerosene storage tank.

3.1 Smoke emission and visibility

Smoke emission is one of the basic elements for characterizing a fire environment. The combustion conditions under which smoke is produced affect the amount and the character of the smoke. The concentration of the smoke and its irritancy to the eyes and upper respiratory tract affect escape decisions and the speed of movement of personnel.

Visibility of emergency signs and objects can also be of great importance to an individual escaping a fire. Visibility depends on many factors, including the scattering and the absorption coefficient of the smoke, the illumination, the wavelength of the light, the individual's visual acuity and so on.

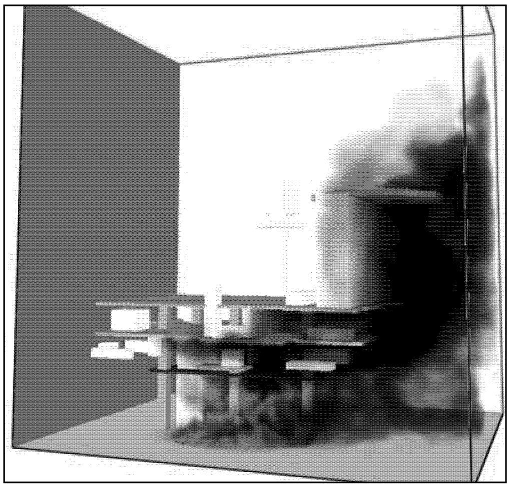

Figure 1: FDS Smoke emission - Pool Fire on sea surface - Offshore Oil Platform

The FDS simulation result, reported in Figure 1, shows that, in case of the hypothetical pool fire, the smoke involve the lower deck, part of the intermediate deck and the upper deck, just close where the living quarter is located. Nevertheless, from other FDS output (not shown here for space reason), it can be inferred that the visibility is not impaired at the living quarter level and neither close the life boats on the lower deck where it reaches 7 m. In this specific case, the FDS results indicated the need to provide smoke detection at the inlet of the HVAC systems, to avoid smoke ingress into the living quarter.

It is to be pointed out how the results depend by the geometric model put in FDS and by the hypothesized location of the oil pool on the sea surface. When smoke emission is of interest, the grated surfaces should be reproduced as realistically as possible, given particular attention to the grid cell size. All the geometry, in fact, is adapted by FDS to the grid cell size. In some cases, if the empty space is not comparable with the used grid cell size, it can be better, conservatively, not to draw the grated object at all. If the empty space is comparable to the grid size, a more realistic result will be obtained put in also this object.

An other important aspect is “where the oil pool will form in case of release?”. This will depend by many factors, difficult to be modeled, like the direction of the release, the location of the leaking item on the deck, the sea state etc. The analysis was therefore done considering the worst case scenario, that is a pool fire just within the platform legs.

3.2 Toxic combustion products dispersion

Toxic smoke products are recognized as being the major cause of death in fire (NFPA, 2002). From the inhalation of irritant smoke (which may be also very hot) breathing difficulties can rise, up to asphyxia, due to laryngeal spasm or bronco-constriction.

The major asphyxiant gas in fires is carbon monoxide, always present to some extent in all fires, irrespective of the material involved or the stage of the fire. Low concentration of oxygen (less than 15%) and very high concentrations of carbon dioxide (greater than 5%) have asphyxiant effects too. Carbon monoxide combines with hemoglobin in the blood, resulting in a toxic asphyxia related to the reduced amount of oxygen supplied to the tissues of the body, especially to brain tissue. It causes confusion and loss of consciousness, impairing or preventing escape. Carbon dioxide, always universally present in fires like carbon monoxide, although is not toxic at concentrations lower than 5 percent, it stimulates breathing, so that at 3% the volume of air breathed during a minute is approximately doubled and at 5% tripled. This hyperventilation can increase the rate at which other toxic fire products, such as CO, are taken up, reducing remarkably the time to incapacitation and death.

From the FDS simulations for all the wind velocities of interest, a negligible CO concentration has been found at the living quarter. On the lower deck, where the life boats are located, the maximum calculated level of CO concentration has been 20 ppm. This level can not be deemed immediately toxic to personnel, also considering the hyperventilation caused by the CO_2 generated within the fire.

3.3 Thermal radiation (onshore tank pool fire)

If an individual is exposed to a hot environment, especially if the humidity is high and the subject is active, there is a danger of incapacitation and death due to hyperthermia. The time to effect and the type of hyperthermia depend principally upon the heat flux to which the individual is exposed and are greatly affected by factors such as the amount and type of clothing. Apart from the immediate pain caused by exposure to heat and by skin burns, and the psychological shock and fear, incapacitation may result from body surface burns during or after a fire due to the physiological shock: loss of body fluids into the burn results in circulatory failure and a fall in blood pressure, which may lead to collapse and even loss of consciousness. Thermal radiation evaluation is very important also to assess the resistance of the equipments in the proximity of the fire and to foresee possible escalation effects.

In Figure 2, the results of the analysis performed with both FDS and Phast for a major pool fire on a tank containment basin are shown (the downwind distances are measured from the border of the pool).

In both the software, the presence of the bund, its material and height are indicated; Phast checks only that the fuel amount does not overflow, neglecting the heat absorbed by the walls, while FDS calculates also the heat absorbed by the bund on the basis of walls thickness and of the material characteristics. This and also the fact that probably the shielding by wall is not considered explain why outside the containment walls Phast foresees higher thermal radiation then the one calculated by FDS: at 20 m downwind from the pool boundary, and at an height of 1.5 m Phast predicts an heat radiation of more than 9 kW/m^2, while FDS less than 1 kW/m^2.

The FDS output also gives the time behavior of heat flux and temperature at a specific location: these information can be useful to determine how long a structure in that position could resist.
It has to be noted the dependence of the FDS results from the grid cell sizes: “small mesh” indicates 25 cm cubic cells, “big mesh” 50 cm cubic cells, “very big mesh” 1 m cubic cells.

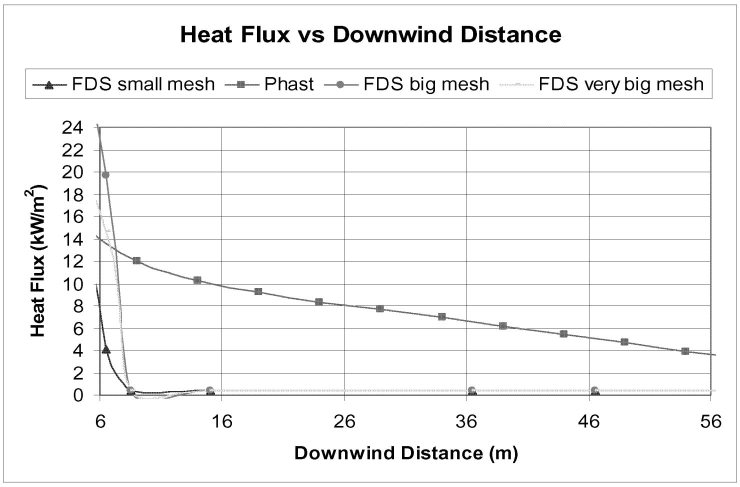

Figure 2: Thermal radiation comparison - Kerosene Storage Tank

4. Conclusions

To assess the possibility for an individual to survive a fire escaping into a safe location, smoke emission, toxic combustion products dispersion, visibility and the temperature profile reached by each component involved in the pool fire should be evaluated, especially in case of offshore oil platforms. FDS allows all these assessments and it is useful also when thermal radiation in presence of obstacles should be evaluated. For the assessment of the fire hazards to equipment and structures, related to the heat radiation received by a target, the use of analytical models can lead to overestimation of the results, in particular in cases where the effect of bunds and containment basin walls can reduce the heat input.

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