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RISK ASSESSMENT OF ENVIRONMENTAL HAZARDS DUE TO OIL TANK FIRE: A NUMERICAL STUDY

Abstract: *The global demand for oil and its derivatives has conditioned their storage in large-capacity reservoirs. However, regardless of preventive fire protection measures, their storage presents certain risks, including potential oil leaks and ignition. This paper examines a fire incident in an above-ground crude oil tank located within the storage area of the Pančevo Oil Refinery as a case study. The Large Eddy Simulation (LES) method of the Fire Dynamic Simulator (FDS) software package has been used to investigate the effects of fire temperature and heat flux on the surrounding environment. The simulation results were used to assess how fire parameters influence the potential spread of fire to neighboring tanks and surrounding buildings. The dimensions of the potentially endangered zones around the refinery complex were determined by comparing calculated heat flux values with the valid standards for exposure to the heat radiation of fire. The results of this study are important not only for assessing the risk to nearby tanks containing oil derivatives but also for assessing human safety - both for individuals in close proximity to the fire and for firefighters and rescuers involved in firefighting operations.*

Keywords: fire, Fire Dynamics Simulator, temperature, heat flux, endangered zone

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INTRODUCTION

In the petrochemical industry, many flammable liquids are usually stored in large-capacity storage tanks. However, the fire and explosion hazards are one of the main risks associated with their storage. Namely, accidents such as leakage and diffusion can occur during the crude oil storage process. Leaking oil or oil vapour can rapidly trigger a fire or explosion when exposed to an ignition source (Wu and Chen, 2016).

If a fire accident occurs in an area with large crude oil tanks, the domino effect may be triggered, which may escalate into disastrous consequences. Abdolhamidzadeh et al. (2011) showed that about 80% of domino accidents caused by fire were the result of pool fires.

On the other hand, a pool fire emits a huge quantity of heat into the surroundings. Namely, burning pools can sustain combustion long enough to generate thermal radiation, posing risks to exposed individuals and neighbouring objects. The effects of thermal radiation are a function of the heat flux and the duration of exposure.

Many researchers have investigated the impact of fire heat flux on people and buildings. Mudan (1984) reported that an incident flux of 1.7 kW/m^2 will not even cause pain, regardless of exposure time. Babrauskas (1979) suggested that the radiant heat tolerance curve indicates a clear exposure limit of 2.5 kW/m^2 for a person without personal protective equipment. Assael and Kakosimos (2010) found that the radiant heat flux of 4.0. kW/m^2 will cause second-degree burns in 20 s. A study on protective clothing for emergency responders in petrochemical plants found that firefighter personal protective equipment could provide safe exposure up to 3 min at 4.6 kW/m^2, with critical limits reached around 5 kW/m^2, indicating insufficient protection beyond this threshold (Heus and Denhartog, 2017). The United States Federal Safety Standards for Liquefied Natural Gas Facilities (1980) suggest an acceptable level of 5 kW/m^2 for direct exposure of persons. At this incident flux, exposure time on bare skin before unbearable pain is about 13 s and second-degree burns may occur in about 40 s. This level can, therefore, be used as a criterion for injury. The level of about 10 kW/m^2 may be used in determining the hazard zone for fatality.

High intensities of the thermal radiation also damage surrounding buildings and facilities. Cozzani et al. (2006) analyzed the thermal response process of different atmospheric storage tanks under the action of thermal radiation. The results showed that when the radiation intensity is less than 15 kW/m^2, the storage tank fails after more than 10 minutes, and when the radiation intensity is less than 10 kW/m^2, the storage tank failure time is greater than 30 min.

High heat radiation levels cause high temperatures in environments that can be harmful to human safety. According to Hoschke (1981), exposure to thermal radiation of 4.0 kW/m² causes pain within 15 seconds, and bare skin sustains burns within 30 seconds. Havenith and Daanen (2013) suggested a maximum skin temperature for pain of 43-45 °C. Hatton and Halfdanarson (1982) showed that skin burns can occur at skin temperatures from 44°C.

In this study, the following heat flux values were adopted as criteria for injury and mortality: 10 kW/m^2 at which exposure for more than 60 s results in death; 5 kW/m^2 which leads to second-degree burns at exposure for more than 60 s; 2 kW/m^2 which leads to a feeling of pain on the skin surface at exposure for more than 60 s (Jones et al., 2013). On the basis of the results of previous studies, it was also suggested that the maximum skin temperature of 43 °C is a relatively safe limit to prevent harmful skin burns. A heat flux of 12.6 kW/m² was also used as the threshold for the ignition of most hydrocarbon combustible materials in the construction industry.

Numerical analysis of the pool fire, as part of the risk analysis and accident modeling, is commonly conducted using various Computational Fluid Dynamics (CFD) tools. Therefore, this study employed the CFD Large Eddy Simulation (LES) method to assess the risk to adjacent tanks, structures, and people, including firefighters involved in firefighting activities. The FDS software package and its graphical user interface PiroSym were used to simulate the intensities of heat fluxes and temperatures in the environment within the storage area of the Pančevo Oil Refinery.

METHODOLOGY

Numerical method

This research was carried out using FDS open-source software with its graphical interface Pyrosim, developed by the National Institute of Standards and Technology. The hydrodynamic model within FDS solves numerically a low Mach number form of the Navier-Stokes equations appropriate for thermally-driven flows, as follows (McGrattan et al. 2023)

Conservation of mass:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0; \qquad (1)$$

Conservation of momentum:

$$\rho\left(\frac{\partial \vec{u}}{\partial t} + \frac{1}{2}\nabla|\vec{u}| - \vec{u} \times \omega\right) + \nabla p - \rho g = \vec{f} + \nabla \tau; \qquad (2)$$

Conservation of energy:

$$\frac{\partial}{\partial t}(\rho h) + \nabla \cdot (\rho h \vec{u}) = \frac{\partial p}{\partial t} + \vec{u} \cdot \nabla \rho - \nabla \vec{q}_r + {} + \nabla(k \nabla T) + \sum_i \nabla(h_i \rho h D_i \nabla Y_i) \qquad (3)$$

where, ρ is density, $\vec{u}$ is a velocity vector, ω is z-direction velocity, p is pressure, g is acceleration of gravity, $\vec{f}$ is external force vector, τ is velocity viscous force tensor, h is sensible enthalpy, $\vec{q}_r$ is radiative heat flux, k is conductivity, T is temperature, D_i is diffusion coefficient, Y_i is mass function of i-th component, and t is time.

Energy transport (Eq. (3)) consists of convection, conduction and radiation. Convection of heat is accomplished via the solution of the basic conservation equations. Gains and losses of heat via conduction and radiation are represented by the divergence of the heat flux vector. The equation associated with the radiative part, $\vec{q}_r$ is the Radiative Transport Equation (RTE) for an absorbing, emitting, and scattering medium, as follows:

$$\mathrm{s} \cdot \nabla I_\lambda(x,s) = -[k(x,\lambda) + \sigma_s(x,\lambda)] I_\lambda(x,s) + {} + B(x,\lambda) + \frac{\sigma_s(x,\lambda)}{4\pi} \int_{4\pi} \Phi(s,s') I_\lambda(x,s') ds', \qquad (4)$$

where: $I_\lambda(x,s)$ is radiation intensity at wavelength λ, s is direction vector of the intensity, $k(x,\lambda)$ is local absorption coefficient, $\sigma_s(x,\lambda)$ is scattering coefficient, $B(x,\lambda)$ is emission source term, describing how much heat is emitted by the local mixture of gas, soot and droplets/particles, $\Phi(s,s')$ is a scattering phase function.

Simulation set-up

In this research, the storage complex of the Pančevo Oil Refinery was selected as a case study for modeling fire dynamics and thermal radiation of a flame to the surrounding environment (Figure 1).

Figure 1. *Pančevo Oil Refinery area*

In order to save simulation time, a segment of the storage area was designed for CFD LES simulations. A computational domain (334 m wide, 337 m long, and 30 m high) was designed for numerical simulation. The ground level of the domain was set as a solid boundary while the other boundaries were designed as open boundaries, allowing free flow of the air and smoke in order to simulate the real conditions of fire impact on the surrounding environment.

Accidental fires originating from fuel leaks typically develop into a large pool fire. Above-ground reservoir with crude oil as a large pool fire was set as a buoyancy source. This research simulates the most unfavourable scenario, assuming that the tank ruptured and that oil spilled into a bund with dimensions of 90 m x 90 m. The fire affected both the oil in the tank and the oil in the bund.

Oil is a mixture of hydrocarbons, with octane (C_8H_{18}) regarded as the main compound. Therefore, according to the FDS reaction database (McGrattan et al. 2023), a reaction type of "N-octane" was specified for generating heat from the fire source.

The heat release rate of a fire is generally quantified by the fire source area and heat release rate per unit area (HRRPUA). The fire source was situated in the tank with 21700 tons of crude oil. Therefore, the heat release rate per unit area (HRRPUA) is 2500 kW/m^2, assuming steady-state conditions for octane combustion.

The T-Square fire was used for the fire growth in the simulations. The ultrafast model was applied to the growing model of the fire source.

The accuracy of LES simulation is largely dependent on the grid size, which should be fine enough to include the turbulence scales associated with the largest eddy motions. To ensure consistency and efficiency in the simulations, a uniform grid size of 1.0 in the three spatial directions was adopted. This approach provides an efficient balance between accuracy and computational resources, allowing for an effective simulation of the entire fire scenario. The number of grid cells was 3376740 (334x337x30 in the x, y and z direction, respectively).

In order to assess the dimensions of the potentially endangered zones, virtual incident heat flux gauges and temperature gauges were placed on the surfaces of fire-exposed tanks (B, C and D), energy facilities and facilities for chemical preparation of water and condensate polishing facing the burning tank A (Figure 2).

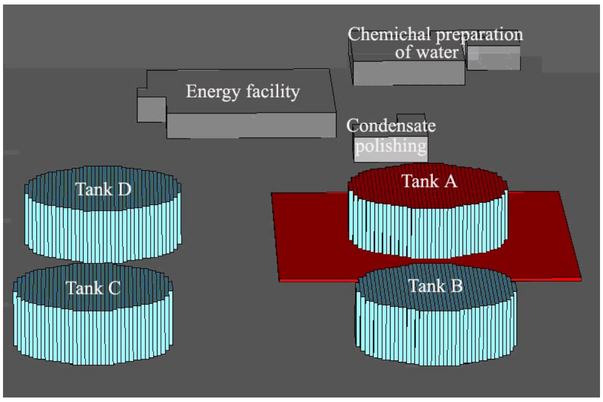

Figure 2. *Fire-exposed objects*

Since this type of fire is a strong buoyancy source with high velocity, the simulations did not consider the effect of the inertial force of wind on the flow of the fire plume. Therefore, the instantaneous or "real" perpendicular wind was specified, e.g., an initial velocity boundary condition of 0.3 m/s with a uniform profile was set at the right side of the simulation domain. The ambient temperature was set to 303 K in the whole computational domain.

To better understand the situation after the combustion of a large crude oil storage tank, the simulation time was set to 3600 s.

RESULTS AND DISCUSSION

Fire dynamics

The maximum values of radiation heat flux of fire flame and hot combustion products from a burning tank with flammable liquids are observed during the fully-developed fire phase. Therefore, for the investigation of fire spreading, it is very important to predict the dynamic regime of the fire. The simulation results of fire dynamics of crude oil are shown in Figure 3.

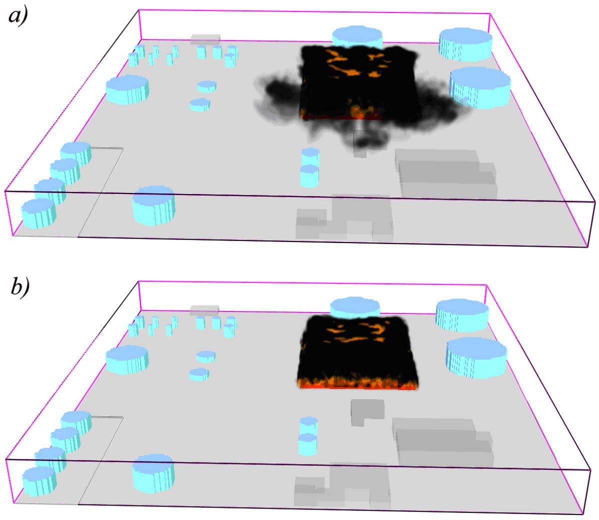

Figure 3. *Fire dynamics: a) 32 s; b) 1800 s*

Since crude oil is a flammable substance, after the tank A caught fire, the flame on the surface of the oil spread rapidly, forming a full-surface fire with stable combustion. However, after the burning oil was poured from the tank into the bund, the fire was also spread to the spilled oil inside the bund.

In this way, the burning surface area was increased, allowing the fire to rapidly reach a steady, fully developed phase characterized by sustained flaming combustion of oil at a constant rate. As a result, there was a large quantity of heat released during the fire. Namely, the heat release rate (HRR) reached a maximum of 21 GW in a short time period, and after that, it had a constant value. A high heat release rate (HRR) resulted in more intense combustion and a greater impact of the fire plume's heat flux on the surrounding environment.

It should be noted that the bund is located under ground level and has the necessary volume to accommodate the entire oil from the tank. Therefore, it prevents the fire from spreading further.

Heat fluxes

After a full-area pool fire occurs in a large crude oil storage tank and its bund, it will have a direct impact on adjacent storage tanks and facilities. The impact range of radiative heat around the fire source is represented by time-averaged incident heat flux fields as shown in Figure 4.

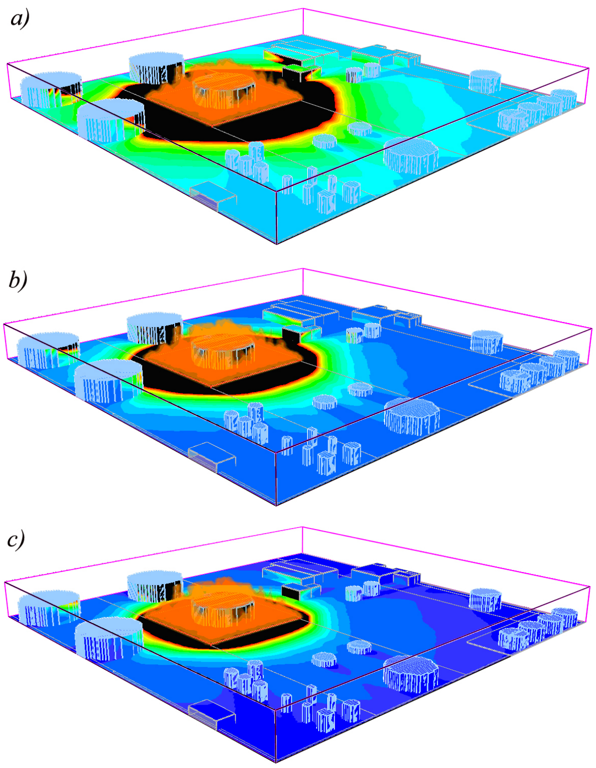

Figure 4. *Field distribution of heat fluxes: a) 2 kW/m^2; b) 5 kW/m^2; c) 10 kW/m^2*

According to the simulation results, the dimensions of the potentially endangered zones inside the storage area of the Pančevo Oil Refinery are given in Table 1.

Table 1. *Endangered zones from fire flame radiation*

Hazard level	Distance from the pool fire
Red (10.0 kW/m^2)	62 m
Orange (5.0 kW/m^2)	77 m
Yellow (2.0 kW/m^2)	101 m

As can be seen in Table 1, the diameter of the zone in which the incident heat flux value is higher than 2 kW/m^2 is about 101 m. In this zone, skin pain can be expected after exposure lasting more than 60 seconds. The zone with an incident heat flux of 5 kW/m2 and more, i.e. a heat flux that can cause second-degree burns when exposed for more than 60 s, has a diameter of 77 m. The area where incident heat flux values exceed 10 kW/m² — a level that may lead to fatal outcomes with exposure longer than 60 seconds — has a diameter of 62 meters.

Tank B, Tank D and the condensate polishing facility are located within endangered zones. Numerical results of the intensity of incident heat fluxes on adjacent tanks and the facade surfaces of facilities exposed to fire are shown in Figures 5 and 6.

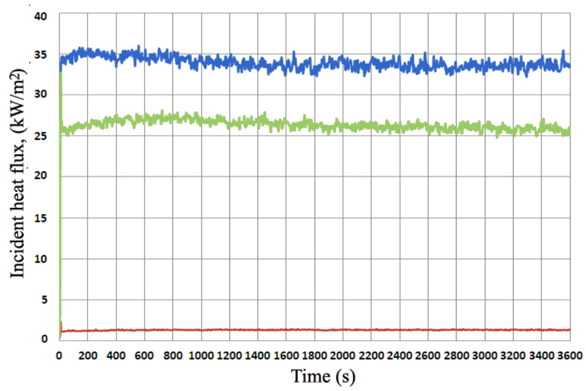

Figure 5. *Incident heat flux:*
- Tank D; - Tank B; - Tank C

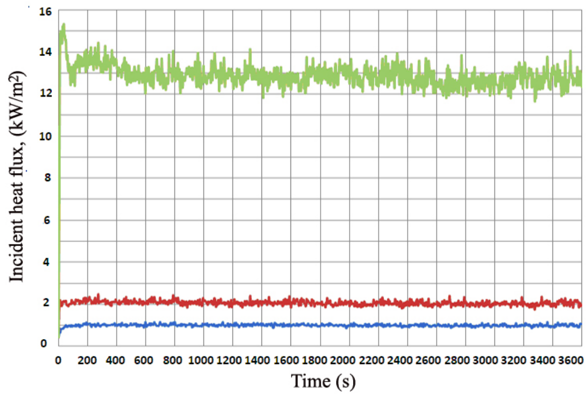

Figure 6. *Incident heat flux:*
- condensate polishing facility; - energy facility; - facility of chemical preparation of water

The highest values of incident heat flux measured on the surfaces of objects in the immediate vicinity of the burning tank were recorded on the crude oil tanks D and B (35.5 kW/m^2 and 26.5 kW/m^2, respectively). At the condensate polishing facility, a heat flux value of approximately 15 kW/m^2 was recorded. These high heat flux values require the implementation of adequate fire protection measures. Generally, the tanks directly affected by the heat radiation need to be cooled by using the fixed cooling system of the tanks themselves. At other facilities within the impact zone, no higher heat flux values were recorded that would require the implementation of fire protection measures.

Temperatures

The separation distance between the burning tank and other tanks and facilities affects the thermal radiation dose received by the adjacent tanks and facilities. The temperatures on the surfaces of neighbouring objects exposed to fire radiation are directly dependent on thermal fluxes on their surfaces. The average values of temperatures on tanks and facilities are given in Figures 7 and 8.

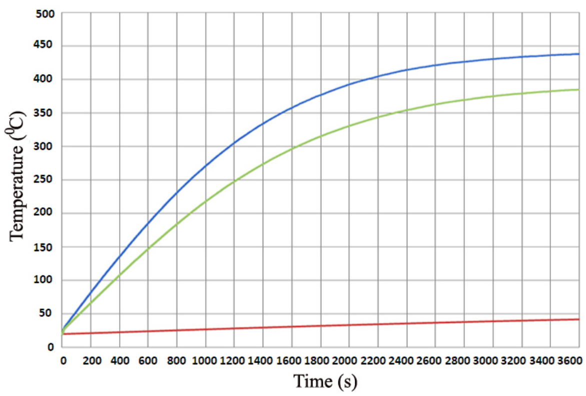

Figure 7. *Temperature:*
— - Tank D; — - Tank B; — - Tank C

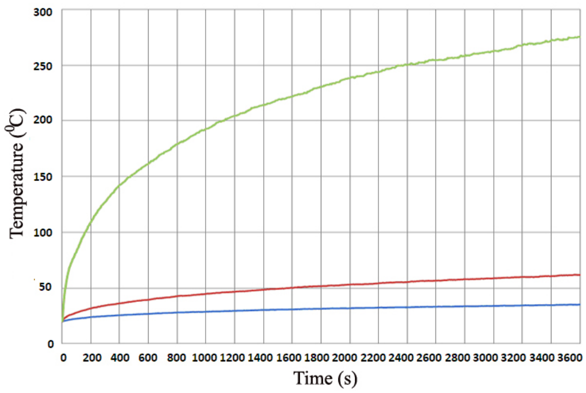

Figure 8. *Temperature:*
— - condensate polishing facility; — - energy facility; — - facility of chemical preparation of water

Temperatures measured by sensors on the surfaces of objects in the immediate vicinity of the burning tank indicated that the highest temperatures were recorded on crude oil tanks D and B (438 °C and 385 °C, respectively), as well as on the condensate polishing facility, where a temperature of 275 °C was recorded. No higher temperatures were recorded on other objects in the affected zone.

Since it is very important to assess the risk for individuals in close proximity to the fire, the field distribution of temperatures higher than 44 °C is given in Figure 9.

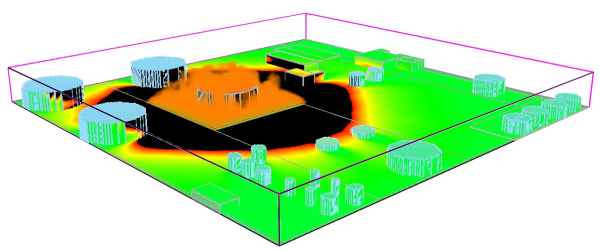

Figure 9. *Field distribution of temperature higher than 44 ^{0}C*

Analyzing the spatial distribution of temperatures of 44 °C and above, i.e., temperatures that can cause pain on human skin after exposure exceeding 60 s, it is observed that the affected zone has a diameter of 112 m. This can be considered to be the closest distance from a burning tank that people can approach without proper protective clothing.

CONCLUSION

CFD simulations were carried out with the aim of studying the fire incident in an above-ground crude oil tank. The FDS LES model was employed to investigate the effects of fire heat flux and temperature on the surrounding environment. The main conclusions can be summarized as follows:

- The heat released during the fire is very high because the spilling of burning oil from the tank caused the fire to also spread to the oil contained within the bund.
- The thermal radiation dose received by the adjacent tanks and facilities decreases with the increase of the separation distance from the burning tank.
- The temperatures on the surfaces of neighbouring objects exposed to fire are directly dependent on incident heat fluxes on their surfaces.

Numerical results are important, not only for the vulnerability of surrounding tanks and facilities in case of fire, but also for planning safe separation distances between tanks for storing flammable liquids. They also provide useful data for developing appropriate firefighting tactics during tank fire incidents, helping to identify safe zones for positioning equipment and personnel.

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