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Numerical Simulation of Kerosene Pool Fires

Ion Anghel[*], Popa Constantin[*], Pavel Alecsandru[**]

[*] Academia de Poliţie "*A. I. Cuza*"- Facultatea de Pompieri, Str. Morarilor nr. 3, Bucureşti
e-mail: anghel.john@gmail.com

[**] Universitatea Petrol – Gaze din Ploieşti, Bd. Bucureşti 39, Ploieşti, Romania
e-mail: infotech@pcnet.ro

Abstract

In the paper below one examines the flame height, temperature distribution and velocity field of kerosene pool fire, using the Fire Dynamics Simulator (FDS), at different pool diameters and wind velocity.

FDS is a computational fluid dynamics (CFD) model of fire-driven fluid flow. The software solves numerically a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow with an emphasis on smoke and heat transport from fires.

Key words: *Computational fluid dynamics, numerical modeling, pool fire*

General Considerations

The term “pool fire” is used to determine the ignited fuel in the liquid phase (pool), but it can also apply to flat slabs of solid fuels which decompose in a similar manner to liquids (e.g., Polymethylmethacrylate and Polyethylene). A pool fire involves a horizontal, upward-facing, combustible fuel.

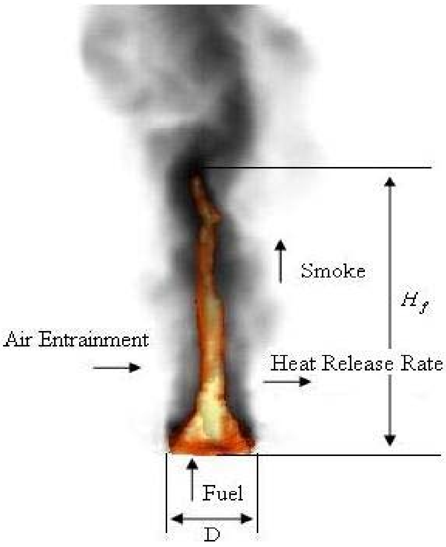

Fig. 1. Characteristics of a pool fire

When it is spilled, the flammable/combustible liquid may form a pool of any shape and thickness, and may be controlled by the confinement of the area geometry (such as a dike or curbing). Liquid fuel may burn in an open storage container or on the ground in the form of a spill. For a given amount of fuel, spills with a large surface area burn with a high Heat Release Rate (HRR) for a short duration, while spills with a smaller surface area burn with a lower HRR for a longer duration.

Once ignited, a pool fire spreads rapidly over the surface of the liquid spill area. The burning rate of a given fuel can also be affected by its substrate (i.e., gravel and sand) in a spill. For flammable/combustible liquids, flame spread rates range from approximately 10 cm/sec to 2 m/sec. Figure 1 shows the dynamic characteristics of a pool fire [5].

Fire Dynamics Simulator

The FDS code is a computational fluid dynamics model for simulation of fire-driven fluid flow developed by the National Institute of Standards and Technology [1].

FDS solves numerically a form of the Navier-Stokes equations appropriate for lowspeed, thermally-driven flow with an emphasis on smoke and heat transport from fires. The core algorithm is an explicit predictor-corrector scheme, second order accurate in space and time. Turbulence is treated by means of the Smagorinsky form of Large Eddy Simulation (LES) [2].

Two types of combustion models have been implemented in the FDS code. The choice depends on the resolution of the underlying grid. However, in an LES calculation where the grid is not fine enough to resolve the diffusion of fuel and oxygen, a mixture fraction-based combustion model is used.[2]

The mixture fraction combustion model assumes a mesh refinement sufficiently dense that large-scale convective and radiative transport phenomena can be simulated directly, but physical processes occurring at smaller length and time scales must be approximated. The approximations employed reflect the spatial and temporal resolution limits of the computation and current limited understanding of the phenomena involved.

In the numerical algorithm implementing the mixture fraction model, the local heat release rate is computed by first locating the flame sheet, then computing the local heat release rate per unit area, and finally distributing the energy to the grid cells cut by the flame sheet. In this way, the genuinely, infinitely thin flame sheet is smeared out over the width of one grid cell, consistent with all other gas phase quantities [3].

As a physical limitation of the mixture fraction approach to modeling combustion, we have the assumption that fuel and oxygen burn instantaneously when they are mixed.

Thermal Properties of Kerosene

Kerosene ($C_{14}H_{30}$) is a colorless flammable hydrocarbon liquid. The name is derived from Greek "keros". Kerosene releases heat when burned, making itself useful as a fuel. Widely used to power jet-engined aircraft, but is also commonly used as a heating fuel, kerosene is obtained from the fractional distillation of petroleum at 150 ^{o}C and 275 ^{o}C.

The table below presents the thermal properties of kerosene, as they already exist in the program’s database.

Table 1. Thermal properties of kerosene

Property	**Value**	**Units**
Molecular weight	198,0	g/mol
Ideal stoichiometric coefficients for O_2,CO_2 and H_2O	21,5	-
	14,0	-
	15,0	-
Energy release per O_2 consumed	12700,0	kJ/kg
Fuel fraction converted to CO	0,012	-
Fuel fraction converted to soot	0,042	-
Ignition temperature	216,0	°C
Heat of vaporization	256,0	kJ/kg
Heat of combustion	42800,0	kJ/kg
Thickness of heated layer	0,10	m
Thermal conductivity	0,109	W/m-K
Density	810,0	Kg/m^3

Criteria and Correlations for Estimating Flame Height

Fire plumes may be divided into three regions: a continuous flame region, an intermittent flame region, and a thermal plume region. Visible flame tips in the intermittent region have temperatures in the range of 320 to 400°C. Flame height is defined as the height at which the flame is observed at least 50% of the time; this height is in the intermittent region. The following correlations of Heskestad and Thomas, respectively, are widely used to estimate the flame height of pool fires [5]:

$$H_f = 0{,}235 \cdot Q^{2/5} - 1{,}02D \tag{1}$$

and

$$H_f = 42D\left[\frac{\dot{m}''}{\rho_a (gD)^{0,5}}\right]^{0,61} \tag{2}$$

Where:

H_f = flame height [m];

Q = heat release rate of the fire [kW];

D = diameter of the fire [m];

$\dot{m}''$ = burning or mass loss rate per unit area [kg/m^2-s];

ρ_a = ambient air density [kg/m^3];

g = gravitational acceleration [m/s^2].

The heat release rate is estimated by

$$Q = \dot{m}'' \Delta H_{c,eff} A_f \left(1 - \ell^{-\kappa\beta D}\right) \tag{3}$$

Where:

$\Delta H_{c,eff}$ = effective heat of combustion [kJ/kg];

A_f = horizontal burning area of the fuel [m^2];

$\kappa\beta$ = empirical constant [m^{-1}].

For the larger pool fires considered herein, the exponential term in Equation 3 is negligible ($\kappa\beta$ is about 3,4 for Kerosene. For non-circular pools, the effective diameter, D_e, to be used in place of D in Equations 1 and 2 is defined by [5]:

$$D_e = \left(\frac{4A_f}{\pi}\right)^{0,5} \tag{4}$$

While several approaches for estimating flame height from FDS output were considered an approach based on the 50% criterion was determined best suited for the current effort. Specifically, point measurements of heat release rates per unit volume (HRRPUV) were recorded at specified heights along the plume centerline using the THCP namelist group in FDS. When burning occurs at the specified height, HRRPUV is positive; otherwise, the value is zero. For the purpose of evaluating these data against the 50% criterion, values less than 0,1 are assigned a zero value and all other values are assigned 1. Summing the 1s and dividing by the total number of readings yields the burn time fraction. Plotting burn time fraction against centerline height yields the flame height when the fraction falls to 0,5 [4].

FDS 3-D Kerosene Pool Fire Models and Results

In the present research one have developed three-dimensional models of square shaped kerosene spills, which, ignited, create the so called pool fires. Were made three simulations: a standard one, and two derived ones – second, involving a wind current (taking into account the speed of wind), and the third, with a bigger surface of the base kerosene spill diameter (side of the square).

The simulations are made in a computational domain with the dimensions: 20 m width, 20 m length, and 50 m height.

Total amount of cells involved in the hydrodynamic calculus is 320000. The liquid fuel used for simulation is kerosene, with a spill thickness of 10 cm, and thermal properties as described in table 1; the ambient temperature is 20° C and the total time duration for each simulation is 300 seconds.

The simulations were conducted on a computer with 2400 MHz, Intel core 2 Duo processor and 1024 MB DDRAM.

The first simulation, e.g. standard one, has the following characteristics: the spill diameter (the side of the square) is 6 m, wind speed is zero, and the program made 47961 reiterations in 23,2 hours. The second one, has the spill diameter is 6 m, wind speed is 2,5 m/s, the program made 44493 reiterations in 22,04 hours. At last, the third one has the spill diameter is 8 m, wind speed is zero, the program made 54052 reiterations in 27,05 hours.

Discussion of Results

First of all, is examined by comparison, the height of the flame for each test, at a 70 seconds time of the simulation. One can observe that the wind reduces, dissipates the height of the flame, while, as expected, the bigger diameter of the spill induces a higher flame (see figure 2 and 3).

Afterwards is examined also by comparison, the temperature of the flame at 70 seconds of simulation. It can be seen that the wind speed influences only the temperatures field repartition, but not the temperature of the flame itself (figure 4), while the bigger diameter gives a rising of flame temperature from 870° C to 1020 ° C (see figure 5).

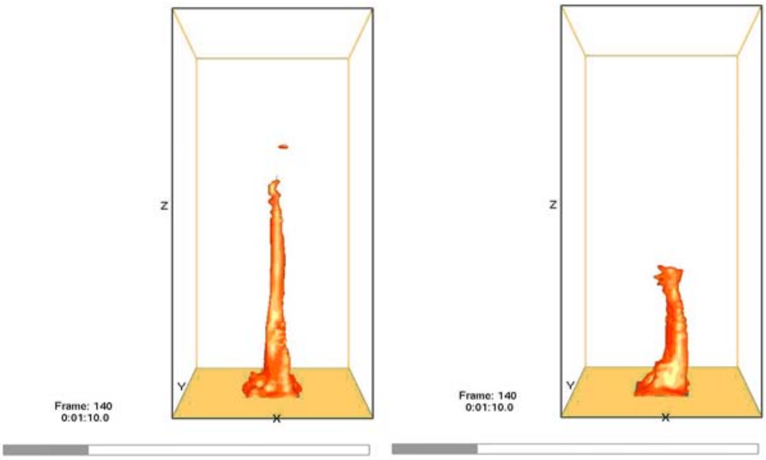

Fig.2. Height of the flame, FDS snapshots - standard simulation (wind speed 0 m/s), compared with second one, involving a wind speed (2,5 m/s); Both images illustrate flames at time t = 70s

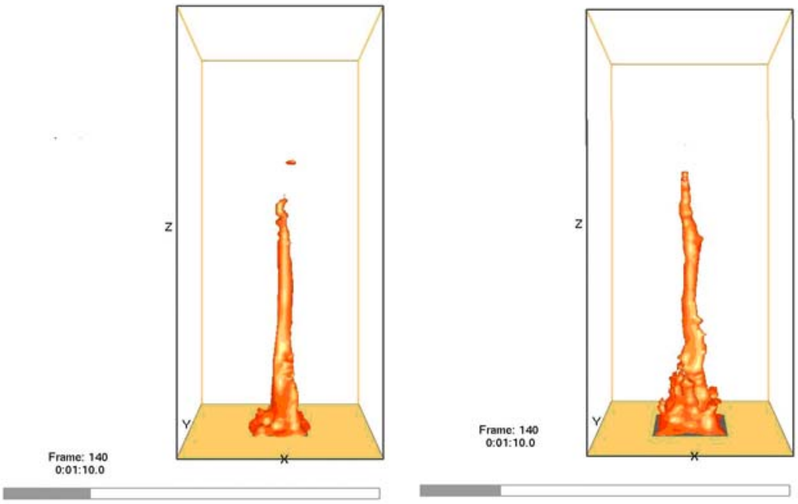

Fig.3. Height of the flame, FDS snapshots - standard simulation (side of the spill square, 6 meters) compared with the third one, which has a bigger surface of the base kerosene spill
(side of the square of spill, 8 meters); Same time t = 70s

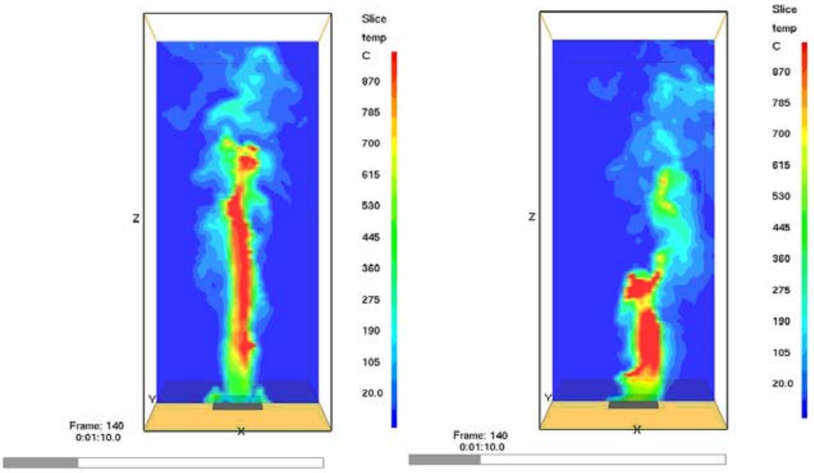

Fig.4. Temperature of the flame – Slice file snapshots of shaded temperature contours in a vertical plane centered at the fire origin – standard simulation compared to the second one, at time t = 70s

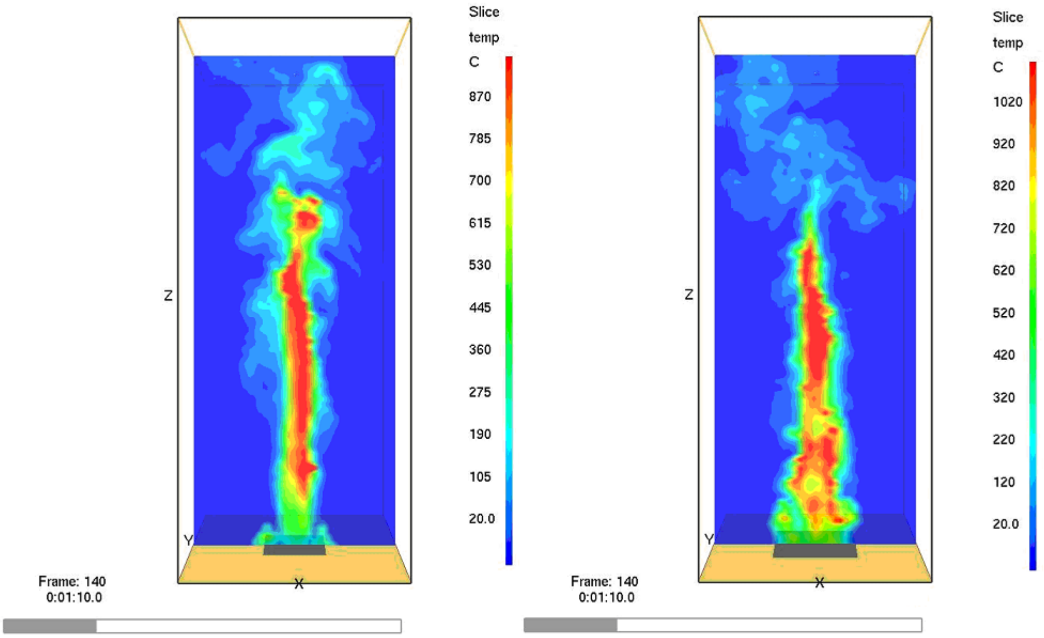

Fig.5. Temperature of the flame – Slice file snapshots of shaded temperature contours in a vertical plane centered at the fire origin – standard simulation compared to the third one, at time t = 70s

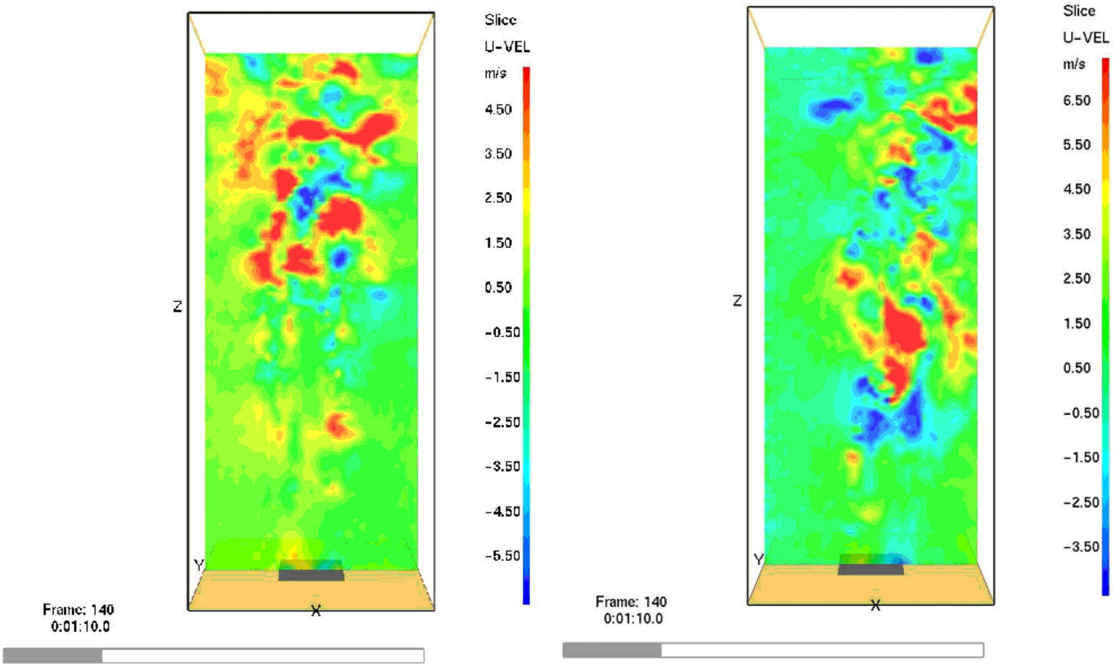

Fig.6. The speed field of the flame – Slice file snapshots for the speed field of the flame in a vertical plane centered at the fire origin – standard simulation compared to the second one, at time t = 70s

Below, are compared the values of the air currents speed field that draws the flame, in the three cases, at the same moment in simulation time, 70 s. One can observe that a wind speed of 2,5 m/s lead to a growth of the air flow top speed from 4,5 m/s to 6,5 m/s (figure 6), and the bigger diameter in the third simulation leads to an increase of top speed from 4,5 m/s to 8,5 m/s (see figure 7).

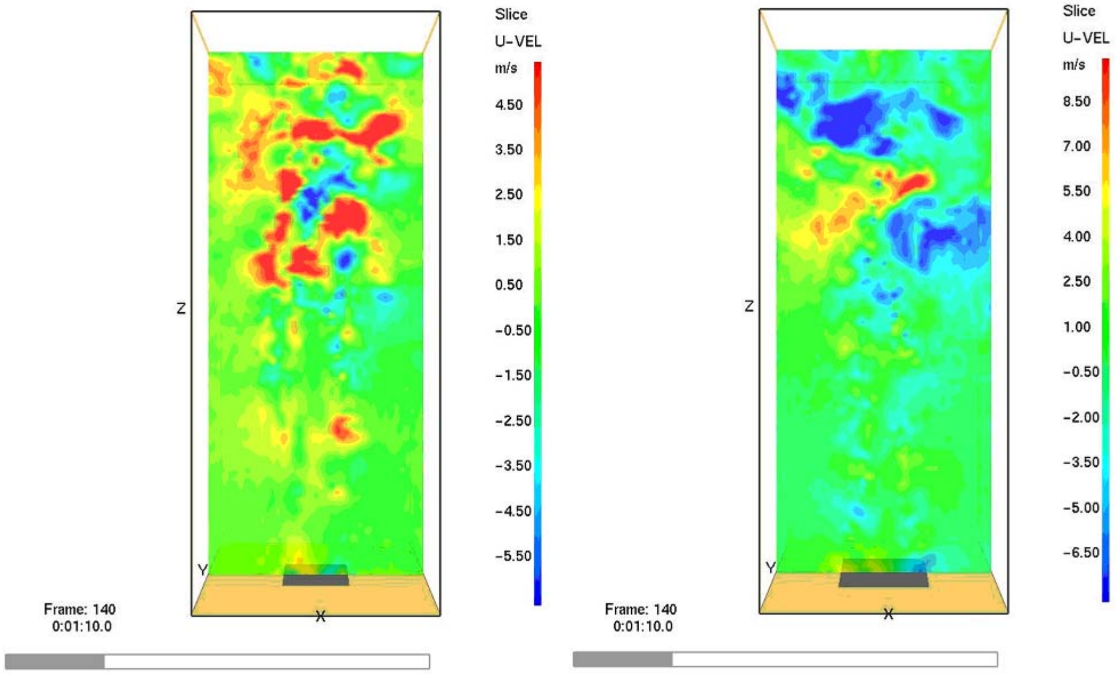

Fig.7. The speed field of the flame – Slice file snapshots for the speed field of the flame in a vertical plane centered at the fire origin – standard simulation compared to the third one, at time t = 70s

Conclusions

The flame height is an important quantitative characteristic of a fire and may affect fire detection and suppression system design, fire heating of building structures, smoke filling rates, and fire ventilation. Flame height typically depends on whether the flame is laminar or turbulent. In general, laminar flames are short, while turbulent flames are tall.

The height of a flame is a significant indicator of the hazard posed by the flame. Flame height directly relates to flame heat transfer and the characteristics of the flame to impact surrounding objects. The size (height) and temperature of the flame are both important in estimating the ignition of adjacent combustibles. As a plume of hot gases rises above the flame, the temperature, velocity, and width of the plume changes as the plume mixes with the gases that surrounds it.

The tree simulations proved to be in accordance with the expected results, that the wind speed can move the flame in the direction it blows, also diminishing the vertical dynamic of the flame, while a wider surface of Kerosene in the spill leads to a much higher flame.

References

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Simularea numerică a incendiilor la scurgeri de kerosen

Rezumat

În lucrare se examinează înălţimea flăcării, distribuţia temperaturii şi a câmpului de viteze pentru incendii la scurgeri de kerosen, folosind programul Fire Dynamics Simulator (FDS), la diferite valori ale diametrului şi vitezei vântului.

FDS este un model de calcul al dinamicii fluidelor (CFD) pentru efluenţii unui incendiu. Programul rezolvă numeric o formă a ecuaţiilor Navier-Stokes pentru viteză redusă, şi curgere ghidată de căldură, cu accent pe transportul fumului şi căldurii rezultate în urma incendiilor.