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CALCULATION OF THERMAL RADIATION LEVEL DURING A POOL FIRE CAUSED BY LEAKAGE OF KEROSENE FROM TANKER WAGON AT RAILWAY CROSSINGS

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Review article

Abstract: The spillages due to collisions related incidents involving the wagon tankers, which carrying hazardous materials (hazmat), can be followed by fires or explosions, presents a severe threat to the safety of residents and nearby buildings. In this study, ALOHA and PHAST was used to evaluate the level of thermal radiation at different distances from the place of accident. Discussed scenario analyze a leakage of kerosene from a tanker wagon, from different opening diameters, where is formed a pool fire. As an assumption for location of possible accident, parts of the railway where it can be expected a large number of people and vehicles were taken. For study area was chosen city of Niš, Serbia.

Keywords: Hazardous materials, thermal radiation, pool fire, accident.

Introduction

The transport of hazardous materials may present a hazard to the transporter, the crew, or the public. The relative importance of these varies between the different modes of transport. The hazards presented by the transport of chemicals are: fire, explosion and toxic release (conventional toxic substances, ultra-toxic substances).

Transport risk assessment involves defining the scope of analysis, describing the system or movement, as well as routes, identifying hazards or initiating events (incident or non-incident), numerating incidents, selecting incidents, incidents outcomes and incident outcome cases, estimating consequence, estimating frequencies, combining frequencies and consequences to estimate risk, and evaluating risk reduction alternatives.

The risk assessment of transportation of chemicals is dynamic due to the movement of the chemical carriers through a variety of locations along the route. Because of that, the risk assessment should consider a variety of factors that determine the exposure at different areas along the route of chemical transportation, such as (Mannan 2012):

- Number of containers;
- Chemical volume per shipment;
- Trip distance;
- Number of trips;

  Number and size of population centers along the route, including very dense populations (Hot-spots);
- Environmental contamination considerations such as municipal water supply reservoirs along the route;
- Proximity to landmarks;
- Proximity to public venues;
- Storage in transit such as rail yards, leased tracks.

A hydrocarbon tank fire is a relatively rare accident that may lead to unexpected consequences for the inhabitants and their environment. These accidents demonstrate not only the large-scale of destruction in the surroundings, together with the implication of potential environmental issues, but also the necessity to prevent similar accidents (Pitbaldo 2010). A lot of researches are related with the estimation of plume dispersion, ground-level concentrations of the toxic pollutants, evaluation of thermal radiation and overpressure impacts, in order to evaluate possible risks zones for different hazardous materials (hazmat). According to the US Department of Transportation, a hazardous materials are defined as any substance or material

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capable of causing harm to people, property, and the environment (Chakrabarti & Parikh 2013). The United Nations sorts hazmats into nine classes and the percentage of accidental release cases involving a particular class of materials, out of which flammable-combustible liquids contribute to 42.3 % and corrosives (e.g. acids and caustics) 37.5 % of cases whereas poisonous substances were involved in 5.2 % of cases (Erkut et al., 2007).

Study area

For study area was taken city of Nis, which is the third largest city in Serbia. The city area occupies 596,73 km^2, and it is administratively divided into five city municipalities: Medijana, Palilula, Pantelej, Crveni Krst and Niška Banja. Various types of transportation that are present on the territory of Nis, railway has higher damage potential, because most of the railway line that passes through the city is in a residential area (see Fig. 1). The safety and efficiency of rail transport must be considered as strategic goal for local government.

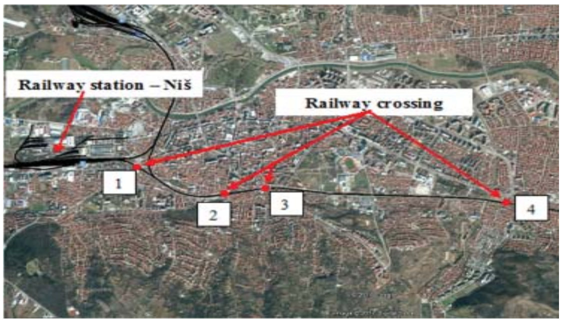

Fig. 1. Railway line that passes through the city with marked railway crossing places

On Figures 1a, 1b, 1c and 1d are shown marked railway crossing.

Fig. 1a. Railway crossing - point 1

Fig. 1b. Railway crossing - point 2

Fig. 1c. Railway crossing - point 3

Fig. 1d. Railway crossing - point 4

Objective

This paper presents an analysis and simulation of an accident which involves a transportation of kerosene in wagon tanker. The scenario where kerosene is leaking from tanker, and start to burn and forms a pool fire was discussed. In that case, the calculation was carried out for evaluation of thermal radiation level on surrounding population and environment. For that purpose, simulation software ALOHA and PHAST are used, and their results are compared, in order to obtain precise results.

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Materials and methods

The air dispersion model ALOHA and PHAST were utilized to predict the thermal radiation level of a kerosene release from wagon tanker. Those programs are based on dispersion model that has ability to estimate vulnerable zones during handling with hazmats, and visually displays endangered zones on the map, which aims to better understand the situation of endangered area.

ALOHA is a computer program designed to model chemical releases for emergency responders and planners. The primary purpose is to provide an estimate of the hazards associated with the short-term accidental releases of volatile and flammable chemicals. It helps in quantifying the impact on human health because of various situations such as inhalation of toxic vapors, thermal radiation of chemical fires, and effect of the pressure wave from vapor cloud explosions (EPA, 2013).

PHAST is the industry standard tool for process hazard analysis. It is the most comprehensive process industry hazard analysis and consequence assessment software, which examines the progress of a potential incident from the initial release to far field dispersion, including modelling of fuel spreading and evaporation, and flammable and toxic effects of fire and explosion.

Table 1 provides a comparative picture of ALOHA and PHAST equations used in computations of pool fire simulations.

Input data

In rail transport, wagon tanker is a type of unpressurized tank for flammable liquids transportation, with minimum plate thickness of 11.1 mm, and maximum capacity of 131 m^3. Tanks may be constructed from carbon steel, aluminum alloy, high alloy steel or nickel plate steel by fusion welding. In our case, approximant dimensions of tanker are: diameter: 3 m; length: 16 m; volume: 118 m^3; mass in the tank is: 97.4 t.

Table 1. Equations used for various parameters in the pool fire models

Parameters	ALOHA	PHAST
Discharge rate (Q_t), kg/s	Chocked $Q_t = C_d A_h \sqrt{\rho_g(t) P_T(t) \gamma_g \left(\frac{2}{\gamma_g+1}\right)^{\frac{\gamma_g+1}{\gamma_g-1}}}\ (kg/s)$ Unchocked $Q_t = C_d A_h \sqrt{2\rho_g P_T \gamma_g \frac{\gamma_g}{\gamma_g-1}\left[\left(\frac{P_a}{P_T}\right)^{\frac{2}{\gamma_g}} - \left(\frac{P_a}{P_T}\right)^{\frac{\gamma_g+1}{\gamma_g}}\right]}\ (kg/s)$	Time varying $Q_t = Q_d min \times [1, r_{jetmass}(1-\eta_{rainout})]\ (kg/s)$
Gas velocity in expanding (u_j), m/s	$u_j = M_j \sqrt{\frac{\gamma_g R_c T_j}{W_{gk}}} (m/s) T_j = \frac{2T_s}{2+(\gamma_g-1)M_j^2} (K)$	$u_j = \frac{Q_t}{\rho_j \pi u_j}$ Expended radius $r_j = \left(\frac{Q_t}{\rho_j \pi u_j}\right)^{\frac{1}{2}} (m)$
Mach number (M_j)	For unchocked flow, Mach number given as $M_j = \left[\frac{\left\{\left(1+2(\gamma_g-1)F^2\right)^{\frac{1}{2}}-1\right\}}{(\gamma_g-1)}\right]^{\frac{1}{2}}; F = 3.6233 \times 10^{-5} \cdot \frac{Q_t}{d_0^2}\sqrt{\frac{T_s}{\gamma_g W_{gk}}}$ For chocked flow, Mach number given as $M_j = \sqrt{\frac{(\gamma_g+1)\left(\frac{P_c}{P_0}\right)^{\frac{(\gamma_g-1)}{\gamma_g}} - 2}{(\gamma_g+1)}};\ P_C = 3.6713 \frac{Q_t}{d_0^2}\sqrt{\frac{T_s}{\gamma_g W_{gk}}} (Pa);\ T_C = \frac{2T_s}{1+\gamma_g} (K)$	For unchocked flow, Mach number given as $M_j = \left[\frac{\left\{\left(1+2(\gamma_g-1)F^2\right)^{\frac{1}{2}}-1\right\}}{(\gamma_g-1)}\right]^{\frac{1}{2}}; T_S = \left(\frac{F \times d_0^2}{3.6233 \times 10^{-5} \times Q_t}\right)^2 \times \gamma_g \times M_{wt}(K)$ $F = \left(\frac{\left(M_j^2(\gamma_g-1)+1\right)^2-1}{2(\gamma_g-1)}\right)^{1/2}$ For chocked flow, Mach number given as $M_j = \sqrt{\frac{(\gamma_g+1)\left(\frac{P_c}{P_0}\right)^{\frac{(\gamma_g-1)}{\gamma_g}} - 2}{(\gamma_g+1)}};\ P_C = \left(\frac{M_j^2(\gamma_g-1)+2}{(\gamma_g+1)}\right)^{\left(\frac{\gamma_g}{\gamma_g-1}\right)} \times P_0(Pa)$ $T_S = \frac{T_C(1+\gamma_g)}{2} (K);\ T_C = \left(\frac{P_C \times d_0^2}{3.6713 \times Q_t}\right)^2 \times \gamma_g \times M_{wt}(K)$
Effective source diameter (D_s), m	$D_S = d_j \sqrt{\frac{\rho_g}{\rho_a}} (m);\ d_j = \sqrt{3.6233 \times 10^{-5} \frac{Q_t}{M_j}\sqrt{\frac{T_j}{\gamma_g W_{gk}}}} (m)$	$2r_j \sqrt{\frac{\rho_j}{\rho_a}} (m)$
Flame length (L_B), m	$L_B = 105.4 D_S [1 - 6.07 \cdot 10^{-3}(\theta_j - 90)]$	$L_B = L_{B0}(0.51e^{-0.4U_W} + 0.49) \times \left(1 - 0.00607(\theta_j - 90)\right)\ (m)$
Flame length in still air (L_{B0}), m	$L_{B0} = \frac{1}{[0.51exp(-0.4v) + 0.49][1 - 6.07 \cdot 10^{-3}(\theta_j - 90)]}$	$0.2 + 0.024 N_R \cdot L_{B0} + P_{\frac{2}{3}} L_B^{\frac{2}{3}} = 0 N_R = \left(\frac{g}{D_S^2 v_j^2}\right)^{\frac{1}{3}};$ $P_{2/3} = -\left(\frac{D_S \beta}{W_{st}}\right)^{\frac{2}{3}}$
Flame lift-off (b), m	$b = L_B \frac{\sin K_\alpha}{\sin \alpha}\ (m)$ $K = 0.815e^{-20R} + 0.015$ $R = \frac{u_w}{u_j}$	$b = L_B \frac{\sin(0.185e^{-20R} + 0.015)\alpha}{\sin \alpha}\ (m)\ b = \begin{cases} 0.2L_B\ \alpha = 0° \\ 0.015L_B\ \alpha = 180° \end{cases}$ $\frac{Z}{L_{B0}} = h(\xi)\left(1 - c(\xi)\Omega_\chi\right)$
Angle between hole and flame axis	$if\ R \le 0.05$ $\alpha = \frac{8000R + \zeta(L_{B0})(\theta_j - 90)(1 - exp(-25.6R))}{\zeta(L_{B0})}$ $if\ R > 0.05$ $\alpha = \frac{[1526\sqrt{R - 0.026} + 134\zeta(L_{B0})(\theta_j - 90)(1 - exp(-25.6R))]}{\zeta(L_{B0})} \zeta(L_{B0}) = L_{B0}\left[\frac{g}{D_S^2 u_j^2}\right]^{\frac{1}{3}}$	$if\ R \le 0.05$ $\alpha = \left\{\frac{(8000R)}{N_R L_{B0}} + (\theta_{jv} - 90)(1 - e^{-25.6R})\right\}$ $if\ R > 0.05$ $\alpha = \frac{(1726\sqrt{R - 0.026} + 134)}{N_R L_{B0}} + (\theta_{jv} - 90)(1 - e^{-25.6R});\ \zeta(L_{B0}) = L_{B0}\left[\frac{g}{D_S^2 u_j^2}\right]^{\frac{1}{3}}$
Length of frustum (R_L), m	$R_L = \sqrt{(L_B^2 + b^2 sin^2\alpha)} - b\cos\alpha\ (m)$	$R_L = \sqrt{(L_B^2 + b^2 sin^2\alpha)} - b\cos\alpha\ (m)$
Width of the Frustum base (W), m	$W_1 = D_S[13.5exp(-6R) + 1.5] \times \left[1 - \left[1 - \frac{1}{15}\left(\frac{\rho_a}{\rho_j}\right)^{\frac{1}{2}}\right] exp(-70\xi(D_S)^{CR})\right]$	$W_1 = D_S[13.5exp(-6R) + 1.5] \times \left[1 - \left[1 - \frac{1}{15}\left(\frac{\rho_a}{\rho_j}\right)^{\frac{1}{2}}\right] exp(-70\xi(D_S)^{CR})\right]$

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For estimating thermal radiation levels, releasing of kerosene was considered for three hole sizes: large - 100 mm, medium - 50 mm and small - 25 mm respectively and formation of various pool radius. In the simulation it was observed that the hole is at the bottom of the tank. Calculation in ALOHA is limited to a 60 min, so it will be analyze the quantity of kerosene which was leaked in that period.

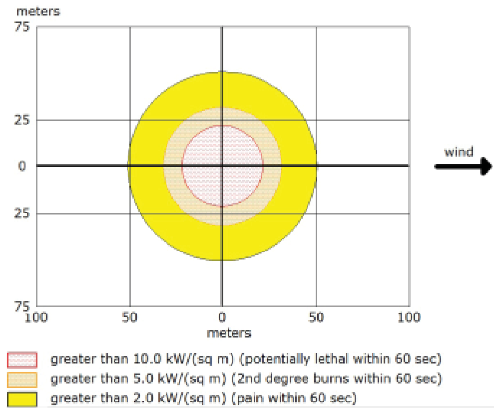
Meteorology

According to the Republic Hydrometeorological Service of Serbia, North-West is the most prominent wind direction in Niš, air temperature is 20 °C and estimated air humidity is 68 %. Based on Regulations about content of prevention policies and methodology for making safety report and accident protection plans (Gazette of RS, no. 41/2010), wind speed is 2-3 m/s and atmospheric stability class is D (neutral).

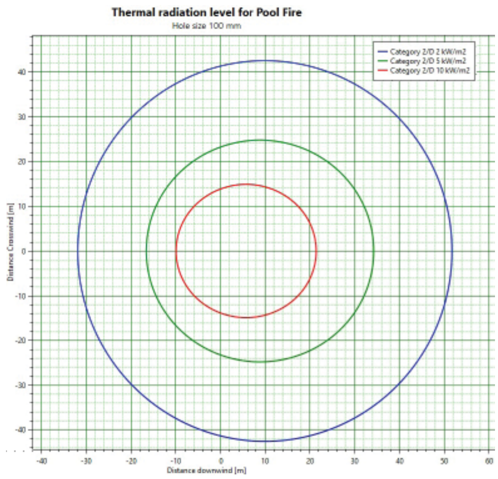
Results and discussions

The thermal radiation level distances have been estimated for different hole sizes and the comparative analysis for ALOHA and PHAST are shown in Table 2.

Figures 2a, 2b and 2c shows the simulation results of thermal radiation levels from the pool fire by using ALOHA and PHAST simulators. The same values of the parameters such as the atmospheric conditions, filling ratio, tanker dimensions etc. were taken for both the simulators.



ALOHA Software



PHAST software

Fig. 2a. Thermal radiation level distances - hole size 100 mm

Table 2. Consequence analysis for pool fire scenario and estimated thermal radiation levels for different hole sizes

ALOHA software

Hole size (mm)	Max flame length (m)	Max burn rate (kg/min)	Total amount burned (kg)	Puddle diameter (m)	Thermal radiation level distances (m)		
					>10kW/m^2	>5 kW/m^2	>2 kW/m^2
100	18	354	20974	10.8	22	32	51
50	11	88.6	5243	5.4	10	16	26
25	7	22.1	1311	2.7	< 10	< 10	15

PHAST software

Hole size (mm)	Max burn rate [kg/min]	Total amount burned (kg)	Puddle diameter (m)	Thermal radiation level distances (m)					
				>10kW/m^2		>5 kW/m^2		>2 kW/m^2	
				Distance downwind	Distance crosswind	Distance downwind	Distance crosswind	Distance downwind	Distance crosswind
100	951	57060	16.3118	15.69	14.86	25.43	24.77	41.8	42.57
50	237.6	14256	8.15	13.03	12.36	19.35	19.43	30.91	31.94
25	59.4	3564	4.077	8.98	8.67	12.92	13.24	20.63	21.47

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After analyzing the results it can be noticed that by reducing the hole size on the tanker, the flow rate and total burning amount of kerosene leakage is drastically decreases. With hole increasing above 100 mm, it can be expected far greater amount of leakage material, as well as the diameter of vulnerable zones.

Significant difference for release rate between ALOHA and PHAST can be noticed. PHAST calculate a larger amount of releasing kerosene from tanker for all three hole sizes.

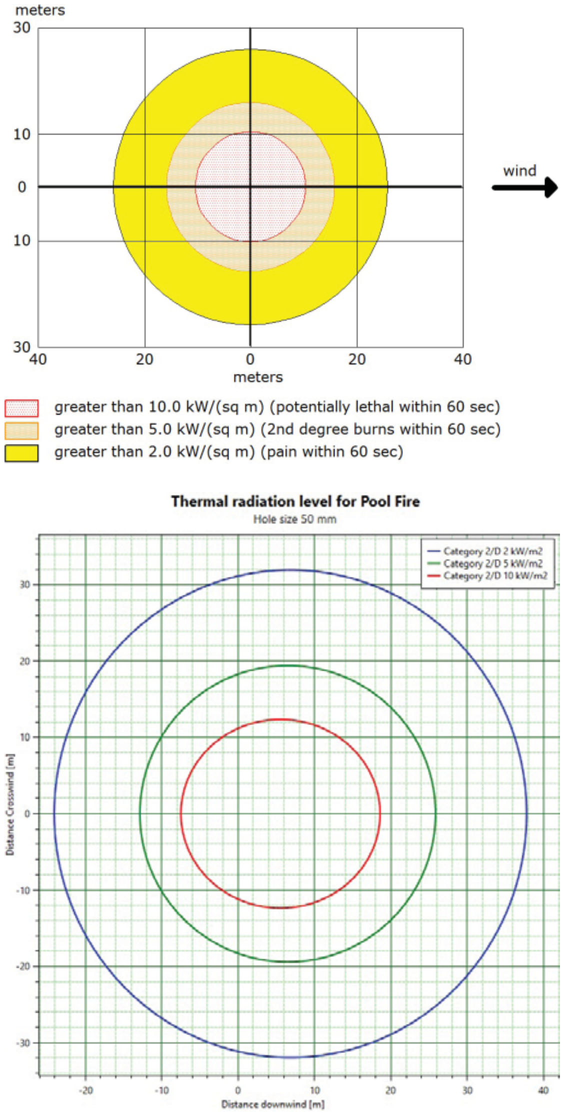

Fig. 2b. Thermal radiation level distances - hole size 50 mm

Since that the observed railway crossings are located in parts of the city where the frequency of traffic is increased, lot of people can be expected at any time, all three zones in all three cases will have extremely high influence on surrounding.

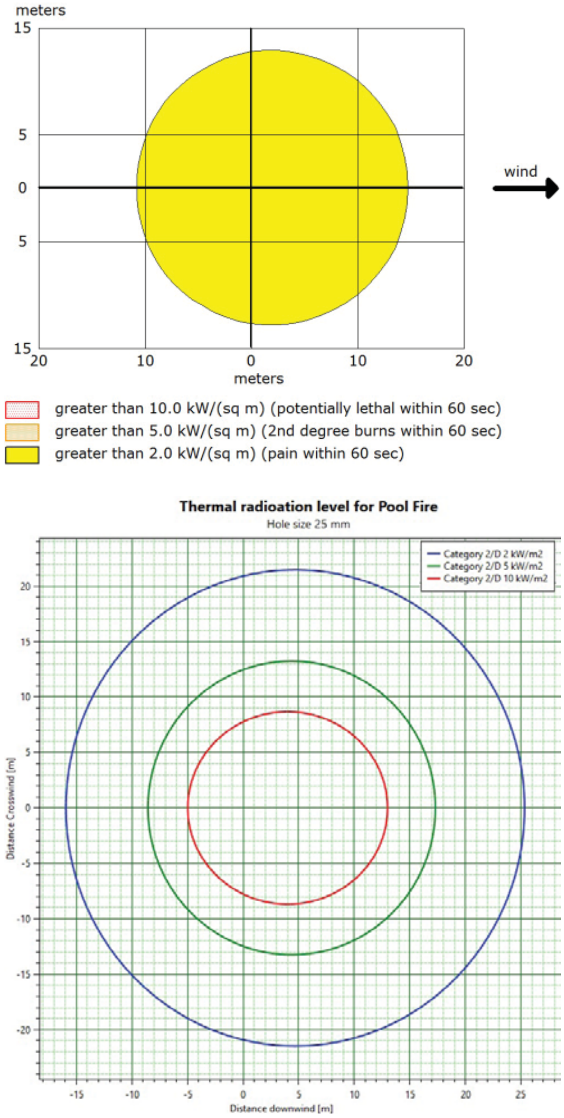

Fig. 2c. Thermal radiation level distances - hole size 25 mm

From compared results, it can be seen that the zone distances from the simulators are similar and that any one of them can be chosen for estimating the pool fire risk zones dimensions.

Death zone stretches in all three cases, for ALOHA in radius up to 22 m, 10 m and less than 10 m. PHAST estimated radius for this zones up to approximately 15 m, 13 m and 9 m. After lethal zone, in second zone it can be expected second degree burns on unprotected skin and pain within approximately 10 seconds of exposure. Diameter of second zones for ALOHA are 32 m, 16 m and less than 10 m, and for PHAST they are 25 m, 19 m and 13 m. Next zone, the last one, can cause pain for exposure durations of 60 seconds or less. It stretches in the radius of 51m, 26 m and 13 m for ALOHA, and for PHAST they are 42 m, 31 m and 21 m.

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Only in the last zone, it is noticed a drastic difference in the reduction of the radius which depends on the size of hole on tanker. In other zones there is no significant difference.

As regards for estimation for max thermal radiation, ALOHA calculate for large release of 112 kW/m^2, downwind from the source at a distance of 5.5 m; for medium release of 91.3 kW/m^2, downwind from the source at a distance of 2.8 m; and for small release of 76.8 kW/m^2, downwind from the source at a distance of 1.4 m (see Fig. 3a, 3b, 3c). In all three cases max thermal radiation values are reached between 2-3 minutes after pool fire was formed. That values are constant for the whole simulation time (60 min).

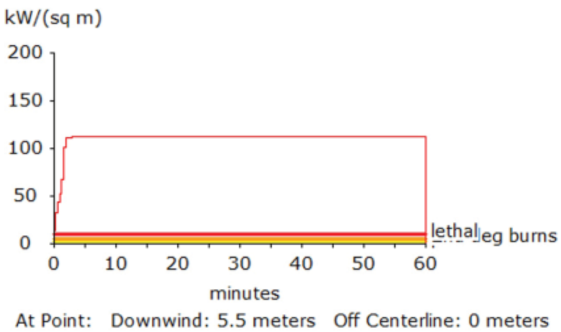

Fig. 3a. Max thermal radiation - hole size 100 mm

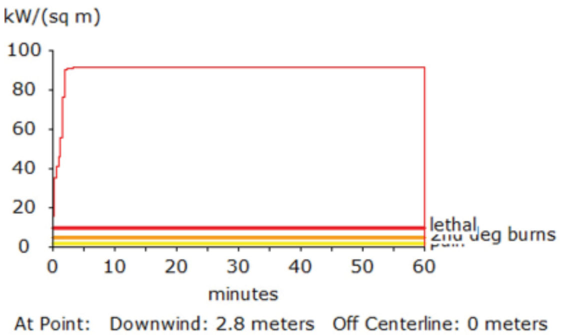

Fig. 3b. Max thermal radiation - hole size 50 mm

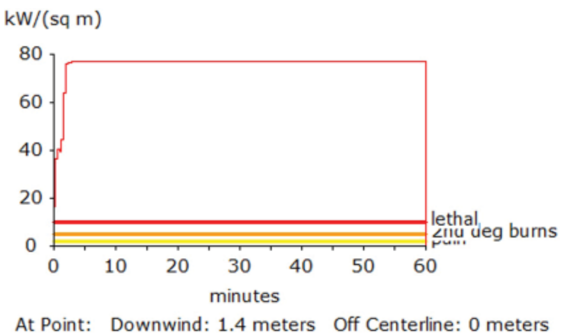

Fig. 3c. Max thermal radiation - hole size 25 mm

At Figure 4a, 4b and 4c can be seen the trend of declining thermal radiation levels. In all three cases, after maximum values are reached, its rapidly decrease as we move away from the source. This type of view can show more precise values, especially when ALOHA cannot draw zones with short distances. That situation is shown in case when hole size is 25 mm. Graphical interpretation shows only yellow zone, but when we perform detailed analyzation of thermal radiation levels, such is shown at Figure 4c, it can be seen all three zones.

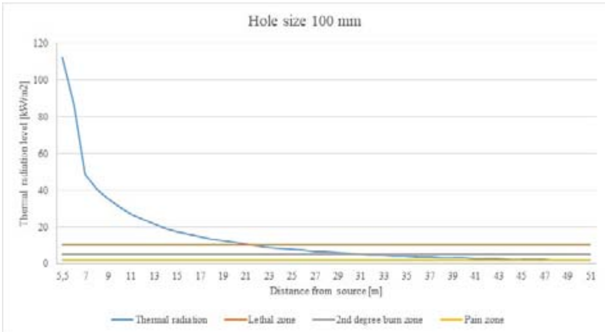

Fig. 4a. Trend of declining thermal radiation level for hole size 100 mm - ALOHA

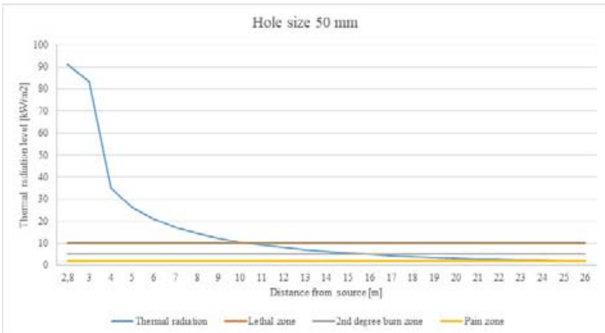

Fig. 4b. Trend of declining thermal radiation level for hole size 50 mm - ALOHA

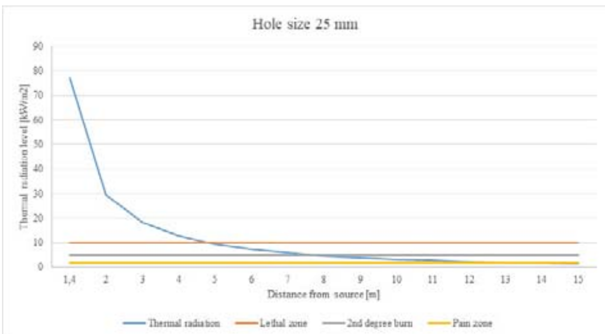

Fig. 4c. Trend of declining thermal radiation level for hole size 25 mm - ALOHA

During calculation of thermal radiation values in PHAST, different maximum values are noticed. Unlike ALOHA, PHAST calculate thermal radiation from failure point, so it is possible to evaluate thermal radiation at tanker. Figure 5a, 5b and 5c shows the thermal radiation emanating from the pool fire against the damage distance. Max thermal radiation, for large release is 93.54 kW/m^2, for medium release is 65.07 kW/m^2 and for small release is 36.93 kW/m^2.

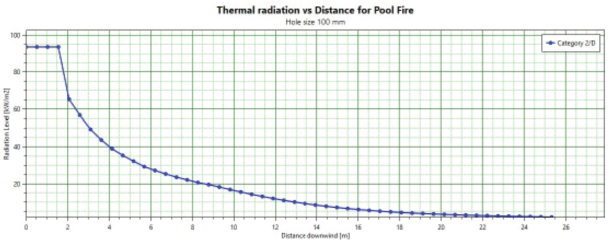

Fig. 5a. Trend of declining thermal radiation level for hole size 100 mm - PHAST

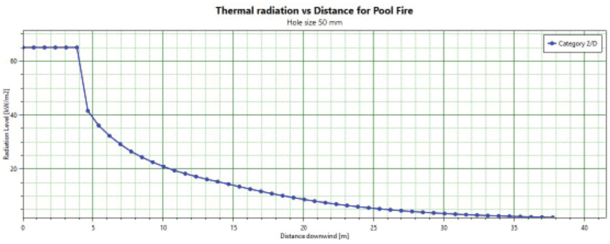

Fig. 5b. Trend of declining thermal radiation level for hole size 50 mm - PHAST

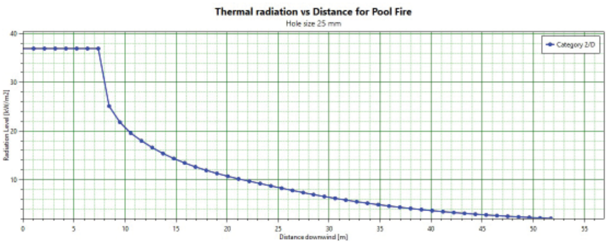

Fig. 5c. Trend of declining thermal radiation level for hole size 25 mm - PHAST

After analyzing the trend of declining thermal radiation, for large release in ALOHA value drops sharply at 47.2 kW/m^2 at 7 m, until PHAST max value holds up to 1.5 m and after that it drops at 65.34 kW/m^2 at 2.06 m. For medium release, in ALOHA value drops at 83 kW/m^2 at 3.3 m, and after that it rapidly decrease at 34 kW/m^2 at 4 m. PHAST for this case holds max value up to 3.85 m. Before long, thermal radiation level drops at 41.57 kW/m^2 at 4.62 m. For small release, in ALOHA max thermal radiation value drops shortly at 29.8 kW/m^2 at 2 m.

In all three cases, for both simulators, after max values of thermal radiation are reached, declining trend of thermal radiation level can be noticed as it move away from the pool fire.

Conclusion

The thermal radiation results obtained were used to calculate the probability of burn injuries due to spillage of kerosene from tanker wagon in real scenarios.

The models used give indications of hazardous zones following the release and dispersion of dangerous substances in densely inhabited areas. Nevertheless, the determination of hazardous zones is important to evaluate the possible consequences of major accidents or terrorist attacks (Bernatik et al., 2008).

Results by this study should be combined with emergency response for dealing with accident in the limit time.

Following a hazmat spillage, it is essential that immediate area within some specified distance be initially isolated from the public and then depending on the situation and behavior of the chemical, more area has to be isolated as ‘protective zone’ for the purpose of minimizing the effect on public in the surrounding area (U.S. Department of Transportation 2008).

Obtained results, for both simulators, shows similarity for estimating vulnerability zones. Hence, for emergency actions following a hazmat release event in the study area, simulation software such as ALOHA, which is open free software unlike PHAST, can be helpful for the responders to estimate ‘Initial Isolation zone’ and ‘Protective Action Zone’, so people will be kept at a safe distance from the spill area, depending on the nature of hazmat involved (Chakrabarti & Parikh 2013).

Local authorities announce the relocation of the railway from the city center for a long time, which would significantly reduce the risk of possible traffic accidents, endangering people's lives, and at the same time reduce the risk of accident in the transport of dangerous goods.

The results could be useful to make better comparisons of possible transport routes of dangerous substances in terms of the likely outcome of an accident.

This study can awaken awareness to local authorities to speed up the relocation of railway. The methodology that has been applied in this study can be used for new potential section of railway line, in order to identify the endangered zones and whether there is a danger to the surrounding.

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