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KNOWLEDGE-BASED EMERGENCY PLANNING FOR STORAGE TANK FARMS

Major accidents in storage tank farms can result in severe threats for emergency responders, neighbouring population and the environment as it was observed in the case of Buncefield (2005). The numerical modelling of dangerous phenomena is an important tool to support emergency planning for such complicated events. For this purpose, the case study in crude oil tank farm involving selection of reference accident scenario, CFD simulation of tank fire and prediction of delay to boilover was performed. The results were used to review the existing emergency plans and to enhance the tactical preparedness of emergency responders.

1. Introduction

Storage tanks are one of the most common types of technological units. They are often located in large industrial areas in the section with other storage equipment or in the close proximity of the different installations containing hazardous chemicals. It's not an exception that the large flammable liquid (especially crude oil) storage tanks with the volume capacity more than 100,000 cubic meters are constructed all over the world. Therefore the accidents in storage tank farms are associated with the strong potential to cause the domino effects and major loss. The historical experience with the accidents in Czechowice (1971), Litvínov (1996) described in [1] and more recently the lessons learned from Buncefield (2005) have confirmed that fires in storage tank farms can result in prolonged emergency situation and severe threats for emergency responders, neighbouring population and the environment. The industrial fires are generally coupled with the dangerous effects thermal radiation, the huge production of smoke (soot particles). In specific cases, the tank fire can be accompanied by boilover phenomenon.

2. Statistical review

Emergency response planning and preparedness for such complicated events requires reliable information concerning the accidental phenomena and their dangerous effects. The LASTFIRE project maps the fires of atmospheric open top floating roof tanks with large diameter (greater than 40 m). During the period of 1981–1995, 55 fires occurred on 2402 tanks observed for the sum of 33,909 tanks a year. 52 out of 55 fires represent the rim seal fires, full surface fire following the sinking of the roof was reported only in one case [2]. Chang and Lin [3] reviewed 207 flammable liquid tank fires in the period of 1960–2003 of which 66 represent the crude oil tank fires. The frequency of floating roof storage tank fires in Europe was statistically estimated to be about 1×10^{-3} per tank a year for rim seal fires. More severe tank fires are expected to occur in order of 3×10^{-5} per tank a year [3]. Tank fire study of Persson & Lonnermark [1] reported 20 cases of boilover (14 of these in the crude oil tanks) during the period of 1951–2003.

3. Modelling as a tool to support emergency preparedness

From the above stated data we can say that the industrial fires of large extent are relatively rare and the majority of fire fighters and emergency responders face up to this kind of situation once or a few times of their professional carrier. Scientific knowledge about this phenomenon is based mainly on the results of experimental observations and the mathematical modelling performed in different scales from the micro-scale laboratory studies to real-scale fire measurements and testing. Hence, the modelling and simulation of dangerous phenomena is an important tool to support decision making in the context of the emergency planning and to improve the tactical preparedness of emergency responders. As a first step needed to set up the efficient emergency plan the selection of relevant accidental scenario should be carried out before the model of given case of interest is employed. The plenty of risk analysis methods useful for this purpose exist, varying from fully qualitative and deterministic methods (e.g. expert judgement, preselected event checklist analysis) to quantitative and probabilistic approaches described extensively in [4, 5].

Recently available ARAMIS methodology [6] represents the alternative semi-quantitative approach to this step of risk analysis. Applicability of "Methodology for the Identification of Major Accident Hazards" (MIMAH) and "Methodology for the Identification of Reference Accident Scenarios" (MIRAS) published by Delvosalle et al. [6, 7] was examined by several case studies performed across Europe [8].

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4. Reference Accident Scenario selection

Above mentioned methodologies (MIMAH and MIRAS), based on combined Fault Tree Analysis (FTA) and Event Tree Analysis (ETA) were employed to perform the initial phase of the case study in a real crude oil tank farm. This tank farm consists of 18 atmospheric open top floating roof crude oil storage tanks and related equipment and infrastructure. The whole tank farm was analysed in five individual sections:

- Storage tanks
- Input and output pipes to storage tanks
- Pipe corridor
- Pump stations
- Pipeline receiving and measuring unit

As the result of MIMAH and MIRAS methodology 25 most dangerous phenomena were selected based on matrixes for each section of the tank farm. These were summarized in 12 representative scenarios (RAS). The original criterion for selection of Reference Accidental Scenario (RAS) proposed by ARAMIS methodology was modified in order to reduce the number of considered scenario to a reasonable value. Although the wide variety of accidental events (e.g. spills or ruptures on pipes, flange fires, flash fires and vapour cloud explosions) could be considered for the above mentioned tank farm, only the selected scenarios are consequently used to estimate the risks (by detailed risk assessment methodology) as well as to give the preliminary list of emergency situations, which should be taken into account. But as the worst case scenario approach is commonly applied in the framework of emergency response planning, the full surface tank fire is often considered as the typical accidental scenario for tank farms.

5. Dangerous effects of storage tank fires

The tank fire is the specific case of pool fire and for the open floating roof tanks the tank fires are only associated with the collapsed or sunken floating roof and following ignition of flammable liquid (crude oil) pool formed within the tank shell. The turbulent diffusion flames characteristic for large hydrocarbon pool fires (tank fires respectively) represent very complex system involving tightly coupled phenomena of fluid dynamics, heat transfer and chemical reactions. The mechanisms such as air entrainment, combustion, and soot/smoke formation have a first-order effect on the local temperatures and radiative transport properties. Underlying these mechanisms is the turbulent fluid motion that creates, and responds to the large temporal and spatial fluctuations [9].

The hazards associated with such fires then occur on two separated length scales. Near the fire, over distances comparable to the flame length, the radiant energy flux can be sufficiently high to threaten both the structural integrity of neighbouring structures and equipment and physical safety of firefighters and plant personnel. At much greater distances, typically several times the plume stabilisation height in the atmosphere, the smoke and gaseous products generated by the fire can reach the ground in concentrations that may be unacceptable for environmental reasons [10]. The phenomenon of smoke plume was extensively studied in the context of in-situ burning of oil spills [11]. Remote-sensing (UV spectroscopic) measurements performed during Buncefield fire in December 2005 revealed elevated trace gas concentrations of SO_2 (70 ppbv), NO_2 (140 ppbv), HONO (20 ppbv), HCHO (160 ppbv) and CS_2 (40 ppbv) [12].

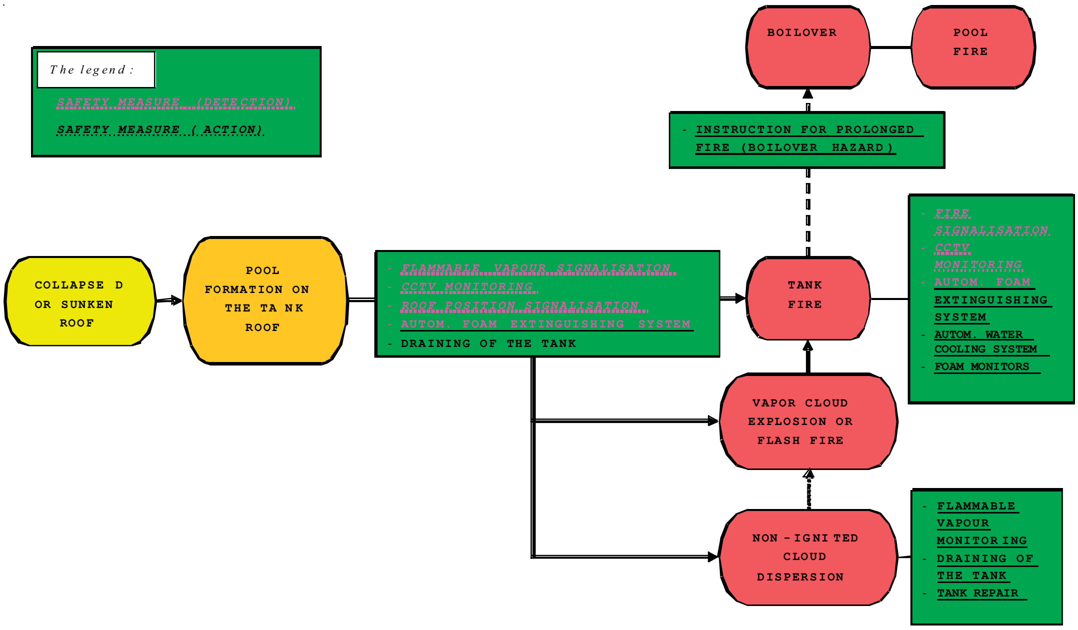

Fig. 1 Event tree for RAS - Collapse of the tank roof with the list of safety measures (barriers)

The special type of hazard associated with the crude oil tank fires is the formation of heat wave (hot zone) which propagates due to distillation process towards the tank bottom. In the case of prolonged tank fire consequent boilover phenomenon can occur. Boilover is a dangerous accidental phenomenon, which can lead to serious injuries to emergency responders. The boilover can occur several hours after the ignition of tank fire. The delay time is an unknown parameter of strong importance when managing the emergency response operations in oil tank farms. Hot zone formation and propagating process is the principal aspect of boilover phenomenon, which was experimentally studied in small and medium scales [13–15].

These experiments confirmed that several conditions and parameters of flammable liquid should be satisfied to enable occurrence of boilover after the prolonged tank fire. These parameters are mainly the range of boiling temperatures of the mixture components and viscosity. By the simplified way we can define that boilover can occur only in viscous flammable liquid mixtures with the mean boiling point above 120 °C and with wide distillation range. Three stages of boilover propagation are distinguished by Fan et al. [13] namely the:

- *Quasi-steady period* – the flame height is rather small and combustion is stable
- *Boilover premonitory period* – the flame height is fluctuating, caused by the water boiling on the fuel-water interface, emitting a ‘crackling’ sound
- *Boilover period* – the flame height increases quickly to the highest point and burning fuel is sprayed out of the tank

6. Approaches to large storage tank fire modelling

Mathematical modelling and simulation of dangerous phenomena allows us to determine desired characteristic features of assessed scenario and to prepare the corresponding safety measures. For emergency response planning and scenario-based training the threat zones (safe distances respectively) need to be estimated for selected scenario and different conditions (e.g. meteorological and technological) based on state-of-the-art modelling tools.

According to [16] the mathematical tools for predicting the radiative heat flux at the tank surroundings can be dividend broadly into three classes:

- Semi-empirical (point source and solid flame) models
- Field models
- Integral models

Point source semi-empirical models simplify the flame as a source term of radiative heat flux to be a single point usually located in the middle of the flame height. The fraction of heat of combustion, which is emitted from this point, is related on properties of fuel (sooting tendency) and diameter of the fire. These models over-estimate the heat radiation flux near the source, thus it should be used only for distances from the flame as far as approximately five pool (tank) diameters.

Solid flame models assume the flame as a surface emitter of heat radiation. This assumption can be enhanced by dividing the flame into two parts; first clear, strongly radiating lower part and second obscured by the layer of smoke soot particles which absorb the huge part of the incident heat radiation. Further refinement of this schema is possible to capture this characteristic feature of large scale hydrocarbons fires.

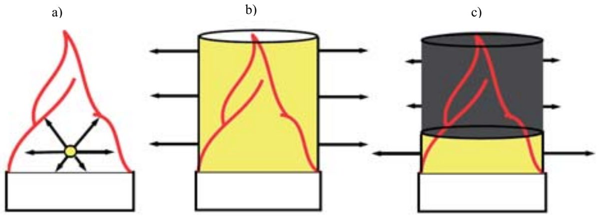

Fig. 2 The schematic typology of semi-empirical tank fire models (radiative source term assumptions modified after McGrattan at al. [19]); point source model a); solid flame (surface emitter) conventional model b); solid flame (surface emitter) modified model c)

As the semi-empirical models are relatively simple to understand and readily embodied in simple computer programs they are ideally suitable for routine risk assessment purposes. Moreover they provide relatively reliable (experimentally verified) prediction for low computational cost (available as on-line calculation tools).

Field models are based on numerical solution of balance equations for mass, momentum, species, energy and other desired variables in the computational domain divided into plenty of grid cells. Computational Fluid Dynamics (CFD) tools used to solve system of partial differential equations (PDE’s) for turbulent flows represent mathematically complex tools with the pronounced requirements for computational time and hardware instrumentation. To carry out the phenomenon of tank fire, which can be described as buoyancy driven turbulent flow involving chemical reactions, several assumptions and sub-models need to be add to this system of equation.

Integral models were developed as the compromise between the field models and semi-empirical models. They are formulated in the similar way as the above-mentioned CFD models. Integral models are based on solution of conservation equations for mass, momentum and scalar variables in chemically inert or reactive flows. These equations are expressed in the integral form assuming the statistical similarity of variations of variables flow and combustion in the direction normal to flame axe. Thus the partial differential equations (PDE’s) solved by the field models are integrated and reduced to form the ordinary differential equations (ODE’s).

Unfortunately, the semi-empirical models implemented in standard computational tools for accidental scenario assessment are suitable for on-land or on-water pool fires rather than for large storage tank fires. These fires are specific by their exceptional dimensions (diameter up to 100 meters) and disposition (base of the flames about 20 meters above ground). To involve the effect of tank height, the calculation algorithm had to be partly modified (in order to correct the view factor). Also there is considerable lack of experimental data for such a large scale of fires to set up and validate the empirical correlations. For these reasons the CFD (field) modelling of full surface tank fire was performed.

7. CFD simulation of crude oil tank fire

The Fire Dynamics Simulator (FDS, version 4.0 described in details in [17]) developed by NIST (National Institute of Standards and Technology) was used to determine the safe distances[1] for fire fighters (based on heat flux levels in the tank surroundings) and to estimate the smoke plume movement in the different atmospheric conditions. The computational domain selected for simulation involves 4 crude oil storage tank (white objects) and fire fighting water reservoir (grey object) which represent the local geometry, see Fig. 3 a). As FDS 4.0 supports only the rectangular grid the entire volume of computational domain was divided into uniform grid consisting of 80 × 100 × 60 cubes with 4 meters side. All of the objects are specified as groups of rectangles fitted to this grid. The diameter of each tank is 84 m, the height 24 m.

The fire was defined on the roof of one crude oil tank. The grid resolution used for these simulations is consistent with the proposal given by Ma and Quintiere [18]. By their results FDS simulation data were found to fit well with empirical correlation for grid size equal to the characteristic length of the fire divided by twenty. The fire was assumed to burn with the heat release rate of 1900 kW.m^{-2}, which is equivalent to mass burning rate of 0.045 kg.m^{-2}s^{-1} and heat of combustion of 42,600 kJ.kg^{-1} (the data adopted from [19]).

The stoichiometric coefficients for the fuel, oxygen and burned gases were set to be that of propane and 13 % of the fuel was estimated to convert into the solid soot particles (in agreement with [20]). The local radiative fraction was determined as the default value, 35 %. Thus, approximately a third of released energy is emitted as thermal radiation. As the thermal radiation penetrates the thick layer of smoke and combustion products, the fraction of this energy is reabsorbed by the burned gas molecules and soot particles. Therefore the effective radiative fraction was found to give much lower values (by the conclusions of Baum [10] about 6 %). The above-described phenomenon is often called the smoke blockage effect, see Fig. 3b).

The results of simulation (both the instantaneous and temporally averaged data) confirmed that for the given accidental scenario relatively low radiative flux intensities can be expected for low speed wind conditions. As the wind speed augments, the flame is more and more tilted and heat flux in the downwind direction becomes dangerous for exposed personnel and equipment, see Fig. 4. Due to possible fluctuations of wind direction the both neighbouring tanks should be cooled by the installed water curtain system to avoid the fire escalation although this scenario is of very limited probability.

8. Boilover phenomenon modelling

As the boilover is the phenomenon, which can cause very serious consequences, the mathematical model was used to esti-

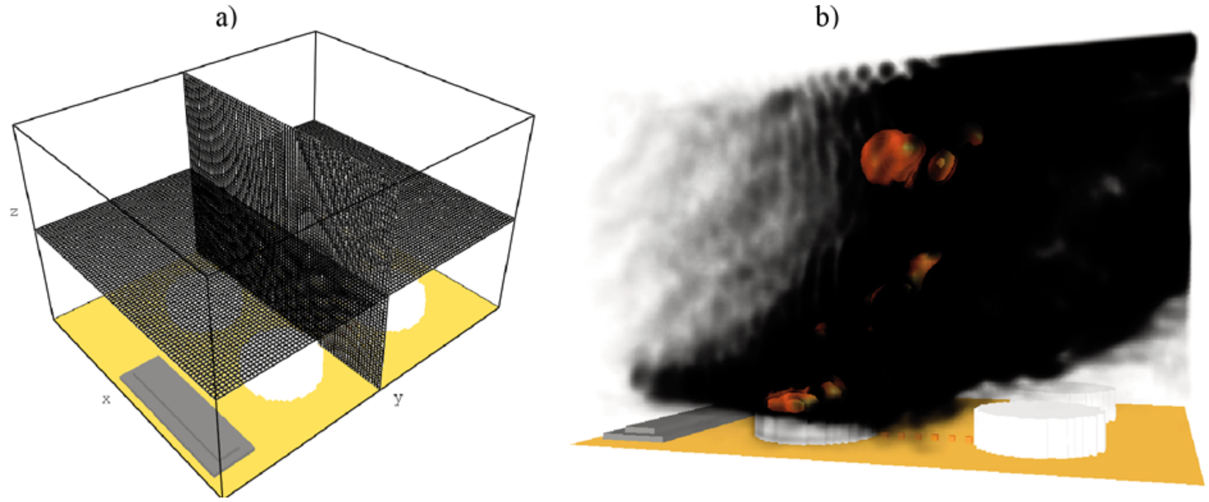

Fig. 3 Computational domain (x = 320 m, y = 400 m, z = 240 m) used for CFD large eddy simulation a); and the instantaneous screenshot from simulation of tank fire b)

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[1] The different data are available for human vulnerability to heat radiation. Commonly the heat flux values in range between 1.5 kW.m^{-2} and 2.0 kW.m^{-2} are recognised as threshold limit for long-term exposition without irreversible effects.

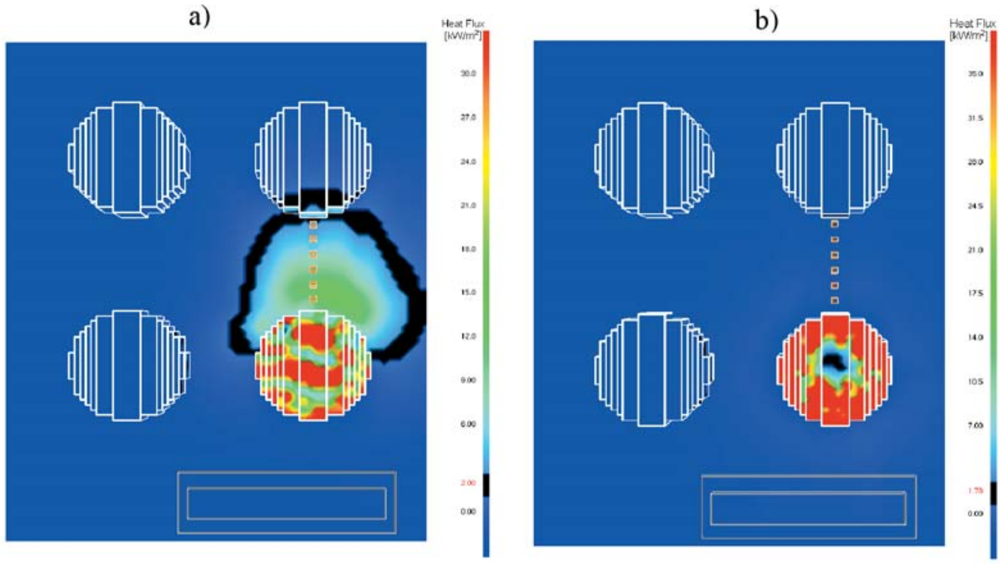

Fig. 4 Instantaneous heat flux profiles at ground level under different atmospheric conditions; plot of 2 kW.m^{-2} isocontours (black coloured) for a wind speed of 5 m/s in the height 3 m above the ground a); and plot of 1.78 kW.m^{-2} isocontours (black coloured) for a wind speed of 1 m/s in the height of 3 m above the ground b)

mate the time delay to boilover which should be understood as the time available for emergency response on site. The model is based on model previously published by Broeckmann [14]. Due to lack of available data for different crude oils the model was simplified to obtain the value of hot zone expansion rate, v_{HZ}, only from distillation curves, densities and basic thermodynamic properties known for a given crude oil, see equation (1).

$$v_{HZ} = \frac{\Phi_R}{\rho_{T_0} \cdot \left(X_{THZ} \cdot \left[\Delta H_{v,T_b} + \int_{T_0}^{\overline{T}_b} c_p dT \right] + (1 - X_{THZ}) \cdot \int_{T_0}^{T_{HZ}} c_p dT \right)} \ \mathrm{m \cdot s^{-1}} \qquad (1)$$

Here Φ_R is the radiation feedback (W.m^{-2}), ρ is the density of crude oil (kg.m^{-3}) and c_p is heat capacity of the crude oil (J.kg^{-1}.K^{-1}) and $\Delta H_{v,Tb}$ the heat of vaporisation at the boiling point (J.kg^{-1}). Temperatures needed for calculation are as follows; T_0 is the storage temperature of crude oil (K), T_{HZ} is the estimated hot zone temperature (K) and $\overline{T}_b$ is mean boiling point of crude oil (K). Vaporized fractions X_{THZ} are determined from the known distillation curve for estimated range of temperatures T_{HZ}. The present model describes the heat wave propagation (hot zone expansion rate), which is the principal aspect of the boilover phenomenon, in a very simplified manner. The following set of hot zone expansion rates, see Tab. 1, was calculated for three representative types of crude oil. The data in the third column are the conservative values recommended for emergency planning purposes.

These values are in agreement with the previously published sets of data but it should be pointed out that this model is not approved by practical experiments or more detail computational analysis. As this model gives only the approximate results, it is necessary to pay attention to the effects which occur during the preliminary phase of boilover. Mainly the sounds coming from the micro-explosions in the tank should serve as the last warning for the present emergency responders. Nevertheless, it should be pointed out that in several boilover experiments no sounds appeared before boilover period.

Calculated and recommended values of hot zone expansion rate for three crude oils. Table 1

Crude oil	Calculated values v_{HZ}	Recommended values v_{HZ},
Light crude oil Saharan Blend (Algiers)	10 - 17 mm/min	20 mm/min
Medium crude oil Flotta Blend (North Sea)	8 - 13 mm/min	15 mm/min
Heavy crude oil Basrah Heavy (Iraq)	6 - 8.5 mm/min	10 mm/min

9. Conclusion

The case study involving CFD simulation of tank fire was performed to support the emergency planning and tactical preparedness for major accidents in crude oil storage tank farm. Methodological approach employed in the framework of this study consists of:

- selection of relevant accidental scenario
- modelling and simulation of selected dangerous phenomena
- scenario-based emergency response training

Although the results of numerical simulation and modelling of accidental events are inherently coupled with different uncertainties there are many important qualitative features of dangerous effects which can be demonstrated by these tools. This theoretical knowledge needs to be understood as the supplement to practical training and fire fighting simulations. The periodically repeated sequence of all above-mentioned steps creates the main pillar of efficient emergency preparedness for industrial accidents.

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References

[1] PERSSON, H. LONNERMARK, A.: *Tank Fires – Review of fire incidents 1951–2003,* BRANDFORSK Project 513-021, SP Fire Technology, 2004.
[2] Ministerie van de Vlaamse Gemeenschap. Afdeling Algemeen Milieu- en Natuurbeleid.: *Handboek kanscijfers – Gecoördineerde versie 2.0.* Brussel, 2004.
[3] CHANG, J.; LIN, C.: *A study of storage tank accidents, Journal of Loss Prevention in the Process Industries, 2006,* 19, pp. 51–59.
[4] MANNAN, S.: *Lee's Loss Prevention in the Process Industries* (3rd Edition), Oxford: Elsevier Butterworth-Heinemann, 2005.
[5] AIChE. Center for Chemical Process Safety: *Guidelines for Chemical Process Quantitative Risk Analysis,* 2nd Edition, 2000, 740 p. ISBN 0-8169-0720-X.
[6] SALVI, O., DEBRAY, B.: *A global view on ARAMIS, a risk assessment methodology for industries in the framework of the SEVESO II directive, Journal of Hazardous Materials,* 2006, 130 (3), pp. 187–199.
[7] DELVOSALLE, C., FIEVEZ, C., PIPART, A., CASAL, J., PLANAS, E.; CHRISTOU, M.; MUSHTAQ, F.: *Identification of reference accident scenarios in SEVESO establishments,* Reliability Engineering and System Safety, 2005, 90, pp. 238–246.
[8] DELVOSALLE, C., FIEVEZ, C., PIPART, A., DEBRAY, B. ARAMIS project: *A comprehensive methodology for the identification of reference accident scenarios in process industries. Journal of Hazardous Materials,* 2006, 130 (3), pp. 200–219.
[9] TIESZEN, S., NICOLETTE, V., GRITZO, L., HOLENT, J., MURRAY,D., MOYAAND, J.: *Vortical Structures in Pool Fires: Observation, Speculation, and Simulation.* SANDIA REPORT SAND96-2607 UC-722. Albaqerque, 1996.
[10] BAUM, H.; Large eddy simulation of fires. *Fire Protection Engineering,* 2000, 6, 36 – 42.
[11] EVANS, D. D.; MULHOLLAND, G. W.; BAUM, H. R.; WALTON, W. D.; MCGRATTAN, K. B.: In Situ Burning of Oil Spills. *Journal of Research of the National Institute of Standards and Technology.* 2001, 106 (1), pp. 231–278.
[12] MATHER, T. A., HARRISON, R. G., TSANEV, V. I., PYLE, D. M., KARUMUDI, M. L., BENNETT, A. J., SAWYER, G. M., HIGHWOOD, E. J.: Observation of the plume generated by December 2005 oil depot explosion and prolonged fire at Buncefield (Hertfordshire, UK) and associated atmospheric changes. *Proceedings of the Royal Society A-Mathematical, Physical and Engineering Sciences.* 2007, 463 (2081), pp. 1153–1177.
[13] FAN, W., HUA, J., LIAO, G.: Experimental study on the premonitory phenomena of boilover in liquid pool fires supported on water. *Journal of Loss Prevention in the Process Industries,* 1995, 8 (4), pp. 221–227.
[14] BROECKMANN, B., SCHECKER, H.: Heat transfer mechanisms and boilover in burning oil-water systems. *Journal of Loss Prevention in the Process Industries,* 1995, 8 (3), 137–147.
[15] KOSEKI, H.: Boilover and crude oil fire. *Journal of Applied Fire Science,* 1993–94, 3 (3), pp. 243–272.
[16] Committee for the Prevention of Disasters. CPR 14E („Yellow Book") *Methods for the calculation of physical effects.* Third edition Second revised print, The Hague, 2005.
[17] BAUM, H., MCGRATTAN, K., REHM, R., HAMINS, A., FORNEY, G.: *Fire Dynamics Simulator – Technical Reference Guide,* National Institute of Standards and Technology, NISTIR 6467, Gaithersburg, 2000.
[18] MA, T. G., QUINTIERE, J. G.: Numerical simulation of axi-symmetric fire plumes: accuracy and limitations. *Fire Safety Journal,* 38, pp. 467–492.
[19] MCGRATTAN, K.; BAUM, H. HAMINS, A.: *Thermal Radiation from Large Pool Fires.* National Institute of Standards and Technology, NISTIR 6546, Gaithersburg, 2000.
[20] MULHOLLAND, G. W., LIGGET, W., KOSEKI, H.: The effect of pool diameter on the properties of smoke produced by crude oil fires. In *Proceeding of 26th Symposium on Combustion.* The Combustion Institute, 1996, pp. 1445–1452.