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# Fuzzy logic approach to calculation of thermal hazard distances in process industries

*Adam Stanisław Markowski, Dorota Siuta**

*Safety Engineering Department, Faculty of Process and Environmental Engineering, Lodz University of Technology, Wolczanska 213, 90-924 Lodz, Poland*

ABSTRACT

In this paper, a general procedure to deal with uncertainties in each stage of consequence modeling is presented. In the first part of the procedure, the sources of uncertainty are identified and confirmed by sensitivity analysis for the source term, dispersion, physical effects and consequence analysis. While the second part comprises an application of the fuzzy logic system to each step of the consequence modeling. The proposed procedure is verified by the case study for a pool fire liquefied natural gas (LNG) on water. The results in terms of thermal radiation distances are compared with calculations obtained using the Monte Carlo method and with experimental data. The consequence model based on fuzzy logic approach provides less uncertain and more precise results in comparison to the deterministic consequence model.



*Keywords:* Hazard distances; LNG; Fuzzy logic system; Monte Carlo simulation; pool fire; uncertainty

## 1. Introduction

The intensive development of new manufacturing technologies, the use of hazardous materials, more complicated installations and extreme conditions of the processes have resulted in a series of major incidents and accidents in recent years. It has led to massive loss of human life, environmental damage and economic loss. At present, the total elimination of potential hazards and their consequences is not possible in chemical industries. Therefore, an important issue is to perform the consequence analysis for all possible undesirable events and fault conditions for a given facility which is an essential part of the risk assessment process and safety reports. This analysis is used to predict hazard distances and the extent of effects associated with the release, dispersion, fire and explosion of hazardous substances, that are expressed in terms of injuries, deaths and damage to buildings, infrastructures and the environment (Markowski and Siuta, 2013). The main scheme of the consequence assessment procedure for combustible materials is presented in Fig. 1.

The above-mentioned steps of this sequence are calculated and analyzed separately, and the final results of the individual stages are the source of input data to a subsequent model in the chain representing an accident scenario. The consequence modeling contains uncertainties that come from the lack or vagueness in model variables, insufficient, incomplete knowledge about the particular phenomenon (e.g. large fire) and models, assumptions in mathematical formulation (e.g. one dimension), constants obtained from limited experimental information and various measurement techniques. Moreover, uncertainties may propagate from one part of a model to another having a significant effect on hazard predictions. One solution to this problem is to propose the general framework to handle the consequence analysis with uncertainties that the prediction of hazard distances will be more accurate. The proposed framework is verified by the case study, concerning

*Abbreviations:* FF, flash fire; FL, model based on fuzzy logic system; JF, jet fire; MC, model based on Monte Carlo simulation; PF, pool fire; RPT, rapid phase transition; CL, classic model; f, fuzzy number.

* *Corresponding author*. Tel.: +48 426313745; fax: +48 426313745.
E-mail addresses: markows@wipos.p.lodz.pl (A.S. Markowski), siutadorota@gmail.com (D. Siuta).

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**Nomenclature**

| | |
|---|---|
| $\Phi$ | coefficient that is a function $h_f/h$ |
| $C_d$ | discharge coefficient |
| $C_r$ | frictional resistance force, m/s$^2$ |
| $D$ | fire diameter, m |
| $d$ | hole diameter, m |
| $D'/D$ | flame drag |
| $A_1$ | the elemental surface area of the emitter viewed by the receiver, m$^2$ |
| $A_2$ | the elemental surface area of the receiver viewed by the emitter, m$^2$ |
| F | geometrical view factor between the flame and the object |
| $F_c$ | combustion Froude number |
| $F_r$ | Froude number |
| $g$ | acceleration due to gravity, m/s$^2$ |
| $g_r$ | reduced gravitational acceleration, m/s$^2$ |
| $H$ | liquid height above the hole, m |
| $h$ | mean pool height, m |
| $h_f$ | pool height at leading edge, m |
| $I$ | radiation heat flux received by the object, kW/m$^2$ |
| $L$ | fire height, m |
| $m_b$ | burning rate, kg/(m$^2$ s) |
| $P_v$ | partial pressure of water vapor at $T_a$, N/m$^2$ |
| $Q_r$ | release rate, kg/s |
| $r$ | pool radius, m |
| RH | relative humidity, % |
| SEP | surface emissive power, kW/m$^2$ |
| $T_a$ | ambient temperature, K |
| $U$ | dimensionless wind velocity |
| $U_w$ | mean wind velocity, m/s |
| $x$ | distance from the center of the fire to the object, m |
| $\rho_a$ | density of air, kg/m$^2$ |
| $\rho_{LNG}$ | LNG density, kg/m$^2$ |
| $\rho_v$ | density of LNG at boiling point, kg/m$^2$ |
| $\rho_w$ | density of water, kg/m$^2$ |
| $\beta_1, \beta_2$ | angles between line joining flame and receptor and line normal to flame surface or receptor surface, degrees |
| $\tau$ | transmissivity of the atmosphere to thermal radiation to fire |
| $S_i$ | sensitivity index |
| $x_i$ | parameter from each physical and consequence model |
| y | output from the model |
| $\theta$ | fire plume tilt angle with respect to the vertical, degrees |
| t | time, s |

a pool fire on water calculations for an incident involving the release of potential liquefied natural gas (LNG) vessel cargo during transit and while at berth.

## 2. General framework for dealing with uncertainties

The general framework for dealing with uncertainties in the consequence assessment of the process industries is shown in Fig. 2. It can be only applied to parameter because of uncertainty connected with imprecision, inaccuracies and variability in the model parameters which are used as inputs to consequence analysis.

The first element of the framework is the selection of the potential representative accident scenario which might be based on historical accident data, the process hazard analysis and expert judgment. The most likely scenario or worst-case scenario is typically considered, although this is a primary source of qualitative uncertainties which will not be undertaken in this project.

The second part focuses on the choice of the consequence model for a type of the material and a given accident scenario TNO (1997). The consequence model consists of different parameters which affect the final calculation. It is primarily to identify uncertainties in the model being analyzed and their importance. Therefore, the third part concerns a sensitivity analysis to identify the most important parameters amongst a large number that affect model outputs. Usually, sensitive parameters are the most uncertain parameters in each step of consequence modeling. Many of the methods are available for conducting sensitivity analysis like local methods, screening methods and variance based methods (Saltelli et al., 2008). The next part provides an application of an uncertainty technique used to include the uncertainty aspects in consequence analysis. The selection of the uncertainty technique depends on the types of uncertainties existing in consequence model. Usually two types of uncertainties can be distinguished – aleatory and epistemic. The aleatory uncertainty is related to the stochastic distribution of the physical parameters in models, and the epistemic uncertainty is connected with insufficient knowledge. Techniques based on Monte Carlo simulations and fuzzy sets are most often chosen. The fuzzy sets technique is particularly recommended when mixed types of uncertainty exist. On the other hand, the Monte Carlo technique is mainly used for representation the aleatory uncertainty. Other techniques are not suitable for consequence modeling e.g. generally, the Bayesian approach and Dempster–Shafer theory of evidence are applied to reliability analysis. Detailed and additional information about the fuzzy sets theory, Monte Carlo simulation and remaining techniques can be found in (Pawlak, 1983; Chen and Pham, 2001). The proposed framework for the calculation of the LNG hazard distance of taking into consideration the uncertainty is demonstrated in the following case study.

## 3. Case study

### 3.1. *Selection of a accident scenario*

The case study concerns the calculation of the extent of thermal radiation hazard distances for the worst case event referring to intentional or accidental spilling of large quantities of LNG on water during transit and while at berth. The most likely root causes that will result in the occurrence of the top event are presented in Fig. 3 using the fault tree diagram. The fault tree is the graphical representation of the sequence of failure events and shows the logical connection of the top event with intermediate events and basic events through logic gates such as: OR, AND. The selected failure path is shown and marked in bold line in Fig. 3.

The credible physical outcomes for LNG release on water are shown in Fig. 4 using the event tree analysis.

The detailed description of the selected accident scenario is presented in Table 1 and recommended by Federal Energy