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A multivariable model for estimation of vapor cloud explosion occurrence possibility based on a Fuzzy logic approach for flammable materials

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ABSTRACT

In this paper, a new method based on Fuzzy theory is presented to estimate the occurrence possibility of vapor cloud explosion (VCE) of flammable materials. This new method helps the analyst to overcome some uncertainties associated with estimating VCE possibility with the Event Tree (ET) technique. In this multi-variable model, the physical properties of the released material and the characteristics of the surrounding environment are used as the parameters specifying the occurrence possibility of intermediate events leading to a VCE. Factors such as area classification, degree of congestion of a plant and release rate are notably affecting the output results. Moreover, the proposed method benefits from experts' opinions in the estimation of the VCE possibility. A refrigeration cycle is used as the case study and the probability of VCE occurrence is determined for different scenarios. In this study, sensitivity analysis is performed on the model parameters to assess their effect on the final values of the VCE possibility. Furthermore, the results are compared with the results obtained using other existing models.

1. Introduction

Events caused by the catastrophic release of a flammable substance in the surrounding environment, such as a storage tank rupture or a hole in a pipe, can lead to a variety of outcomes. The occurrence of these outcomes depends on factors such as operating conditions of the source, type of released material and surrounding conditions. Events such as pool fire, fire ball, Vapor Cloud Explosion (VCE), flash fire, and BLEVE are some of the possible outcomes.

Vapor cloud explosions (VCEs) are a major hazard in industrial plants where large amounts of flammable materials are stored or processed. In the last few decades, several VCEs have occurred in process plants resulted in almost total destruction of the those plants (Sharma et al., 2013). Several studies about past accidents indicate the importance of VCEs (Abdolhamidzadeh et al., 2011; Sharma et al., 2013; Salzano and Cozzani, 2005). Today, Quantitative Risk Assessment (QRA) has become an efficient tool in decision making for safety and process experts. To assess the risk of any accident scenario, it is necessary that the probability of that event be determined in addition to estimating the probable consequences. Event tree analysis is known to be a standard tool for calculating the frequency of incident outcomes. However, the existence of many effective and sometimes neglected parameters causes uncertainties in the calculations of event frequencies. A better understanding of the influencing factors for each accident scenario will lead to a more precise estimation of event frequencies. Several studies on uncertainties in event trees have been performed which indicate the importance of this tool for incident frequencies' estimation (Neri et al., 2008; Catalyurek et al., 2010; Julwan Hendry Purba, 2014).

For instance, while developing conventional event trees, the type of released material does not play a role in determining the intermediate probabilities that build the overall structure on the event tree. Nonetheless, it is proven in several studies such as

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Abdolhamidzadeh et al. (2011) that the type of material has a significant effect on the outcome of an event tree.

Badri et al. (2013) proposed a model based on event tree analysis to calculate the vapor cloud explosion frequency, in which they have tried to consider the effect of various parameters influencing the frequency of events. Their idea was to convert the unit into subsets such that the material properties and operating conditions in each specific subset are constant and for each subset, the VCE frequency is calculated and finally the frequencies of all subsets are added together.

Wiekema (1984) analyzed VCEs in past accidents and tried to determine the effect of parameters such as the amount of released material, the ignition duration, reactivity of released material on the VCE occurrence probability. But there are different parameters affecting the occurrence mechanism and probability of VCEs. Some of these parameters are well established and embedded in the existing models for prediction of VCE occurrence, while some other factors are frequently missing in the evaluations.

In problems where there is ambiguity and uncertainty about the influencing parameters, the opinion of an expert on the parameters influencing the event tree, which is based on knowledge of the circumstance, process and past events, can make the model more accurate. One of the drawbacks of the existing models for VCE probability estimation is that the expert vision cannot be intervened.

In this research mathematical models based on the theory of accidents occurrence, data from past events and experiences of experts are all integrated in order to provide a comprehensive model for estimation of VCE probability. For this purpose, a Fuzzy algorithm, as an efficient mathematical model for problems in which there isn't a complete understanding in parameters dependence and there is no parameter certainty on the issue, is used.

Some recent research has been performed on using Fuzzy set theory in different safety analyses. For instance Markowski (2007) proposed a method for analyzing layers of protection against explosion (EXLOPA) based on Fuzzy algorithm. Forming Fuzzy sets associated with different factors affecting the explosion in any protection layer, they presented their model and finally compared their model results with the previous model results. Huang and Wang (2001) have proposed a model based on the Fuzzy logic for event-tree analysis. Their main aim was to include human error into event-tree by using Fuzzy concepts. Yuhua and Datao (2005) presented a model based on Fuzzy set theory to detect pipe failure probability based on fault tree model. They tried to gather the probability of early events together and obtain more accurate answers compared with the previous models, by combination of expert opinion and Fuzzy theory. Markowski and Mannan (2009) present the application of Fuzzy logic for risk assessment of accident scenario expressed by fault and event tree combined in the "bow–tie" approach. Mure and Demichela (2009) uses Fuzzy logic in the procedure proposed to quantitatively assess the risk of occupational accident for different industrial and site activities and to identify the most efficient intervention measures that can be taken to reduce risk.

In general, the use of fuzzy logic in various applications, including safety, is performed in two ways: first when there is uncertainty in the data or information (subjective uncertainties), hence, in case that the limit and certainties of numbers are not clear. Secondly, fuzzy logic is employed when there is uncertainty in the model (objective uncertainties), that is, when the relationship between the variables is not entirely clear. Fuzzy logic, with the help of variability, according to available data, as well as the empirical and theoretical relationships in the past and the experience of experts, and by creating fuzzy rules in the form of IF-THEN conditions, specifies the relationship between the independent and dependent variables. In the field of process safety, a variety of articles regarding this application of fuzzy logic has been developed recently (Markowski et al., 2011; Gentile et al., 2003; Markowski and Mannan, 2008).

The main advantage of the proposed Fuzzy model is that it has high flexibility in applying an expert opinion in forming effective dependencies in event-tree. In this case it is not permissible to use the term probability; instead the term possibility should be used; because the probability of an event in a variety of experimental conditions tends to unity. In this case, however, since the expert opinion, social, economic, management and other conditions are included, various possibilities can be achieved based on different condition (Zimmermann, 2001).

In this new approach, instead of having several scenarios and consequently several event-trees, a general event-tree is introduced for which, considering operating and surrounding conditions and also the type of released material, the frequency of each of the event scenarios can be achieved. Finally, a sensitivity analysis is performed on the model, so that the effect of certain factors such as the type of released material and environmental conditions (humidity, ambient temperature, unit type, etc.), is examined.

2. Event tree calculations

Having the frequency of a catastrophic release as the initiating event, Event Tree is used for calculating the frequency of different possible outcomes. Upon a flammable chemical release, these outputs can be pool fire, jet fire, VCE, VCF and BLEVE. Fig. 1 shows a typical Event Tree developed for a flammable vapor release:

For calculation of each branch frequency in an event tree, the following parameters shall be specified:

2.1. Initial event frequency

For specifying the frequency of initial event, using failure frequency databanks which are constructed based on past accident records, is quite common. There are several databanks available such as API 581 (2008), OGP (2010b), Handbook failure frequencies (LNE, 2009), and methods for adjusting failure rates based solely on the thickness of the equipment relative to typical industry practice (Thomas, 1981) (Table 1).

2.2. Probability of immediate ignition

As it is shown in Fig. 1, after a release, the outcome can be different based on the presence or absence of an immediate ignition source. Presence of an immediate ignition source will lead to formation of a jet fire, while lack of any immediate ignition source will let the released material to form a cloud. So one of the key parameters in calculating an Event Tree, is specifying the probability of immediate ignition. Different values are reported in literature (Bond, 1991; Bevi, 2009; Uijt de Haag and Ale, 2005). Many of these available values are fixed quantities independent of release rate or nature of chemical which is released.

Moosemiller (2011) proposed an equation in terms of the auto ignition temperature, the ambient temperature, operation pressure and the minimum ignition energy, based on which probability of immediate ignition is calculated (Equation (1)).

$$P_{\text{imm.ignition}} = \left(1 - 5000e^{-9.5\left(\frac{T}{T_{\text{Auto ignition}}}\right)}\right) + \left[0.0024 \times \frac{P^{\frac{1}{3}}}{\text{MIE}^{\frac{2}{3}}}\right] \tag{1}$$