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The assessment of the damage probability of storage tanks in domino events triggered by fire

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ABSTRACT

An approach aimed to the quantitative assessment of the risk caused by escalation scenarios triggered by fire was developed. Simplified models for the estimation of the vessel time to failure (ttf) with respect to the radiation intensity on the vessel shell were obtained using a multi-level approach to the analysis of vessel wall failure under different fire conditions. Each vessel "time to failure" calculated by this approach for the specific fire scenario of concern was compared to a reference time required for effective mitigation actions and related to the escalation probability. The failure probability of each vessel was correlated to the probability of scenarios involving multiple vessel failure as a consequence of the primary fire, thus allowing a comprehensive assessment of domino scenarios triggered by fire. The application of the methodology to the analysis of several case-studies allowed the estimation of the quantitative contribution of escalation events triggered by fire to the overall individual and societal risk indexes.

1. Introduction

Domino effect is responsible of severe accidents that took place in the chemical and process industry (CCPS, 2000; Khan and Abbasi, 1999; Lees, 1996). Several studies pointed out that the more critical step in the quantitative assessment of domino hazards is the availability of reliable models to estimate the effects caused by the escalation of primary accidents (Cozzani and Zanelli, 2001; Delvosalle, 1998; Gledhill and Lines, 1998; Khan and Abbasi, 1998). In particular, the damage probability of process and storage vessels involved in fires is often calculated by the use of arbitrary threshold values that do not take into account site-specific factors, as the possible mitigation due to effective emergency response (Cozzani et al., 2005a). On the other hand, very complex and time consuming approaches are available for the detailed calculation of the time to failure (ttf) of storage vessels, requiring a detailed description of vessel geometry and other design data. The present study is focused on the development of a simplified approach to the calculation of the damage probability of storage and process vessels, aimed to the quantitative assessment of domino effect. The methodology is based on simplified correlations for the time to failure of vessels as a function of the radiation intensity. These were obtained from an integrated approach, based on the use of available experimental data, of finite elements modelling for complete thermal and mechanical simulations of the behaviour of vessels exposed to fires, and of a simplified model for vessel failure based on thermal nodes. The available experimental data set was integrated by finite elements simulations of the behaviour of atmospheric and pressurized vessels under different fire conditions: full engulfment, partial impingement and distant radiation. An extended data set was obtained from the simulations that were integrated with experimental data. The data set was used for the development of the simplified correlations for time to failure as a function of radiation mode and of radiation intensities. The correlations were obtained for atmospheric as well as for pressurized storage vessels. Specific correction factors were introduced in order to take into account the effect of thermal protections. Damage probability was estimated by a site-specific probabilistic function that takes into account the calculated time to failure with respect to the time required for effective mitigation. The damage model obtained was used for the assessment of the damage probability of equipment. Several case-studies were defined to analyze model performance and to quantify the possibility of escalation in actual lay-outs.

2. Lumped model for the estimation of vessel time to failure

Fire may affect a process or storage vessel by one or more than one of the following modes: (i) distant source radiation; (ii) full or partial fire engulfment; and (iii) jet fire flame impingement.

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Modelling vessel time to failure in these three situations is extremely difficult given the high complexity of the flame geometries. The wall temperature behaviour in a vessel exposed to an external fire would require a detailed 3D analysis of the thermal flux over the vessels shell, of the thermal gradients in the fluid contained in the vessel and of the effects due to the mixing of the content due to the natural convection. However, running a model based on this approach for each vessel present in a process plant would require a prohibitive run time, not justified in a QRA framework due to the uncertainties that usually affect the characterization of the fire scenarios. In this specific context, a simplified model able to yield a conservative estimation of the time to failure by a straightforward approach is more useful. The model developed in the present study was based on a lumped approach for the modelling of the time and temperature profile, but was improved by an extended validation work, based on the use of an experimental data set for the vessel time to failure, extended by the use of a 3D finite element model implemented for this purpose.

The development of the lumped model was based on the definition of a limited number of "thermal nodes" where the actual properties of the vessel were lumped. As shown in Fig. 1, this approach attempted to divide the equipment in different zones (or nodes), each of which was described by a simple set of parameters. The parameters represent physical quantities (e.g. temperature, pressure, thermal conductivity, etc.) averaged over each node. Conservation conditions at the boundaries between different regions, together with global conservation laws, lead to a system of equations which determines the parameters of interest and in particular the temperature at each node (Gubinelli, 2005). This allows the calculation of temperature-time profiles as a function of the radiation mode and intensity on the vessel. The estimation of these parameters allows the evaluation of the mechanical stresses at which each zone of the vessels shell is subjected and to compare it with the admissible tensile strength of the vessels material that depends on temperature. Specific simplified failure criteria were introduced to assess the time to failure and the failure conditions.

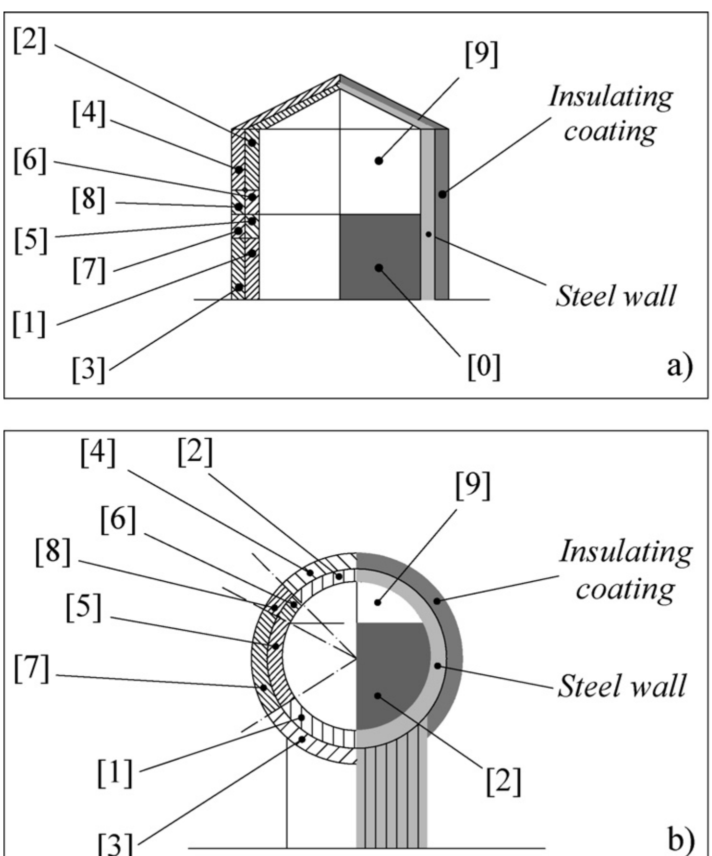
3. Validation of the lumped model

3.1. Approach to the validation of the lumped model

Although a significant number of case-studies resulted available, in particular for pressurized vessels, the number of available experiments was not sufficient to carry out an extended validation of the lumped model covering the entire field of vessel geometries and of radiation modes and intensities of practical interest. Thus, a finite element model (FEM) was developed and validated on the basis of the available experimental data. The FEM was used to generate a second data set used for the extension of the validation data set of the lumped model.

3.2. Features of the FEM used to extend the validation field

The FEM was developed using a commercial code with which a detailed simulation of the thermal and mechanical conditions on vessel shells under fire radiation was possible. The model also allowed a detailed simulation of the radiation mode, of the wall temperature and of the stress over the vessel shell. In the following, few details on the model are reported.



NODE	DESCRIPTION
[0]	Liquid space
[1]	Vessels wall in contact with the liquid phase but not in the zone impinged by the flame
[2]	Vessels wall in contact with the vapour phase but not in the zone impinged by the flame
[3]	Insulated material layer (if present) at the level of the liquid phase but not in contact with the flame
[4]	Insulated material layer (if present) at the level of the vapour phase but not in contact with the flame
[5]	Vessels wall in contact with the liquid phase and in the zone impinged by the flame
[6]	Vessels wall in contact with the vapour phase and in the zone impinged by the flame
[7]	Insulated material layer (if present) at the level of the liquid phase and in contact with the flame
[8]	Insulated material layer (if present) at the level of the liquid phase and in contact with the flame
[9]	Vapour space.

Fig. 1. "Thermal nodes" definition for the lumped model for atmospheric tanks (a) and pressured vessels (b).