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Analyzing effective factors on leakage-induced hydrogen fires

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ABSTRACT

Currently, novel energy resources are receiving increasing attention as a response to the limitation in fossil fuels as well as their adverse effects on human health. Hydrogen, one of the most abundant elements on the earth, can be regarded as a new energy source to replace fossil fuels. Therefore, safety assessment of the relating processes is very crucial by increasing use of hydrogen as a fuel source. In this regard, consequence analysis for risk assessment and power reduction is very important. The present study aims at modeling hydrogen dispersion along with consequence analyses for such events as jet fire and flash fire. The model was validated by using the data derived from a study on hydrogen leakage in supply pipelines in the laboratory of the University of Pisa. Modeling results reveal that ambient conditions will impose a milder impact on leakage consequences if internal pressure is high in release source. The safe distance was also estimated to be 14 m. Dispersion consequence modeling was performed, followed by the evaluation of the effect of environmental (i.e., stability, ambient temperature, surface roughness, wind speed, and humidity) and process (i.e., vessel temperature and pressure, leakage diameter, and releasing point height) parameters on maximum size flammable vapor cloud and maximum level jet fire radiation on the ground. The size of flammable vapor cloud (consequence dispersion index) and the maximum flux of radiation were affected by process parameters more than ambient parameters. Leakage diameter and the vessel pressure were found to have the highest impact on the operational parameters.

1. Introduction

Energy is the basis of human life. The ever-increasing application of fossil fuels, notably oil and gas, and considerable demands from industries have caused substantial decline of these resources. Consequently, renewable energy resources are necessary due to reduced fuel reserves, air pollution, higher energy demand, and environmental concerns (Hepbasli, 2008; Varun et al., 2009; Zhou et al., 2010).

Hydrogen is considered a very important source of energy with a high potential of energy generation, very low environmental pollution, and large quantity all around the world. It is widely mixed with oxygen for combustion and mainly used for ammonia synthesis. Hydrogen is used in refineries in many processes such as hydrocracking, hydro-alkylation, and hydrodesulphurization (HDS). Delivery methods (i.e., pipelines, water, or road) greatly affect technical and economic issues from hydrogen production to consumption. Hydrogen is usually delivered through supply pipelines in pressurized form.

Safety is an inevitable industrial concern to reduce personal and process risks. One of the most common risks in industry is the leakage from pipelines, vessels, etc., as a result of corrosion, human errors, and mechanical failures. Unexpected leakages from equipment may lead to toxic dispersion, fire, and/or explosion leading to catastrophic losses of work force, equipment, and system. Safety issues need to be specified in order to avoid potential incidents or reduce their intensity. Gas dispersion risk assessment is one of the principal objectives of industrial processes so as to enhance the level of safety.

Hydrogen has a high potential of explosion and combustion with low combustion temperature. Various models, e.g., DEGADIS, SLAB, PHAST, HGSYSTEM, and ALOHA, are implemented to determine dangerous materials leakage and its consequences. PHAST (DNV. PHAST, 2012) is known as one of the best software programs with accurate results (Sanchez et al., 2012; Jafari et al., 2012; Pandya et al., 2012; Witlox et al., 2014).

Several studies have been performed on hydrogen safety. The consequences of gaseous hydrogen fire in a refueling station were

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studied by Zhiyong et al. (2010). The results of Zhiyong et al. show that physical explosion and the worst case of a confined vapor cloud explosion produces the longest harm effect distances for instantaneous release and continuous release, respectively. In another study, jet fire impact distance in hydrogen supply vessels was found to be 400 m (Moonis et al., 2010). Jet fire and flash fire were found to occur in varying distances of 30 and 13 m from hydrogen leakage in supply pipelines, respectively (Gerboni and Salvador, 2009); the difference in the distance was attributed to different process and environmental situations.

Sensitivity analysis is used to determine how "sensitive" a model is to changes in the value of the parameters of the model and to changes in the structure of the model. The advantages of this method can be its ability to predict effective factors and the extent of their impact on the studied models and output corrections in models used in predicting the results. For example, the results of the sensitivity analysis on the emissions accumulated in the Buncefield incident (Gant and Atkinson, 2011) showed that the slope of the ground and obstacles are very effective in changing the results of the model.

This type of uncertainty that can be reduced through more information of the system is known as the epistemic uncertainty.

The subject of sensitivity and uncertainty in consequence modeling has long been appreciated, and a number of examples can be found in the literature (Carpentieri et al., 2012; Jahn et al., 2008; Khoudja, 1988; Witlox et al., 2011).

Another purpose of sensitivity analysis is to identify the non-effective input parameters in the model. This reduces the number of simulations required to evaluate a phenomenon. For example, if it is proved that wind speed has no effect on radiation in jet fire risk assessment, several simulations in a range of wind speeds for risk assessment are not required, resulting in reduced calculation and savings in time and money.

The present study was formulated in order to determine the consequences caused by hydrogen dispersion, jet fire, and flash fire and model validation was performed on data adopted from the study of Ganci et al. (2011). Among several case studies on consequence modeling, very few have focused on the effect of different factors. A protective combination needs to be optimally selected in order to control hydrogen pipelines and make the most suitable decision in emergencies. Therefore, the present study tries to identify the most effective factor causing process incidents related to a hydrogen leakage.

2. Consequence modeling

A series of incidents resulting in consequences like toxic dispersion, explosion, and fire will be investigated. A scenario should be sufficiently representative. Operation parameters such as temperature and pressure, released material, chemical properties of material (e.g., combustion and toxicity), and environmental situations greatly affect incidents.

The first step to determine incident severity is the scenario modeling with two stages, i.e., material release modeling and relative consequences modeling. The former is usually performed by a Gaussian distribution profile which is assumed to be perpendicular to the wind direction and a normal Gaussian function. PHAST is a hazard-assessment software package produced by DNV Software for modeling atmospheric releases of flammable or toxic chemicals (Jafari et al., 2012; Witlox et al., 2014). PHAST was also adopted in the present study. Since discharge, dispersion, jet fire, and flash fire are consequences of a hydrogen release, equations related to these consequences are determined.

2.1. Discharge

The first step in modeling is the discharge modeling to predict the distribution of the dispersed fluid. Discharge estimations are based upon the energy conservation equation. Material discharge model is suitable for predicting material discharge intensity and rate, total discharged material, and physical status of material during discharge. The discharge flow rate (Casal, 2007) is derived as follows:

$$\dot{m} = C_D \cdot AP_1 \sqrt{\frac{2g_c}{R_g} \cdot \frac{M}{T_1} \cdot \frac{k}{k-1}\left(\left(\frac{P_2}{P_1}\right)^{\frac{2}{k}} - \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}\right)} \quad (1)$$

where $\dot{m}$, P_1 and P_2, T_1, A, R_g, g_c, M, C_D and K stand for the flow rate (kg/s), pressure before and after discharge (kPa), temperature before discharge (K), rupture area (m^2), gas constant (Pa m^3/mole K), gravity constant (N s^2/kg m), gas molecular mass (kg/mol), discharge coefficient and specific heat ratio of fixed pressure to fixed volume, respectively.

2.2. Dispersion

Dispersion is the first step to initiate the consequence evaluation. Dispersion models predict variations of cloud of pollutants as a function of the position and time. Vapor cloud behavior is determined predominantly by the density of the gas relative to air, the rate of release over time and weather conditions. It is convenient to classify the clouds according to whether they are heavier than, the same density as or lighter than air (negative, neutral or positive buoyancy). Gases with a lower density than that of air, e.g., hydrogen, have a positive buoyancy. A Gaussian model is adopted for modeling the dispersion of gases with a positive buoyancy. The Gaussian model defines the distribution of concentration for continuous hydrogen release (Casal, 2007) as follows:

$$[C](x,y,z) = \frac{Q_m}{2\pi \cdot \sigma_y \cdot \sigma_z \cdot u} \cdot \exp\left[-\frac{u}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \cdot \left(exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right]\right) \quad (2)$$

where Q_m, U, H, σ_z, σ_y, z, and y denote the discharged flow rate (kg/s), wind speed (m/s), release area height (m), dispersion coefficients in different directions (m), distance in perpendicular direction to earth (m), and distance in perpendicular direction to wind direction (m), respectively.

2.3. Flash fire

Flash fire is the non-explosive combustion of a flammable gas in open air with very low speed, duration, and radiation. The power and height of a flash fire flame are estimated (Casal, 2007) as:

$$I_r = \sigma\left(T_g^4 - T_a^4\right) \quad (3)$$

where I_r, T_a, T_g, and σ stand for the effective heat flux (kW/m^2), the ambient absolute temperature (K), the hot absolute temperature (K), and the Stefan–Boltzmann constant ($5.67*10^{-8}$ W/m^2 K^4), respectively.

2.4. Jet fire

Jet fire is the combustion of high pressure flammable material