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Framework for the quantitative assessment of the risk of leakage from LNG-fueled vessels by an event tree-CFD

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ABSTRACT:

Liquefied natural gas (LNG) is used as fuel in various kinds of vessels, e.g., passenger ship, ferry, cargo vessel and platform supply vessel (PSV). It is an eco-friendly bunker fuel with many advantages, like decreasing the emissions of SO_X and particulate materials (PM) and meeting the international maritime organization (IMO) MARPOL Annex VI requirements on NO_X emissions, and economic benefits compared to heavy fuel oil (HFO). However, the leakage of LNG-fuel is a threat for the safety of LNG-fueled vessels, due to its inflammable and explosive characteristics. This paper illustrates a framework for the quantitative risk assessment of LNG-fueled vessels with respect to potential leakage. For illustration purposes, reference is made to a typical LNG-fueled ship, as a representative case. Event tree analysis (ETA) and computational fluid dynamics (CFD) simulation are integrated for the investigation of the hazard, the analysis of the consequences, and the quantification the risk of the LNG leakage. The results of the study are used to provide risk control options (RCOs), in terms of optimal risk mitigation for LNG-fueled vessels.

1. Introduction

LNG is a valuable and eco-friendly bunker fuel produced by compressing and cooling natural gas down to approximately −162 °C, after desulfurizing and removing particulate matters (Kumar et al., 2011; Woodward and Pitbaldo, 2010). The use of this pure chemical product (with few sulphur elements and zero PM) as power source in the marine engine allows LNG-fueled vessels not only to meet the requirements of the international convention for the prevention of pollution from ships (MARPOL Annex VI, 1998) for both worldwide trade and operations in the emission control areas (ECAs), without the need for the extra exhaust gas treatment, but also to fit the regulations of international code of safety for ships using gases or other low-flashpoint fuels (IGF code). Due to the huge reserves of natural gas and the policies on exhaust emission reduction of NO_X, SO_X and PM, LNG is considered as a prior alternative marine fuel for the future (El-Gohary et al., 2012).

Substantial effort has been made on design, survey/experiment, standardization, safety research for LNG-fueled vessels. Wartsila designed marine LNG-diesel dual fuel engines with less release of NO_X, SO_X and PM than the same power diesel engines (Brett, 2008). In 2009, IMO authorized an interim guideline MSC 285(86) (IMO, 2009), which officially accepted natural gas as a legitimate power source for various types of ships. Det Norske Veritas (DNV) surveyed several dozen newly built LNG-fueled ships before the end of 2009 (Bagniewski, 2010). In 2014, IMO approved the international code for ships using gases or other low-flashpoint fuels (IGF code, 2014). The IGF code became mandatory and was adopted in June 2015, and will be come into force in 2017. In addition, American Bureau of Shipping (ABS) adopted a guide “Propulsion and auxiliary systems for gas fueled ships” (ABS, 2011), and DNV and Germanischer Lloyd (GL) published a research report on the safety assessment of generic LNG-fueled vessels (DNV and GL, 2012). Also, Chinese shipping enterprises have transformed twelve diesel-fueled vessels into LNG-fueled vessels before June 30, 2013 (Fu

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et al., 2014).

Despite the benefits of LNG implementation (Kumar et al., 2011), the inherent hazardous characteristics of LNG cannot be neglected, such as inflammability, explosiveness and ultralow temperature. For instance, if LNG went to spill from the storage equipment, the liquid would vapor and diffuse very fast, and the risks of fire and explosion would increase with the spread of natural gas. Hence, the importance of safety for LNG technologies attracts global attention. At present, not only academia but also practitioners have adopted approaches to investigate the risks of LNG terminals or LNG carriers. Specifically, Raj and Lemoff (2009) discussed and compared the differences between risk associated standards NFPA 59 A standard (2009 edition) and EN 1473 (2006) for LNG facility siting, Yun et al. (2009) proposed a risk assessment methodology for LNG important terminals by incorporating Bayesian and LOPA approaches, and using relevant offshore reliability data (OREDA) (SINTEF Industrial Management., 2002), Paltrinieri et al. (2015) used a dynamic procedure for atypical scenarios identification (DyPASI) to identify atypical accident scenarios in LNG terminals, and Lee et al. (2015) compared the fire risk assessments of the two types of LNG fuel gas supply (FGS) systems. Taking into consideration the evaporation losses of water spill areas, Fay (2003, 2007) provided an analysis of the spread of a large LNG spill, the duration time of pool fire, and the pattern of heat release, and Davies and Fort (2013) summarized the release likelihood data used and provided an example of its use for a simplified LNG fueling system. As for LNG carriers, Vanem et al. (2008) presented a generic risk assessment of the global operations of ocean-going LNG carriers on the basis of Event Tree Analysis (ETA), Chang et al. (2008) investigated the availability and safety concerns of the conventional and prospective propulsion systems for LNG carriers, Elsayed (2009) developed a multiple attributes risk assessment approach to investigate the LNG carrier's loading and offloading risks at the terminal sites, Pitblado and Woodward (2011) highlighted some experiment and modeling approaches for risk analysis of LNG carriers, Nwaoha et al. (2013) constructed a mathematical model of the LNG carrier control system and carried out a corresponding risk assessment combined with genetic algorithms.

From an in-depth analysis, the majority of the proposed research appears to focus on studying the risk of large scale LNG infrastructures, such as LNG terminals and carriers. For LNG as the power onboard, it appears that limited work has been performed on quantitative risk assessment, except for LNG carriers. To fill the gap, this paper proposes a framework for quantitative risk assessment of LNG-fueled vessels with respect to potential leakage, including hazard identification and frequency analysis, accident scenario analysis and consequence simulation. ETA and CFD simulation are integrated for the probability estimation of accident scenarios and three-dimensional consequences simulation of the LNG-fueled vessels leakage events, respectively. The primary feature of the framework is that it enables to measure the probability of accident scenarios for various initiating events, which are the likelihoods of fire and explosion accidents for LNG-fueled vessels leakage events in this paper. The severity of consequence for the accident scenarios can be also analyzed and evaluated by CFD simulation. The dimension and arrangement of the vessel used in the CFD simulation are from a typical LNG-fueled ship. The results are compared and validated with several relevant studies from DNV and GL (2012), and the results of the validation show strong agreement. The framework provides an insight into the combined of effect of hazardous events on the probability and consequence of fire and explosion accidents for LNG-fueled vessels. In principle, it can assist in providing risk control options (RCOs) in terms of optimal risk mitigation for LNG-fueled vessels.

The remaining sections of the paper are structured as follows. In section 2, a systematic framework of risk assessment of LNG-fueled vessels, including the hazard identification, probabilistic modeling and consequences simulation, is developed. In section 3, a typical LNG-fueled vessel is chosen as a reference system to conduct the quantitative assessment of LNG leakage events. Its feasibility is validated by comparison with several relevant studies in section 4. Finally, section 5 consists of conclusions and remarks on the work and its results.

2. Methodology and framework

2.1. Risk concept

Risk is a function of the initiating event, the state of the system and of its environment, and the time frame (Haimes, 2009). A traditional perspective for risk metric/description is presented as follows (Aven, 2012): Risk = Probability and scenarios/(severity of) consequences (R = P&C). Namely, risk is a measure of the probability and severity of adverse effects (Lowrance, 1976), the combination of probability and extent of consequences (Ale, 2002) or magnitude/severity of consequences (SRA, 2015).

The above metrics/definitions of the concept of risk indicate that risk should be analyzed in both aspects of likelihood/probability of accident occurrence and associated consequences. In this paper, we take the following description of risk with reference to a generic *i*-th initialing event, which combines probabilities and consequences (Ren et al., 2005):

$$Risk_i = p_i * \left[\sum_{j=1}^{N} \mathrm{C}_{i,j} * q_{i,j} \right) \Bigg] \quad (1)$$

where i is the index of the element of the set A of initiating events, whose generic element A_i is a specific initiating event, p_i is the likelihood of occurrence of the initiating event A_i, j is the index of the possible consequences deriving from scenario A_i, $\mathrm{C}_{i,j}$ is the magnitude of the possible consequences caused by event A_i and $q_{i,j}$ is the conditional probability that these consequences develop, given that the accident A_i occurred.

Consequence categories are described in Table 1: the definitions conform to the consequence scale for hazard identification (HAZID) of generic LNG-fueled vessels (DNV and GL, 2012).

2.2. Event tree analysis

ETA is an inductive logic, graphically supported approach for identifying the various accident sequences that may result from a given initiating event (Reason, 1997; Zio, 2007; Zio et al., 2009). The probability of each accident sequence can be estimated by multiplication of the conditional probabilities of each node along the sequence from the initiating event to the end.

Table 1
Consequence scale used in the risk assessment.

Severity	Definition
Moderate (1)	On site: no permanent effects External: no effect
Serious (2)	On site: permanent effects External: non- permanent effects
Major (3)	On site: one fatality and/or several permanent invalidities External: permanent effects
Catastrophic (4)	On site: several fatalities External: one fatality; many physical injuries
Disastrous (5)	On site: many fatalities External: several fatalities