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Effects of forced convection and thermal radiation on high expansion foam used for LNG vapor risk mitigation

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ABSTRACT

Liquefaction of natural gas is an effective way of easily storing and transporting natural gas because of its high ratio of liquid to vapor densities. Any spill of liquefied natural gas (LNG) can result in the formation of a vapor cloud, which cannot only cause asphyxiation but can also migrate downwind near ground level because of a density greater than air and has the potential to ignite. The NFPA recommends the use of high expansion foam to mitigate the vapor risk due to cryogenic LNG. This paper studies the effects of heat transfer mechanisms, such as forced convection and thermal radiation on high expansion foam breakage, with and without a cryogenic liquid. A lab scale foam generator was used to produce high expansion foam and carry out experiments to evaluate the rate of foam breakage, the amount of liquid drained from foam, the vaporization rate of the cryogenic liquid, and the temperature profile through the foam. High expansion foam breakage was found to depend on the amount of wind induced forced convection and thermal radiation. At the highest wind speed (2.5 m/s) and thermal radiation intensity (270 W/m^2) measured, foam breakage was found to be nearly 3 and 5 times the value without any wind or thermal radiation, respectively. Liquid drainage from the foam was found to affect the vaporization rate of the cryogenic liquid, especially immediately after foam application. Accounting for external factors such as forced convection and thermal radiation can help provide a better estimate for the amount of foam that needs to be applied for effective vapor risk mitigation.

1. Introduction

Natural gas consumption is expected to increase by nearly 40 percent over the next few decades as it is a cleaner source of energy compared to oil or coal and produces lower amounts of carbon dioxide, sulfur oxide and nitrogen oxide per unit of energy produced (US EIA, 2015a, 2015b, 2017). In addition, advances in fracking technology have enabled its extraction from shale reserves previously considered as economically infeasible (US EIA, 2016). Liquefaction of natural gas can be an effective way of storing and transporting it because its volume is nearly 600 times lower in its liquid form. In addition, exports of LNG from the US are expected to increase in the future (US EIA, 2015b).

A leak of liquefied natural gas (LNG) can result in the formation of a vapor cloud, which can migrate downwind near ground level, exhibiting dense gas behavior, as the density of methane at low temperatures is higher than atmospheric air. This vapor cloud has the potential to ignite and presents the danger of asphyxiation to any population in its vicinity. There have been several documented instances of LNG activity related incidents, which have been summarized in Table 1 (Department of Transportation, 2007; Hamutuk, 2008; Powell, 2016; Weinberg, 1975; Mannan et al., 2005). An incident in 2004 at an LNG facility in Skikda, Algeria claimed 27 lives and resulted in over 70 injuries (Romero, 2004). Another incident occurred in Plymouth, Washington, in 2014, in which an LNG tank was pierced by debris, resulted in an LNG leak and also injured 5 workers (Schneyer et al., 2014; Anand et al., 2006).

The NFPA suggests the use of high expansion foam to mitigate the vapor risk of an LNG spill (National Fire Protection Association, 2016). Expansion foam forms a vapor barrier containing the hazardous cryogen. In case there is a fire, the bubbles will help suffocate the flames and prevent re-ignition (Chemguard, 2017). They are also gaining more attention as they tend to be biodegradable, making them environmentally friendly (Conroy et al., 2013; Suardin et al., 2009; Guevara et al., 2013).

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Table 1
List of select LNG related incidents and their consequences.

Ship/Facility Name	Location	Year	Effect on human life
East Ohio Gas LNG Tank	Cleveland, OH	1944	128-133 deaths
LNG Import Facility	Canvey Island, UK	1965	1 person burned
LNG export facility	Arzew, Algeria	1977	1 worker frozen to death
Columbia Gas LNG import terminal	Cove Point, MD	1979	1 killed, 1 injured
LNG export facility	Bontang, Indonesia	1983	3 workers died
Skikda I	Algeria	2004	27 killed, 72–74 injured
Atlantic LNG (Train 2)	Port Fortin, Trinidad	2006	1 person injured
LNG Facility	Plymouth, WA	2014	5 workers injured

There are several mechanisms that can affect the vaporization rate of LNG in the presence of foam (Zhang et al., 2014). The foam blocks the effect of both forced convection and thermal radiation on LNG vaporization and is called as the "blocking effect" of foam. Liquid from the foam can drain over time and can increase the rate of vaporization of LNG. This is termed as the "boil-off effect" of foam. Over time, an ice layer forms since the temperature of the cryogenic liquid is far lower than the freezing point of water. This acts as a physical barrier preventing direct contact of foam with LNG. However, as this ice is porous, it allows vapor to pass through. The "blocking effect" and "boil-off effect" are combined together and termed as the "blanketing effect" of foam which highlights the net effect of foam addition and determines the vaporization rate of LNG (Zhang et al., 2014). The vapors that pass through the foam layers exchange heat with the foam as they pass through, increasing their temperature. This increases the density of vapors leaving the foam making them more buoyant, which makes their dispersion easier. This is termed as the "warming effect" of foam.

A study in the 1970's by University Engineers involved testing the effectiveness of high expansion foam in mitigating the vapor risk of LNG (Suardin, 2008; Zuber, 1975; Mitchell and Mannan, 2006). It was found that foam application reduced the size of the LNG vapor cloud, and vapors of LNG which passed through the foam layers were found to rise as they were warmed sufficiently. Takeno et al.(1996) also performed experiments to study the ability of high expansion foam to increase the temperature of vaporized cryogenic liquids. Their experiments corroborated the ability of high expansion foam to raise the temperature of dispersed gas. In addition to these experiments, they also modeled the heat transfer phenomena and performed calculations using heat balances. They concluded that over 90% of the heat provided by high expansion foam was used to increase the temperature of the vaporized gas while the rest was used to vaporize additional liquid. In 2005, experiments involving LNG spills mitigated by high expansion foam were conducted and found 10 L/min/m^2 as an effective foam application rate (Suardin, 2008). The fire control time, defined as the time required for a 90% reduction in thermal radiation, was also found to reduce with increasing foam application rates. In addition, field experiments were conducted to estimate the vaporization rate of LNG, temperature profile through foam layers, concentration of vapor above foam and effective foam depth to study the effectiveness of foam in vapor dispersion (Yun, 2010). A minimum effective foam depth 0.64 m was determined for LNG vapor risk mitigation was recommended along with a suitable safety margin for practical applications. High expansion

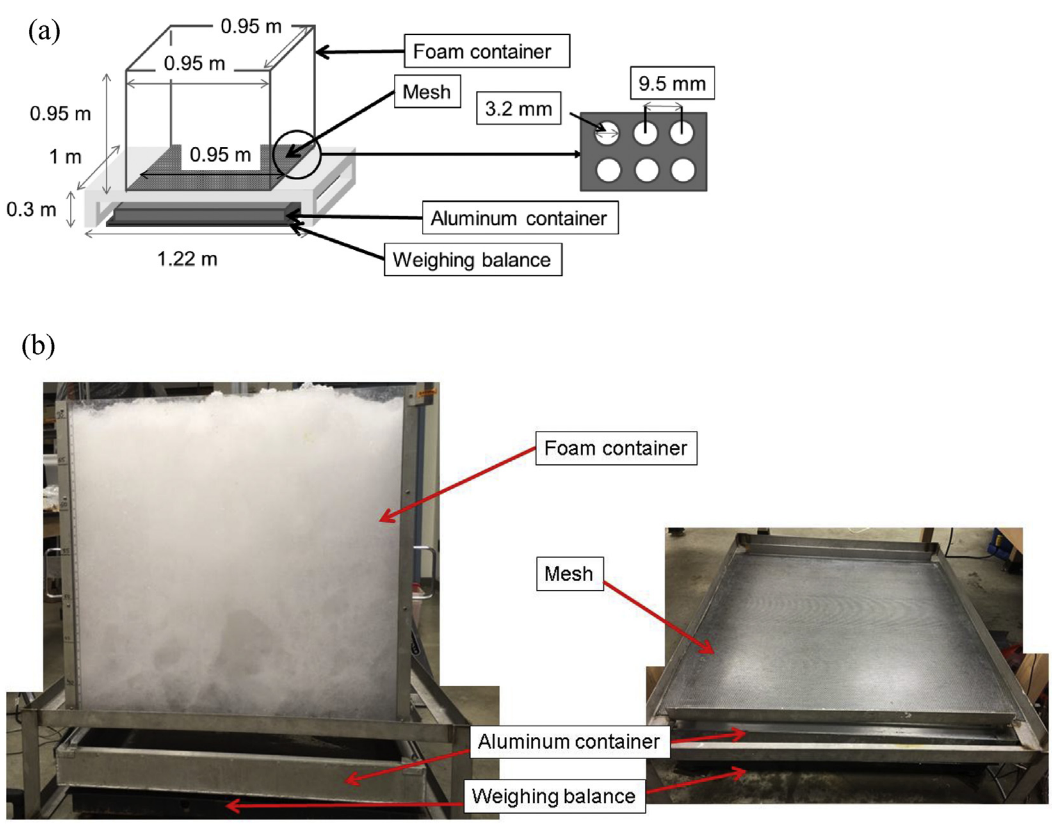

Fig. 1. Mesh setup to measure liquid drainage a) schematic with dimensions (not to scale) b) images of the actual setup.