RECENT PROGRESS IN LNG SAFETY AND SPILL EMERGENCY RESPONSE RESEARCH

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Liquefied natural gas (LNG) is expected to play a significant role in providing a diversified energy portfolio and adding flexibility to the growing demand of natural gas. With the liquefaction capacity expected to double by 2035, the concerns over the safety and security of LNG facilities have promoted continuous research on risk assessment and improvement of mitigative measures for an accidental LNG spill. Mary Kay O'Connor Process Safety Center (MKOPSC) at Texas A&M University has been conducting experimental and theoretical research to improve LNG safety and spill response since 2005. The main focuses include LNG vapor dispersion, underwater LNG release phenomenon, and LNG specified mitigation measures using water curtain and expansion foam applications. A total of five consecutive LNG outdoor spill experiments have been conducted at Brayton Fire Training Field (BFTF). In parallel to the experimental work, theoretical modeling has been conducted to gain a better understanding of the complex LNG vapor dispersion phenomena and design effective safety measures for LNG facilities. Theoretical understanding of LNG vapor dispersion is essential in developing LNG specific emergency response guidelines to prevent the catastrophic consequence of an LNG spill. Discussed are the experimental work conducted at BFTF by MKOPSC and theoretical modeling approach using computational fluid dynamics (CFD) to provide an advanced assessment tool for complex LNG release scenarios. The MKOPSC LNG research aims to support development of improved risk assessment for the LNG industry and definitive guidelines on engineering design criteria for LNG mitigation and fire suppression.

1. INTRODUCTION

The natural gas market is expected to grow dramatically as natural gas is recognized as one of the most economic and cleanest fossil fuels (IEA 2011). The recent nuclear crisis and the development of unconventional gas supply from breakthroughs in drilling technology expedited the market growth of natural gas (Economides). Transportation of natural gas by pipeline has been limited within the continental region, and liquefied natural gas (LNG) has been a preferred way to develop natural gas trade intercontinentally (Foss 2007). As the liquefaction capacity is expected to double by the 2035 (IEA 2011), the security and safety around LNG facilities have raised public concern. The continued research of LNG hazards and mitigation measures to alleviate the consequence of an accidental LNG release has been a common interest for the LNG industry as well as the public.

The Mary Kay O'Connor Process Safety Center (MKOPSC) has been involved in joint research and a development program with BP Global Gas SPU since 2005 to study LNG safety and spill emergency response. Five consecutive outdoor spill experiments have been conducted at Brayton Fire Training Field (BFTF) of Texas Engineering Extension Service (TEEX) in College Station, Texas. The main fields of interest are LNG vapor dispersion and vapor behavior of a spill on and under water; application of various mitigative measures, such as water curtain, expansion foam, and suppression materials; and characterizing LNG pool fires. The theoretical modeling work using computational fluid dynamics (CFD) provides in-depth understanding of complex behavior and interaction of LNG vapors. The main objective of the LNG research program at MKOPSC is to provide an engineering analysis applicable directly to the LNG industry to improve the safety and security at current LNG facilities. This paper discusses a general overview of the recent progress of the current LNG research program at MKOPSC.

2. LNG RESEARCH PROGRAM

Five outdoor spill experiments have been conducted by MKOPSC together with TEEX at BFTF. There are four different spill pools available in different configurations, designed for various spill experiments. The main focus of the tests were LNG vapor dispersion and various safety measures to mitigate the consequences of an accidental enhanced or suppressed flammable vapor dispersion, and to mitigate the pool fire risk. LNG dispersion experiments were conducted by creating LNG spills on and under water (Cormier 2009; Qi 2010; Qi 2011). A water curtain was directly applied to LNG vapor clouds to evaluate the effectiveness of water curtains in dispersing a vapor cloud (Rana 2010; Rana 2010). Different types of expansion foam materials were tested to determine the effectiveness for vapor control and pool fire mitigation (Suardin 2009; Yun 2011b; Yun 2011c). A small-scale LNG pool fire was investigated to evaluate the mass burning rate (Herrera C. 2010). A total of four spill pools are available for LNG spill depending on the types of release.

Applying computational fluid dynamics (CFD) has been recommended for evaluating a high level of risk related to an accidental LNG spill (Hightower 2004). CFD codes can provide solutions to complex flow problems of LNG vapor dispersions, whereas the traditional integral-type models raise concerns due to the limitation in describing the LNG vapors adequately (Gavelli 2008). Theoretical study using CFD can provide in-depth understanding of complex behavior of LNG vapor and fill the existing gaps of experimental results. Commercial type CFD codes, such as CFX, Fluent, and FLACS, have been utilized to set up a validation model to study the complex behavior of LNG dispersion, forced dispersion using water curtain application, and key parameters involved in expansion foam application.

3. LNG VAPOR CLOUD DISPERSION/BEHAVIOR RESEARCH

US federal regulations require the use of LNG dispersion modeling tools to evaluate the consequences and to assess the exclusion zones for LNG facilities during an accidental LNG spill. However, the conventional modeling tools have limitations of accounting for the interaction of vapor clouds with complex geometries. More advanced simulation tools, such as computational fluid dynamics (CFD) are suitable for these types of scenario. However, there is no specific guideline on how to address the complex site-specific scenarios for evaluating LNG dispersion modeling. The proper numerical and physical parameters for achieving better accuracy in simulation predictions still require further understanding.

With the purpose of evaluating the key parameters involved in the vapor dispersion of LNG, the medium-scale experiments were performed to understand the physical processes involved under different release conditions. The essential parameters involved in the simulation prediction were identified and used as inputs for the simulations. The data collected from the experimental work were subsequently analyzed to validate the dispersion model using ANSYS CFX (Qi 2011). A sensitivity analysis on the key parameters was performed to illustrate their effect on the accuracy of the simulation results. Additionally, a source term study on LNG underwater release was performed in order to determine the characteristics of pool formation and vapor cloud generation in this scenario. The results of this experiment were used to validate a previously published mathematical model (Raj 2010; Qi 2011).

3.1. EXPERIMENTAL WORK ON VAPOR DISPERSION/UNDERWATER RELEASE

The LNG dispersion experiments were conducted using LNG with 98–99.8% methane. The LNG spill was set up inside the concrete pits available at BFTF; two of them with dimensions of 10.06 m × 6.4 m × 1.22 m and 6.71m × 6.71 m × 2.44 m. The pits were previously filled with water to promote a constant vaporization rate of the LNG spilled, essentially equal to the LNG discharge rate. A metal plate was located under the pipe discharge end, in order to reduce the vertical fluid momentum of the LNG release.

The essential key parameters which affect the dispersion behavior were measured throughout the tests, for instance, weather conditions such as wind speed and direction, humidity, atmospheric temperature, and pressure. Vapor dispersion parameters such as gas concentration and temperature were also measured along the predicted path of the vapor cloud. In the 2007, 2008, and 2009 tests; 6 feet high wooden boards were used around the pit to simulate fences and to study their effects on the LNG vapor dispersion. These experiments demonstrated that fences help reduce the hazardous downwind distance, as they hold up the vapor cloud and promote the turbulence within the inside of the vapor fence perimeter; enhancing the positive buoyant properties of the vapor before it disperse towards the outside of the fence. Figure 1 shows the comparison between the plume shape in the experimental work (left

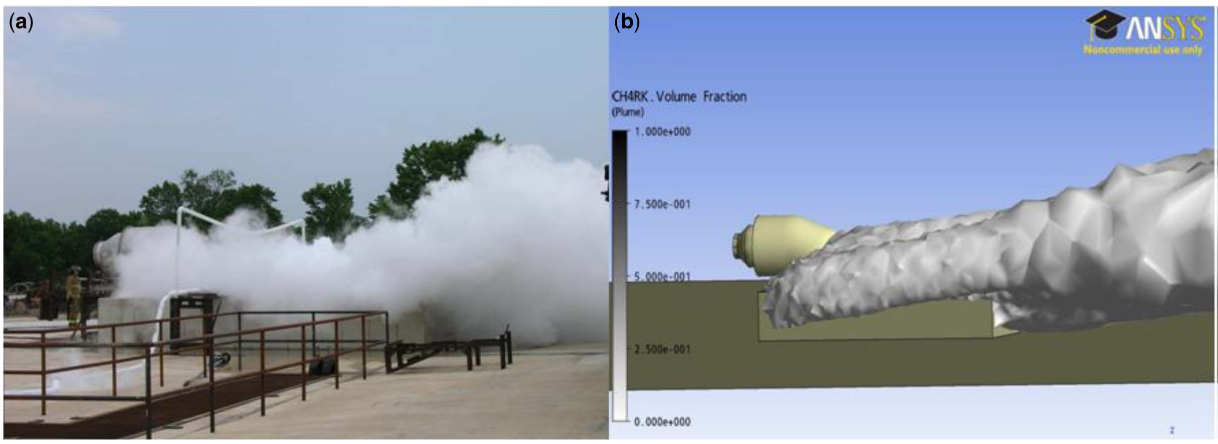

Figure 1. Comparison of the plume shape of experimental work and CFX simulation. (a) Experimental work (b) ANSYS CFX simulation (Qi 2010)

side) and the simulation using ANSYS CFX (right side). The snapshot shows the moment when the LNG plume goes out of the pit. Simulation results obtained with ANSYS CFX showed a similar plume behavior with the experiments, although a slightly under prediction in the cloud height (lower height) was obtained (Qi 2010).

An underwater LNG release test was also conducted to understand the physical transition occurring during an underwater release; determining the pool formation and the vapor cloud generated from the release. LNG was discharged inside a pit of dimensions 10.06 m × 6.4 m × 1.22 m, filled with water. The discharge was performed vertically at a depth of 0.71 m below the water surface. The duration of the test was 6.5 minutes and the data collected included LNG flow rate, meteorological conditions, temperatures, and the concentration at various downwind locations and heights. Figure 2 shows the different vapor dispersion behavior of LNG during an underwater and on-water release.

The temperature was about -1°C for the vapor emanating from the water surface, which indicates a buoyant behavior. The concentration measurements downwind along with the visual records were analyzed to provide better an understanding of an underwater LNG release. No pool formation was observed on the water surface. A previously published theoretical model was validated against test data, showing good agreement (Qi 2011).

3.2 COMPUTATIONAL MODELING OF LNG VAPOR DISPERSION

CFD modeling has been recommended to provide a better approach in evaluating the potential hazards of an accidental LNG release, however, there has not been a sufficient amount of research or literature regarding the effects of various parameters in setting up models (Cormier 2009; Qi 2010).

The ANSYS CFX code was utilized to simulate vapor dispersion phenomena, and the various effects of the essential parameters, such as the mesh size and shape, atmospheric conditions, source term turbulence, ground surface roughness height, and the effects of vapor fences were evaluated. The k-□ turbulence model was used to describe the turbulence effects above the pool caused by vapor evaporation.

A sensitivity analysis was performed for main two parameters in setting up the simulation: mesh size and source term turbulence intensity. A strong correlation was found between the physical parameters and the simulation accuracy. Further simulation work is planned to verify the effects of the parameters to estimate and reduce the errors related to numerical solution methods. Figure 3 shows the comparison between ANSYS CFX and test data for methane volume fraction contours. The highest contour value is plotted in red and the lowest one in blue, at a 0.3 m elevation and a time of 600 seconds after the release. Comparison of these contour shapes indicates that ANSYS CFX predicts the physical dispersion behavior of the LNG reasonably well with well-defined physical parameters.

The study of the effects which the passive barriers have on LNG vapor behavior is currently analyzed using CFD modeling. The main objective of this simulation is to verify how the passive barrier such as a dike could help to hold up the vapor and affect the buoyancy of the vapor cloud. The results from this work are expected to provide engineering guidelines in developing the design criteria for passive barriers.

4. FORCED DISPERSION OF LNG VAPORS USING WATER CURTAIN APPLICATION

Water curtains have been recognized as one of the most effective and economic mitigative measures in the hydrocarbon industry. Water droplets from the nozzle can reduce

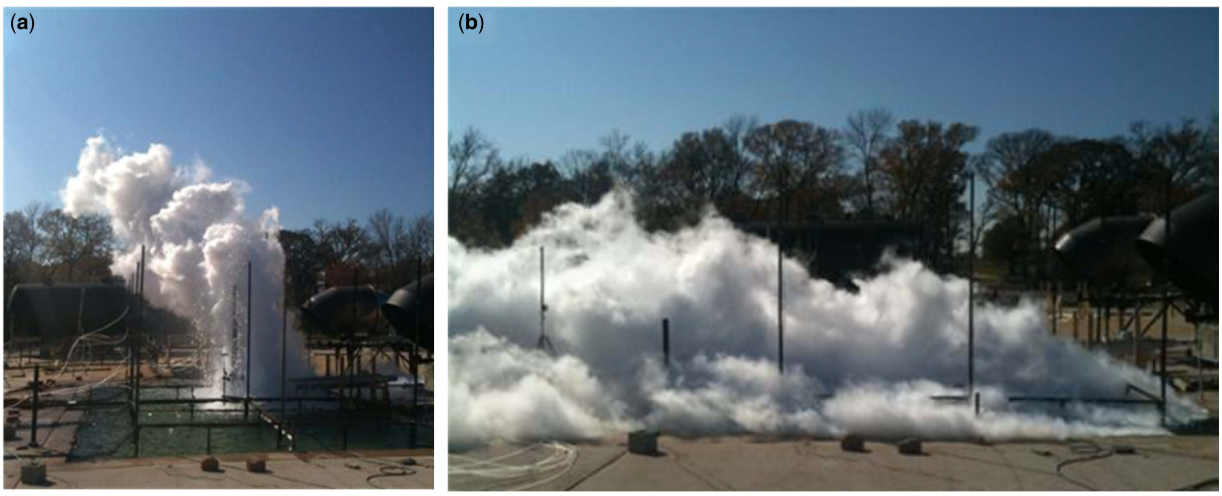

Figure 2. Behavior of LNG vapor cloud emanating from the water surface. (a) LNG release underwater, (b) release onto water surface (Qi 2011)

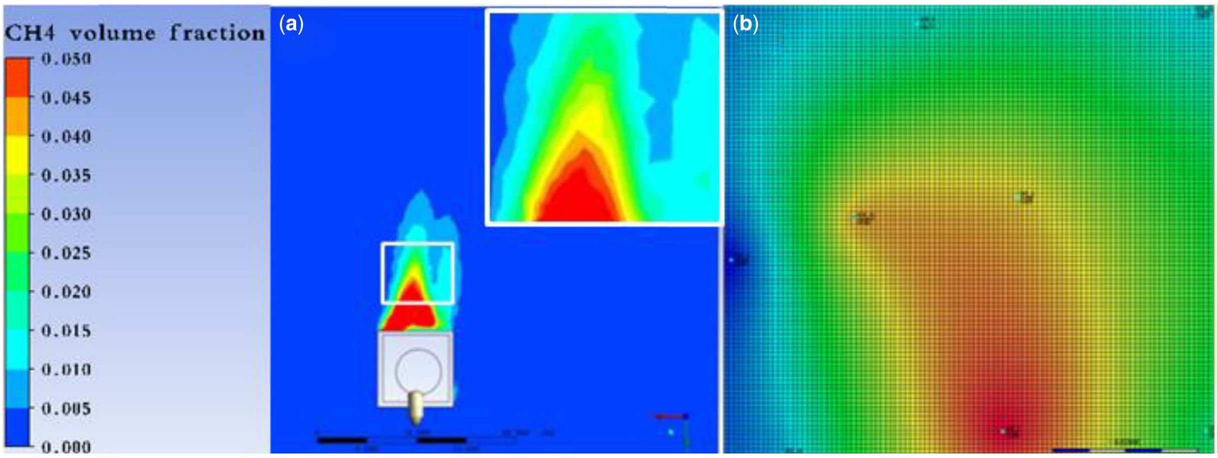

Figure 3. Methane volume fraction contours at 0.3 m elevation downwind and at time = 600 s. (a) ANSYS CFX simulation and (b) Test data (Qi 2010)

the concentration of hazardous gas below the flammability or toxic level and reduce overpressure in case of an explosion (Uznanski 1998; Van Wingerden 2000). The water curtain system, if properly designed, can reduce the hazard during an accidental LNG spill by enhancing the dispersion of the vapor cloud from the ground level (Rana 2010a). Previous experimental work conducted by the US Coast Guard in the 1970s evaluated the effectiveness of applying the flat-fan nozzle in dispersing LNG vapor clouds (Martinsen 1977). The research program by the Gas Research Institute in the 1980s developed theoretical models based on the air entrainment rate of spray nozzles, and small-scale experiments were designed based on the results (Heskestad 1981; Heskestad 1983). However, there had not been any definite design criteria for effective water curtain application for LNG facilities, mainly due to the complex interactions between the droplets and air-vapor mixture. The external factors, such as the atmospheric conditions, for all the previous experimental works have varied, therefore, no conclusive findings were presented and some specific recommendations were made only for certain scenarios. Also, there are still experimental gaps, which need to be addressed in order to have a better understanding of the water droplet and vapor cloud interactions. MKOPSC has conducted five consecutive experimental tests applying a water curtain for forced dispersion of LNG vapors (Rana 2009). Theoretical modeling of forced dispersion of LNG vapor cloud has been conducted using CFD to study the underlying phenomena of complex interaction of a water droplet-vapor system (Kim 2011).

4.1 EXPERIMENTAL WORK ON WATER CURTAIN APPLICATION

A series of five sets of outdoor LNG spill experimental works have been conducted to determine and evaluate the effectiveness of water curtain application in dispersing LNG vapors (Rana 2009). The main objective of this part of the research is to verify the different dominant mechanisms in controlling and dispersing LNG vapors using various commercial type water nozzles. The theoretical understanding of water spray application was conducted to achieve a better understanding of the underlying physical phenomenon of forced dispersion using water curtain application. The field experiments were carefully designed to understand the dominant mechanisms of forced dispersion, and determine the effect of several essential parameters in controlling the physical process involved during the dilution phenomena. Three different types of water nozzles were tested in this work: flat-fan upwards, full cone upwards, and full cone downwards. The "Hydroshield HSE" from Angus was used for flat-fan upwards application, which produced a shear sheet water barrier. An upwards full cone (60° 1″ TF 48 NN BETE Fog Nozzle) and downwards full cone (60° 1/2″ TF 24 NN BETE Fog Nozzle) were tested in different configurations.

The concentration and temperature data were analyzed to determine the overall mechanisms in diluting LNG vapors for each nozzle (Rana 2010b). Figure 4 summarizes the concentration data from the water curtain experiments. The flat-fan type creates a barrier in direction of LNG vapors covering larger crosswind length and height. The coarse droplet with high water pressure allows for the largest momentum effects, however, provides limited thermal effects to the LNG vapors. The downward full cone produced water droplets with a small diameter, providing sufficient heating effects. The upwards full cone, with the wider spray angle and medium droplet size, created high turbulence around the spray region. With the highest air entrainment, the upwards full cone type has proved to be the most effective in diluting the LNG vapors in the downwind region (Rana 2010b).

4.2 THEORETICAL MODELING OF FORCED DISPERSION OF LNG VAPORS

The CFD tool has been used to study the underlying physical phenomena of complex interaction between the droplets

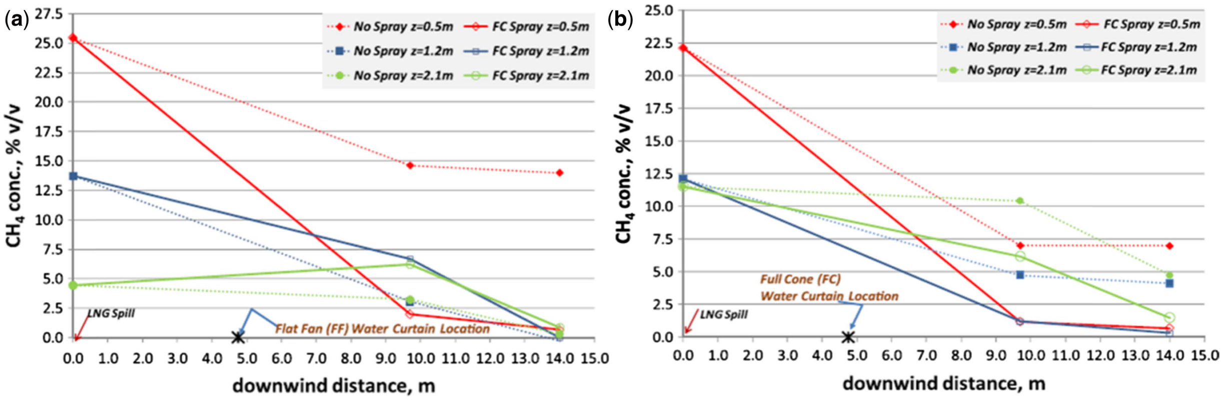

Figure 4. Downwind concentration at three different heights with and without (a) flat fan and (b) full-cone water curtain (Rana 2010)

and the air-vapor mixture. The CFD codes have evolved significantly in solving the complex flow problem of multiphase interactions, which can be applied in water curtain modeling (Crowe 1998). The Eulerian-Lagrangian approach in simulating water spray in the spatial domain has been preferred as it provides a more flexible approach in solving wider applications with more accurate characteristics of spray (Alessandri 1996; Nijdam 2004; Gant 2006). The discrete particle model (DPM) using ANSYS Fluent solver had been used to apply the Eulerian-Lagrangian reference frame in simulating water curtain application. ANSYS Fluent had been widely recognized as one of the CFD tools to predict LNG vapor behavior well (Hightower 2004; Gavelli 2008; Gavelli 2009). The DPM provides solutions based on the fundamental equations of momentum and heat transfer from the droplets to the air-vapor mixture (Kim 2011).

The physical parameters for forced dispersion modeling using ANSYS Fluent were initially calibrated using the results from MKOPSC outdoor LNG spill experiments (Kim 2011). Figure 5 shows the contour of the methane concentration with and without the forced dispersion applied. The natural dispersion of LNG vapors shows dense gas behavior where the gas propagates at lower level until sufficiently warmed up to be positively buoyant. With the spray applied, the vapor clouds are pushed towards the upper level as they interact with the water droplets. The two dominant mechanisms involved in forced dispersion of LNG vapors, momentum and heat transfer, were evaluated. The momentum transfer effect from the droplets to the vapor cloud using the DPM showed agreeable trends to the mitigation study using water curtain application on diluting hazardous gas conducted by the von Karman Institute (Hald 2005), as shown in Figure 6(a). The thermal effect of various droplet temperatures was also tested. The heating effect increased as the droplet temperature increased and the effectiveness of dilution also increased. The simulation captured the buoyancy gain from the increased thermal effect, causing the concentration to decrease at the lower level. Figure 6(b) shows the dilution factor and the heat transfer rate based on varied water droplet temperature.

Further theoretical work is planned to evaluate different effects of essential design parameters in operating the water curtain. The results from this work will provide detailed analysis, which can be used to understand the physical phenomena of the forced dispersion of LNG vapor using a water curtain.

5. EXPANSION FOAM APPLICATION FOR LNG HAZARD MITIGATION

Expansion foam is one of the safety measures available to mitigate hazards caused by LNG spills at LNG facilities. As the expansion foam warms up, the LNG vapors pass through the foam and help minimize the effects from convection and radiation of the surroundings. Expansion foams can be categorized into three different types: low, medium, and high expansion foams based on their expansion ratio. The expansion foam with expansion ratio

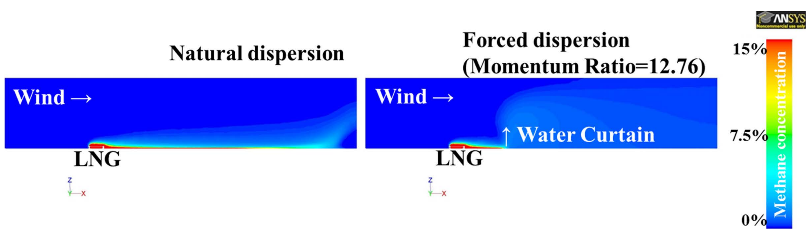

Figure 5. Vapor contour without/with water curtain application (Kim 2011)

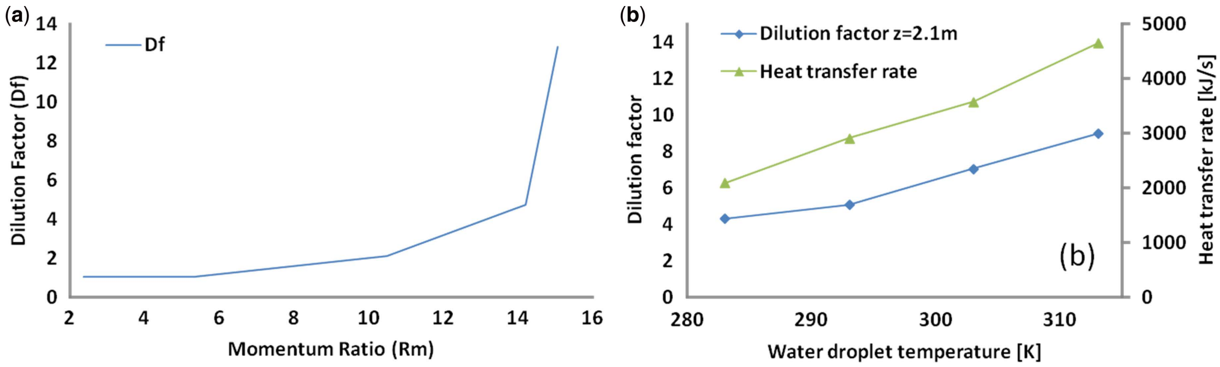

Figure 6. Dilution effectiveness of different (a) momentum and (b) heat transfer effects

ranging from 200 to 1000 is defined as high expansion foam by NFPA 11(NFPA 2009), which is widely used to mitigate LNG spill hazards. Expansion foam can reduce LNG hazards by controlling LNG vapor dispersion and suppressing the LNG pool fire. The effectiveness of expansion foam was evaluated through measuring methane concentrations in vapor dispersion control and radiant heat fluxes in fire suppression by University Engineers, Inc (Welker, Wesson et al. 1974). It was concluded from this work that the expansion foam can reduce the gas concentration and provide effective control over the pool fire by reducing the level of the flame emissive power. Takeno (1996) studied the effect of high expansion foam on cryogenic vapor dispersion at atmospheric conditions by measuring vapor temperatures with a thermocouple and vaporization rate with a mass balance under the container (Takeno, Ichinose et al. 1996). The result indicated that expansion foam can warm up cryogenic vapor passing through it and reduce the vaporization rate. However, previous work has not provided design criteria and operation guidance for expansion foam application at LNG facilities. MKOPSC has been involved in LNG safety research with respect to high expansion foam to investigate key parameters for different types of expansion foam applications (Suardin 2009; Yun 2011b; Yun 2011c). Theoretical study of effects of high expansion foam on LNG vapor dispersion is being conducted to study the interaction mechanism of expansion foam with LNG vapor.

5.1 EXPERIMENTAL WORK ON EXPANSION FOAM APPLICATION

The experimental research of the expansion study aimed to evaluate the key parameters of a foam application system in vapor dispersion control and pool fire suppression. High expansion foam with an expansion ratio of 500:1, which was proven to be effective in controlling the flammable vapors in previous research, was used in the outdoor LNG spill tests. Figure 7 shows the high expansion foam used during the outdoor LNG spill experiments at BFTF. The results were analyzed to provide a direct recommendation of foam application to meet the current industrial needs. Experimental observations were also used to establish schematic models of interaction between expansion foam and LNG in both vapor dispersion and pool fire scenarios.

Experimental work was designed to verify the effect of different foam application rates: 3.5 $L/min/m^2$ and 10 $L/min/m^2$. The results indicated that a foam application rate of 10 $L/min/m^2$ is effective to mitigate hazards caused by an LNG spill in the test pit, which is three times the minimum effective application rate (3.5 $L/min/m^2$) under ideal conditions according to NFPA 11. Pits with different sizes and configurations were used to study the effects on foam application. The 45 m^2 pit with an extra 1.2 m wall above the ground showed different fire control behavior compared to the 65 m^2 pit with a 1.32 m wall under the ground. The concrete of the 45 m^2 pit was heated from the fire and the heated LNG vapors interacted more actively with the foam, which made it harder for the expansion foam to control the fire due to the chimney effect. Expansion foam characteristics and behavior were identified and studied in LNG vapor control and pool fire scenarios. The effect of

Figure 7. Expansion foam application on LNG vapor dispersion (Yun 2011)

Figure 8. Expansion foam application on LNG pool fire suppression (Yun 2011)

vapor warming, ice formation, and water boiling were observed during the experiments.

The effectiveness of expansion foam in controlling LNG vapor dispersion and suppressing the pool fire was evaluated through experiments with more than one hundred thermocouples and a couple of gas detectors and radiometers. The minimum effective foam depth was defined and determined for both vapor dispersion and pool fire scenarios. Reduction of the vapor and thermal exclusion zone after foam application was presented to demonstrate the effectiveness of expansion foam in these experiments. Two schematic models were established based on experimental observation, which were expanded to set up a CFD simulation. The experiments conducted in 2009 for both vapor dispersion control and pool fire suppression are shown in Figure 8. Foam application provided an initial negative effect by increasing the vaporization significantly, however the effect was minimized as the LNG pool fire was gradually suppressed.

5.2 THEORETICAL STUDY OF EFFECTS OF EXPANSION FOAM ON LNG VAPOR DISPERSION

The effect of expansion foam on LNG vapor dispersion has proven successful by experimental results, however, there is no CFD model established to simulate the complex interaction between expansion foam and LNG. A mathematical model was established for LNG vapor passing through high expansion foam by a quasilinearization alternating-direction implicit (QADI) numerical method (Yen 1974); a multiphase Navier-Stokes model was also developed to study the effects of expansion foam on a jet diffusion flame (Ananth and Farley 2010).

The mechanism of expansion foam on LNG vapor dispersion control has been identified through both small and medium scale experiments. The expansion foam can increase the LNG vapor temperature by heat transfer between the foam and the vapors, and reduce the vaporization rate by blocking convection and radiation from the surroundings. A preliminary work has been conducted to study the effects of expansion foam on LNG vapor passing through it, in which expansion foam was simulated by a porous media with a constant LNG vapor mass flux input at boiling temperature. The preliminary results shown in Figure 9 indicate that expansion foam can warm up LNG vapor passing through it. A dispersion model will be established using the simulation results demonstrated in this work.

6. CONCLUSIONS

The LNG industry is expected to grow dramatically as the demand for natural gas increases worldwide. The potential hazards imposed from an accidental release of LNG promoted the continued study on the safety and security of

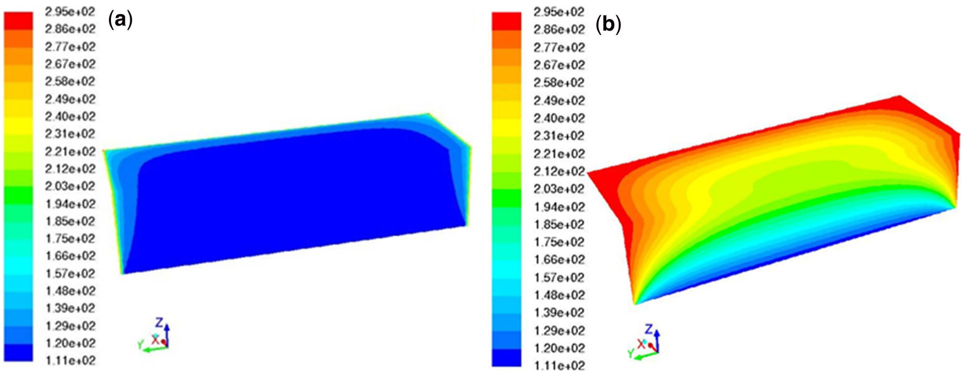

Figure 9. Effects of expansion foam on increasing LNG vapor temperature; (a) Contours of temperature without foam (k) (b) Contours of temperature with foam (Zhang 2012)

the LNG facilities. The MKOPSC in collaboration with BP Global Gas SPU and BFTF successfully conducted a series outdoor LNG spill experiments. The main areas of interest were LNG vapor dispersion, and the effects of various mitigative measures, such as the water curtain application and the expansion foam. The data collected from these works were utilized to set up a validated CFD model to understand the complex behavior of LNG vapors. The modeling work aims to understand the underlying physical fundamentals and provide guidance in designing a spill emergency response program for current LNG facilities.

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