Forced Dispersion of LNG Vapor with Water Curtain

Morshed A. Rana and M. Sam Mannan

Artie McFerrin Department of Chemical Engineering
Mary Kay O’Connor Process Safety Center
Texas A & M University, College Station

Mary Kay O’Connor Process Safety Center International Symposium

October 28, 2009
Introduction

- **LNG** is natural gas (NG) converted to liquid state at 111K (-260F)
- **Liquid vaporizes** immediately if released (boiling point 111K)
- **Vapor disperses** close to the ground: CH₄ vapor at ambient T & P is lighter than air (by 0.54), hence LNG vapor is **heavier than air** (by 1.52)
- **LNG vapor** is **flammable** between 5-15% by volume concentration
- **Massive LNG tanks poses fire and explosion hazards**

Effective vapor and fire mitigation techniques are critical
Why Water Spray Curtain?

A line of spray nozzles which can create a curtain of water droplets in the path of a dispersing cloud /heat

- **Fire fighting**: protect firefighters and equipment from radiant heat
- **Absorption & dispersion**: control and mitigate toxic and/or flammable vapor cloud from a release
- **Reliable, inexpensive, easy installation (fixed or mobile)**
- **Types**: Fog, Conical (full, full square, hollow) and Flat-fan
  → water droplet sizes and flow patterns
- **Orientation/application method**: downward and upward, vertically or inclined

Able to show different physical effects → suggested as one of the most economic and effective LNG vapor suppressing techniques
Parameters of Water Curtain Application

Physical Effects

- **Entrain air** into the spray & change in gas cloud concentration by mixing
  - Momentum transfer from drops to surrounding air (& turbulence) and mixing of air-vapor
- Change in **temperature** of the cloud (and air)
  - Heat transfer from drops to cloud (and air)
- Change in the cloud **path/flow direction**
  - Impart momentum from the spray to the cloud

Parameters of Water Curtain Application

Spray Characteristics

**Spray type & drop size:**
Fog: medium to fine; Cone: medium; Fan: large/coarse

**Drop size & mechanism:**

![Spray type & drop size diagram]

**Spray angle (width) & mechanism:**
Sprays with same drop ranges but different angles (widths) will have different overall effect
Effectiveness of Water Curtain to Disperse LNG Vapor

- Effective LNG vapor control method


Water Curtain Research at MKOPSC

- Study of water curtain effects on LNG vapor cloud
  - overall study from spill experiments
  - theoretical study of air entrainment and momentum effects

LNG spill experiments since 2006
Brayton Fire Training Field
LNG Firefighter Training Facility

- Continuous LNG spill on ground/water from pipe
- Different commercial upward water curtains to disperse vapor cloud
Spray Specifications

Types of upward sprays

Conical: TF 48  Fan: Hydro

Experimental Setup

LNG Spill Location

- Gas detectors & thermocouples
  - different downwind positions and elevations
  - based on CFD simulation & past experience
- Water curtain away from spill
  - To avoid water spillage into the spill
Experimental Procedure & Data

**Vapor dispersion without water curtain**

Water curtain activated @ 480s
LNG discontinued @ 550s

**Vapor dispersion with water curtain**

Data at 0.5m elevation


Overall Effects of Water Curtains

Point values of concentrations at different downwind distances & heights:

Average concentration (within 1 to 1½ min) without and with the water curtain activation

Sunny day: 2.2 m/s (4.9 mph) wind

\[ T_{\text{a}}(\text{Air}) = 22.5 \, ^{\circ}\text{C}, \quad T_{\text{w}}(\text{Water}) = 19 \, ^{\circ}\text{C} \]

RH = 25.5%, Solar Flux = 250 W/m²

LNG spill on concrete (1.52 m × 1.52 m × 0.31 m)
Spill rate: 3 × 10⁻³ m³/s (50 gpm)

Water rate (conical): 15.5 × 10⁻³ m³/s (245.5 gpm)

Water rate (fan): 15.5 × 10⁻³ m³/s (245.5 gpm)

Ground (0.5m) conc. reduction:

conical spray: 30.5%
fan spray: 70%

Mary Kay O'Connor Process Safety Center
Overall Effects of Water Curtains

Point values of concentrations at different downwind distances & heights:

Average concentration (within 1 to 1½ min) without and with the water curtain activation

**Sunny day**: 5.1 m/s (11.4 mph) wind  
$T_a (\text{Air}) = 28.3 \, ^\circ\text{C}, \quad T_w (\text{Water}) = 26.5 \, ^\circ\text{C}$  
RH=38%, Solar Flux = 590.7 W/m²

LNG spill on water (1.52 m × 1.52 m × 0.31 m)  
Spill rate: $3.15 \times 10^{-3}$ m³/s (50 gpm)

Water rate (conical): $36.5 \times 10^{-3}$ m³/s (578.2 gpm)  
Water rate (fan): $11.4 \times 10^{-3}$ m³/s (180.6 gpm)

Ground (0.5m) conc. reduction:  
**conical spray**: 83%  
**fan spray**: 86%
Water Spray Mechanisms
Change in Spray Temperature

2007 tests
T_w = 19.64 (±0.51) °C

2009 tests
T_w = 28 (±0.5) °C

Test 1: Conical Average: 4.5 C
Test 2: Fan Average: 2.5 C
Water Spray Mechanisms

Heat from the spray

\[ q = c_{p,\text{water}} \left( \bar{T}_{\text{water}} - T_{\text{reading}} \right) \]

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Water Curtain [# of nozzle]</th>
<th>Water flow rate/nozzle ( \times 10^3 ) [m(^3)/s]</th>
<th>Droplet size (SMD) [mm]</th>
<th>Change in spray temperature, ( \Delta T_w ) [°C]</th>
<th>Heat transfer by spray, ( q_{\text{avg}} ) [J/gm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>Full Cone [7]</td>
<td>2.2 ±0.70</td>
<td>1.35 ±0.05</td>
<td>6.61 ± 2.2</td>
<td>27.67</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.2 ±0.14</td>
<td></td>
<td>8.03 ± 0.65</td>
<td>33.61</td>
</tr>
<tr>
<td></td>
<td>Flat Fan [1]</td>
<td>15.1 ±0.46</td>
<td>1.55 ±0.05</td>
<td>5.47 ± 0.98</td>
<td>22.90</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15.5 ±2.30</td>
<td></td>
<td>5.68 ± 0.50</td>
<td>23.78</td>
</tr>
<tr>
<td>2009</td>
<td>Full Cone [8]</td>
<td>4.6 ±0.70</td>
<td>0.935 ± 0.045</td>
<td>4.50 ± 0.4</td>
<td>18.84</td>
</tr>
<tr>
<td></td>
<td>Flat Fan [1]</td>
<td>11.4 ±0.50</td>
<td>1.94 ±0.05</td>
<td>2.50 ± 0.27</td>
<td>10.47</td>
</tr>
</tbody>
</table>

Simple calculation by ADL, 1974 (gross heat balance of water):
To change T from 111K – 165K of LNG vapor (from 104 – 15X104 gpm spill)
Heat input needed from a spray curtain: 380-386 J/gm → spray at 1300 -1500 gpm
Water Spray Mechanisms

Air Entrainment into the Upward Sprays

Model*:

\[
\frac{du_d}{dz} = -\frac{g}{u_d} - \frac{3}{4} B V^2 \left( \frac{\rho_a}{\rho_w} \right) d_a^{-3} \left( u_d - u_a \right)^{3/2}
\]

\[
\frac{du_a}{dz} = -\frac{1}{2 A_s} u_a \cdot \frac{dA_s}{dz} + \frac{3}{8} Q_w B v^2 d_a^{-3} \left( u_d - u_a \right)^{3/2}
\]

![Graph of entrained air velocity into the spray, \( u_a \) (m/s)]

![Graph of volumetric air rate inside the spray, \( Q_a \) (m³/s)]

* Similar model by Heskestad et al. (1977, 1981) for downward conical spray

Mary Kay O'Connor Process Safety Center
Water Spray Mechanisms
Momentum (Force) Applied by the Sprays (inside the spray, along the axis)
Overall Results

*Concentration contour (from 2009 expt. data): distance and height*

**Conical spray**
- Without water curtain
- With full cone water curtain application

**Fan spray**
- Without water curtain
- With fan water curtain

**Conc. CH₄ conc. Range**
- 4 – 20% v/v
- 4 – 25% v/v
Conclusions

- **Effectiveness of water curtain on LNG vapor**
  - Underlying physical phenomena of different water sprays
  - Effect of several parameters during LNG vapor-water spray interaction
  - Dominant mechanism

- **Water curtains are able to control a drifting LNG vapor cloud and change the concentration along the cloud height**
  - Water curtain mechanisms vary depending on drop size, drop velocity, spray angle, flow direction
  - Cloud dilution varies because of the roles the different mechanisms play
  - Theoretically, heat transfer is considered the most important mechanism for LNG vapor characteristics. In reality, it is unrealistic to get significant heat from commercially available spray in outdoor situations.
  - Over all **UPWARD CONICAL SPRAYS** with medium drop sizes, which provide higher air entrainment and dilution with some heat and momentum were **MORE EFFECTIVE**
Acknowledgements

- BP Global Gas SPU
- Brayton Fire Training School
  - Kirk Richardson & his LNG team
- All members of MKOPSC
THANK YOU!

Forced Dispersion of LNG Vapor with Water Curtain

Morshed A. Rana & M. Sam Mannan

Mary Kay O’Connor Process Safety Center