Variations in the evaporation rate of a cryogenic liquid on a water surface

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Timothy L. Morse, Ph.D.
Biography of the Authors

Dr. Harri K. Kytömaa, Ph.D., P.E.
Corporate Vice President and Director of the Thermal Science Practice, Exponent Inc.

- Performs research in cryogenic fluid mechanics, heat transfer and phase change phenomena.
- Worked on numerous LNG projects with the industry in the US and internationally and has published extensively in this area.
- Member of the ISO TC67, WG10 working group that is developing a guidance document on the major hazards associated with the planning and design of onshore LNG facilities and associated marine activities.
- Has held several positions, including that of Associate Professor of Mechanical Engineering at the Massachusetts Institute of Technology.

Dr. Timothy L. Morse, Ph.D.
Senior Associate, Thermal Science Practice, Exponent Inc.

- Performs research in thermal and flow processes, including cryogenic fluid mechanics.
- Extensive experience in experimental techniques for fluid dynamic and thermodynamic systems.
- Previously a researcher in the Fluid Mechanics Research Laboratories at Cornell University. Conducted research in fluid-structure interaction.
# Background: Previous studies on LNG evaporation

<table>
<thead>
<tr>
<th>Authors</th>
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<th>Test name</th>
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Range: 0.02 to 0.30

- Identified turbulence as an important factor
- Defined a “turbulence factor” to adjust the heat transfer coefficient between water and LNG
- “Turbulence factor” determined empirically from LNG evaporation tests
- “Turbulence factor” depends on spill velocity
Background: LN$_2$ Tests
Presented at AICHE 2010 Spring Meeting

- Liquid nitrogen thickness has a large effect on evaporation rate (unexpected result)

- Quantified evaporation rate dependence on turbulence intensity
Modeling LNG spills

Models typically assume a constant evaporation rate.

- Spill rate
- Evaporation rate
- Spread rate
Factors affecting evaporation rate

- Air temperature
- Wind speed
- Spill thickness
- Interface speed
- Turbulence intensity
- Water temperature
- Water salinity
Testing Setup

- **Double-walled acrylic tube**
  ID = 17.3 cm

- **Submerged jet**
  - Centrifugal pump
  - Control valve
  - Nozzle (1.3 cm diameter)

- LNG poured on top
  up to ~7 cm thick
Testing Setup

Top view:
- Fill Port
- Vent Port
- Orifice
- Pressure Relief Valve

Front view:
- Jet nozzle
Experimental measurements

Evaporation rate

- Pressure (in cylinder)
- Temperature at orifice
- Orifice size

\[ \text{Mass flow rate through orifice} \]

Turbulence intensity

Measure water height fluctuations at the centerline

\[
\langle u^2 \rangle = 2g \sqrt{\langle \Delta h^2 \rangle} \]

\[
u_{rms} = \sqrt{\langle u^2 \rangle} \]
Water surface height measurements
Water surface height measurements

Optical setup

Image processing $\rightarrow h(t)$

Example image
Water surface height measurements

![Diagram showing water surface height measurements with a graph plotting turbulence intensity vs. jet flow rate. The graph compares present results with those from Hu (1993).]
Example LN$_{2}$ evaporation run \[ u_{rms} = 0.12 \text{ m/s} \]
Effect of liquid nitrogen height

3 runs
Varying initial thickness

Plot vs. thickness remaining

Data collapses onto single trend
Effect of cryogenic liquid height (LN$_2$)
Effect of water turbulence (LN₂) (avg. thickness ~ 2 cm)

Increasing turbulence intensity
Example LNG evaporation run

$u_{\text{rms}} = 0.22 \, \text{m/s}$
Thicknesse Effect: LNG vs. LN$_2$

Evaporation rate much more dependent on liquid thickness for liquid nitrogen.
Effect of water turbulence (LNG) (avg. thickness ~ 2 cm)

Increasing turbulence intensity
## Previous investigations

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Range of LNG Evaporation Data

- Present results
- Extrapolated to zero turbulence
Conclusions

1. Evaporation rate can vary significantly

2. Depends on:
   - Turbulence intensity (strongly)
   - Liquid layer thickness (less so for LNG)
   - (other factors)

3. These factors should be included in spill models
Future Work

1. Incorporate results into spill model
2. Quantify other factors affecting evaporation rate
3. Determine underlying mechanism for thickness effect
Acknowledgements

- Distrigas of Massachusetts – Frank Katulac
  - For providing the LNG used in these tests

- MIT Cryogenic Laboratory – Prof. Joseph Smith
  - For use of cryogenic equipment
Supplemental Material
Why is there a layer thickness effect?

Increased pressure at interface?

Nucleate Boiling

Height effect

1 cm LN$_2$: hydrostatic pressure = 0.01 psi

Film Boiling

Varying orifice size (¼” to ½”)

Cylinder pressure = 0.05 to 1 psi

No noticeable effect on Evaporation
Effect of water turbulence ($\text{LN}_2$) (avg. thickness ~ 2 cm)

- Increasing turbulence intensity

### Table: Orifice Size, Evaporation Rate, and Typical Pressure

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<td>1/2&quot;</td>
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<td>0.06</td>
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<td>3/8&quot;</td>
<td>0.1897</td>
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<td>1/4&quot;</td>
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Why is there a layer thickness effect?

Heat transfer through walls?

- Based on simple 1-D heat transfer, with LNG thickness of 1 cm (LN$_2$ similar)
  \[ \approx 2 \text{ W} \]

- Based on a typical evaporation rate of 0.2 kg/m$^2$ s
  \[ \approx 1000 \text{ W} \]

Also: evaporation tests on iced over water shows no thickness effect