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# Small-scale experimental study of vaporization flux of liquid nitrogen released on ice

Nirupama Gopalaswami [a], Luc Vechot [b], Tomasz Olewski [b], M. Sam Mannan [a, *]

[a] Mary Kay O'Connor Process Safety Center, Artie McFerrin Department of Chemical Engineering, Texas A&M University System, College Station, TX 77843-3122, USA
[b] Mary Kay O'Connor Process Safety Center – Qatar, Texas A&M University at Qatar, PO Box 23874, Doha, Qatar

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ABSTRACT

One of the LNG accident scenarios is the collision of an LNG carrier on an iceberg during marine transportation. A collision can result in damages to the vessel and lead to the leakage of the contents on ice or an ice-water mixture. When cryogenic liquid comes in contact with ice, it undergoes rapid vaporization due to the difference in temperature between the ice and cryogenic liquid. This process is different from the heat transfer between water and cryogenic liquid as ice is a solid and thus heat transfer to the pool occurs primarily through conduction. In this paper, the heat transfer phenomenon between ice and cryogenic liquid was studied through a small-scale experiment and the resulting vaporization mass fluxes were reported. The experiment involved six spills with varying amount of liquid nitrogen on different ice temperature to determine its effect on vaporization mass flux. The vaporization mass fluxes were determined by direct measurement of the mass loss during the experiment. The results indicated that the vaporization mass flux was a function of release rate and ice temperature. When the release rate and ice temperature was high, the vaporization mass flux follows a decreasing trend. With further reduction in release rate and ice temperature, the vaporization mass flux was found to be independent with time. The one dimensional conduction model was validated against experimental results. The predicted temperatures and heat flux were found to be in good agreement with the experimental data.


## 1. Introduction

One of the potential LNG accident scenarios is the collision of an LNG ship with an iceberg during marine transportation (Lee and Nguyen, 2011). Detailed consequences analysis considering various scenarios and hypotheses through calculations are required for LNG carriers. Consequence analyses in such cases depend on features of the ice and the structural strength of the LNG carrier. Two of the common types of collision that can occur are the side collision between side of the LNG vessel and iceberg and bow collision between forward part of hull and iceberg (Dahl, 2012). Special carriers like 'ice class LNG carrier' are being designed which have a strengthened hull to enable them to navigate through sea ice. However a collision with an iceberg can result in damage of the vessel and allow leakage of contents on ice or ice-water mixture. Such a scenario is common in areas where ice is predominantly present throughout the year like the Arctic Circle. Upon spillage of contents, one of the most important factors that affect cryogenic liquid release on ice is the heat flux from ice to cryogenic liquid. This process is different from the heat transfer between water and cryogenic liquid as ice is a solid and conduction phenomena is more dominating than convection due to boiling.

Very few experiments were performed by releasing cryogenic liquids on ice. In 1971, Nakanishi observed that when cryogenic liquids like Condensed Pipeline Gas (CPG, with composition CH4 92.7%, N2 7.3%; boiling point about −111.6 K) and Liquid Nitrogen ($LN_2$, boiling point −77 K) were poured on an ice layer maintained at −150 °C, there was no vapor film formation under the cryogen's layer and both liquids were found to be boiling in the nucleate regime (Nakanishi and Reid, 1971). When the experiment was repeated by pouring onto an ice layer maintained at −5 °C, a vapor film was observed to occur for liquid nitrogen alone, but not for CPG. It was concluded that when CPG was spilled on ice, it stays in film boiling for a brief period. This might have been due to the fact that the temperature difference between ice and CPG would have been small to sustain film boiling

* Corresponding author.
*E-mail address:* mannan@tamu.edu (M.S. Mannan).

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for a long period. This phenomenon was not addressed in detail in their research work.

In another study, small-scale experiments were performed with liquid nitrogen and LNG (Burgess et al., 1970). The primary objective of this study was to measure the heat flux and the vaporization rates. The experiments were performed at laboratory-scale, (spill area – 0.18 $m^2$) where cryogenic liquid was poured onto a flat tray (30.5 × 61 cm) of ice. The ice was made 4 cm thick and covered the entire surface of the tray such that the cryogenic liquid contacted only ice. LNG and $LN_2$ were released on ice. An array of thermocouples was placed below the ice to measure the time dependent temperature and associated heat transfer. However, wrinkling of the ice–cryogen interface disturbed the position of thermocouples and a spatial variation of heat transfer was not obtained in the test. The amount of cryogenic liquid poured was varied and the vaporization rate was reported for the experiment. The vaporization rates of nitrogen on ice varied from 0.08 to 0.12 kg $m^{-2}s^{-1}$. The small-scale tests showed a lot of variation in the vaporization rates reported for liquid nitrogen. The vaporization rates were reported for discrete values of time rather than for a continuous time interval.

A heat transfer model for growing ice thickness involving conduction and convection phenomena for release of cryogenic liquids on shallow water was undertaken by Vesovic (2007). However, the model was not validated with any experimental data. In all these experiments the source term and the heat flux from the substrate (ice) to the pool was calculated by measuring the temperature difference between the substrate and cryogenic liquid pool with time. This was possible by measuring the temperature difference between the substrate and cryogenic pool and using analytical expressions to determine the heat flux. The conclusions of small-scale experiments had limited effects due to the small confined space of the boiling cell. Most of the tests were also qualitative in nature and currently there are very few quantitative results for cryogenic liquids released on ice. It is also important to note that the current results do not show the time dependent behavior of vaporization rates.

An experimental investigation is undertaken here to improve the understanding of cryogenic liquid releases on ice and to provide benchmark qualitative and quantitative results. The small-scale experimental study was performed to verify the heat transfer mode of cryogenic liquids released on ice and independently validate the one dimensional conduction for cryogenic liquid released on ice. In doing this, the vaporization mass flux of liquid nitrogen was determined by mass loss in the experiment and temperature measurement. The results of the experiment were reported with respect to time to understand the variation of vaporization rates with respect to time.

## 2. Experimental setup and procedure

The experimental setup designed for small-scale spills of liquid nitrogen on ice is shown in Fig. 1. The small-scale experiments were performed in Fire Station 2 of the Ras Laffan Industrial City, Qatar. The setup consisted of a metallic cylinder with an inner diameter of 58.5 cm and a height 87.5 cm made of carbon steel. A stainless steel chimney (box) with dimensions 35 × 35 × 80 cm was placed inside the metal cylinder to protect it from fractures resulting from a cryogenic liquid spill. The stainless steel chimney was a square shape in cross-section and devoid of top and bottom. The square cross-sectional area was 0.13 $m^2$. The stainless steel chimney was lowered into the metallic cylinder using a steel support in such a way that the metallic cylinder is half filled with water at any point of time during the experiment and the liquid nitrogen was spilled inside the chimney. The setup ensured that liquid nitrogen interacted only with stainless steel walls of the chimney and water thereby protecting it from fractures. An ice slab of length 25 cm, breadth 25 cm and height 10 cm was placed inside the stainless steel chimney on top of water. A thermocouple to measure the temperature of the ice was embedded into the ice slab. Additional ice cubes were added around the ice slab to create an ice-water mixture and to limit contact of $LN_2$ with water. The temperature of ice, water below ice, liquid nitrogen and nitrogen vapor was monitored by distributed N-type thermocouples. The thermocouples were mounted on two polycarbonate boards and each included sixteen thermocouples distributed vertically. One board was mounted near the wall of the stainless steel box and another was held in the center of the box. The dimensions of the thermocouples relative to top surface of ice are given in Table 1. Each of these

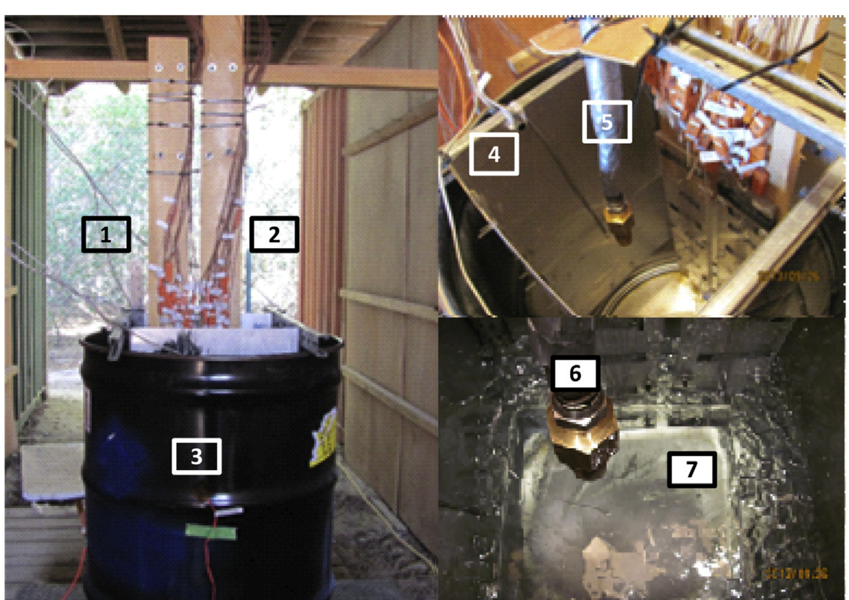


**Fig. 1.** Top and lateral views of experiment setup (1) Thermocouple Board 1 (2) Thermocouple Board 2 (3) Metallic Cylinder (4) Stainless Steel Chimney (5) $LN_2$ Discharge Pipe (6) Thermocouples (7) Ice substrate.