Influences of a spill rate on spread and evaporation of cryogenic liquid on land

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Abstract. This paper deals with spread and evaporation of a cryogenic liquid on land. The evaporation velocity, the vaporized volume of the liquid per unit area and unit time, is measured for the first time as a function of a release flow rate and time for liquid nitrogen that is spreading radially. The evaporation velocity is one of the main parameters that govern the phenomena of a pool spreading with evaporation, and it has been assumed as a constant within many of numerical modelling studies. Liquid nitrogen is spilled with finite flow rates onto an unbounded concrete ground. The experiments were conducted for various spill rates to assess the effects of this factor on spread and the evaporation velocity. It is found that a greater spill rate resulted in a faster spreading pool and a greater evaporation velocity.

1. Introduction  
Cryogenic liquids, e.g. liquid hydrogen, liquefied natural gas, liquid nitrogen, etc., have been playing important roles in a wide spectrum of industries as energy sources or coolants. However, most of them are toxic or flammable. The hazards associated with an accidental leakage of these liquids out of their containments need to be remarkably considered. The reason is that the liquid pool boils vigorously while it spreads on the ground. This is due to the big difference between the ground temperature and the boiling point of cryogenic liquid. As a result, a vapor cloud forms quickly and disperses around. The vapor cloud may cause an explosion or fire if ignited sources are presently available. Hence, the study of spread and evaporation of the liquid pool is necessary for the risk management. The evaporation velocity, i.e. the volumetric liquid evaporation rate per unit area, may be employed as an input to numerical investigations of the pool spread.

Many contributions involved in this phenomenon can be found in the literature in terms of numerical and experimental works. Briscoe and Shaw [1] derived a system of ordinary differential equations for describing cryogenic liquid spills on water and on land. Webber [2] developed a model for pool spreading and vaporization and its implementation in the computer code GASP. Vorfondern and Dienhart [3], [4] developed the LauV shallow layer model which consists of a system of two-dimensional partial differential equations. Kim et al. [5] presented experimental results of the evaporation of spreading liquid nitrogen. Regarding to experimental works, Vorfondern and Dienhart [3] investigated the spreading and evaporation of liquid hydrogen on two different grounds, i.e. water and aluminum. Olewski et al. [6] conducted experiments on a non-spreading pool to study the
vaporization rate of liquid nitrogen. Reid and Wang [7] studied the boiling rate of liquefied natural gas on various dike floor materials. Takeno et al. [8] investigated the evaporation rates of liquid hydrogen and liquid oxygen spilled on bounded ground.

To the best of our knowledge, experimental results except the authors’ work have not been found in the literature for the cryogenic liquid pool spreading on land regarding to the evaporation velocity of the spreading pool. The evaporation rate for non-spreading pools, which is confined to a bund, has been investigated only. In addition, the evaporation velocity has been assumed as a constant within many of numerical models such as a GASP model, a shallow-layer model and the model in Briscoe and Shaw [1].

In this work, liquid nitrogen was continuously spilled onto a concrete plate to reflect an accidental spill of the cryogenic liquid on land. The aims of the present work are to perform a comprehensive investigation of the effects of the spill rate on the spread and the evaporation velocity, and also to present a methodology to obtain the evaporation velocity as an empirical function of the spill rate and time.

2. Experimental setup
The overall experimental apparatus designed for laboratory-scale spills of liquid nitrogen on concrete ground is shown in Figure 1. The setup consisted of a cone-shape funnel, a circular concrete plate, fifteen thermocouples, a digital balance and a data acquisition system.

The liquid nitrogen was spilled on the center of the concrete plate through a discharge nozzle from the cone-shape funnel. To obtain the effect of various spill rates experiments were performed for seven discharge nozzles with a diameter of 6, 7, 8, 9, 10, 11, 12 mm. The funnel was well insulated to prevent heat transfer from the ambient to the liquid nitrogen through the wall. Thus, liquid nitrogen surface was almost stable during discharge. The concrete plate with a diameter of 1 m and a thickness of 0.02 m presented a solid ground.

Thermocouples were used to obtain the arrival time of a spreading pool. The thermocouples were mounted in the concrete plate in two radial directions, as shown in Figure 2. The distances of thermocouples with reference to the center of the concrete plate are given in Table 1. The thermocouple TC-0 at the center of the plate was employed to determine the time when the experiment started, while two thermocouples TC-107 and TC-207 were used to determine the time when the liquid pool spread out of the plate.

The concrete plate was placed on the digital balance with a resolution of 0.1 g to measure the weight of the spreading liquid pool on the concrete plate. The DEWETRON data acquisition system was used to record data from the thermocouples and the balance. With the experimental apparatus described in the preceding paragraph, twenty-eight experiments were conducted for seven cases of spill rate, i.e., four runs for each case.
The measurement method of the discharge flow rate of liquid nitrogen using the funnel was well described in Kim et al. [5]. The results are shown in Figure 3 and Table 2. The spill rates were not constant but varied slightly, i.e. less than 15.8 %. It is convenient to define the nominal spill rate for each case as the averaged value during the spill time.

Table 1. Thermocouple position

| i | Distance from the center of the plate, m | Thermocouple number |
|---|----------------------------------------|---------------------|
| 0 | 0                                      | TC-0                |
| 1 | 0.20                                   | TC-101, TC-201      |
| 2 | 0.25                                   | TC-102, TC-202      |
| 3 | 0.30                                   | TC-103, TC-203      |
| 4 | 0.35                                   | TC-104, TC-204      |
| 5 | 0.40                                   | TC-105, TC-205      |
| 6 | 0.45                                   | TC-106, TC-206      |
| 7 | 0.50                                   | TC-107, TC-207      |

Figure 3: Mass spill rate versus time

Table 2. The nominal spill rate

| Case | Spill time, s | Nominal mass spill rate, kg/s | Nominal volume spill rate, m³/s |
|------|---------------|------------------------------|---------------------------------|
| 1    | 198           | 0.0402                       | 4.9806 × 10⁻⁵                   |
| 2    | 135           | 0.0546                       | 6.7755 × 10⁻⁵                   |
| 3    | 87            | 0.0739                       | 9.1709 × 10⁻⁵                   |
| 4    | 67            | 0.0877                       | 1.0873 × 10⁻⁴                   |
| 5    | 51            | 0.1050                       | 1.3024 × 10⁻⁴                   |
| 6    | 37            | 0.1319                       | 1.6358 × 10⁻⁴                   |
| 7    | 27            | 0.1629                       | 2.0203 × 10⁻⁴                   |
The spill rate varied less than 6.6% when the pool spread between two thermocouples in every experiment. Therefore, it can be approximately considered to be constant during this period and defined as

\[
\overline{Q_{1i}} = \frac{Q_{1,i+1} + Q_{1,i}}{2}
\]

(1)

The spreading rate \(Q_{2i}\) of the pool when it spread from thermocouple \(i\) to \(i+1\) was calculated based on the pool weight and the arrival time as follows:

\[
Q_{2i} = \frac{W_{i+1} - W_i}{t_{i+1} - t_i} = \frac{\Delta W}{\Delta t}
\]

(2)

It was experimentally found that \(W_{i+1} < W_i + \overline{Q_{1i}} \Delta t\). The difference between both sides of the inequality is accounted for the evaporated liquid amount. Then, the evaporation velocity when the pool spread from thermocouple \(i\) to \(i+1\) was defined as

\[
E_i = \frac{\overline{Q_{1i}} \Delta t + W_i - W_{i+1}}{\rho A_i \Delta t} = \frac{\overline{Q_{1i}} - Q_{2i}}{\rho A_i}
\]

(3)

Then, uncertainty analysis proceeded to estimate the combined standard uncertainty of the experimental data. In the preceding procedure, the evaporation velocity was approximately considered to be constant when the pool spread from thermocouple \(i\) to \(i+1\). Hence the result will be more accurate if the distances between thermocouples are reduced.

3. Result and discussion

By following the procedures outlined in the previous section, the experimental results are shown in Figure 4.

![Figure 4: Pool radius versus time](image)

As can be seen in Figure 4, the liquid pool spread faster in case of higher spill rate. Briscoe and Shaw [1] demonstrated that the main driving force for pool spread was gravity. The force on a liquid element acts in the direction of decreasing pool height and decreases as the pool spreads and becomes thinner. The higher the spill rate, the more the liquid was supplied into the pool, possibly following by a greater instant pool height. As a result, the pool in case of the higher spill rate spread faster than that in case of the lower spill rate. To normalize the experimental data and to reduce the number of parameters, the characteristic time and length scale are introduced as follows:

\[
r = \frac{R}{L_{ch}}, t_1 = \frac{t}{\tau}, \varepsilon = \frac{\tau E}{L_{ch}}
\]

(4)
Characteristic time, \( \tau \), and length scale, \( L_{ch} \), are defined as follows:

\[
\tau = \left( \frac{\beta}{\chi^3} \right)^{0.2}, \quad L_{ch} = \left( \frac{\beta^2}{\chi} \right)^{0.2}
\]  

(5)

The dimensionless radius and the dimensionless evaporation velocity were obtained as shown in Figures 5-6.

A curve fitting for experimental data in Figure 5-6 was figured out as follows:

\[
r = 3.2453i^{0.2812}
\]  

(6)

\[
\varepsilon = 0.1161 \ r^{-1.7209}
\]  

(7)

Substituting Eq.6 into Eq.7 yields

\[
\varepsilon = 0.0153i^{-0.4839}
\]  

(8)

Transforming the dimensionless quantity to the dimensional one, the evaporation velocity is revealed as a function of spill rate and time as follows:

\[
E = 0.0212 \beta^{0.2968} r^{-0.4839}
\]  

(9)

Substituting the spill rates into Eq.9, the evaporation velocities versus time are obtained and shown in Table 3. It can be seen that the greater the spill rate is, the greater the coefficients becomes.

| # | Nominal volume spill rate, m³/s | Evaporation velocity versus time, m/s |
|---|---------------------------------|--------------------------------------|
| 1 | 4.9806 × 10^{-5}               | \( E = 0.0011r^{-0.4839} \)          |
| 2 | 6.7755 × 10^{-5}               | \( E = 0.0012r^{-0.4839} \)          |
| 3 | 9.1709 × 10^{-5}               | \( E = 0.0013r^{-0.4839} \)          |
| 4 | 1.0873 × 10^{-4}               | \( E = 0.0014r^{-0.4839} \)          |
| 5 | 1.3024 × 10^{-4}               | \( E = 0.0015r^{-0.4839} \)          |
| 6 | 1.6358 × 10^{-4}               | \( E = 0.0016r^{-0.4839} \)          |
| 7 | 2.0203 × 10^{-4}               | \( E = 0.0017r^{-0.4839} \)          |
Figures 7-13 depict comparison between the experimental data and the empirical functions shown in Table 3. In general, the results appear to show good agreements except the discrepancy in the short period of initial time, in which the experimental results are greater than those obtained from the empirical functions. Hence, the empirical function, i.e. Eq.9, will be able to predict the evaporation velocity-versus-time for other spill rates.

Figure 7: Case 1

Figure 8: Case 2

Figure 9: Case 3

Figure 10: Case 4

Figure 11: Case 5

Figure 12: Case 6
The figure of Case 7 is omitted because of limitation, and it illustrates the same trend as other cases.

Experimentally, for a non-spreading pool, Olewski et al. [6] reported that the average conductive heat flux from the ground to the pool is proportional to the inverted square root of time as

$$ q = 135.2t^{-0.5} $$

(10)

Using a density of 806.11 kgm$^{-3}$ and a latent heat of 199.18 kJkg$^{-1}$ of liquid nitrogen, the evaporation velocity is equal to

$$ E = 0.0008t^{-0.5} $$

(11)

In the non-spreading pool study, the evaporation velocity is a function of time only. The graphical form of Eq.11 was shown in Figure 7 for comparison. It can be seen that the evaporation velocity obtained in this study is higher than that in the non-spreading study because the liquid pool in this work spread outward continuously to receive heat from the warm ground. On the other hand, in the non-spreading pool, the ground temperature decreases continuously with time.

4. Conclusion

In summary, the results of the present study support the idea that the spill rate plays an important role in spread and evaporation processes of the cryogenic liquid pool. The relationship between the spill rate and the evaporation velocity was experimentally obtained for the first time. To be more specific, a greater spill rate makes the pool spread faster and results in a greater evaporation velocity. In addition, the present work was compared to the non-spreading pool study to discover that the evaporation velocity in this work is greater than that in the non-spreading pool study.

A robust methodology for obtaining an empirical function of evaporation velocity for a spreading pool of cryogenic liquid has been clearly demonstrated in this study. This methodology may be applied quite reliably for the spreading pool of other cryogenic liquids.

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Nomenclature

- $A_i$: pool area at thermocouple $i$, m$^2$
- $\bar{A}_i$: $0.5(A_i + A_{i+1})$ average pool area, m$^2$
- $C_d$: discharge coefficient
- $D_n$: nozzle diameter, m
- $E$: evaporation velocity, ms$^{-1}$
- $E_i$: evaporation velocity when the pool spread from thermocouple $i$ to $i + 1$, ms$^{-1}$
- $g$: acceleration due to gravity, ms$^{-2}$
- $h$: instant height of the liquid level, m
- $h_i$: initial height of the liquid level, m
- $h_n$: length of the nozzle, m
- $K$: the Froude number
- $k$: thermal conductivity of the ground, Wm$^{-1}$K$^{-1}$
- $L$: latent heat of the liquid, kJkg$^{-1}$
- $L_{ch}$: characteristic length scale, m
- $\bar{m}_i$: mass vaporization rate, kgm$^{-2}$s$^{-1}$
- $Q_1$: mass spill rate, kgs$^{-1}$
- $Q_{1,i}$: spill rate when the pool spread to thermocouple $i$, kgs$^{-1}$
- $Q_{2,i}$: average spill rate when the pool spread from thermocouple $i$ to $i + 1$, kgs$^{-1}$
- $Q_{2i}$: spreading rate of the pool when it spread from thermocouple $i$ to $i + 1$, kgs$^{-1}$
q  heat flux, kJm$^{-2}$s$^{-1}$
R  pool radius, m
r  dimensionless pool radius
$T_a$  ambient temperature, K
$T_B$  boiling point of the liquid, K
$t$  time from release, s
$t_1$  dimensionless time
$t_i$  arrival time at thermocouple i, s
$\tau$  spill time, s
$V$  instant volume of liquid in the funnel, m$^3$
$W_i$  pool weight at thermocouple i, kg
$\alpha$  thermal diffusivity of the ground, m$^2$s$^{-1}$
$\beta$  volume spill rate, m$^3$s$^{-1}$
$\gamma$  =2g, ms$^{-2}$
$\varepsilon$  dimensionless evaporation velocity
$\theta$  cone-angle of the funnel, radian
$\rho$  liquid density, kgm$^{-3}$
$t_i$  characteristic time, s
$\Delta t$  difference in arrival time, s
$\Delta W$  difference in pool weight, kg

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