Journal of Loss Prevention in the Process Industries 39 (2016) 68–73

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

journal homepage: www.elsevier.com/locate/jlp

Experimental study of the evaporation of spreading liquid nitrogen

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ARTICLE INFO

Article history:
Received 1 June 2015
Received in revised form
11 November 2015
Accepted 21 November 2015
Available online 30 November 2015

Keywords:
Liquid nitrogen
Spreading pool
Release flow rate
Evaporation velocity

ABSTRACT

The investigation of cryogenic liquid pool spreading is an essential procedure to assess the hazard of cryogenic liquid usage. There is a wide range of models used to describe the spreading of a cryogenic liquid pool. Many of these models require the evaporation velocity, which has to be determined experimentally because the heat transfer process between the liquid pool and the surroundings is too complicated to be modeled. In this experimental study, to measure the evaporation velocity when the pool is spreading, liquid nitrogen was continuously released onto unconfined concrete ground. Almost all of the reported results are based on a non-spreading pool in which cryogenic liquid is instantaneously poured onto bounded ground for a very short period of time. For the precise measurement of pool spreading and evaporation weight with time, a cone-type funnel was designed to achieve a nearly constant liquid nitrogen release rate during discharge. Specifically, three nozzles with nominal flow rates of 3.4×10^{-2} kg/s, 5.6×10^{-2} kg/s and 9.0×10^{-2} kg/s were used to investigate the effect of the release rate on the evaporation velocity. It is noted that information about the release rate is not necessary to measure the evaporation velocity in case of the non-spreading pool. A simultaneous measurement of the pool location using thermocouples and of the pool mass using a digital balance was carried out to measure the evaporation velocity and the pool radius. A greater release flow rate was found to result in a greater average evaporation velocity, and the evaporation velocity decreased with the spreading time and the pool radius.

1. Introduction

Cryogenic liquids, such as liquefied natural gas, liquid hydrogen and liquid nitrogen, are commonly used. However, accidents during transportation and storage are a serious problem.

When cryogenic liquid leaks out of its container unwantedly, a liquid pool is created and spreads rapidly. At the same time, the boiling process occurs violently because the ambient temperature is much greater than the boiling temperature of the cryogenic liquid. As a result, a vapor cloud is formed due to heat flux into the pool from various sources: conduction heat flux from the ground, convection heat flux from the air and radiation heat flux from the sun. Moreover, if the cryogenic liquid is flammable, the potential of a pool fire and explosion are obvious. Additionally, if the leaked cryogenic liquid is toxic and is spilled with large flow rate, the air will be polluted and people's health may be put in danger. Therefore, a study of the spreading and vaporization of a cryogenic liquid pool is an important procedure for hazard assessment of the cryogenic liquid storage system.

There have been a number of different studies, including analytical work (Briscoe and Shaw, 1980) and numerical works (Brandeis and Kansa, 1983; Stein and Ermak, 1980). Regarding the analytical and the numerical work, models have been created to predict and calculate pool spread. However, to make the models solvable, the authors neglected radiation heat flux from the sun and convection from the ambient air and only considered one-dimensional heat conduction from the ground. Another approximation parameter was the evaporation velocity, defined as the evaporated volume of liquid per unit area of the liquid pool per unit time. In this case, the evaporation velocity should be determined experimentally. This is the reason why experiments, which can precisely measure the evaporation velocity, are still important.

In many experimental studies (Reid and Wang, 1978; Takeno et al., 1994; Olewski et al., 2013), to measure the evaporation velocity, cryogenic liquid was poured onto bounded ground

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http://dx.doi.org/10.1016/j.jlp.2015.11.018
0950-4230/

instantaneously so that the discharge time was much smaller than the evaporation time. In other words, measurements were made for a non-spreading pool. As a result, heat flux into the non-spreading pool decreased continuously due to a decrease in the ground temperature. In real accidents, a cryogenic liquid spills and spreads over a large or unbounded ground such that the pool spreading process should be taken into account. In contrast with a non-spreading pool, a spreading pool is continuously in contact with new warm ground in front of the pool. Therefore, the heat flux into the spreading pool is obviously greater than the heat flux of the non-spreading pool with the same release volume of liquid.

For the present work, a cone-type-funnel was designed to maintain a constant release rate during discharge so that the evaporation velocity for the spreading pool could be measured. Additionally, we required a simultaneous measurement of the pool boundary arrival time using thermocouples and the weight of the spreading pool using a digital balance.

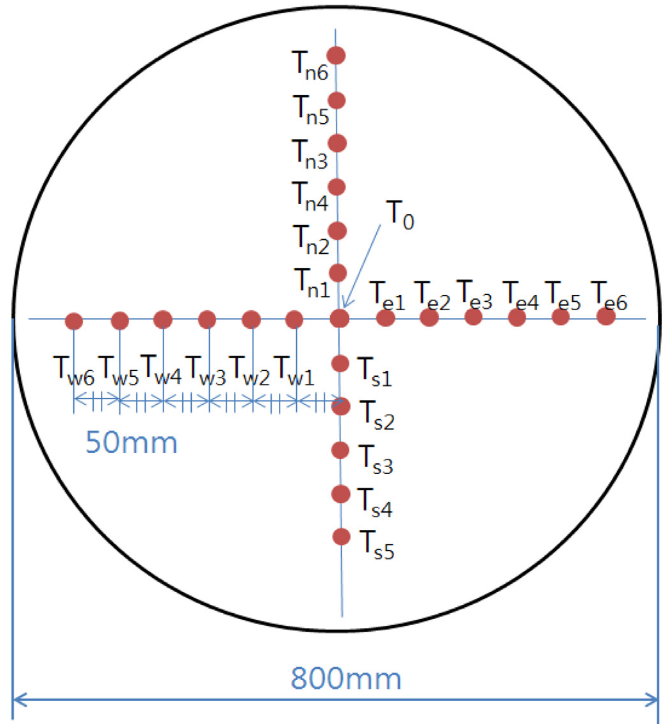

Fig. 2. Concrete ground with the thermocouples.

2. Experimental set up and procedure

The experimental apparatus was set up within a laboratory with three main components: a funnel, a concrete flat plate and a balance, as shown in Fig. 1. The funnel, which supplies liquid nitrogen for experiment, was insulated to avoid conduction through the funnel wall and was placed above the concrete plate. Dimensional parameters of the concrete plate are 0.8 m in diameter and 0.025 m in thickness. Liquid nitrogen is spilled onto the concrete plate. The precise digital balance with a resolution of 0.1 g was used to measure the mass of the liquid nitrogen that was spreading over the concrete plate. The balance was connected to a computer to record the spreading mass.

To measure the arrival time of the pool front, there were 24 thermocouples that were mounted along four concurrent horizontal lines from the concrete plate center. Along each line, the thermocouples were spaced 0.05 m apart starting at the center of the plate. The thermocouple arrangement is shown in detail in Fig. 2. A thermocouple is considered to be within the liquid pool if the thermocouple temperature falls below −190 °C because the boiling point of liquid nitrogen is −196 °C. The thermocouples were also connected to the computer to record the temperature data simultaneously with the mass data.

A cone-type funnel was designed as the liquid nitrogen supplier. The key factor in maintaining an approximately constant release flow rate during the experiment is the design of the funnel with a large cone angle and high throat. Three nozzles with a diameter of 6 mm, 8 mm and 10 mm were utilized to change the release flow rate. Their nominal flow rates are 3.4×10^{-2} kg/s, 5.6×10^{-2} kg/s and 9.0×10^{-2} kg/s respectively.

The outlet of the funnel was blocked using a pad before 7.5 L of liquid nitrogen was poured into the funnel from the tank. Once the liquid nitrogen was poured into the funnel, it boiled violently for a few seconds due to the significant difference in temperature between the liquid nitrogen and the funnel. After several minutes, the liquid nitrogen became very stable. This is because the funnel is well isolated and the temperature difference between the funnel and the liquid nitrogen becomes small. The stability of the liquid nitrogen in the funnel is very important because of the influence on the release flow rate. Next, the pad stopping the outlet was removed and the liquid nitrogen was released onto the concrete plate. The thermocouple T_0 at the center of the concrete plate was used to determine the moment when the experiment started. Six experiments were carried out and were recorded with a video camera to observe the experimental process.

3. Results and dicussion

Two experiments were conducted for the three nominal flow rates of 3.4×10^{-2} kg/s (Case1, Case 2), 5.6×10^{-2} kg/s (Case 3, Case 4), and 9.0×10^{-2} kg/s (Case 5, Case 6). In each experiment, the period of time that the liquid nitrogen pool required to reach a particular radius was calculated by averaging the four times corresponding to the four thermocouples in four directions to compensate for several non-isotropic conditions caused by manufacturing.

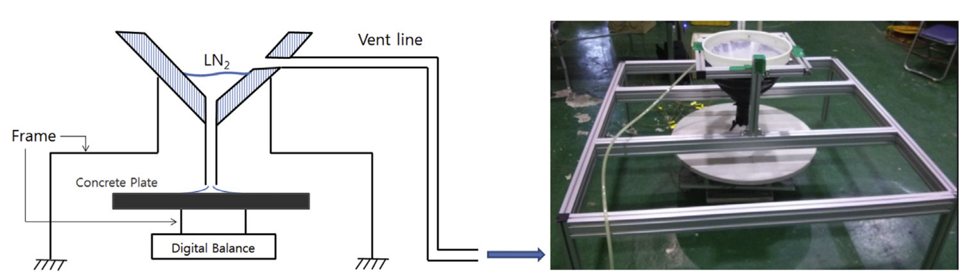

Fig. 1. The experiment apparatus in schematic form (left) and original form (right).