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Study of the conductive heat flux from concrete to liquid nitrogen by solving an inverse heat conduction problem

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ABSTRACT

The conductive heat flux from concrete to liquefied natural gas (LNG) is important to evaluate the hazards of LNG spills. In this paper, experiments are conducted to investigate the conductive heat flux from concrete to liquid nitrogen (LN_2), which was used as a safe cryogenic analogue to LNG. During experiments, LN_2 was spilled onto a concrete block instantly and thermocouples were embedded inside the concrete at different depths to monitor the temperature data during LN_2 vaporization. The solution procedure for inverse heat conduction problems is employed to reconstruct the dynamic heat flux profile at concrete surface, using the measured temperature data and concrete thermal properties as inputs. The results indicated that the perfect thermal contact model (PTCM) well matches the calculated heat flux at later stage of spill. While at initial stage the heat flux values are restricted by the vapor cushion caused by vigorous boiling of LN_2, which is also responsible for the error distribution trend in data fitting by PTCM. Evaporation rate of LNG is evaluated based on present heat flux results and it is found to be lower than when LNG spilled on water. The results in this paper provide insights for the applicability of PTCM in predicting conductive heat flux from concrete to cryogenic liquids. The results are also expected to improve the source term model involved in hazard evaluation of LNG spills.

1. Introduction

With the increasing demand of clean energy, liquefied natural gas (LNG) is getting a wide range application in the world (Chen et al., 2016; Lee et al., 2016). However there exist safety concerns with respect to the transportation and storage of LNG. An accidental failure of LNG tanker during transportation or storage can lead to spills of LNG on ground. Upon released on ground, LNG would boil violently by absorbing heat from ground surface, air flow and sunshine radiation. The resulted vapor cloud of LNG and its dispersion can pose serious threats to public safety as the vapor cloud is flammable and explosive (Bariha et al., 2016; Gopalaswami et al., 2015a, 2015b). Two models are required to evaluate the hazards caused by LNG spill, one is the source term model which determines the spread and evaporation rate of LNG, the other is the vapor dispersion model which describes the motion and dispersion of LNG vapor (Véchot et al., 2013). Currently, accurate data for the evaporation rate of LNG are limited due to, on one hand, the complexity of the boiling heat transfer of cryogenic liquids and on the other hand, due to the uncertainty of the thermal properties of solid substrates such as concrete.

Previous studies indicated that the conductive heat flux from ground predominantly contributes to the early stage vaporization of LNG (Briscoe and Shaw, 1980; Burgess et al., 1962). In order to quantitatively determine the conductive heat flux from concrete to LNG, the perfect thermal contact model (PTCM) was normally employed in different studies (Briscoe and Shaw, 1980; Olewski et al., 2013, 2015). The PTCM assumes that the concrete surface reaches and remains at LNG's boiling point immediately after contact, thus the heat conduction in concrete is subject to Dirichlet boundary condition. With PTCM, the surface heat flux of concrete can be analytically calculated when thermal properties of concrete are known. Olewski et al. (2015). inserted thermocouples and heat flux sensor into concrete block to investigate conductive heat flux from concrete to liquid nitrogen (LN_2), which was used as a cryogenic analogue to LNG. The thermal properties of concrete were estimated by fitting to the data recorded by thermocouples and heat flux sensor, and then conductive heat flux to liquid pool was calculated based on PTCM. The same authors (Olewski et al., 2013) also directly obtained the evaporation rate of LN_2 by measuring the

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mass loss rate of LN_2 pool and the conductive heat flux was calculated proportional to evaporation rate of LN_2. Their results indicated that the conductive heat flux could be well matched by the PTCM at later stage. While the initial heat flux was not obtained due to the unknown LN_2 discharge rate.

Nevertheless, the applicability of PTCM has not been fully validated as the data fitting in (Olewski et al., 2015) showed a trend in error distribution, for which the vapor blocking effect on heat transfer is a potential reason. Actually, the initial temperature difference between concrete and LN_2 is large and the boiling of LN_2 is violent. The resulted vapor cushion would influence the heat transfer between LN_2 and concrete. This is confirmed by Cha et al. (2014). who measured the surface temperature of sandstone when submerged in LN_2. They found that about 7 min was needed for the surface to reach LN_2's temperature. Their results indicated that considerable errors can be introduced when applying PTCM in analyzing heat flux from solids to cryogenic liquids.

Unlike the method using PTCM, the techniques of solving inverse heat conduction problems (IHCP) provide an opportunity to independently calculate the conductive heat flux without PTCM. The IHCP involves determining a thermal boundary condition using the measured temperature information inside a heat conduction body (Prud'homme and Hung Nguyen, 2001). The dynamic boundary condition which is hard to directly measure can be reconstructed from the accessible internal temperature information by solving an IHCP. Therefore in order to fully investigate the conductive heat flux from concrete to LNG, the solution procedure for IHCP is employed in this paper to calculate the dynamic heat flux profile at concrete surface. The internal temperature data were experimentally measured by thermocouples installed inside a concrete block. During experiment LN_2 was used as a safe cryogenic analogue to LNG and the thermal properties of concrete were tested in laboratory. By solving the IHCP, conductive heat flux within the whole time duration can be obtained without measuring the mass loss rate of LN_2 pool. The present results can be independently compared to those based on PTCM such that insights of the applicability of PTCM can be given. The present results are also expected to improve the source term model involved in hazard evaluation of LNG spill.

2. Experimental setup

Fig. 1 illustrates the experimental setup in this work. A rectangle box made of expanded polystyrene (EPS) is used as the container of concrete and LN_2. The inner dimension of the EPS box is 180 mm × 180 mm × 260 mm and the wall thickness is 20 mm. The concrete is made of cement and fine sand in proportion 1:1 and with a height of 165 mm. The concrete is air-cured in the EPS box for 24 h and then the containment space above concrete is filled with water to eliminate micro cracks on concrete surface. The water treatment lasted for 20 days at room temperature (298 K) before the experiments.

Totally five T-type thermocouples (TT-T-24-SLE from OMEGA, measuring range: 73–323 K) were embedded in the concrete to monitor temperature data. The actual depths of TC 1–3# were inspected by cutting the concrete block after experiment and are marked in Fig. 1. TC 4# was at the bottom of concrete and was used to validate the bottom boundary condition. The experimental duration was controlled such that the temperature of TC 4# remained unchanged, thus the concrete could be treated as a semi-infinite conduction body. 25min was chosen to be the experimental duration based on preliminary experiments. TC 5# is attached on the top surface of concrete to record the beginning time of LN_2 spill (not shown in Fig. 1). Before experiment all thermocouples were calibrated by a TP-100 temperature sensor within the range of

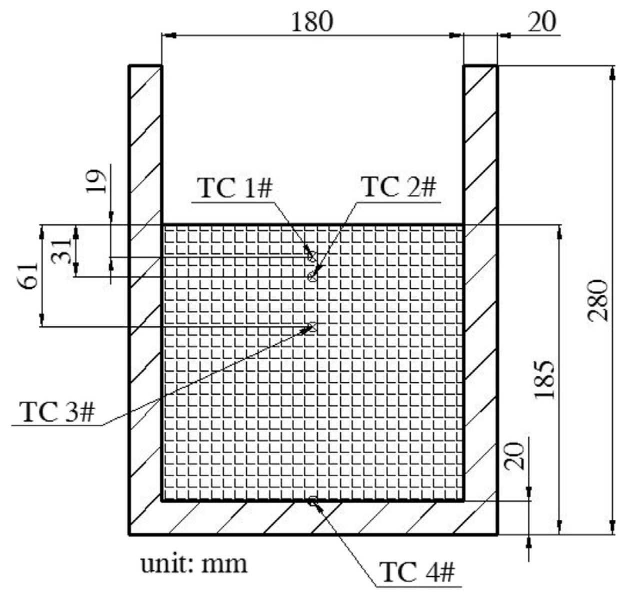

Fig. 1. Schematic of experimental setup.

77–298 K and the precision after calibration was ±0.5 K. During experiments all the thermocouples were connected to a data acquisition system and the temperature data were recorded every 0.1s.

In experiments, LN_2 was poured onto the concrete instantaneously and a LN_2 pool was formed instantly. The starting time was recorded by TC 5# and the experiment was stopped 25 min after discharge of LN_2. After experiment the thermal properties of concrete sample were tested in laboratory at room temperature (298 K). The thermal conductivity was tested by the Thermal Conductivity Scanning (TCS) device developed by Yuri Popov et al. (1985). The specific heat was tested by the Rock and Soil Specific Heat device (model: XY-BRR). Thermal property tests were repeated for three times and the mean values are listed in Table 1.

3. IHCP solution for conductive heat flux

When thermal boundary conditions are given, the direct problem of heat conduction can be solved by various analytical and numerical methods, including Laplace transform and finite element methods. The objective of IHCP is to reconstruct the unknown boundary condition using internal temperature data as input information. The solution of IHCP is much more difficult than the corresponding direct problem and is mathematically ill-posed (Beck, 2008; Qian and Wang, 2013; Shen, 1999). An effective solution procedure is to convert IHCP into an optimization problem with a goal of minimizing the square deviation between calculated and measured temperature data. The calculated temperature data are obtained by solving the direct heat conduction problem described by (Carslaw and Jaeger, 1986)

Table 1
Thermal properties of concrete.

Density ρ, kg/m^3	Thermal conductivity λ, W/m/K	Specific heat c_p, J/kg/K	Thermal diffusivity a, m^2/s
2205.8	1.519	1064	6.5×10^{-7}