Computational study of LNG evaporation and heat diffusion through a LNG cargo tank membrane

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The seepage of the cryogenic LNG through the cracks in membrane insulation may result in cold spots within the hull structures of LNG vessels. At the cold spot, the hull structure will be crystallized and brittle. Also, the loss of LNG containments may lead to a potentially significant hazard. The estimation of the temperature distribution along the insulation panel and the heat diffusion speed through the insulation materials are crucial to assess the safety of LNG vessels. The prediction of the flow and thermal behaviors of the leaked LNG requires complex multiphase flow numerical simulation. The CFD (computational fluid dynamics) model is proposed to simulate the diffusion behavior and the heat transfer characteristics of leaked LNG including the liquid-to-gas phase change through porous structure. The CFD model considers phase change, gas–liquid reactions in the porous media and the accompanied rates of heat transfer. It also considers the geometry of NO96 membrane storage facilities with glass wool and plywood. In the numerical simulation, the LNG pool spreading, heat diffusion, and the evaporation are investigated. The simulation indicates that the predicted speed of seepage is too high to evaporate the LNG after the leakage.

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1. Introduction

Natural gas (NG) is a nontoxic, colorless, odorless, and non-corrosive fossil fuel, which mainly contains methane, ethane, propane, butane, and trace amounts of nitrogen and carbon dioxide (Hasan et al., 2009). The supply chain of NG includes the liquefaction (boiling point of -163°C) and the transportation. Due to its cryogenic nature, LNG (liquefied natural gas) is continuously vaporized and lost as boil-off gas (BOG). For membrane type LNG carrier, the current estimated natural boil-off gas rate (BOR) is 0.15% of cargo volume per day. In 2007, at least 3.3 mtpa (million metric tons per annum) from the total LNG movement of 165.3 mtpa were lost due to boil-off during transportation only, which costs more than 1.275 billion USD (Petroleum, 2008; Hasan et al., 2009). Also, market demands improved efficiency in propulsion systems as well as flexibility in LNG carrier operations (including change of route, spot trade, and temporary storage of LNG); all of which require significant reduction of BOR value.

LNG cargo insulation systems are designed to minimize the heat loss from the cryogenic liquid at −163 °C to ambient as well as to withstand various external impacts during the voyage. Many research efforts have been given to novel insulation materials and structures at low temperatures (Presley and Christensen, 1997; Demharter, 1998; Caps and Fricke, 2000; Choi et al., 2013; Zakaria et al., 2013) and reliquefaction systems (Shin and Lee, 2009; Chu et al., 2012; Li et al., 2012) to meet the demands of lower BOR. Since the BOR is proportional to the heat transfer amount from ambient through cargo containment systems (CCS), the thermal properties and the structure of the CCS insulation system are important. Safety issues due to sloshing load have been vigorously investigated (Ito et al., 2008; Lee et al., 2011a, 2011b; Hwang et al., 2012; Nho et al., 2012), because CCS can be damaged by various reasons including static/rupture/dynamic loads and sloshing (Rhee, 2005; Vanem et al., 2008; Wang and Shin, 2009; Lee et al., 2013), which results in leakage of cryogenic LNG through the cracks. The leaked LNG can significantly weaken the strength of the inner plate of hull by yielding “cold spots” of which temperature is under the ductile-to-brittle transition temperature (−60°C) by the heat exchange with the cryogenic fluid (Choi et al., 2012).

The membrane CCSs used in LNG carriers are largely divided into the Mark III and NO96 systems (Choi et al., 2012) (Fig. 1). The present Mark III membrane is composed of a primary stainless steel 304 L membrane positioned on top of an insulation panel which incorporates the composite secondary barrier (a layer of triplex, which is a thin aluminum foil with glass fiber cloths...
attached on both sides). The insulation consists of a load-bearing system made of prefabricated panels in reinforced polyurethane foam (RPUF) (Fig. 1(a)). The thickness of the insulation panel can be varied from the standard 270 mm up to 400 mm, thereby reducing the BOR down to 0.1% per day. In the NO 96 system, both the primary and secondary barriers are made of thin sheet of nickel alloy, called ‘invar’. The insulation system is composed of two layers of plywood boxes filled with “perlite” (granules of crushed volcanic rock) (Fig. 1(b)). The primary membrane contains the LNG cargo, while the secondary membrane, identical to the primary, ensures a redundancy in case of leakage. Each of the 500 mm wide invar strakes is continuously spread along the tank walls and is evenly supported by the primary and the secondary insulation layers. In order to attain lower BOR in the conventional NO 96 system, the insulation performance can be improved by replacing perlite with glass wool (NO96 GW) or by adding an intermediate layer of RPUF insulation (NO96 L3).

The variations of NO 96 system affect the insulation capacity under leakage condition. When LNG starts to spill into the leaked hole on an insulation panel, it rapidly diffuses and the vaporization can take place forming evaporated NG mixed with nitrogen. The diffusion speed and the thermal change characteristics due to the leakage in LNG cargo containment have been studied. Choi et al. (2012) performed numerical analysis on LNG leakage through Mark III insulation boxes with the experimentally measured thermal properties and Bae et al. (2007) conducted comprehensive safety evaluation for Mark III LNG carriers. Kim and Lee (2008) and Lee et al. (2011a, 2011b) investigated the leakage characteristics of LNG through the Mark III type composite secondary barriers. Most of the investigations were focused on Mark III.

The insulation layers can act as buffer layers, which could delay transport of the leaked LNG to inner hull. Also, the leaked LNG can be preheated and vaporized through the insulation layers to form evaporated gas which has greatly lower heat transfer coefficient than liquid and thereby further delay the temperature decrease of the inner hull in contact (Livingston et al., 2009). Also, once the insulation boxes are filled with leaked LNG (or evaporated NG gases), the heat transfer rate from outside to the LNG inside the cargo is greatly changed; usually the insulation performance is significantly degraded leading to considerable amount of LNG loss. Thus, in this paper, the diffusion speed and the vapor/liquid composition changes of the leaked LNG through the modified NO96 (NO96 GW) insulation box will be numerically investigated (Fig. 2, GTT). The diffusion and thermal characteristics of leaked LNG flow have not been explored for the modified NO96 systems. Since this paper is dealing with very fundamental aspect, the

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Description</th>
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<tbody>
<tr>
<td>$A_{\text{eff}}$</td>
<td>interfacial area density (m²/m³)</td>
</tr>
<tr>
<td>$C_D$</td>
<td>drag coefficient (dimensionless)</td>
</tr>
<tr>
<td>$D_D$</td>
<td>kinetic diffusivity (m²/s)</td>
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<tr>
<td>$D_{\text{drag}}$</td>
<td>interfacial drag force (kg/m² s²)</td>
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<td>$d_{\text{eff}}$</td>
<td>interfacial length scale (m)</td>
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<tr>
<td>$e$</td>
<td>specific energy (J/kg)</td>
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<tr>
<td>$G$</td>
<td>mass flux (kg/m² s)</td>
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<tr>
<td>$h$</td>
<td>heat transfer coefficient (W/m² K)</td>
</tr>
<tr>
<td>$i$</td>
<td>specific enthalpy (J/kg)</td>
</tr>
<tr>
<td>$k$</td>
<td>thermal conductivity (W/mK)</td>
</tr>
<tr>
<td>$K_{\text{loss}}$</td>
<td>loss coefficient (m⁻¹)</td>
</tr>
<tr>
<td>$K_{\text{perm}}$</td>
<td>permeability (m²)</td>
</tr>
<tr>
<td>$Nu$</td>
<td>Nusselt number (dimensionless)</td>
</tr>
<tr>
<td>$p$</td>
<td>pressure (Pa)</td>
</tr>
<tr>
<td>$Q$</td>
<td>total heat per unit volume (W/m³)</td>
</tr>
<tr>
<td>$S^*$</td>
<td>momentum source vector (kg/m² s²)</td>
</tr>
<tr>
<td>$T$</td>
<td>temperature (K)</td>
</tr>
<tr>
<td>$\bar{u}$</td>
<td>velocity vector (m/s)</td>
</tr>
<tr>
<td>$V$</td>
<td>volume (m³)</td>
</tr>
<tr>
<td>$Y$</td>
<td>mass fraction (kg/kg)</td>
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<table>
<thead>
<tr>
<th>Greek Symbols</th>
<th>Description</th>
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<tr>
<td>$\Gamma$</td>
<td>mass flow rate per unit volume (kg/m³ s)</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>phase volume fraction (dimensionless)</td>
</tr>
<tr>
<td>$\rho$</td>
<td>density (kg/m³)</td>
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<table>
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<tr>
<th>Subscripts</th>
<th>Description</th>
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<tbody>
<tr>
<td>i</td>
<td>interface</td>
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<tr>
<td>s</td>
<td>solid</td>
</tr>
<tr>
<td>sat</td>
<td>saturation</td>
</tr>
<tr>
<td>$\alpha, \beta$</td>
<td>phases</td>
</tr>
</tbody>
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Fig. 1. LNG cargo containment systems: (a) Mark III and (b) NO96 (http://www.gtt.fr/product/no-96-evolution/) GTT.
results can be applied to Mark III system as well. This paper also suggests a referential CFD setup and the numerical schemes in order to predict the LNG spill and leakage scenario. We will discuss the important parameters for the LNG leakage CFD simulation.

2. Governing equations

The modeling of the LNG flow requires the consideration of coupled flow/heat transfer complexities such as the multi-phase flow (gas/liquid), evaporation, and flow in a porous medium. The leakage flow is described by the multi-fluid model based on the Eulerian–Eulerian approach on the commercial CFD solver CFX. The Eulerian modeling framework is based on ensemble-averaged mass and momentum transport equations for all phases. The phases are treated separately and one set of conservation equations are solved for each phase. Coupling between the phases is achieved through a shared pressure and interphase exchange coefficients. In addition to the regular transport equations, a transport equation for the volume fraction is also solved for each phase. The sum of the volume fractions should be equal to one.

The volume fraction of phase $\alpha$, $\epsilon_{\alpha}$, is defined by the volume $V_{\alpha}$ occupied by the phase in a small volume $V$ around a point, which is given by

$$\epsilon_{\alpha} = \frac{V_{\alpha}}{V}$$

With the volume fraction, the mixture density of the fluid is defined by $\rho_m = \sum_{\alpha} \epsilon_{\alpha} \rho_{\alpha}$. The interfacial area density $A_{\alpha\beta}$ is the area of contact between the fluid and the porous domain per unit volume, which can be determined by

$$A_{\alpha\beta} = \frac{\epsilon_{\alpha} \epsilon_{\beta}}{d_{\alpha\beta}}$$

where $d_{\alpha\beta}$ is an interfacial length scale. The equations for conservation of mass and momentum are given by

$$\frac{\partial}{\partial t} (\epsilon_{\alpha} \rho_{\alpha} \mathbf{u}) + \nabla \cdot (\epsilon_{\alpha} \rho_{\alpha} \mathbf{u} \mathbf{u}) = \sum_{\beta} \Gamma_{\alpha\beta}$$

and

$$\frac{\partial}{\partial t} (\epsilon_{\alpha} \rho_{\alpha} \mathbf{u}) + \nabla \cdot (\epsilon_{\alpha} \rho_{\alpha} \mathbf{u} \mathbf{u}) - \nabla \cdot \left( \epsilon_{\alpha} \mu_{\alpha} \left( \nabla \mathbf{u} + (\nabla \mathbf{u})^T \right) \right)$$

$$= -\epsilon_{\alpha} \nabla p + \tilde{S}_{\alpha} + \tilde{D}_{\alpha} + \sum_{\beta} \left( \Gamma_{\alpha\beta} \mathbf{u} - \Gamma_{\beta\alpha} \mathbf{u} \right) + \rho_{\alpha} \tilde{\mathbf{u}}$$

where $\mathbf{u}$ and $\mu$ are the true velocity vector and the dynamic viscosity, respectively. $\Gamma_{\alpha\beta}$ is the mass flow rate per unit volume from phase $\beta$ to $\alpha$, which is given by

$$\Gamma_{\alpha\beta} = \Gamma_{\alpha\beta}^+ - \Gamma_{\beta\alpha}^+$$

where $\Gamma_{\alpha\beta}^+$ represents the positive mass flow rate per unit volume from phase $\beta$ to $\alpha$. Thus the term $\left( \Gamma_{\alpha\beta}^+ \mathbf{u} - \Gamma_{\beta\alpha}^+ \mathbf{u} \right)$ represents momentum transfer induced by interphase mass transfer from phase $\beta$ to $\alpha$.

The multi-phase model of LNG leakage can be represented by three fields: continuous gas of nitrogen, continuous liquid of methane and continuous gas of methane in the porous media (Table 1). In modeling of methane liquid flow through the glass wool, permeability-based Darcy’s law was employed. The additional pressure drop is modeled using a quadratic form of

Fig. 2. (a) Inside view of NO96, (b) the configuration of flat NO96 insulation and (c) the modified NO96 insulation system (GTT).
Forchheimer equation by considering the non-Darcy flow in porous media (Presley and Christensen, 1997). The losses through the porous media are considered as a momentum source per unit volume acting on the fluid utilizing permeability and loss coefficients as described by

\[ S_i = -\frac{\mu}{K_{\text{perm}}} u_i - K_{\text{loss}} \rho \frac{\partial u_i}{\partial x_i} \]  

(6)

where \( u_i \) is the superficial velocity vector, \( \mu \) the viscosity of the fluid, and \( \rho \) the pressure. \( K_{\text{perm}} \) is the permeability, which is a measure of ability of a porous structure to allow fluids to pass through it, and the loss coefficient \( K_{\text{loss}} \) provides a correction for inertial losses in the porous medium. Thus, the linear term including the permeability for this source represents viscous losses and the quadratic term with the loss coefficient represents inertial losses. In the limit of large resistance; i.e., the first two terms on the right-hand side of the momentum equation (Eq. (4)) are dominant, the convective and diffusive terms on the left-hand side can be neglected. The interfacial drag force per unit volume \( D_{ij} \) can be determined by

\[ D_{ij} = C_D A_{ij} \rho_{ij} \left( \vec{u}_\beta - \vec{u}_\alpha \right) \left( \vec{u}_\beta - \vec{u}_\alpha \right) \]  

(7)

where \( C_D \) is the flow-regime dependent drag coefficient and can be obtained by the Ishii-Zuber drag model. The continuity equation was used with the conservation equation which constrains the sum of the volume fraction to be unity, i.e.

\[ \sum_\alpha e_\alpha = 1 \]  

(8)

The energy conservation equation is given by

\[ \frac{\partial}{\partial t} (\epsilon_\alpha \rho_\alpha u_\alpha e_\alpha) + \nabla \cdot (\epsilon_\alpha \rho_\alpha \vec{u}_\alpha e_\alpha) - \nabla \cdot (\epsilon_\alpha \rho_\alpha T_\alpha) = \epsilon_\alpha T_\alpha \]  

(9)

where \( \epsilon_\alpha \), \( K_\alpha \), and \( T_\alpha \) denote the internal energy, the thermal conductivity and the temperature of phase \( \alpha \) respectively. The term \( \left( \Gamma_{\alpha\beta} \epsilon_\beta - \Gamma_{\beta\alpha} \epsilon_\alpha \right) \) represents heat transfer induced by interphase mass transfer from phase \( \beta \) to \( \alpha \). The total heat per unit volume transferred to phase \( \alpha \) due to interaction with other phases is denoted by \( Q_\alpha \), and is given by

\[ Q_\alpha = \sum_{\beta \neq \alpha} A_{\alpha\beta} (T_\alpha - T_\beta) \]  

(10)

Heat transfer across a phase boundary is described in terms of a heat convection coefficient \( h_{\alpha\beta} \) which is expressed in terms of Nusselt number in Eq. (11)

\[ h_{\alpha\beta} = \frac{k_{\alpha\beta} N_{\alpha\beta}}{\Delta T_{\alpha\beta}} \]  

(11)

where mixture thermal conductivity, \( k_{\alpha\beta} = \epsilon_\alpha k_\alpha + \epsilon_\beta k_\beta \). The Nusselt number is evaluated using Ranz and Marshall correlation (Ranz and Marshall, 1952).

\[ N_{\alpha\beta} = 2.0 + 0.66 Re^{1/2} Pr^{1/3} \]  

(12)

The volumetric interphase heat transfer \( Q_\alpha \) in Eq. (10) can be expressed by the combination of sensible and latent heat transfers between the phase and the interface, which is given by

\[ Q_\alpha = h_{\alpha} (T_1 - T_\alpha) + G_{\alpha\beta} \Delta T_{\alpha\beta} \]  

(13a)

and

\[ Q_{\beta} = h_{\beta} (T_1 - T_\beta) - G_{\alpha\beta} \Delta T_{\alpha\beta} \]  

(13b)

where \( h_\alpha \) and \( h_\beta \) are the phase heat transfer coefficients and \( T_1 \) is the interfacial temperature which can be assumed as the saturation temperature \( T_{sat} \). \( i_\alpha \) and \( i_\beta \) represent interfacial enthalpy values which are determined by

when \( G_{\alpha\beta} > 0 \),  \( i_\alpha = i_{\alpha, sat} \) and \( i_\beta = i_{\beta, sat} \)  

(14a)

and

when \( G_{\alpha\beta} < 0 \),  \( i_\alpha = i_{\alpha, sat} \) and \( i_\beta = i_{\beta, sat} \)  

(14b)

Due to the energy balance through the interface, \( Q_\alpha + Q_{\beta} = 0 \), which gives

\[ G_{\alpha\beta} = \frac{h_{\beta} (T_1 - T_{\beta}) + h_\alpha (T_1 - T_{\alpha})}{i_{\beta, sat} - i_{\alpha, sat}} \]  

(15)

Then, the volumetric interfacial mass transfer can be expressed by

\[ \Gamma_{\alpha\beta} = A_{\alpha\beta} G_{\alpha\beta} \]  

(16)

Along with the governing equations, transport equation for the mass fractions of components \( Y_{\alpha} \) is solved, which is given by

\[ \frac{\partial}{\partial t} (\epsilon_\alpha \rho_\alpha Y_{\alpha}) + \nabla \cdot (\epsilon_\alpha \rho_\alpha \vec{u}_\alpha Y_{\alpha}) = \nabla \cdot (\epsilon_\alpha \rho_\alpha D_{\alpha} \nabla Y_{\alpha}) \]  

(17)

where \( D_{\alpha} \) is the kinematic diffusivity. The energy transport equation for the solid has the following form,

\[ \rho_s c_{ps} \frac{dT_s}{dt} = \nabla \cdot (k_s \nabla T_s) \]  

(18)

where \( \rho_s \), \( c_{ps} \) and \( k_s \) are the density, the specific heat and the thermal conductivity of the solid.

### 3. Simulation model

In the present work, ANSYS-CFX 13 was used to simulate the behavior of LNG leakage. ANSYS-CFX13 employs the node-centered finite volume method (the control volume-based finite element method) to convert the governing differential equations into a set of algebraic equations by discretizing the domain of both fluid and solid.

The schematic diagrams of CCS insulation system and the primary insulation box of the modified NO96 are shown in Fig. 3. The primary insulation box is composed of plywood box filled with glass wool (Fig. 3(a)). One inlet port is placed on top of the box at the center and two outlets are located left and right sides of the box. The diameter of the outlets are 30 mm, which is the typical hole size of plywood insulation box. The dimension of the plywood box is 113 cm x 21 cm x 10 cm with the thickness of 1 cm. Glass wool is modeled as porous media. It is assumed that the LNG is composed of methane (CH4) and nitrogen. Liquid CH4 enters into the box through inlet and is vaporized as flows through box. All the fluids are modeled as continuous fluid. Interfacial momentum, heat and mass transfers are considered.

The morphology of the materials and interfacial interactions between the materials and phases are shown in Table 1 and Table 2, respectively. The domain was defined by a segment of upper plywood, lower plywood, side plywood and glass wools inside the box and glass wools on the wall. Conjugated heat transfer analysis model was created using ANSYS CFX. This model solves discretized Reynolds-averaged Navier–Stokes equations for the leaked LNG flow. For turbulence closure of gas mixture, the

### Table 1

<table>
<thead>
<tr>
<th>Component</th>
<th>Morphology in domain</th>
<th>Material</th>
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</thead>
<tbody>
<tr>
<td>LNG</td>
<td>Continuous fluid</td>
<td>CH4 liquid</td>
</tr>
<tr>
<td>Gases in glass wool</td>
<td>Continuous fluid</td>
<td>N2 and CH4 gas</td>
</tr>
<tr>
<td>Glass wool</td>
<td>Porous solid</td>
<td>Glass wool</td>
</tr>
<tr>
<td>Plywood</td>
<td>Continuous solid</td>
<td>Plywood</td>
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### Table 2

<table>
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<tr>
<th>Component Morphology in domain</th>
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<tr>
<td>Upper plywood</td>
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</tr>
<tr>
<td>Lower plywood</td>
<td>Plywood</td>
</tr>
<tr>
<td>Side plywood</td>
<td>Plywood</td>
</tr>
<tr>
<td>Glass wools</td>
<td>Plywood</td>
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</table>

The volumetric interphase heat transfer \( Q_\alpha \) in Eq. (10) can be expressed by the combination of sensible and latent heat transfers...
standard k-Epsilon model in combination with scalable wall functions was employed. Separate energy equations for both fluid and solids were simultaneously solved. Hexahedral grid was used; 75,788 nodes and 35,043 elements which were proved to obtain mesh independent result with an average speed of heat diffusion. The inlet boundary condition for the LNG release is specified by a static pressure condition. A static pressure, which is estimated based on the filling ratio of LNG cargo containment, is typically assumed at the inlet crack of 10 mm diameter. The filling ratio is defined by the volume of LNG to the volume of the cargo containment ($\sim H/D$ in Fig. 4). For 30 m height ($D$) containment cargo, assuming filling ratio of 98.5% (Bae et al., 2007), the hydrostatic pressure at the bottom, where the crack is located, is slightly over 1.0 atm. Accordingly, the inlet pressure of 1 atm and for comparison, 0.5 atm corresponding to filling ratio of 50% or the crack location of 15 m ($h$, in Fig. 4) from the top of the cargo containment were employed for the analysis. On the inlet boundary the turbulence intensity of 5% and free stream velocity components were set. Ambient pressure (zero gauge pressure) was imposed on the outlet boundary. Opening outlet boundary condition was also assigned on the side holes so that it allows the fluid to cross the boundary surface in either direction. This condition assumes that the flow can be bidirectional at the outlet and variables can be changing in the flow direction. The temperatures of top and bottom of the insulation box were set at $-163^\circ$C and $-50^\circ$C.

As LNG evaporates, the methane vaporizes faster than the heavier components due to its lower boiling point. Also, LNG primarily consists of methane. As a result, vaporized gas will be preferentially methane rich, whereas the heavier components will stay in the liquid pool. Therefore, the thermodynamic properties of methane can be used as a proxy to LNG properties (Qi et al., 2010). Three fluid components, nitrogen, methane liquid, and methane gas are included by fluid domain and they also consider interphase heat transfer present in the liquid and gases. Real gas model with temperature and pressure dependent transport properties are used for Methane and Nitrogen. The thermal equation of state was also described as a function of both temperature and pressure. The Aungier Redlich–Kwong equation of state (Aungier, 1995) is selected to simulate real gases of methane and nitrogen. This equation of state is quite useful because it only requires the fluid critical temperature and pressure. The fourth order polynomial functions are selected to assess the heat capacities of CH$_4$ and N$_2$. The properties of glass wool were adopted from Choi et al. (2012), Bae et al. (2007) and Lee et al. (2011a), (2011b), and are shown in Table 3.

4. Results and discussion

Fig. 5 shows the temperature distribution of the plywood box and the glass wool at $t=1.22$ s. The top of the plywood is in contact with the LNG at $-163^\circ$C and under the bottom of the box, $-50^\circ$C free convection was applied. For both plywood and the glass wool, the temperature distributions were linear. Due to the lack of experimental data conducted under similar or equivalent operating conditions (e.g., LNG leakage in NO96 system), direct comparison was not available to verify the validity of the numerical analysis. However, Choi et al. (2012) also showed the linear

<table>
<thead>
<tr>
<th>Interactions</th>
<th>CH$_4$ liquid and gas</th>
<th>CH$_4$ liquid and N$_2$</th>
<th>CH$_4$ gas and N$_2$</th>
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<tr>
<td>Heat transfer</td>
<td>Two resistance</td>
<td>Heat convection</td>
<td>Heat convection</td>
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Fig. 3. Schematic diagrams of modified NO96 (a) CCS insulation system and (b) primary insulation box.

Fig. 4. LNG CCS with leakage spot.
temperature variation across the insulation box in Mark III system, which evidences that the numerical scheme used in the present study was sound. In Fig. 6, the diffusion characteristics of the leaked LNG through the glass wool are plotted with respect time. The diffusion speed of the LNG through the glass wool was very fast. Within 0.4 s, the leaked LNG reached the outlets and most of the fluid exiting through the outlets was the LNG after 4.7217 s elapsed. The predicted velocity of leaked LNG by Bae et al. (2007) was around 16 m/s with the crack location at 15 m, which was even faster than the result of present study by factor of 2. However, the prediction by Bae et al. (2007) was insulation box inlet velocity, which did not consider the flow resistance through the porous glass wool. Therefore, considering the additional flow resistance through the porous glass wool, the time scales in this study is reasonable and presumably comparable to the results demonstrated by Bae et al. (2007). The outlet pressures were set at zero gauge pressure and the inlet gauge pressure was at 1 atm which is equivalent to the hydrostatic pressure due to the LNG depth of ~24 m in the CCS. The glass wool insulation did not satisfactorily delay the LNG diffusion. Considering the streamline shown in Fig. 7, the flow distance from inlet to outlet can be very roughly estimated as ~1.5 m. Assuming that the traveling time of the leaked LNG from inlet to outlet as 0.4 s, the average velocity of the LNG flow through the glass wool can be approximated 3.75 m/s. As shown in Fig. 7, the leaked LNG was ejected from the inlet like jet; the local velocity was as high as 80 m/s at the inlet. Most of the kinetic energy, however, was lost due to friction through the porous glass wool as soon as the LNG exiting the inlet, which resulted in the flow velocity of ~3 m/s at the outlets. The speed of sound of LNG at -163°C is ~1300 m/s, which is way higher than the choking condition; thus substantial amount of cryogenic LNG flow could leak through a small crack. The diffusion speed could be decreased by increasing the porosity. However, higher porosity increases the effective conductivity of the glass wool, which could yield the increase of BOR. As a matter of fact, the effect of porosity is much more complicated. Once LNG leaked and filled the insulation box, the LNG can act as “cold wall” between the ambient and LNG inside CCS, at the same time, the thermal conductivity is significantly increased compared to the nitrogen gas filled insulation box. Also, to study the effect of porosity, the relation between the permeability and loss coefficient needs to be experimentally determined, which will be conducted as a future work. Eventually, the results will be useful to select the insulation material and property considering both economic feasibility and the safety. The LNG flows at different inlet pressures are shown in Fig. 8. As shown, diffusion speed is significantly delayed with the reduced inlet pressure. At t=4.7217 s, LNG barely reached the outlets with the inlet pressure of 0.5 atm, while most of the insulation box was occupied by LNG with 1 atm. Thus, the containment cargo filling ratio is also very important for the safety of LNG carriers regarding LNG leakage. Fig. 9 shows the effect of inlet diameter on LNG diffusion speed. Due to the reduced inlet diameter, it was expected that the flow resistance was increased. When compared to Fig. 8(a) and (c), it is apparent that the diffusion speed of LNG was significantly reduced. However, the effect of inlet diameter reduction from 10 mm to 5 mm was not as effective as that of inlet pressure reduction by 50% to delay the diffusion speed of LNG. Fig. 10(a) shows that more than 98% of the NG was liquid at the outlet, which means the evaporation of the LNG was not vigorously taken place. The only heat source for the LNG vaporization was the convective heat transfer at the bottom of the insulation box, which generated the linear temperature change. The plywood and the glass wool temperatures were higher than the saturation temperature of the cryogenic fluid. However, heat transfer rate was very low and was not enough to provide the latent heat for the phase change. As shown in Bae et al. (2007), for the enhancement of vaporization, injection of large amount of nitrogen with relatively high temperature (above the boiling point of LNG) can be helpful. Initially, the insulation box as well as the outlet was

Table 3

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>50 [kg/m³]</td>
</tr>
<tr>
<td>Specific heat capacity</td>
<td>670 [J/kg K]</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>0.04 [W/mK]</td>
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<tr>
<td>Porosity</td>
<td></td>
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<tr>
<td>Volume porosity</td>
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</tr>
<tr>
<td>Permeability</td>
<td>3.75 x 10⁻¹¹ [m²]</td>
</tr>
<tr>
<td>Resistance loss coeff.</td>
<td>1242 [m⁻¹]</td>
</tr>
<tr>
<td>Interfacial area dens.</td>
<td>500 [m⁻¹]</td>
</tr>
<tr>
<td>Heat convective coeff.</td>
<td>10 [W/m²K]</td>
</tr>
</tbody>
</table>

![figure](image.png)

Fig. 5. Temperature variations of (a) plywood and (b) glass wool at t=1.22 s.
occupied by the nitrogen. However, the inflow of leaked LNG into the insulation box drove out most of the nitrogen, which explains the reduction of nitrogen fraction in Fig. 10(a). Also, the insulation box was in thermal equilibrium with the glass wool, which lead to identical initial temperatures of all the fluids at the outlet to the temperature of the glass wool (Fig. 10(b)). As the LNG fills the outlet, the temperature is rapidly decreased and settled down at the saturation temperature of the LNG. Since the heat transfer coefficient of nitrogen is very low, it takes more time for the nitrogen temperature to reach the steady state. The local velocity and the flow rate of the LNG at steady state were 3 m/s (Fig. 10(c)) and 8 g/s (Fig. 10(d)), respectively. In other words, in 10 s after the accident (leakage), 8 g/s of cryogenic fluid spills out of the insulation box.

5. Conclusion

The main purpose of the present study was to simulate and characterize the LNG leakage flow and thermal behaviors for modified NO96 CCS through the glass wool insulation box, which has not been investigated by other workers. However, this is very important and urgent issue because the leaked cryogenic liquid can cause severe safety issue in LNG carriers. To deal with the LNG leakage, the hydraulic and thermal diffusion processes were of interest in the present study, which required significant theoretical

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Fig. 6. Time history of leaked LNG (CH₄ liquid).

Fig. 7. Streamline of the leaked LNG flow at t = 1.22 s.
Fig. 8. Effect of inlet pressure on the leaked LNG flow.

Inlet pressure 1.0 atm, time = 1.2217 sec
Inlet pressure 0.5 atm, time = 1.2217 sec

Inlet diameter 5 mm, time = 1.22 sec
Inlet diameter 5 mm, time = 4.72 sec

Fig. 9. Effect of inlet diameter (10 mm) on the leaked LNG flow; (a) time = 1.22 s; (b) time = 4.72 s.
background (from numerical scheme to analysis) to handle the complexity stemming from the multiphase, multispecies numerical simulation. ANSYS CFX was used. The numerical results showed that the diffusion speed through the insulation box was very fast and the evaporation was not vigorously taken place. Under the inlet pressure of 1 atm, it took only 4.7 s for the leaked LNG to be fully filling the insulation box. After 10 s from the accident, the 8 g/s of cryogenic fluid spills out of the insulation box, which could result in serious safety issues. The glass wool was not suitable to satisfactorily delay the leaked flow. The effect of porosity on the leaked flow diffusion characteristics needs to be investigated as a future work. Also, the corresponding variations in BOR need to be identified simultaneously. Since the multiphase porous media flow and heat transfer have been of crucial importance for numerous science and engineering applications, however, the maturity and reliability of numerical approach are relatively low. The modeling framework of this study can be employed for numerical analyses in multiphase flow through soils (Van Genuchten, 1980; Kondo et al., 1990; Hughes et al., 1998) and multiphase bio-drying process (Cai et al., 2012), porous media approach of food processes/drying (Datta, 2007), and multiphase transport modeling through porous membrane/fiber in fuel cell (Wang et al., 2001; You and Liu, 2002; Chapuis et al., 2008).

Acknowledgments

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![Diagram](http://example.com/diagram.png)

**Fig. 10.** (a) Volume fractions, (b) temperature, (c) velocity, and (d) mass flow rates of the fluids at the outlet.

References


Chapuis et al., 2008.


