Performance analysis of liquefied natural gas storage tanks in refueling stations

Amir Sharafian, Omar E. Herrera, Walter Mérida*

Clean Energy Research Centre, The University of British Columbia, 2360 East Mall, Vancouver, BC, V6T 1Z3, Canada

Abstract

Liquefied natural gas (LNG) could replace diesel in the transportation sector. However, fugitive emissions including boil-off gas (BOG) across the LNG supply chain have revealed uncertainties on the overall environmental benefits of such replacement. In this study, time-dependent thermodynamic models were developed to study the LNG holding time of storage tanks in refueling stations before BOG releases to the atmosphere. Previously overlooked factors, such as the thermal mass of storage tanks and the actual operating conditions at refueling stations, were included explicitly in the models. The effect of the thermal mass of storage tanks on holding time is illustrated by an analysis of 57.20 m³ storage tanks filled with LNG at −150 °C and −126.5 °C. The tank with the lower temperature fills shows 3.7-times longer holding time. Further investigations highlight the importance of the ratio of heat transfer surface area to the LNG volume as a key factor in proper sizing of storage tanks to maximize the holding time. Finally, the modeling of a 57.20 m³ storage tank with a heat transfer coefficient of 0.022 W/m²K shows that fuel delivery rates as low as 1.89 m³/day are sufficient to maintain the tank pressure within allowable limits.

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1. Introduction

Climate change is one of the main concerns of today’s world (Richter, 2014), but greenhouse gas (GHG) emissions from industrial and transportation processes have steadily increased (Global greenhouse, 2016; Sources of greenhouse gas emissions, 2016; Limatainen et al., 2014). For instance, the GHG emissions from the U.S. medium- and heavy-duty trucks increased by 76% between 1990 and 2014 and reached 407.4 Mt CO₂eq (Inventory of U.S., 2016). According to the announcements at the 21st Conference of Parties in Paris, mitigation of climate change and reaching the 2 °C scenario targets would require immediate and significant changes over the next three decades (as opposed to changes occurring over centuries) (21st session of the Conference of the Parties et al., 2015).

It has been claimed that replacing conventional petroleum fuels, e.g., diesel and gasoline, with low-carbon content fuels reduces GHG emissions and climate change (van Der Hoeven, 2015). Natural gas (NG) is considered a low-carbon content fuel (Van Den Broek et al., 2015) and several studies reported the benefits of NG on economic and market growth (Van Den Broek et al., 2015; Imran et al., 2016; Hao et al., 2016; Wang and Li, 2016; Furuoka, 2016; Balitskiy et al., 2016; Wang et al., 2016; Ševik, 2015; Wang and Lin, 2014; Kakae et al., 2014; Wang et al., 2014; Khan et al., 2015). However, and despite this significant body of work, recent studies revealed uncertainty in the overall benefits associated with NG use (Alvarez et al., 2012; Howarth et al., 2011; Venkatesh et al., 2011; Davis and Shearer, 2014; McJeon et al., 2014; Delgado and Muncrief, 2015). According to the Global Warming Potential (GWP), methane emissions contribute up to 72 times more to climate change than CO₂ in a 20-year horizon (Solomon, 2007). Therefore, the reduction in CO₂ emissions from NG use must be compared to the impact of the corresponding methane emissions. Without reliable data on the actual deployment technologies, most of the models and analyses comparing widespread NG use to the existing energy options will remain incomplete.

Liquefied natural gas (LNG) is the condensed form of natural gas with 60% volumetric energy density of diesel (Study on natural gas, 2014). The combustion of LNG in comparison with ultra-low sulfur diesel can reduce CO₂, NOₓ, and particulate matter emissions by up to 20%, 90%, and 100%, respectively (International Gas Union, 2015). These features make LNG a candidate fuel in the transportation sector to reduce GHG emissions, especially for large, mobile applications, such as heavy-duty trucks (Bassi, 2011; Nicotra, 2013), trains (Dunn and LeBlanc, 2014; Energy Carriers, 2014; Al Ali, 2015),...
and ships (Esey et al., 2011; Seo et al., 2016). Nevertheless, fugitive emissions from LNG are a major concern. LNG is a cryogenic liquid stored at temperatures as low as −162 °C. Due to its large temperature gradient with the environment, LNG is gradually heated and evaporates (boil-off gas (BOG)). Methane (the major component in LNG mixtures) is a potent GHG and has more impact on climate change than CO2 due to methane higher radiative forcing (Solomon, 2007). The BOG leads to undesirable pressurization across the LNG distribution chain (Chen et al., 2004). In large LNG carriers, the BOG is re-liquefied or used as fuel to keep the LNG at atmospheric pressure and low temperature (Miana et al., 2015). In large LNG regasification plants and storage facilities, the BOG can be used to generate electricity (Querol et al., 2010). However, in small-scale applications, such as LNG refueling stations, the BOG management is more challenging. BOG generation and methane emissions from LNG facilities are originated from (Lowell et al., 2013): 1) heat transfer to LNG and pressurization of storage tanks, 2) ventilation of displaced BOG when filling a tank, 3) heat transfer to hoses, lines, and pumps, 4) precooling of equipment prior to LNG transfer, and 5) LNG transfer from a high pressure tank to a low pressure tank. According to Burnham et al. (2015), classified the natural gas (NG) well-to-tank in four sectors according to fugitive emissions rate: 1) gas field, 2) processing, 3) transmission and storage, and 4) distribution. Their analysis showed that on average 1.12%–1.15% of NG was emitted to the atmosphere across the value chain. Their investigations also indicated that transportation and storage sector accounted for 35% of methane emissions followed by the distribution sector, which includes refueling stations and fuel processing, with 28%. Therefore, the transportation, storage, and distribution sectors have significant opportunities to improve by preventing the BOG release and fixing existing leaks. The main focus of this study is on the distribution sector.

According to Burnham et al. (2015), the average methane venting from LNG refueling stations was about 0.32% per delivery of LNG. Hailer’s measurements from two LNG refueling stations in the U.S. indicated that one of the operating stations had methane emissions of 0.1%–1.5% of fuel dispensed to vehicles (Hailer, 2015). However, the second station had methane emissions of 0.9%–5.3%.

Field surveys from 2400 LNG refueling stations in China demonstrated that more than 1600 stations had daily methane emissions of greater than 5% and in some cases 10% due to improper insulation (G boil off gas (G) em, 2015). China has currently about 3200 LNG refueling stations (development status, 2015) which account for 94% of the total refueling stations around the world (Sharaifan et al., 2016). It is expected that the number of LNG refueling stations in the U.S. and China will reach 223 and 5000 by 2020, respectively.

Developing appropriate thermodynamic models to determine the weaknesses in the design of LNG infrastructures and quantify their BOG generation rates is the first step toward the design of zero or near zero fugitive emissions LNG facilities. A summary of relevant thermodynamic studies on LNG infrastructures are listed in Table 1.

The LNG facilities investigated in Table 1 illustrate the recent work on LNG storage tanks (Chen et al., 2004; Barclay et al., 1998; Adom et al., 2010; Pellegrini et al., 2014), unloading (tank-to-tank transfer) (Yan and Gu, 2010), regasification terminals (Querol et al., 2010; Park et al., 2012; Fahmy et al., 2015; Kurle et al., 2015), and LNG weathering (Miana et al., 2010; Pellegrini et al., 2014). There are limited studies available in the literature on LNG storage tanks with less than 113.5 m³ capacity for LNG refueling station applications, such as Refs. (Chen et al., 2004; Barclay et al., 1998; Pellegrini et al., 2014).

LNG storage tanks can hold LNG at pressures about 1300 kPa which are higher than those of large storage tanks (100,000–300,000 m³) used in tanker ships with operating pressures close to atmospheric pressure. The difference between these operating pressures affects the thermo-physical properties of LNG, LNG holding time, and the BOG generation rate. LNG holding time refers to the time a storage tank can hold the LNG without venting (Delgado and Muncrief, 2015).

In this study, we analyze LNG storage tanks of refueling stations by using practical parameters such as tank storage size, LNG initial temperature, tank thermal insulation, and fuel delivery rate. The main differences between this study and previous models in Refs (Chen et al., 2004; Barclay et al., 1998; Adom et al., 2010; Pellegrini et al., 2014), are to consider the thermal mass of storage tank and use real operating temperatures and pressures for the LNG at refueling stations. Previous studies used LNG at −162 °C (the dew point of NG at atmospheric pressure) for the modeling which is not the case in a LNG refueling station. This study highlights the importance of these parameters on the model predictions, such as heat transfer rate to tank, LNG holding time, and the BOG generation rate.

2. LNG refueling stations and vehicles’ fuel supply system

LNG is dispensed to vehicles in two conditions: 1) Unsaturated (cold) LNG at a less than −143 °C and 340 kPa, and 2) saturated (warm) LNG at −125 to −131 °C, and 690–930 kPa (Roche, 2009). This is due to variations in vehicles’ fuel supply systems (Sharaifan et al., 2016; Powars, 2010; Wiens et al., 2001). In a simple vehicle’s fuel supply system, the tank pressure transfers the LNG to the vaporizer and engine at appropriate temperature, pressure, and flow rate (Powars, 2010; Wiens et al., 2001). It is customary to fill these LNG tanks with saturated LNG, which has been heated prior to filling to increase its saturation pressure, to supply the required fuel flow rate. Other, more sophisticated fuel supply systems have auxiliary equipment, such as a pump or compressor, for transferring the LNG from the onboard tank to the vaporizer and engine (Sharaifan et al., 2016; Powars, 2010). These fuel supply systems are capable of accepting unsaturated LNG.

The process of heating the LNG to increase its saturation temperature and pressure is known as “LNG conditioning”. There are two methods of LNG conditioning at refueling stations: bulk and on-the-fly conditioning. Fig. 1a shows a simplified schematic of a LNG refueling station with bulk conditioning. After filling the storage tank with unsaturated LNG, the pump pushes the LNG to the heater to rise its temperature and pressure. This process continues until the LNG pressure stored in the storage tank reaches the set point.

In contrast, a LNG refueling station with on-the-fly conditioning increases the pressure and temperature of unsaturated LNG simultaneously with the fueling process, as shown in Fig. 1b. This method helps the storage tank to store more LNG with higher density for a longer time. However, the heater needs to be precisely designed to heat the LNG on-the-fly within a short time without overheating it.

3. LNG storage tank modeling and assumptions

LNG storage tanks in refueling stations with 22.7–113.5 m³ capacity have a maximum allowable working pressure (MAWP) of about 1300 kPa (Powars, 2010). Fig. 2 shows a schematic of a double-wall LNG storage tank with a net capacity of 572 m³.

A combination of Aspen Plus and Aspen Plus Dynamics software (Aspen Engineering, 2016) was used to model a LNG storage tank. The LNG storage tank was initially designed in Aspen Plus and was
Table 1
Thermodynamic modeling of different LNG facilities across the value chain to determine their BOG generation rates.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Scope of modeling</th>
<th>Approach*</th>
<th>Results</th>
</tr>
</thead>
</table>
| Barclay et al., 1998 | Optimization of LNG storage tank capacity for a fleet-size refueling station | • Conducted a thermo-economic analysis to size LNG storage tanks with respect to the fleet size  
• Investigated the effects of LNG storage capacity, insulation material, and tank pressure on the capital cost of LNG refueling stations | • Capacity and capital cost of LNG storage tanks showed a linear relationship  
• Use of onsite liquefier assisted to use less efficient and less expensive storage tanks  
• A single-wall storage tank with polyurethane insulation equipped with a liquefier had lower life-cycle cost than a double-wall LNG storage tank |
| Chen et al., 2004 | Thermodynamic modeling of LNG storage tank and refueling station | • Developed steady-state and dynamic models  
• Analyzed the effects of number of vehicles fueled every day on methane emissions  
• Modeled 22.7–113.6 m³ LNG storage tanks | • Thermal conductance of LNG storage tanks could be calculated indirectly by using dynamic thermodynamic modeling and measuring temperatures and pressure over time when no fuel is delivered  
• Delivering more than 2.8 m³ LNG per day eliminated methane emissions from a 49.0 m³ storage tank with thermal conductance of 2 W/K  
• An electric generator was recommended to be used for the BOG management and power generation  
• A liquefier was recommended to be used for the BOG management |
| Hasan et al., 2009 | BOG management in LNG transportation from liquefaction plant to regasification terminal | • Used Aspen HYSYS for thermodynamic modeling  
• Used Soave-Redlich-Kwong (SRK) equation of state | • Important factors on the BOG generation during LNG transportation were LNG sloshing, LNG composition, ambient temperature, tank thermal conductance, and tank pressure  
• The BOG generation was increased by increase in voyage distance  
• The BOG generation rate was minimized at a specific LNG flow rate and pump head  
• Increasing the elevation difference of pipelines between two tanks increased the BOG generation rate  
• Larger pipe diameter reduced the BOG generation rate and pump head  
• Pipe roughness had negligible effect on the BOG generation rate |
| Yan and Gu, 2010 | Thermodynamic modeling to determine important parameters on BOG generation during LNG unloading in LNG terminals | • Used Aspen Plus software for thermodynamic modeling  
• Used Peng-Robinson (PR) equation of state  
• Analyzed the effects of LNG flow rate, and pipe elevation change, roughness, and diameter on the BOG generation rate | • Structure of the tank affected the BOG generation rate  
• Smaller tanks had larger BOG generation rate because of large surface area to volume ratio  
• The BOG generation rate decreased as the tank pressure increased  
• Constant temperature and density during the whole process were reduced the accuracy of modeling  
• The BOG generation rate did not necessarily mean methane emissions to the atmosphere |
| Adom et al., 2010 | Thermodynamic modeling to calculate the BOG generation rate of LNG storage tanks | • Used Lee-Kesler-Plockler (LKP) and the Starling modified Benedict-Webb-Rubin (BWRs) empirical models to simulate compressibility factor and equation of state  
• Assumed LNG evaporation only at the liquid-vapor interface  
• Assumed constant LNG temperature and density during the whole process | • Recondenser was the best option to manage the BOG due to its low power consumption and maintenance  
• Integration of cogeneration plants with LNG terminals were proposed to manage the BOG and generate the electricity required for operating terminals  
• The BOG was a mixture of methane and nitrogen not heavy hydrocarbons  
• The intelligent neural network model had better prediction in LNG composition at the destination than thermodynamic modeling because of using historical data  
• For new tank designs, thermodynamic modeling provided better results  
• Proper design of receiving terminals could reduce the operating cost of compressors for handling the BOG  
• Optimal design of receiving terminals provided 23% more energy savings and a payback period of less than 0.2 year  
• Direct compression of the BOG had higher costs than recondensation |
| Querol et al., 2010 | Thermodynamic modeling to determine the daily BOG generation rate in LNG terminals | • Used Aspen Plus software for thermodynamic modeling  
• Analyzed the usage of recondenser, compressor, and liquefaction plant on the BOG management in receiving terminals | • LNG composition had to be considered for an accurate thermo-economic analysis  
• Using average BOG value reported in previous literature was misleading in prediction of LNG composition and density change |
| Miana et al., 2010 | Thermodynamic and intelligent neural network modeling to determine LNG weathering in tanker ships | • Used MOILAS software to predict LNG composition and thermophysical properties  
• Used a lumped body model which is independent from the shape of LNG storage tanks | • The intelligent neural network model had better prediction in LNG composition at the destination than thermodynamic modeling because of using historical data |
| Park et al., 2012 | Thermodynamic modeling to calculate the BOG generation rate in receiving terminals | • Used Aspen Plus combined with Sequential Quadratic Programming (SQP) optimization solver in Matlab software for thermodynamic modeling  
• Used Peng-Robinson (PR) equation of state | • LNG composition had to be considered for an accurate thermo-economic analysis  
• Use of onsite liquefier assisted to use less efficient and less expensive storage tanks  
• A single-wall storage tank with polyurethane insulation equipped with a liquefier had lower life-cycle cost than a double-wall LNG storage tank  
• Removing heavier hydrocarbons from LNG resulted in higher net gain  
• A recondensation plant with appropriate heavy hydrocarbon removal provided $14M/year net gain  
• Usage of the BOG as fuel gas was the most effective way to manage the BOG |
| Pellegrimi et al., 2014 | Thermodynamic modeling to study LNG weathering in LNG storage tanks | • Developed an in-house code for thermodynamic modeling of LNG storage tanks  
• Used Soave-Redlich-Kwong (SRK) equation of state  
• Assumed constant heat flux on walls of a 190 L storage tank | • LNG composition had to be considered for an accurate thermo-economic analysis  
• Use of onsite liquefier assisted to use less efficient and less expensive storage tanks  
• A single-wall storage tank with polyurethane insulation equipped with a liquefier had lower life-cycle cost than a double-wall LNG storage tank  
• Removing heavier hydrocarbons from LNG resulted in higher net gain  
• A recondensation plant with appropriate heavy hydrocarbon removal provided $14M/year net gain |
| Fahmy et al., 2015 | Thermodynamic modeling and cost optimization of regasification plants | • Used Aspen HYSYS software to determine the minimum lower heating value range of natural gas by recovering heavier hydrocarbons and allowing maximum net gain  
• Used Peng-Robinson-Stryjek-Vera (PRSV) equation of state | • LNG composition had to be considered for an accurate thermo-economic analysis  
• Use of onsite liquefier assisted to use less efficient and less expensive storage tanks  
• A single-wall storage tank with polyurethane insulation equipped with a liquefier had lower life-cycle cost than a double-wall LNG storage tank  
• Removing heavier hydrocarbons from LNG resulted in higher net gain  
• A recondensation plant with appropriate heavy hydrocarbon removal provided $14M/year net gain |

*Approach* indicates the simulation tools or methods used for the thermodynamic modeling.
The model was exported to *Aspen Plus Dynamics* where the inlet and outlet valves were closed to model a stationary tank with no fuel delivery. The thermodynamic model included time-dependent conservation of mass and energy, heat and mass transfer equations and equation of state. In this study, pure methane was considered as the LNG because more than 90% of NG is composed of methane. A constant ambient temperature boundary condition was applied on the walls of the storage tank. The liquid-vapor phases, i.e., LNG and BOG, were assumed to be in equilibrium. The Peng-Robinson (PR) equation of state was used to determine the density of vapor phase for a given temperature and pressure.

According to technical recommendations ([Powars, 2010](#)), LNG storage tanks at refueling stations should be filled to a maximum of 80% of their volume with unsaturated LNG. In the case of saturated LNG, storage tanks should not be filled more than 90% of their volume. In this study, the rationale behind this practical suggestion is discussed. To have a fair comparison, the initial volumes of unsaturated and saturated LNG in *Aspen Plus Dynamics* were set at 80% of the tank net volume. The pressure and temperature of LNG in the tank increased until the tank pressure reached its MAWP due to the

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### Table 1 (continued)

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Scope of modeling</th>
<th>Approach*</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kurle et al., 2015</td>
<td>Thermodynamic modeling to determine the energy required to liquefy the BOG of 100,000 to 300,000 m³ LNG storage tanks</td>
<td>Used Soave-Redlich-Kwong (SRK) equation of state</td>
<td>Less than 20% of the liquefied BOG energy was consumed for the BOG recovery</td>
</tr>
<tr>
<td>Liu et al., 2015</td>
<td>Not clarified modeling software and assumptions</td>
<td>Developed an in-house code for thermodynamic modeling of LNG storage tanks</td>
<td>The liquefier powered by the Claude cycle driven by a spark-ignition engine had the highest BOG energy recovery</td>
</tr>
<tr>
<td>Migliore et al., 2015</td>
<td>Thermodynamic modeling to investigate LNG weathering in storage tanks of regasification terminals</td>
<td>Used the revised Kloseke-McKinley method (an empirical correlation) for calculating the LNG density</td>
<td>Initial composition and thermal mass of LNG affected the BOG generation rate</td>
</tr>
</tbody>
</table>

* Common assumption in all studies: 1) Liquid-vapor phases are in equilibrium, and 2) steady-state assumption unless otherwise noted.

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### Fig. 1

LNG conditioning at a refueling station by: (a) bulk conditioning method ([Wiens et al., 2001](#)) and (b) on-the-fly conditioning method.

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### Fig. 2

Schematic of a double-wall LNG storage tank with the net capacity of 57.2 m³. The dimensions on the figure belong to the inner tank ([LNG storage vessels, 2016](#)).

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solved for the steady-state condition. Then, the model was exported to *Aspen Plus Dynamics* where the inlet and outlet valves were closed to model a stationary tank with no fuel delivery. The thermodynamic model included time-dependent conservation of mass and energy, heat and mass transfer equations and equation of state. In this study, pure methane was considered as the LNG because more than 90% of NG is composed of methane. A constant ambient temperature boundary condition was applied on the walls of the storage tank. The liquid-vapor phases, i.e., LNG and BOG, were assumed to be in equilibrium. The Peng-Robinson (PR) equation of state was used to determine the density of vapor phase for a given temperature and pressure.

According to technical recommendations ([Powars, 2010](#)), LNG storage tanks at refueling stations should be filled to a maximum of 80% of their volume with unsaturated LNG. In the case of saturated LNG, storage tanks should not be filled more than 90% of their volume. In this study, the rationale behind this practical suggestion is discussed. To have a fair comparison, the initial volumes of unsaturated and saturated LNG in *Aspen Plus Dynamics* were set at 80% of the tank net volume. The pressure and temperature of LNG in the tank increased until the tank pressure reached its MAWP due to the
heat transfer from the environment. This time is defined as the “LNG holding time” of the tank with no methane emissions. During the modeling, there is no LNG flow in and out of the storage tank unless otherwise specified. Further details about the specifications of LNG storage tank, ambient temperature, initial LNG level in the tank, and temperatures and pressures of saturated and unsaturated LNG are listed in Table 2.

The overall heat transfer coefficient, $U_{\text{tank}}$, of the storage tank was calculated based on LNG at (2) and (3),

$$Q_i = \frac{\text{BOG}_{\%}}{h_{\text{fg}}} \times V_{\text{tank}} \times h_{\text{fg}} = \frac{0.3\%}{24 \times 3600} \times 423.0 \left( \frac{\text{kg}}{\text{m}^3} \right) \times 57.20 \left( \frac{\text{m}^3}{\text{m}^3} \right) \times 512.59 \left( \frac{\text{kJ}}{\text{kg}} \right) = 430 \text{ W}$$

(1)

$$\frac{Q_i}{\text{ambient}} - \frac{Q_i}{\text{LNG}} = \frac{430\text{W}}{25} = -162 \text{W/K}$$

(2)

$$U_{\text{insulation}} = \frac{(UA)_{\text{tank}}}{A_{\text{tank}}} = \frac{2.3\text{(W/K)}}{104.35\text{(m}^2\text{)}} = 0.0222\text{W/m}^2\text{K}$$

(3)

where, in Eq. (1), $Q_i$ is the heat transfer rate to the tank, $h_{\text{fg}}$ are the LNG density and heat of evaporation at the given temperature and pressure, and $V_{\text{tank}}$ is the storage tank net volume. In Eqs. (2) and (3), $(UA)_{\text{tank}}$ is the thermal conductance of the storage tank and $A_{\text{tank}}$ is the total heat transfer surface area of the inner tank, as shown in Fig. 2.

The average daily BOG generation rate in the model is calculated by Eq. (5):

$$\text{BOG}_{\%} = \frac{0.3\%}{h_{\text{fg}}} \times \frac{Q_i}{V_{\text{LNG}}} \times h_{\text{fg}} \times 100$$

(4)

$$\text{BOG(\%/day)} = \frac{\text{BOG}_{\%} \times \text{time interval}}{\text{holding time}} \times 24 \times 3600$$

(5)

where in Eq. (4), $BOG_{\%}$, $Q_i$, and $t_{\text{holding time}}$ are the BOG generation, the heat leak rate to the tank, and the time interval at time step $i$, respectively.

For solving the time-dependent governing equations, the mixed Newton method was selected in Aspen Plus Dynamics. The relative error differences for all variables, namely, density, temperature, pressure, and liquid and vapor mass fractions, were set at $10^{-4}$ at each time step. The mixed Newton method uses the Newton method for initialization and the fast Newton method for dynamic iterations. Therefore, it provides a fast iteration speed and high convergence rate for most of time-dependent simulations (Aspen Plus Dynamics user, 2016).

4. Results

4.1. Model validation

Experimental data (Advanced LNG onboard storage system, 2003) of a horizontal onboard tank with net capacity of 0.257 m³ were used to validate the model. The holding time of the tank was measured according to the SAE J2343 Recommended Practice standard (Society of Automotive, 2008). The tank was filled to 75% of its net capacity and changes in its pressure was recorded over time until the tank pressure reached its MAWP. Further details about the tank and initial temperature and pressure are shown in Table 3.

Fig. 3 shows the comparison of experimental data and the results of the model. The LNG pressure stored in the tank increased gradually due to the heat leak rate to the tank and after about 5.7 days (137 h), it reached the MAWP. As shown in Fig. 3, the model predicted the experimental data with good accuracy. The maximum and average relative differences between the experimental and numerical modeling were 6.2% and 3.1%, respectively.

4.2. Baseline model analysis

Variations in LNG pressure, temperature and level in the tank, and heat leak rate to the tank over time are discussed in this section for the given values in Table 2. Fig. 4a and Fig. 4b show the pressure and temperature variations of unsaturated and saturated LNG in a 57.2 m³ tank over time. Unsaturated LNG with initial pressure of 230 kPa is gradually heated and after about 87 days, the tank pressure reaches its maximum allowable working pressure (MAWP). Whereas, the pressure of saturated LNG initially at

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank net capacity, $V_{\text{tank}}$</td>
<td>57.20 m³</td>
<td>A vertical double-wall storage tank with a vacuum insulation between two walls (LNG storage vessels, 2016)</td>
</tr>
<tr>
<td>Length of inner tank, $L_{\text{tank}}$</td>
<td>12.64 m</td>
<td>Calculated from the length of outer tank</td>
</tr>
<tr>
<td>Outer diameter, $D_o$</td>
<td>2.896 m</td>
<td>Ref. (LNG storage vessels, 2016)</td>
</tr>
<tr>
<td>Inner diameter, $D_i$</td>
<td>2.4 m</td>
<td>Calculated from the net capacity of the tank</td>
</tr>
<tr>
<td>Insulation thickness, $t_{\text{insulation}}$</td>
<td>0.248 m</td>
<td>Calculated from the tank inner and outer diameters</td>
</tr>
<tr>
<td>Mass of storage tank (empty)</td>
<td>21,455 kg</td>
<td>Ref. (LNG storage vessels, 2016)</td>
</tr>
<tr>
<td>Specific heat capacity of storage tank, $c_{p,\text{tank}}$</td>
<td>477 J/kgK</td>
<td>Assumed from stainless steel 304</td>
</tr>
<tr>
<td>Surface area of inner tank, $A_{\text{tank}}$</td>
<td>104.35 m²</td>
<td>Calculated from inner tank geometry</td>
</tr>
<tr>
<td>Overall heat transfer coefficient of tank, $U_{\text{insulation}}$</td>
<td>0.022 W/m²K</td>
<td>Calculated from BOG generation rate of 0.3%/day for methane at -162 °C and 101.325 kPa (Powars, 2010)</td>
</tr>
<tr>
<td>Thermal conductance of tank, $(UA)_{\text{tank}}$</td>
<td>2.30 W/K</td>
<td>(Powars, 2010)</td>
</tr>
<tr>
<td>Ambient temperature, $T_{\text{ambient}}$</td>
<td>25 °C</td>
<td></td>
</tr>
<tr>
<td>Maximum allowable working pressure of storage tank (MAWP)</td>
<td>1300 kPa</td>
<td>(Powars, 2010)</td>
</tr>
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<table>
<thead>
<tr>
<th>Initial conditions</th>
<th></th>
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<tbody>
<tr>
<td>Initial LNG level in tank</td>
<td>10.11 m</td>
<td>Calculated based on 80% of the length of inner tank</td>
</tr>
<tr>
<td>Unsaturated LNG temperature</td>
<td>-150 °C</td>
<td></td>
</tr>
<tr>
<td>Unsaturated LNG pressure</td>
<td>230.65 kPa</td>
<td></td>
</tr>
<tr>
<td>Saturated LNG temperature</td>
<td>-126.5 °C</td>
<td></td>
</tr>
<tr>
<td>Saturated LNG pressure</td>
<td>900 kpa</td>
<td></td>
</tr>
</tbody>
</table>
The heat leak rate to the tank increases over time as the LNG temperature gradually increases. The Fig. 4d shows the heat leak rate to unsaturated and saturated LNG decreases from its initial value.

Comparing changes in LNG pressure between experimental data (Advanced LNG onboard storage system, 2003) and the model developed in this study. The results are shown in Fig. 6. The thermal mass of the tank stores a portion of the heat transferred to the LNG.

This will be discussed further in Fig. 6.

The BOG generation of the storage tank filled with unsaturated and saturated LNG are depicted in Fig. 4e and f, respectively. The BOG generation of the tank filled with unsaturated LNG is greater than that of the tank filled with saturated LNG. This is due to a larger temperature gradient between the unsaturated LNG and the environment.

Comparison of changes in LNG pressure between experimental data (Advanced LNG onboard storage system, 2003) and the model developed in this study. The results are shown in Fig. 6. The thermal mass of the tank stores a portion of the heat transferred to the LNG.

The BOG generation of the storage tank filled with unsaturated and saturated LNG are depicted in Fig. 4e and f, respectively. The BOG generation of the tank filled with unsaturated LNG is greater than that of the tank filled with saturated LNG. This is due to a larger temperature gradient between the unsaturated LNG and the environment. As shown in Fig. 4e and f, the BOG generation decreases over time to a minimum and then increases. In the pressure of the LNG storage tank minimizes the BOG generation. However, as the tank temperature and pressure increase, the heat of evaporation of LNG steadily decreases. For example, the enthalpy of evaporation of LNG decreases by 24% from 488.9 to 394.8 kJ/kg by increasing the LNG temperature and pressure from 150 °C and 230.65 kPa to −118 °C and 1300 kPa. Therefore, a competing trend between increase in the pressure and decrease in the enthalpy of evaporation controls the BOG generation. These results refute the assumption of constant BOG generation and BOG generation reduction by increase in the tank pressure, Refs (Hasan et al., 2009; Adom et al., 2010), for instance.

Fig. 5 shows the LNG holding time and average daily BOG generation rate of the 57.2 m³ storage tank at the baseline operating conditions. It can be seen from Fig. 5 that storage of unsaturated LNG in comparison with saturated LNG increases the LNG holding time by almost 3.74 times from 23.4 days to 87.4 days. As a result, the average daily BOG generation rate of the tank filled with unsaturated LNG is 12.5% less than that of the tank filled with saturated LNG.

Effects of the thermal mass of storage tank on the modeling results are shown in Fig. 6. The thermal mass of the tank stores a portion of the heat transferred from the environment to the LNG as shown in Fig. 6a and b, as an example. The tank with zero thermal mass filled with saturated LNG has faster pressure and temperature rise than the tank with thermal mass. Also, the LNG level increases in a shorter time for the tank with zero thermal mass compared to that with thermal mass as shown in Fig. 6c. These results indicate that thermodynamic models with zero thermal mass for storage tanks underestimate the LNG holding time and overestimate the average daily BOG generation rate.

Fig. 6d shows that the heat leak rate to LNG in the storage tank with zero thermal mass decreases linearly with time. Whereas, the heat leak rate to the LNG in the storage tank with thermal mass initially reduces because a portion of the heat is stored in the walls of the storage tank. The remainder of the heat is transferred to the

900 kPa exceeds the MAWP of the tank after 23 days. As shown in Fig. 4b, temperatures of unsaturated and saturated LNG increase linearly from −150 °C and −126.5 °C, respectively, to −118.3 °C.

Fig. 4c demonstrates the LNG level variations in the tank due to the heat transfer from the environment and changes in the LNG density. Unsaturated and saturated LNG levels are initially at 0.4212 m (corresponding to 80% of the length of the inner tank, as shown in Fig. 2). The unsaturated LNG level increases by increasing the LNG temperature and reaches 11.77 m when the tank pressure reaches its MAWP. This shows a 1.66 m change between the initial and the end levels of LNG in the tank due to decrease in the LNG density by 16.5% from 405.7 to 348.2 kg/m³. Saturated LNG level also increases by 0.46 m and reaches 10.57 m. The level of saturated LNG increases less because the density of saturated LNG only decreases by 4.5% from its initial density. These data support the practical recommendation on filling storage tanks up to 80% and 90% of their net volume with unsaturated and saturated LNG, respectively.

The amount of heat leak rate to the LNG storage tank is shown in Fig. 4d. The heat leak rate to unsaturated and saturated LNG decreases over time as the LNG temperature gradually increases. The heat leak rate to the tank filled with saturated LNG is less than that filled with unsaturated LNG. As shown in Fig. 4d, the heat leak rate to the tank shows an exponential decay in the first few days and then linearly decreases. This is because of the thermal mass of the storage tank that stores a portion of heat transferred to the LNG.

Table 3: Specifications of LNG storage tank and initial operating conditions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of inner tank, L&lt;sub&gt;tank&lt;/sub&gt;</td>
<td>0.909 m</td>
<td>Calculated from the capacity of the tank</td>
</tr>
<tr>
<td>Inner diameter, D&lt;sub&gt;i&lt;/sub&gt;</td>
<td>0.6 m</td>
<td>Ref. (Advanced LNG onboard storage system, 2003)</td>
</tr>
<tr>
<td>Insulation thickness, t&lt;sub&gt;insulation&lt;/sub&gt;</td>
<td>0.03 m</td>
<td>Calculated from the tank inner and outer diameters</td>
</tr>
<tr>
<td>Mass of storage tank (empty)</td>
<td>175 kg</td>
<td>Ref. (Advanced LNG onboard storage system, 2003)</td>
</tr>
<tr>
<td>Specific heat capacity of storage tank, c&lt;sub&gt;p,tank&lt;/sub&gt;</td>
<td>477 J/kgK</td>
<td>Assumed from stainless steel 304</td>
</tr>
<tr>
<td>Surface area of inner tank, A&lt;sub&gt;insulation&lt;/sub&gt;</td>
<td>2.279 m²</td>
<td>Calculated from inner tank geometry</td>
</tr>
<tr>
<td>Overall heat transfer coefficient of tank, U&lt;sub&gt;insulation&lt;/sub&gt;</td>
<td>0.075 W/m²K</td>
<td>Calculated from average heat leak rate of 20.9 W given in Ref. (Advanced LNG onboard storage system, 2003)</td>
</tr>
<tr>
<td>Thermal conductivity of tank, (kA)&lt;sub&gt;tank&lt;/sub&gt;</td>
<td>0.17 W/K</td>
<td>Assumed</td>
</tr>
<tr>
<td>Ambient temperature, T&lt;sub&gt;ambient&lt;/sub&gt;</td>
<td>25 °C</td>
<td>Ref. (Advanced LNG onboard storage system, 2003)</td>
</tr>
<tr>
<td>Maximum allowable working pressure of storage tank (MAWP)</td>
<td>1585 kPa</td>
<td>Ref. (Advanced LNG onboard storage system, 2003)</td>
</tr>
</tbody>
</table>

Initial conditions

- Initial LNG level in tank: 0.4212 m
- LNG temperature: −147.4 °C
- LNG pressure: 283 kPa

Fig. 3: Comparison of changes in LNG pressure between experimental data (Advanced LNG onboard storage system, 2003) and the model developed in this study.
When the thermal mass of storage tank cannot store more heat, the heat leak to the tank is transferred mostly to the LNG. At this point, the slope of the heat leak rate curve is parallel to that of the storage tank with zero thermal mass, as shown in Fig. 6d. This analysis highlights the importance of thermal mass of storage tanks that has been overlooked in the literature (Chen et al., 2004; Adom et al., 2010; Pellegrini et al., 2014; Migliore et al., 2015).

4.3. Performance analysis of LNG storage tanks without fuel delivery

Proper usage of insulation materials in LNG infrastructures can minimize the heat transfer to LNG. In a storage tank, the thermal resistance of metallic walls can be neglected in comparison with those of insulation materials. The heat transfer resistances due to insulation materials on the side walls, roof, and ceiling of the LNG. When the thermal mass of storage tank cannot store more heat, the heat leak to the tank is transferred mostly to the LNG. At this point, the slope of the heat leak rate curve is parallel to that of the storage tank with zero thermal mass, as shown in Fig. 6d. This analysis highlights the importance of thermal mass of storage tanks that has been overlooked in the literature (Chen et al., 2004; Adom et al., 2010; Pellegrini et al., 2014; Migliore et al., 2015).

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Fig. 4. Variations in unsaturated and saturated LNG (a) pressure, (b) temperature, and (c) level in tank, (d) heat leak rate to tank, (e) BOG generation% of unsaturated LNG, and (f) BOG generation% of saturated LNG vs. time.

Fig. 5. Unsaturated and saturated LNG holding time and average daily BOG rate of a 57.2 m³ storage tank at the base operating conditions given in Table 2.
storage tank are assumed to be in parallel. Equation (6) gives the thermal conductance of the storage tank, \((UA)_{tank}\):

\[
(UA)_{tank} = \frac{1}{\ln \left( \frac{D_o}{D_i} \right)} + \frac{1}{k_{insulation} / A_{roof}} + \frac{1}{k_{insulation} / A_{ceiling}}
\]  

(6)

The parameters in Eq. (6) are given in Tables 2 and 4. By replacing \((UA)_{tank}\) in Eq. (3), the overall heat transfer coefficient, \(U_{insulation}\), of the storage tank can be calculated. The thermal conductivity, \(k_{insulation}\), thermal conductance, \((UA)_{tank}\), and the overall heat transfer coefficient of the tank, \(U_{insulation}\), for different insulation materials are summarized in Table 4.

Effects of \(U_{insulation}\) ranging from 0.01 to 0.25 W/m²K on the unsaturated and saturated LNG pressures and heat leak rates to the tank are shown in Fig. 7. For \(U_{insulation}\) of 0.01 W/m²K, the unsaturated and saturated LNG pressures take more than 80 and 20 days, respectively, to reach the MAWP of the storage tank as shown in Fig. 7a and b. While, the storage tank with \(U_{insulation}\) of 0.25 W/m²K can only hold unsaturated and saturated LNG for about 10 and 3 days, respectively, before releasing the BOG to the atmosphere. As shown in Fig. 7c and d, the heat leak rate to the tank varies from 165 to 2870 W for unsaturated LNG and 154 to 2500 W for saturated LNG under \(U_{insulation}\) of 0.01–0.25 W/m²K. The amount of heat leak rates shown in Fig. 7c and d can be used as benchmark values in the design or selection of proper liquefier in LNG refueling stations.

Fig. 8 shows the LNG holding time and average daily BOG generation rate of the storage tank filled with unsaturated and saturated LNG under different \(U_{insulation}\). It can be seen in Fig. 8a that the tank with \(U_{insulation}\) of 0.01 W/m²K (similar to that of LCI insulation material under vacuum pressure of 133.3 Pa listed in Table 4) can hold unsaturated and saturated LNG for 188 and 50 days, respectively. Using conventional insulation materials, such as polyurethane with \(U_{insulation}\) of 0.10 W/m²K, and no vacuum results in unsaturated and saturated LNG holding times of 22 and 5.7 days, respectively; more than 8 times reduction in the LNG holding time compared to that of \(U_{insulation}\) of 0.01 W/m²K.

Fig. 6. Variations in saturated LNG (a) pressure, (b) temperature, and (c) level in a 57.2 m³ storage tank with and without thermal mass (Other parameters are as given in Table 2).

### Table 4
Thermal properties of different insulation material with/without vacuum pressure.

<table>
<thead>
<tr>
<th>Insulation material (Fesmire and Augustynowicz, 2005)</th>
<th>Vacuum pressure [Pa]</th>
<th>(k_{insulation}) [W/m.K]</th>
<th>((UA)_{tank}) [W/K]</th>
<th>(U_{insulation}) [W/m²K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layered composite insulation (LCI)</td>
<td>133.3</td>
<td>0.0016</td>
<td>0.735</td>
<td>0.007</td>
</tr>
<tr>
<td>Aerogel blanket</td>
<td>133.3</td>
<td>0.0034</td>
<td>1.561</td>
<td>0.015</td>
</tr>
<tr>
<td>Multi-layer insulation (MLI)</td>
<td>133.3</td>
<td>0.010</td>
<td>4.592</td>
<td>0.044</td>
</tr>
<tr>
<td>Fiberglass</td>
<td>133.3</td>
<td>0.014</td>
<td>6.429</td>
<td>0.062</td>
</tr>
<tr>
<td>Perlite powder</td>
<td>133.3</td>
<td>0.016</td>
<td>7.348</td>
<td>0.070</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>No vacuum</td>
<td>0.021</td>
<td>9.644</td>
<td>0.092</td>
</tr>
<tr>
<td>Cellular glass foam</td>
<td>No vacuum</td>
<td>0.033</td>
<td>15.155</td>
<td>0.145</td>
</tr>
</tbody>
</table>

* 133.3 Pa = 1 torr.
Fig. 7. Effects of $U_{\text{insulation}}$ on unsaturated and saturated LNG (a)–(b) pressure, and (c)–(d) heat leak rate to tank (Other parameters are as given in Table 2).

Fig. 8. Effects of $U_{\text{insulation}}$ on (a) LNG holding time and (b) average daily BOG generation rate of a 57.2 m³ storage tank filled with unsaturated and saturated LNG (Other parameters are as given in Table 2).

Fig. 9. Effects of $T_{\text{ambient}}$ on (a) LNG holding time and (b) average daily BOG generation rate of a 57.2 m³ storage tank filled with unsaturated and saturated LNG (Other parameters are as given in Table 2).
fuel throughput LNG refueling stations, one idea is to only refill half of
the storage tanks to increase their LNG holding time. Fig. 10 shows
the effects of LNG filling level in a 57.2 m$^3$ storage tank on
LNG holding time and average daily BOG generation rate. Initial
LNG level in the tank represents the volume percentage of the tank
occupied with LNG. As shown in Fig. 10a, increasing the initial LNG
level in the tank from 50% to 90% increases the holding times of
unsaturated and saturated LNG from 63 and 17 days to 95 and 25
days, respectively. Lower thermal mass of LNG, e.g., 50%, in the tank
causes higher BOG generation rate as shown in Fig. 10b. These data
disprove the idea of filling the tank partially in order to increase the
LNG holding time in refueling stations.

Smaller LNG storage tanks can be used in low throughput LNG
refueling stations. Table 5 shows the dimensions of LNG storage
 tanks with 21.84–107.32 m$^3$ net capacity. The surface area to tank
net capacity ratio, $A_{tank}/V_{tank}$, affects the BOG generation rate of
LNG storage tanks (Adom et al., 2010); Larger tanks have smaller
$A_{tank}/V_{tank}$ as indicated in Table 5. This means that small $A_{tank}$
and large thermal mass of LNG stored in storage tanks are desirable
features to reduce the BOG generation rate and increase the LNG
holding time.

Fig. 11 demonstrates the holding time and average daily BOG
generation rate of LNG storage tanks ranging from 21.84 to
107.33 m$^3$. It can be seen in Fig. 11a that a 21.84 m$^3$ storage tank
filled with unsaturated LNG has a holding time 56% shorter than a
107.33 m$^3$ storage tank. Accordingly, the average daily BOG generation
rates of the 21.84 m$^3$ storage tank filled with unsaturated and
saturated LNG are equal to 0.43% and 0.48% which are higher than
those of the 107.33 m$^3$ storage tank. This analysis shows that storing LNG in a storage tank with the right size provides longer
holding time than storing the same amount of LNG in two or three
lower-capacity storage tanks.

The 57.2 m$^3$ storage tank filled to 60% of its net capacity, as
shown in Fig. 10, holds the same amount of LNG as the 41.49 m$^3$
storage tank filled to 80% of its net capacity, as shown in Fig. 11.
However, the 41.49 m$^3$ storage tank holds the LNG for a longer time
with lower average daily BOG generation rate than the 57.2 m$^3$
storage tank. This is because of the difference between the surface
area to LNG volume ratios, $A_{tank}/V_{LNG}$, of these tanks. The $A_{tank}/V_{LNG}$
of the 41.49 m$^3$ storage tank is equal to 2.36 ($= 78.19 m^2/(80 \times 41.49 m^3)$) whereas that of the 57.2 m$^3$ storage tank is equal to
3.04 ($= 104.35 m^2/(60 \times 57.20 m^3)$). It can be concluded that
when comparing storage tanks of different sizes, smaller $A_{tank}/V_{LNG}$
is preferred in order to achieving longer LNG holding time.

### 4.4. Performance analysis of LNG storage tanks with fuel delivery

In this section, the performance of a 57.20 m$^3$ LNG storage tank
with fuel delivery to vehicles is investigated similar to the study of
Powars (2010). Three fleet sizes of 5, 10, and 20 vehicles with fuel
requirements of 189, 3.79, and 7.56 m$^3$/day, respectively, are

---

**Table 5**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Storage tank sizes and specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank net capacity, $V_{tank}$ (LNG storage vessels, 2016)</td>
<td>21.84 m$^3$</td>
</tr>
<tr>
<td>Length of inner tank, $L_{tank}$</td>
<td>9.29 m</td>
</tr>
<tr>
<td>Outer diameter, $D_o$</td>
<td>1.978 m</td>
</tr>
<tr>
<td>Inner diameter, $D_i$</td>
<td>1.73 m</td>
</tr>
<tr>
<td>Insulation thickness, $t_{insulation}$</td>
<td>0.248 m</td>
</tr>
<tr>
<td>Mass of storage tank (empty)</td>
<td>9525 kg</td>
</tr>
<tr>
<td>Surface area of inner tank, $A_{tank}$</td>
<td>55.19 m$^2$</td>
</tr>
<tr>
<td>Initial LNG level in storage tank</td>
<td>5.94 m</td>
</tr>
<tr>
<td>Surface area of inner tank to net capacity ratio, $A_{tank}/V_{tank}$</td>
<td>2.53 l/m</td>
</tr>
</tbody>
</table>
modeled. In this model, it is assumed that each vehicle is fueled with a 0.38 m$^3$ of LNG. The fueling process is started every day at 6 p.m. and takes 5 min per vehicle with a fuel delivery rate of 0.076 m$^3$/min. There is a 5 min time interval between the fueling of two consecutive vehicles. For example, fueling process for a fleet size of 5 vehicles takes 45 min (= 25 min fueling + 20 min intervals). Fig. 12 shows the unsaturated and saturated LNG pressures and levels in the tank for daily fuel delivery rates of 1.89, 3.79, and 7.56 m$^3$/day.

Fig. 12a and b show that unsaturated and saturated LNG pressures do not reach the MAWP of the tank and decreases gradually, especially for fuel delivery rates of 3.79 and 7.57 m$^3$/day. LNG removal from the tank causes a portion of LNG evaporate to displace the liquid volume. LNG gains heat from the LNG thermal mass to evaporate and the LNG temperature reduces. Accordingly, the LNG pressure reduces. Fig. 12c and d show that the unsaturated and saturated LNG levels in the tank steadily decrease and the tank is fully depleted without releasing the BOG to the atmosphere. It should be noted that these data is true for the case of regular fuel delivery with appropriate rate. In the case of low fuel delivery rates, the LNG tank pressure can reach the MAWP of the tank, such as ones reported by Chen et al. (Chen et al., 2004).

Fig. 13 shows the idea of using a single-wall storage tank insulated with conventional insulation materials and no vacuum condition, such as polyurethane, and daily fuel delivery rates of 1.89, 3.79, and 7.56 m$^3$/day to fleet sizes of 5, 10, and 20 vehicles, respectively. $U_{\text{insulation}}$ in this modeling is equal to 0.1 W/m$^2$K corresponds to that of polyurethane listed in Table 4. For the storage tank filled with unsaturated LNG, Fig. 13a indicates that fuel delivery rate of 1.89 m$^3$/day fails to maintain the storage tank pressure below its MAWP. At this condition, 25% of unsaturated LNG is still available in the tank as shown in Fig. 13c. However, higher fuel delivery rates of

![Fig. 11. Effects of storage tank size on (a) LNG holding time and (b) average daily BOG generation rate for unsaturated and saturated LNG (Other parameters are as given in Table 2).](image1)

![Fig. 12. Effects of fueling fleet sizes of 5, 10, and 20 vehicles on unsaturated and saturated LNG (a)–(b) pressure, and (c)–(d) level in tank ($U_{\text{insulation}}$ is equal to 0.022 W/m$^2$K. Other parameters are as given in Table 2).](image2)
3.79 and 7.56 m³/day would be sufficient to contain the BOG in the tank with no release to the atmosphere.

Fig. 13b shows that the single-wall tank with $U_{\text{insulation}}$ of 0.1 W/m²K and fuel delivery rates of 1.89 and 3.79 m³/day cannot hold saturated LNG for more than 6.5 and 8.6 days, respectively, below the MAWP of the tank. At these times, 62% and 27% of saturated LNG is still available in the tank, as shown in Fig. 13d. These results highlight that a single-wall storage tank cannot be used for LNG applications if the on-site liquefier does not operate efficiently and the refueling station has not a high fuel throughput greater than 7.56 m³/day. In this model, the insulation thickness corresponding to $U_{\text{insulation}}$ of 0.1 W/m²K was equal to 0.248 m. In order to achieve $U_{\text{insulation}}$ of 0.02 W/m²K (similar to that of the baseline model), the insulation thickness made out of polyurethane should be 1.5 m thick which is not practical. As a result, using a single-wall storage tank with conventional insulation materials and on-site liquefier cannot be a practical solution to reduce the BOG emissions and upfront capital cost of equipment in LNG refueling stations.

5. Conclusions

In this study, the performance of LNG storage tanks in refueling stations with and without fuel delivery were studied. Our main findings are summarized in the following list:

- Storage tanks filled with unsaturated LNG provided more than 3 times longer LNG holding time than those filled with saturated LNG.
- The thermal mass of storage tanks had direct impact on LNG holding time and the BOG generation rate.
- High vacuum insulation materials, such as LCI at vacuum pressure of 133.3 Pa, assisted to increase the LNG holding time up to 188 days.
- Changes in the ambient temperatures ($-10^\circ C$ to $45^\circ C$) and geographic location of refueling stations reduced LNG holding time up to 50%.
- The ratio of heat transfer surface area to LNG volume, $A_{\text{tank}}/V_{\text{LNG}}$, was introduced as a crucial factor in comparing the holding times of storage tanks with different sizes.
- Storage tanks with proper vacuum insulation ($U_{\text{insulation}}$ of 0.022 W/m²K) could function with no BOG emissions under fuel delivery rates as low as 1.89 m³/day.
- The single-wall tank insulated with polyurethane ($U_{\text{insulation}}$ of 0.1 W/m²K) could not hold BOG for fuel delivery rates less than 3.79 m³/day and was not a reliable solution for LNG refueling stations.

Acknowledgment

The authors gratefully acknowledge the financial support of the Natural Sciences and Engineering Research Council of Canada (NSERC), Mitacs Elevate, and Westport Power Inc.

Nomenclature

- $A$ area (m²)
- BOG boil-off gas
- $D$ diameter (m)
- $\Delta t$ time interval (s)
- GHG greenhouse gas
- $h_{\text{lg}}$ heat of evaporation (J/kg)
\[ k \text{ thermal conductivity (W/mK)} \\
L \text{ length (m)} \\
LCI \text{ Layered composite insulation} \\
\text{LNG} \text{ liquefied natural gas} \\
\text{MAWP} \text{ maximum allowable working pressure} \\
\text{MLI} \text{ Multi-layer insulation} \\
\rho \text{ density (kg/m}^3) \\
T \text{ time (s)} \\
P \text{ temperature (°C)} \\
U \text{ heat transfer coefficient (W/Km)} \\
UA \text{ thermal conductance (W/Km)} \\
V \text{ volume (m}^3) \\
\]

**Subscripts**
- ambient: ambient conditions
- ceiling: tank ceiling
- holding time: holding time
- \( i \): \( i \)th step, inner
- insulation material: outer
- \( o \): outer
- roof: tank roof
- \( \tau \): tank storage tank

**References**


