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Analysis of temperature and pressure changes in liquefied natural gas (LNG) cryogenic tanks

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Abstract

Liquefied natural gas (LNG) is being developed as a transportation fuel for heavy vehicles such as trucks and transit buses, to lessen the dependency on oil and to reduce greenhouse gas emissions. The LNG stations are properly designed to prevent the venting of natural gas (NG) from LNG tanks, which can cause evaporative greenhouse gas emissions and result in fluctuations of fuel flow and changes of fuel composition. Boil-off is caused by the heat added into the LNG fuel during the storage and fueling. Heat can leak into the LNG fuel through the shell of tank during the storage and through hoses and dispensers during the fueling. Gas from tanks onboard vehicles, when returned to LNG tanks, can add additional heat into the LNG fuel. A thermodynamic and heat transfer model has been developed to analyze different mechanisms of heat leak into the LNG fuel. The evolving of properties and compositions of LNG fuel inside LNG tanks is simulated. The effect of a number of buses fueled each day on the possible total fuel loss rate has been analyzed. It is found that by increasing the number of buses, fueled each day, the total fuel loss rate can be reduced significantly. It is proposed that an electric generator be used to consume the boil-off gas or a liquefier be used to re-liquefy the boil-off gas to reduce the tank pressure and eliminate fuel losses. These approaches can prevent boil-off of natural gas emissions, and reduce the costs of LNG as transportation fuel.

Keywords: Liquefied natural gas; Transportation fuel; Cryogenics; Thermodynamics; Heat transfer

1. Introduction

The transportation sector accounted for 66% of the total US petroleum consumption and 26% of total US greenhouse gas emissions in 1997 [1]. To address issues related to reliance on foreign oil, greenhouse gas emissions, and pollutant emissions, alternative transportation fuels such as compressed natural gas (CNG) and liquefied natural gas (LNG) have been proposed. There will be immense economic and environmental benefits if even 10% of the transportation energy from petroleum can come from LNG. Natural gas consumption in the United States is expected to exceed 33 tcf/year by 2020, increasing from 22 tcf/year in 1997 [2,3].

Most of the vehicles using natural gas instead of diesel fuel run on compressed natural gas (CNG), which is typically stored in cylindrical steel tanks at pressures up to 3600 psi. One of the drawbacks of CNG is that only limited amount of fuel can be stored in trucks or buses, which reduce the driving range significantly.

Compared with CNG, LNG can provide vehicles with longer driving ranges per refueling. LNG takes up about 1/600th of the volume that CNG occupies at room temperature and atmospheric pressure. Currently, LNG is being promoted primarily for heavy-duty vehicles such as trucks and transit buses. Another advantage is that LNG can be transported via ocean tankers. The disadvantage is that the boil off of LNG can cause excessive pressure buildup in LNG tanks, and therefore we have to find methods to reduce the pressure of the boil-off gas and to prevent venting of the boil-off natural gas in storage vessels, transportation tanks, and/or on-board tanks.

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Nomenclature

C	thermal conductance (W/K)
c_p	isobaric specific heat (J/kg K)
D	diameter (m)
h	enthalpy (J/kg)
Δh	wall thickness of tank (m)
ΔH	heat of vaporization (J/kg)
k	thermal conductivity (W/m K)
M	molecular weight (kg/mol)
p	pressure (Pa)
q	heat flow rate (W)
R	universal gas constant (8.314 N m/mol K), thermal resistance (K/W)
r	boil-off rate (kg/kg day)
S	area (m^2)
t	time (S)
T	temperature (K)
v	specific volume (m^3/mol)
V	volume (m^3)

Greek Symbols

α	ratio of the junction area and total area, S_s/S
β	area density (1/m), S/V
ε	emissivity
ρ	density (kg/m^3)
σ	Stefan–Boltzmann constant 5.670×10^{-8} (W/m^2 K^4)

Subscripts

g	gas
i	inner
l	liquid
m	multilayer superinsulation
o	outer
s	steel
v	vacuum
∞	ambient

In this paper, we use the thermodynamic and heat transfer methods to analyze the pressure and temperature changes in LNG tanks. The evolving of properties and composition of LNG fuel inside tanks as a function of time is simulated. The effect of number of buses fueled each day on the total fuel loss rate due to venting will be discussed. Some approaches to preventing fuel loss at LNG stations are also proposed. For example, the boil-off gas of LNG can be used to power an electric generator or be re-liquefied to reduce the gas pressure.

2. Thermal analysis of boil-off of LNG in cryogenic tanks

A typical LNG fueling system consists of LNG storage vessels, LNG fueling pumps and LNG dispensers. LNG storage vessel is a vacuum insulated pressure vessel ranging in capacity from 6000 to 30,000 gal [4]. LNG storage vessel consists of a 9% nickel steel inner liner and a carbon steel outer liner, using double wall construction with super insulation under high vacuum. The maximum working pressure for these tanks is normally 250 psig or lower, with product stored at 50–120 psig. The LNG fueling pump is a single or multistage centrifugal pump submerged in the storage tank or in a separate vacuum-insulated sump allowing on-demand LNG fueling. The LNG dispenser module shown in Fig. 1 features two types of fuel connectors: MOOG [5] and PARK [6]. The LNG dispenser assembly consists of a control valve assembly, a volumetric meter or Coriolis mass flow meter and valves for cool-down recirculation (Fig. 1). Before fueling a vehicle with

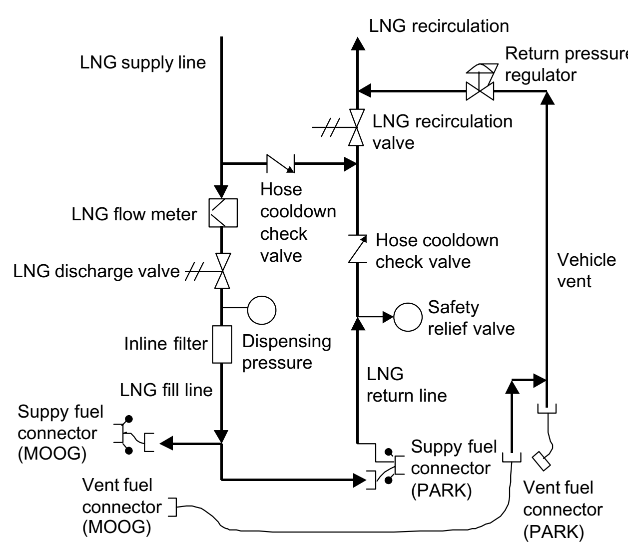

Fig. 1. LNG dispenser module with MOOG and PARK fuel connectors.

LNG, the hoses and LNG dispenser are flushed with LNG. The time required to cool down and bring the LNG system on line can be up to about 5 min, particularly when fueling is intermittent [4,7].

Boil-off of LNG from these LNG tanks usually takes place at LNG stations and can cause excessive pressure build up in LNG tanks. Boil-off is caused by heat added to LNG fuel during the storage and fueling. Heat can leak through the shell of tank, and be added to the LNG fuel during the operation. For example, cooling down the hose and dispenser before fueling a vehicle tank can add heat into the LNG fuel. If natural gas vapors in vehicle tanks are returned to the bulk storage tank, this additional heat must be taken into account. The following are several mechanisms, which add heat into the LNG fuel and may cause boil-off.

2.1. Heat leak through shell of LNG storage tank

The thermal resistance of the shell of tank can be estimated as [8]

$$R = 1/(1/R_m + 1/R_s), \tag{1}$$

where resistance of the multilayer superinsulation, $R_m = \Delta h/(k_m S)$ [9], parasitic heat resistance of the support connecting the inner and outer shells of tank $R_s = \Delta h/(k_s S_s)$ [9], S is the area of inner shell of tank, S_s is the area of support junction, Δh is the thickness of multilayer superinsulation, k_m is the average thermal conductivity of superinsulation, and k_s is the conductivity of stainless steel. The heat flow rate across the shell of LNG tank is estimated as

$$q = \Delta T/R = \Delta T * \left(\frac{k_m S}{\Delta h} + \frac{k_s S_s}{\Delta h}\right) = \Delta T(k_m S + k_s \alpha S)/\Delta h = \Delta T(k_m + k_s\alpha)\beta V/\Delta h, \tag{2}$$

where the ratio of the support junction area and total area $\alpha = S_s/S$, the area density of tank $\beta = S/V$, and V is the capacity of LNG tank. The temperature difference between the ambient and the LNG is $\Delta T = T_\infty - T$, where T_∞ is the ambient temperature. For a plain tube the area density is $\beta = 4/D$, where D is the diameter of the tube. From Eq. (2) the heat conductance of the tank shell is

$$C = (k_m + k_s\alpha)\beta V/\Delta h. \tag{3}$$

The thermal conductivity of superinsulation k_m is generally estimated as 5×10^{-5} W/m K [10], and conductivity of 1% chrome steel at 0 °C, k_s as 43 W/m K. This nearly six orders of magnitude difference in thermal conductivity necessitates a low value of the ratio of the support junction area to the total area of nearly five orders of magnitude.

The boil-off rate of LNG due to heat leak through the shell of LNG storage tank is estimated as

$$m_l = q/(h_g - h_l), \tag{4}$$

where h_g and h_l are the enthalpies of methane in gaseous and liquid states, respectively. From the above equation, the boil-off rate of LNG can be estimated as

$$r = m_l/(V\rho) = \Delta T(k_m + k_s\alpha)\beta/[\rho\Delta h(h_g - h_l)], \tag{5}$$

where ρ is the density of LNG. Enthalpy of liquid methane, $h_l = \int_0^T c_p \, dT$. Correlation for heat capacity of liquid methane is based on a series expansion in temperature, $c_p = A + BT + CT^2 + DT^3$, where $A = 5149$, $B = -43.249$, $C = 0.301449$, and $D = -4.49243 \times 10^{-4}$ [11]. The enthalpy of gaseous methane can be obtained as $h_g = h_l + \Delta H$ where the heat of vaporization is based on the Watson correlation [11], $\Delta H = \Delta H_1 [\frac{T_c - T}{T_c - T_1}]^n$, and the heat of vaporization of methane $\Delta H_1 = 0.5095 \times 10^6$ J/kg at $T_1 = 111.65$ K, $T_c = 190.55$ K, and $n = 0.38$ for $90.55 \text{ K} < T < 190.55$ K.

Fig. 2(a) shows the boil-off rate as a function of insulation thickness for $\beta = 2$ and $T = -162$ °C. The boil-off rate here means what percentage of fuel to be boiled off to keep the same temperature when heat is added into the fuel. The boil-off rate strongly depends on the area of the cross-section of the support strut, which links the outer and inner shells of the tank. For junction area ration $\alpha = 0.005\%$, the boil-off rate for insulation of 1.5-in. thickness is 0.83% per day. With a reduction in the area of strut cross-section, e.g., $\alpha = 0.002\%$, the boil-off rate is reduced to 0.34% per day for the insulation of the same thickness. From Eqs. (4) and (5), boil-off rate $r = 0.83\%$ for 13,000 gal (49.2 m^3)

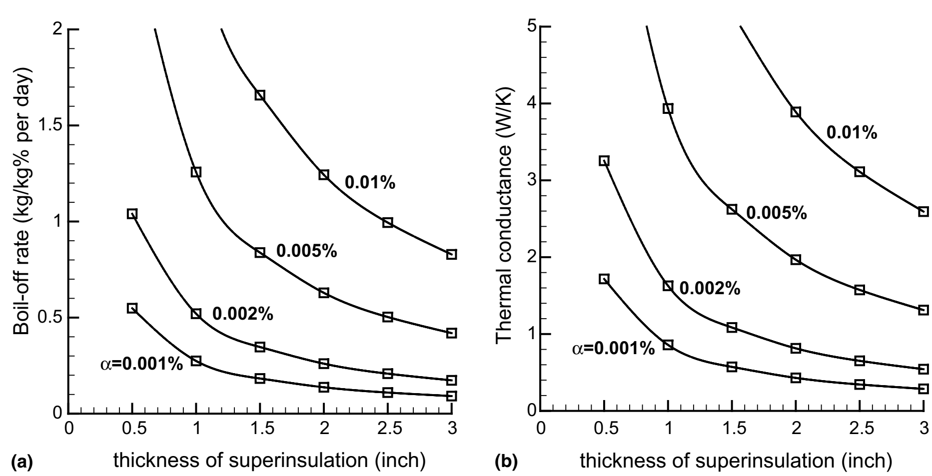

Fig. 2. (a) Boil-off rate and (b) thermal conductance as a function of thickness of multilayer superinsulation for a tank with an area density of $\beta = 2$, which is filled with LNG at −162 °C.

tank at $T = -162$ °C corresponds to a heat leak rate, $q = \rho Vr(h_g - h_l) = 1014$ W, where $(h_g - h_l) = 506,169$ J/kg and $\rho_l = 424.2$ kg/m^3 at $T = -162$ °C.

Fig. 2(b) shows the thermal conductance as a function of thickness of insulation. For junction area ratio $\alpha = 0.005\%$, the thermal conductance for 1.5-in. thickness insulation is 2.6 W/K. With a reduction in the area of strut cross-section, e.g., $\alpha = 0.002\%$, the thermal conductance is reduced to 1.0 W/K. However, the junction area ratio has to be large enough for the strut to support the weight of the tank.

2.2. Natural gas returned from the vehicle tank

The natural gas vapors inside the vehicle's fuel tanks can be returned to the bulk storage tank. The density of natural gas vapor can be estimated from the Benedict–Webb–Rubin (B–W–R) equation [12]

$$p = \frac{RT}{v} + \left(BRT - A - \frac{C}{T^2}\right)\frac{1}{v^2} + \frac{(bRT - a)}{v^3} + \frac{a\alpha}{v^6} + \frac{c}{v^3T^2}\left(1 + \frac{\gamma}{v^2}\right)\exp\left(-\frac{\gamma}{v^2}\right), \tag{6}$$

where v is the specific volume. Since natural gas is mainly composed of methane, we use properties of methane as that of natural gas. For methane, the constants are converted from [12] as, $R = 8.314$, $a = 5.01 \times 10^{-6}$, $A = 0.18796$, $b = 3.380 \times 10^{-9}$, $B = 4.260 \times 10^{-5}$, $c = 0.2579$, $C = 2.287 \times 10^3$, $\alpha = 1.244 \times 10^{-13}$, $\gamma = 6.0 \times 10^{-9}$. The density of vapor $\rho = M/v$, where the molecular weight of methane $M = 0.016$ kg/mol. Table 1 lists densities of liquid methane and vapor methane at different pressures. The returned gas from vehicle vessels to storage tank can be estimated as

$$m_2 = \rho V. \tag{7}$$

For onboard storage tank which can be refilled with 150 gal (0.5678 m^3) LNG, vapor to be returned to the LNG tank amounts to $m_2 = 6.0$ kg at pressure $p = 100$ psi and density $\rho_g = 10.6$ kg/m^3.

2.3. Heat leak through dispenser

Before fueling a vehicle tank, the hoses and dispenser are recirculated with LNG. Boil-off of LNG due to cooling of the dispenser can be estimated as

$$m_3 = c_{p_s}(T_\infty - T)m_s/(h_g - h_l). \tag{8}$$

Assuming mass of the steel in the dispenser $m_s = 10$ kg, the cooling of dispenser at $T_\infty = 20$ °C causes $m_3 = 1.7$ kg boil-off of LNG at $T = -162$ °C each day where $c_{p_s} = 480$ J/kg K.

2.4. Heat leak through fuel hose

Cryogenic insulated hose is used to transfer fuel to the vehicle tank. It is equipped with LNG nozzles ranging from 10 to 50 gpm (Fig. 1). Suppose the length of cryogenic insulated hose is $L = 3.66$ m (12 ft), and inside radius $r = 0.016$ m (0.625 in.), and thickness $\Delta h = 0.038$ m (1.5 in.), then it requires up to 5 min to cool down and refill the 150 gal vehicle vessel using a 50 gpm Moog LNG nozzle. The heat resistance of the hose is

$$R = 1/(1/R_v + 1/R_s) \tag{9}$$

where the thermal resistance of vacuum insulation $R_v = 1/[\varepsilon_{eff}\sigma(T_i^2 + T_0^2)(T_i + T_0)S]$, thermal resistance of junction $R_s = \Delta h/[k_s S_s] = \Delta h/[k_s\alpha S]$, and effective emissivity $\varepsilon_{eff} = 1/[1/\varepsilon_i + r_i/r_0(1/\varepsilon_0 - 1)]$. The heat leak rate is therefore

$$q = \Delta T/R = \Delta T * \left(\frac{1}{R_v} + \frac{k_s\alpha S}{\Delta h}\right). \tag{10}$$

The boil-off rate due to heat leak through the fuel hose is

$$m_4 = q/(h_g - h_l). \tag{11}$$

Fig. 3 shows boil-off rate of LNG at $T = -162$ °C contributed by heat leak from the hose as a function of the length of hose. For $\alpha = 0.05\%$, hose length of 3.66 m, and fueling time of 5 min, the boil-off caused by heat leak through the hose will amount to $m_4 = 1.4$ kg LNG (Fig. 3).

The total boil-off for fueling one bus is thus

$$m = (m_2 + m_3 + m_4) \tag{12}$$

If one bus with a 150 gal LNG tank is fueled each day, then the boil-off for fueling this bus to keep the saturated pressure at zero psi is about $m = 9.1$ kg using the above equation. In real operation, the fueling can cause the pressure build-up in LNG tanks, and the heat added to the LNG fuel for fueling one bus is equal to the

Table 1
Methane pressure and density at liquid [13] and gaseous states [Eq. (6)]

Pressure (psi)	Temperature (°C)	Liquid density (kg/m^3)	Gas density (kg/m^3)
0	−162.2 (−260 °F)	424.2 (3.54 lb/gal)	0
50	−140.0 (−220 °F)	390.6 (3.26 lb/gal)	5.43
100	−128.8 (−200 °F)	370.3 (3.09 lb/gal)	10.60
150	−120.5 (−185 °F)	357.1 (2.98 lb/gal)	15.77

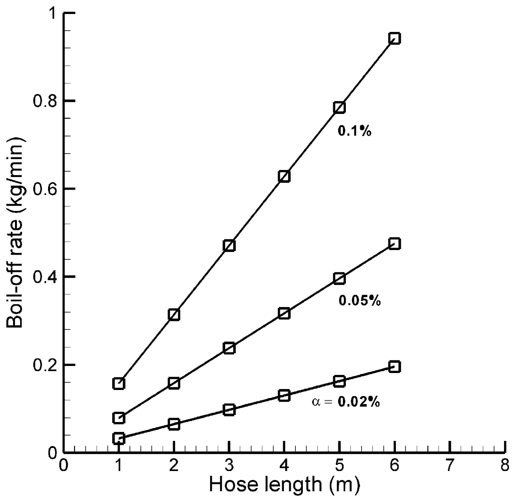

Fig. 3. Boil-off LNG as a function of length of hose to fuel a vehicle.

heat taken out by boiling off the amount of gas in Eq. (12) for keeping the saturated pressure at zero psi.

2.5. Heat release by boil-off

When heat is added into the LNG, the vapor pressure inside the tank will increase. Venting of natural gas can be used to reduce the vapor pressure and thus the LNG temperature. We assume that the vapor is in the saturated state, so that the relationship between the vapor pressure and temperature of LNG is known. If the initial mass of LNG is m_l, and temperature is reduced by ΔT after venting a certain amount of LNG, m; the following equation is valid for small ΔT

$$[h_g(T) - h_l(T)] * m = [h_l(T) - h_l(T - \Delta T)] * (m_l - m) \quad (13)$$

From the above equation, the boil-off rate is then

$$r = m/m_l = [h_l(T) - h_l(T - \Delta T)]/[h_g(T) - h_l(T - \Delta T)]. \quad (14)$$

The percentage of LNG to be boiled off in order to reduce vapor pressure is shown in Fig. 4. For example, to reduce the saturated vapor pressure from 150 psi to 0, 28.9% LNG is to be boiled. Similarly, to reduce the saturated vapor pressure from 150 to 100 psi, 7.7% LNG has to be boiled off, and from 100 to 50 psi, 9.2% LNG has to be boiled off. Evidently, the venting of boiled off gas can result in the loss of a large amount of LNG.

Certainly, venting is not an efficient way to reduce the vapor pressure and has to be avoided. Options to reduce the vapor pressure include arranging LNG delivery schedule, e.g., to fill the station storage tank when the vapor pressure is high, or to use vapor in the station storage tank to power an electric generator or a liquefier.

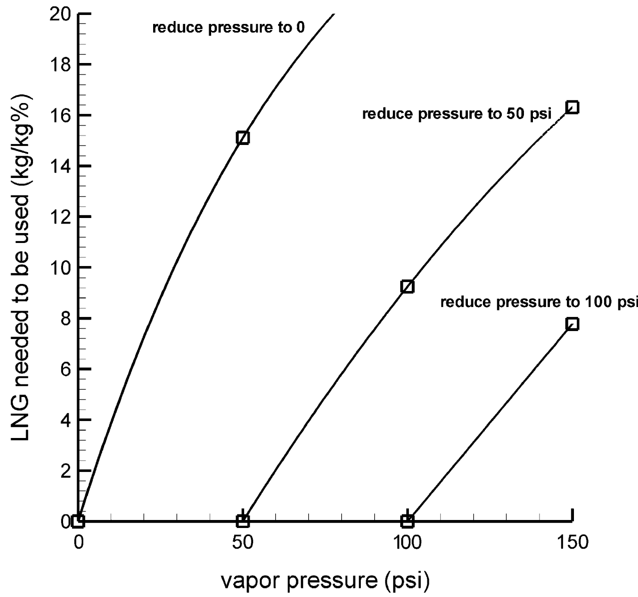

Fig. 4. Percentage of LNG to be boiled to reduce saturated vapor pressure.

3. Dynamic process during LNG storage and fueling

To get a picture of how the properties and composition of LNG in an LNG tank change we need to use a dynamic model to simulate the storage and fueling process. A heat transfer model can be used to describe the thermal history while a thermodynamic model can be used to obtain the properties and composition of LNG. During storage and fueling, the properties of LNG, such as enthalpy, mass, vapor pressure, temperature and density, also change with time. The changes in enthalpy, H, and mass, M, of cryogenic LNG can be described using the following equations

$$\frac{dH}{dt} = \dot{V}_{fill} * \rho_{l_0} h_l(T_0) + C(T_\infty - T) - nV_{bus}\rho_l c_{p_l} T + n * h_{fueling} - \dot{m}_{over} c_{p_l} T - \dot{m}_{vent} c_{p_g} T, \quad (15)$$

$$\frac{dM}{dt} = \dot{V}_{fill}\rho_{l_0}\dot{m}_{over} - \dot{m}_{vent} - nV_{bus}\rho_l, \quad (16)$$

where T_0 is the temperature of LNG to be filled into the storage vessel, T_∞ is the ambient temperature, C is the thermal conductance of the shell of cryogenic tank, $\dot{V}_{fill}$ is the rate of filling the storage tank, $\dot{m}_{over}$ is the overflow rate when the volume of LNG is larger than the capacity of tank, $\dot{m}_{vent}$ is the venting rate, V_{bus} is onboard tank capacity, and $h_{fueling}$ is the enthalpy added to the LNG fuel when fueling a bus. By knowing the total enthalpy and mass, temperature of the cryogenic natural gas can be obtained by solving the following equations

$$H = M_l h_l(T) + M_g h_g(T), \quad (17)$$

$$M = M_l + M_g, \quad (18)$$

$$V = M_l/\rho_l + M_g/\rho_g. \quad (19)$$

To solve the above three equations, an iteration scheme is used. In this iteration scheme, we first set the temperature of LNG as T^0, the temperature is then updated as $T = T^0 + [H - (M_l h_l(T^0) + M_g h_g(T^0))]/(M_l c_{p_l} + M_g c_{p_g})$ using Eq. (17). The gas density is then $\rho_g = M_g/(V - M_l/\rho_l)$ from Eq. (19). From Eq. (6), the vapor pressure is known once ρ_g and T are known. The mass of liquid natural gas is then updated as $M_l = M_l^0 + \chi(p - p^*)$, where p^* is the equilibrium vapor pressure, and $\chi = MV_g/(RT)$ is a coefficient. Repeat the above steps until $|p - p^*| \leqslant \varepsilon$, where ε is a small value, such as $\varepsilon = 0.1$ Pa.

3.1. Storage process without fueling buses

We considered a cryogenic tank of 15,000 gal at an LNG station built in Beijing (Chart NexGen). The pressure changes measured in the LNG station are listed in Table 2. The saturated pressure changes from 140.2 to 153.3 psi after 5 days without filling and venting. In our calculation, we assumed that the initial fill is 2571 gal with a saturation pressure of 140.2 psi. The thermal conductance of the LNG tank is estimated to be about $C = 1$ W/K. Changes of the vapor pressure and temperature in the LNG tank are shown in Table 3. The saturated vapor pressure increases about 3 psi at about 2500 gal fill and 140 psi saturated pressure. We plot the predicted saturated vapor pressure with time in Fig. 5, the two solid symbols are experimental data as listed in Table 2.

We further consider a commonly used 13,000 gal cryogenic tank with 10,000 gal initial fill at 50 psi, and thermal conductance $C = 1$ W/K. Table 4 lists the data such as pressures and temperatures in the LNG tank changing with time. It is shown from Table 4 that the vapor pressure increases about 1 psi each day after a fill of 10,000 gal of LNG at a saturated pressure of 50 psi.

Table 2
Measured pressure build-up in a 15,000 gal cryogenic tank at an LNG station in Beijing

Date	Content (gallon)	Saturated pressure (psi)
May 23, 2003	2571	140.2
May 28, 2003	2404	153.3

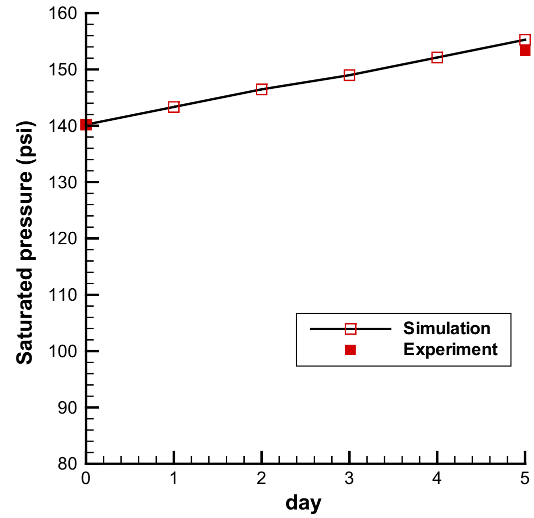

Fig. 5. Predicted saturated pressure for a 15,000 gal tank with an initial fill of 2571 gal LNG at saturated pressure of 140.2 psi and $C = 1$ W/K. Solid symbols are experimental data taken from an LNG station in Beijing.

3.2. Venting rate with number of buses

The effect of number of buses fueled each day on fuel loss rate is analyzed by considering a LNG tank of 13,000 gal and thermal conductance varying from 1 to 5 W/K. It is assumed when the pressure is higher than 160 psi, the storage vessel is automatically vented until the pressure is less than 160 psi. When the fuel in the tank is less than 2000 gal, the tank will be filled with 10,000 gal LNG at 50 psi. The heat added into LNG when fueling one bus is taken as $h_{\text{fueling}} = 506,169 \times 9.1$ J (Eq. (12)), heat of evaporation of 9.1 kg LNG at −162 °C; the real value of h_{fueling} may change for different buses. Each bus can be refilled with 150 gal. The pressure of returned gas in vehicle tanks is 100 psi. The fuel loss is calculated after 300 days. The fuel loss with number of buses is shown in Fig. 6(a). For thermal conductance of 2 W/K, the total fuel loss is about 4.3% of the total filled fuel,

Table 3
Predicted changes of vapor pressure for a cryogenic tank of 15,000 gal, which has a thermal conductance of 1 W/K

Day	p (psi)	T (K)	V (gal)	H (J)	Vent (kg)	Overflow (kg)	Liquid (kg)	Gas (kg)
0	140.20	150.87	2571.00	0.246E+10	0.0	0.0	3500.6	695.5
1	143.33	151.39	2565.67	0.247E+10	0.0	0.0	3485.3	710.8
2	146.46	151.91	2560.33	0.248E+10	0.0	0.0	3470.0	726.0
3	148.98	152.33	2556.07	0.250E+10	0.0	0.0	3457.8	738.2
4	152.12	152.85	2550.74	0.251E+10	0.0	0.0	3442.6	753.5
5	155.27	153.38	2545.41	0.252E+10	0.0	0.0	3427.4	768.7

Table 4
Pressure build-up in a 13,000 gal cryogenic tank with 10,000 gal initial fill at 50 psi and $C = 1$ W/K

Day	p (psi)	T (K)	V (gal)	H (J)	Vent (kg)	Overflow (kg)	Liquid (kg)	Gas (kg)
0	50.00	133.00	10000.00	0.675E+10	0.0	0.0	14785.8	61.7
1	50.96	133.21	10009.29	0.677E+10	0.0	0.0	14784.9	62.6
2	51.89	133.42	10018.41	0.678E+10	0.0	0.0	14783.9	63.6
3	53.30	133.74	10032.14	0.680E+10	0.0	0.0	14782.5	65.0
4	54.23	133.95	10041.30	0.681E+10	0.0	0.0	14781.6	65.9
5	55.63	134.26	10055.06	0.682E+10	0.0	0.0	14780.3	67.2
6	56.56	134.47	10064.23	0.684E+10	0.0	0.0	14779.4	68.1
7	57.49	134.68	10073.42	0.685E+10	0.0	0.0	14778.5	69.0
8	58.88	134.99	10087.24	0.687E+10	0.0	0.0	14777.2	70.3
9	59.80	135.20	10096.46	0.688E+10	0.0	0.0	14776.3	71.2
10	61.19	135.51	10110.28	0.690E+10	0.0	0.0	14775.1	72.4
11	62.11	135.71	10119.52	0.691E+10	0.0	0.0	14774.2	73.3
12	63.03	135.92	10128.77	0.692E+10	0.0	0.0	14773.4	74.1
13	64.41	136.23	10142.66	0.694E+10	0.0	0.0	14772.2	75.3
14	65.32	136.43	10151.92	0.695E+10	0.0	0.0	14771.4	76.1
15	66.69	136.74	10165.84	0.697E+10	0.0	0.0	14770.2	77.3

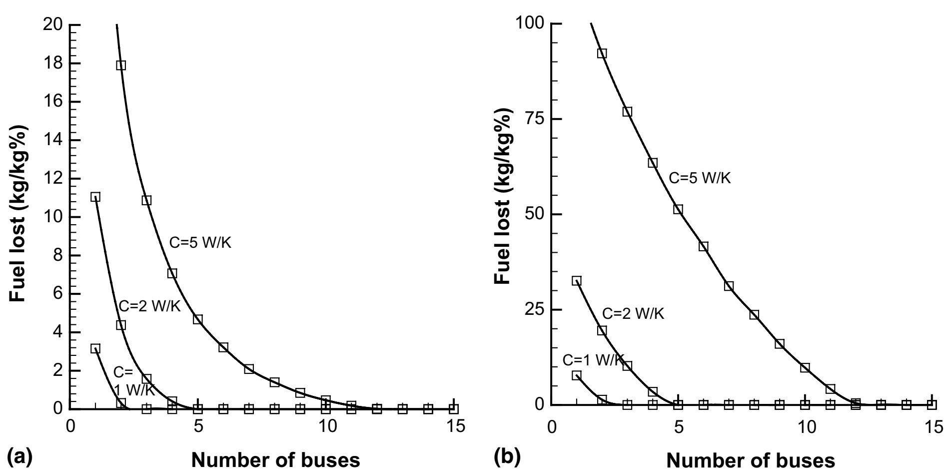

Fig. 6. (a) Total fuel loss and (b) fuel loss per day with number of buses.

when fueling two buses everyday. The fuel loss is reduced 0.4% when fueling four buses every day. The vented gas as a function of number of buses is shown in Fig. 6(b). For thermal conductance of 2 W/K, the average fuel loss rate is 19.5 kg each day when fueling two buses everyday. The fuel loss rate decreases to 3.4 kg each day when fueling four buses every day. It is evident that increasing number of buses fueled each day can reduce the fuel loss, as a percentage of total fuel delivered. The venting can be avoided when fueling more than five buses each day using an LNG cryogenic tank with $C = 2$ W/K or fueling more than three buses each day using a tank with $C = 1$ W/K. It is important to reduce the thermal conductance of the shell of tank and the thermal conductance is related to the steel strut support between shells of tank.

4. Boil-off gas to power an electric generator or be re-liquefied

The pressure of boil-off gas may build up inside the LNG tank if few buses are fueled each day. When venting is not favorable to reduce the storage tank pressure, boil-off gas can be used to power an electric generator or be re-liquefied. Power to be supplied by using LNG is estimated as

$$P = (m\rho/M) \; * \; \Delta H_c \; * \; \varepsilon_w, \tag{20}$$

where ΔH_c is the heat of combustion of methane and ε_w is the efficiency to convert methane to electricity. For a boil-off rate of 9.7 kg/day, heat of combustion $\Delta H_c = 890$ kJ/mol, and efficiency $\varepsilon_w = 35\%$ [2], the supplied power is about $P = 188,846$ kJ/day or 2.9 hp.

The boil-off natural gas can be used to power an electric generator or be re-liquefied using a 200-gpd liquefier. Generally, two types of engines can be used for the liquefier, naturally aspirated spark ignition natural gas (SING) engine and port-injected dual-fuel or pilot ignition natural gas (PING) engine. The SING engines with simple gas mixers, which are used in prior-generation light-duty and medium LNG vehicles, requires fuel supply pressures of 20 psig or less [14]. For SING engines that are turbocharged, the fuel supply pressure requirement is typically in the 30–40 psig range if a gas mixer is used. However, current-generation heavy-duty SING engines are turbocharged and use microprocessor-controlled fuel metering systems to optimize performance and minimize emissions. Even though these engines inject the gas at intake manifold pressure, a significant pressure differential is required to ensure accurate injection system operation. Fuel supply pressure requirements in the range of 60–100 psig are typically required for SING engines of this type. Another type of natural gas engine that is currently used in many heavy-duty vehicles is the dual-fuel engine that meters natural gas by port injection and initiates combustion by direct injection of diesel fuel [11,15]. These turbocharged engines are variously referred to as port-injected dual-fuel or pilot ignition natural gas (PING). The fuel pressure requirements are in the range of 100–130 psig. Most of the current LNG-fueled heavy-duty fleet vehicles use one of the two types of engines, SING with microprocessor-controlled fuel metering, or port-injected duel fuel. For other types of engines, refer to [15].

A typical storage LNG tank with electric generator or liquefier module is shown in Fig. 7. The LNG tank pressure should be below 175–200 psi. LNG tank needs to be vented or vented gas be used when head pressure exceeds 150–175 psi. In this model, a pressure-activated valve is used to keep the tank pressure below 80 psi. When the tank pressure exceeds the set-point, e.g., 80 psi, the three-way pressure-activated valve shown in Fig. 7 routes ullage vapor instead of liquid to the engine. This decreases the tank pressure the same way as venting. When the fuel tank pressure is below a set-point (e.g., a pressure slightly higher than the engine fuel supply requirement), liquid is drawn from the tank to the engine.

5. Conclusions

We analyzed the mechanisms that may contribute to the boil-off of LNG in LNG station storage tanks. Heat leak through the shell of storage tank is the main factor for the boil-off of LNG. Special design of the strut can be used to reduce the heat leak rate of an LNG tank.

Thermal conductance can be used to characterize the potential heat leak of an LNG tank. Using dynamic analysis of heat transfer in the LNG system without fueling buses, one can estimate the thermal conductance of an LNG tank. We calculated the pressure changes in a 15,000 gal tank at an LNG station in Beijing, and the predicted pressure changes compare well with the measured pressure changes.

We further considered an LNG station with a 13,000 gal tank. The number of bus fueled each day has a large effect on the total loss of fuel. By increasing number of buses fueled each day in an LNG station the total fuel loss can be greatly reduced. The total fuel loss for four buses each fueled with 150 gal amounts to 0.4% kg/kg when an LNG tank of $C = 2$ W/K is used. The fuel loss can be eliminated when more than five buses are fueled each day in a station with a tank of $C = 2$ W/K thermal

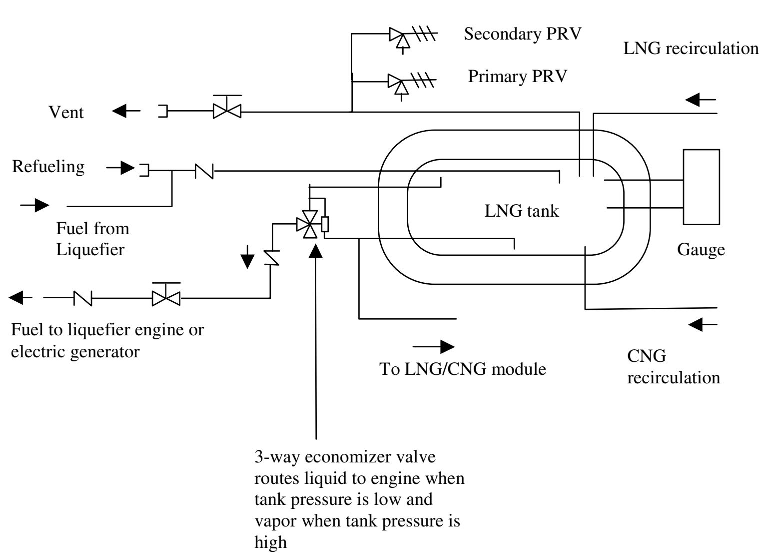

Fig. 7. LNG storage tank with module of electric generator or liquefier.

conductance, or when more than three buses are fueled each day in a station with a tank of $C = 1$ W/K.

To eliminate the fuel loss, an on-site electricity generator can used to generate electricity using the ullage vapor in the LNG tank. Or a liquefier can be used to liquefy the vapor and to prevent fuel loss in LNG stations. These techniques can prevent the boil-off gas from venting and reduce fuel cost.

However, in most cases, the minimum throughput capacity of the liquefier is above the boil-off rate. Such as for a 13,000-gal LNG tank, 3.9 gal LNG will be boiled-off each day assuming boil-off rate of 0.03% per day [7]. The LPMRC liquefier size ranges from 200 to 8000 gpd according to [7]. The electricity generator may be more feasible to consume the ullage gas when the tank pressure is high, and to consume the fuel when the tank pressure is low.

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