Numerical computation of Boil off Rate (BoR) in shipboard LNG tanks

A K Eswara\(^1\) and P Sandilya\(^2\)

\(^1\) Marine Engineering & Technology, Indian Maritime University, P-19, Taratala Road, Kolkata 700088, India
\(^2\) Cryogenic Engineering Centre, Indian Institute of Technology, Kharagpur 721302, India

E-mail: eswara.arun@gmail.com

Abstract. Natural gas is an environment-friendly fuel and a raw material for many chemicals. Its offshore transport is economical when the gas is transported in liquefied form as Liquefied Natural Gas (LNG) over distances (exceeding 2000 kilometers) by sea. LNG is stored at near-atmospheric pressure and about 112 K in these tanks. Heat inleak from the ambient into the stored LNG causes considerable boil-off of the LNG due to low latent heat of vaporization of LNG. Boil off Gas (BoG) generation should be reduced to minimize the loss of LNG as well as environmental pollution. Determination of the boil-off rate (BoR) poses a challenge because it involves interplay of multitude of phenomena and considerations, like liquid sloshing that is likely to generate heat and increases the interfacial area between the liquid and the ullage, variation in LNG composition due to BoG generation, and thermal stratification. In this paper we present a numerical analysis of the BoG generation, including some of the effects just mentioned. A model including transport phenomena based-equations and thermodynamic phase relations has been developed for this purpose. The simulation results would help in carrying out more in depth study of BoG generation that is useful in the design and operation of the prismatic membrane tanks.

1. Introduction

Boil-off Rate (BoR) is an important design parameter for shipboard LNG tanks as it specifies the likely amount of liquid loss during the maritime transportation. BoR leads to the loss of deliverable cargo, loss of freight rate, transportation efficiency and increased climate impact. Ships’ machinery and propulsion plant design and ratings are influenced by the BoR and the resulting Boil-off Gases (BoG). The shipping industry widely adopted carriage of LNG at near atmospheric pressure in insulated prismatic membrane tanks due to several benefits.

Qu et al. (2019) presented a new model to compute BoR in shipboard LNG tanks using proprietary knowledge on membrane tanks and discussed difficulties in bringing the influence of sloshing into calculations. The difficulties include prediction of phase interface surface area and the dissipation of liquid sloshing energy in the tank among other difficulties.

In the present paper we demonstrated the inclusion of the influence due to changes in interfacial surface area and energy dissipation with liquid sloshing in BoR calculations for a shipboard LNG tank. To achieve this, we have developed BoR calculation as an iterative process in solving a system of differential equations developed from the first principles of energy and mass balance. Energy interactions with vapor and liquid systems by heat in-leak, sensible heat exchange and sloshing energy dissipation are separately computed and brought into the iteration process for each time step. The BoR in the tank with respect to time and as a function of ullage pressure are simulated for different ambient conditions.
2. Model description

**Figure 1.** Schematic representation of a shipboard membrane LNG tank. Heat inleak is established due to thermal gradient between the cargo and the ambient through the tank walls and insulation. The dynamics of the ship at sea causes the liquid to slosh inside the tank. Only roll motion is considered in the model for simplification.

The Figure 1. shows a shipboard LNG membrane tank containing cargo in two phases. The liquid undergoes sloshing due to rollmotion of the ship, which is the oscillatory angular motion of the vessel about ‘y’ axis. The external energy interacts with the liquid and vapor systems by way of heat inleak and a fraction of sloshing energy is dissipated as heat in the liquid. As a result, the initial equilibrium after loading is disturbed. As ship’s are employed for transport of large quantities of LNG, the mass of liquid is too large compared with the mass of the vapor in a loaded passage. Also, their properties such as thermal conductivity, diffusivity, heat capacity, density are different. Hence, the liquid and the vapor phases are treated as separate control volume systems that may not be at phase equilibrium. The vapor and liquid regions are in thermal contact, open to mass transfer with boiling or condensation and at mechanical equilibrium. LNG is assumed to be pure Methane to simplify the BoR computation and focus on the effects of sloshing. The phase interfacial surface area is enhanced due to formation of surface waves. These waves travel across the breadth of the tank and strike against the tank walls dissipating some amount of energy as heat. The enhanced interfacial surface area increases sensible heat transfer between the phases.

The formation and breaking of the surface waves and local pressure variations may cause vapor bubbles in the liquid phase. The bubbles may have influence on the liquid phase, which was studied in a recent paper by Saha & Sandilya (2020). The quantification of such a phenomenon with sloshing is highly complex and may not be feasible without experimentation. To keep focus on the issues to be brought out, only a mild liquid motion is considered in the paper where the chances of bubbles causing significant effects are minimal and hence neglected. Under the assumption, the chance of a slosh wave reaching a large amplitude striking the roof of the tank is remote and such a case is not considered. BoG venting is an operational factor and is triggered when the ullage pressure nears the maximum operating range for the tank. Cargo inside the tank can be considered to undergo an irreversible constant specific volume process as long as the vent is closed.

3. Governing equations

3.1. Mass & Energy conservation

For liquid system, the conservation of mass can be stated as

\[ \frac{dm_L}{dt} = -\dot{m}_{boil} \] (1)
Energy conservation for liquid system can be written as Equation 2

\[
\frac{d(m_L C_{PL} T_L)}{dt} = \dot{Q}_{\text{in leak, L}} - \dot{m}_{\text{boil}} h_V + \dot{Q}_{\text{interface}} + \dot{Q}_{\text{slosh}}
\]  

(2)

For vapor system, the conservation of mass can be written as

\[
\frac{dm_v}{dt} = \dot{m}_{\text{boil}} - \dot{m}_{\text{vent}}
\]  

(3)

Energy conservation for vapor system can be written as

\[
\frac{d(m_V C_{PV} T_V)}{dt} = \dot{Q}_{\text{in leak, V}} - \dot{Q}_{\text{interface}} + \dot{m}_{\text{boil}} h_V - \dot{m}_{\text{vent}} h_V
\]  

(4)

The total volume of liquid and vapor systems is constant and also the sum of their specific volumes as long as \( \dot{m}_{\text{vent}} = 0 \). The equations are solved using implicit finite difference methods in the time domain using forward differences. Isochoric properties of Methane between 95 ∼ 130 K for a density value corresponding to the simulation setup are obtained from the NIST database, which is based on the equation of state presented by Setzmann & Wagner (1991). Linear interpretation is used between known temperature steps for determining unknown properties of Methane corresponding to each state point in the numerical methods. The interpreted values are then used at each step in the iterative scheme to compute mass boil-off, pressure rise over a period of time.

### 3.2. Sloshing in ship’s roll motion and energy dissipation

Sloshing is studied extensively to understand the dynamic loading on the tank walls and other phenomenon. Solaas (1995), Faltinsen & Timokha (2014) has presented great insights on velocity potentials that can exist for certain types of ship motions. Our interest is in particular on the roll motion of ships among other motions. The case also simplifies our effort to demonstrate use of our model equations in BoR calculations. Contributory effects of other ship motions can be included by similar approach. Demirbilek (1983) has carried out analysis on quantifying amount of dissipation of energy during sloshing in rectangular tanks and presented the theory, model, solution by numerical techniques. However, we found that due for the large ship scale and their motions, the values of Reynold’s numbers and the Froude numbers suggested by Demirbilek (1983) exceeded the presented data and hence could not be used. In the paper the linear velocity potentials presented by Solaas (1995) were used to study liquid motion and to create input in the simulation. The dissipation of the sloshing energy as heat in the liquid is estimated using the metholodolgy developed by Bouscasse et al. (2014).
3.3. Heat in-leak

The value of UA can be found out by individual resistances in the path from ambient to LNG as shown in Figure 1. Data for relevant heat transfer correlations are obtained from Se-Yun-H & Jang-Hyun-L (2016) and Korean Register (2020)

\[ \dot{Q} = UA(T_{ambient} - T_{cargo}) \]  

Where \( T_{cargo} \) can be either temperature of the liquid or vapor as the case may be.

Figure 3. Heat in-leak from sides (top left) and from bottom and top (top right) for shipboard LNG tank.

Figure 4. Thermal resistance model for the heat in-leak
3.4. Thermal design conditions used in the assessments

Table 1. IGC conditions used in the simulation are shown below. Wind is assumed to be static.

| Parameter         | IGC Cold  | IGC Warm |
|-------------------|-----------|----------|
| Air Temperature   | 5.0 °C    | 45.0 °C  |
| Sea water Temperature | 0.0 °C    | 32.0 °C  |

3.5. Interface heat transfer (sensible) from vapor to liquid

The sensible heat transfer from the vapor to liquid can be written using Newton’s laws of cooling as

\[
\dot{Q}_{\text{interface}} = h_{\text{interface}} S_{\text{interface}} (T_V - T_L)
\]

(6)

Where, \( h_{\text{interface}} \) is the convective heat transfer coefficient for the sensible heat transfer between the phases. It is evaluated from the Klimentko (1990) Nusselt number relationship shown in Equation 7.

\[
Nu_c = 0.087 \left( \frac{\rho_v}{\rho_L} \right)^{0.6} Pr_L^{1/6} \left( \frac{\rho_v}{\rho_L} \right)^{0.2} \kappa_{\text{relative}}^{0.09}
\]

(7)

\( S_{\text{interface}} \) is calculated from the free surface condition of Solaas (1995). The free surface (phase interface) coordinates with time are obtained from a simulation with velocity potential using in-house developed code using Python Matplotlib for specified input conditions, such as the tank and liquid fill dimensions and the roll motion. A construction of a curve connecting the free surface coordinates during dynamic roll conditions makes it possible to calculate the interface (curve) length in 2D. Since it is assumed that the vessel is only rolling and the 2D model captures only the transverse cross-section of the tank, it is assumed that the profile furrows along the length of the ship.

4. Simulations and results

4.1. Energy dissipation from liquid sloshing due to ship’s roll motion, ‘\( \dot{Q}_{\text{slosh}} \)’

Ship’s cargo tank filled with Methane is considered for evaluating our model Equations 1 to 4. The natural slosh period for the tank is calculated to be 4.4227 seconds. Liquid sloshing due to the rolling motion excitation is determined as a sinusoidal function below:

\[
\theta = \theta_0 \sin(\omega t)
\]

(8)

The velocities of liquid particles in x and z direction (refer to Figure 1.) during the roll motion are determined for 10 oscillations using linear model presented by Solaas (1995). The enhancement in the free surface area inside the tank undergoing roll motion in the time periods 8.9 ∼ 62.8 s is found out. Ship tank’s Reynold’s number suggested by Demirbilek (1983) was evaluated for the case and found to be in the range of 172224 ∼ 1205567 corresponding to the circular frequencies in the range of 0.1 ∼ 0.7 s−1. The value is higher than the data provided in the cited work. Research on scaling studies to benefit modern ship’s assessments are desirable.

The liquid under sloshing in the case, is approximately the top +2.3m to -2.3m from the mean liquid vapor phase while the deeper liquid particles are relatively unaffected. This presents the case for treating the sloshing liquid to be shallow. Boucasse et al. (2014) improvised the understanding developing relationship to predict energy dissipation in shallow rectangular tanks with liquid under sloshing. The energy dissipation in ship’s tank is calculated per unit length (along ship’s longitudinal) for the top 4.6m of sloshing liquid only. For small roll amplitude ships’ undergo angular oscillatory roll motion about its transverse metacenter with an equivalent pendulum length of its transverse
Table 2. Heat in-leak assessment for GTT Mark III membrane tank - calm weather

| Description                                      | Material | Thickness (mm) | κ (W/m·K) | h (W/m²·K) | Resistance (m²·K/W) |
|--------------------------------------------------|----------|----------------|------------|-------------|---------------------|
| Outer convection                                 | Air      | 13.79          | 0.0725163  |             |                     |
| Outer hull                                        | Sea Water| 7473.70        | 0.0001338  |             |                     |
| Convection in ballast space - vertical plate     | NVD Steel| 15.0           | 57.0       | 0.0002632   |                     |
| Convection in ballast space - horizontal plate   | Air      | 18.71          | 0.0534474  |             |                     |
| Inner hull                                        | NVD Steel| 26.19          | 0.0381825  |             |                     |
| Plywood                                           | Birch plywood| 300.0        | 0.030      | 10.0        |                     |
| Secondary insulation panel                        | R-PUF    | 0.6            | 70.440     | 0.0018210   |                     |
| Triplex Secondary Membrane                        | Aluminum-glass cloth laminate| 100.0       | 0.025      | 4.0         |                     |
| Primary insulation panel                          | R-PUF    | 12.0           | 0.025      | 0.480       |                     |
| Primary Membrane                                  | Birch plywood| 0.0125       | 0.168      | 0.074405    |                     |
| Convection in cargo space                         | Liquid   | 3000.0         | 0.0003333  |             |                     |
| Convection in cargo space                         | Vapor    | 3000.0         | 0.0003333  |             |                     |

Table 3. Particulars of LNG Ship used in simulation (existing ship data)

| Description                                      | Value        |
|--------------------------------------------------|--------------|
| Displacement                                     | 128277.5 MT  |
| Moulded breadth                                  | 45.8m        |
| Length between perpendiculars                    | 292m         |
| Summer draft                                     | 12m          |
| Block coefficient                                | 0.78         |
| Natural Roll motion time period                  | 7.58 s       |
| Tank width                                       | 28 m         |
| Liquid fill depth                                | 14 m         |
| Tank height                                      | 22 m         |

where \( \theta \) is the metacentric radius. Therefore, the ‘\( BM_{\text{slosh}} \)’, which is the distance between ship’s metacenter and the bottom level of equivalent mass of liquid under slosh, \( M_{\text{sloshing}} \) is used in the relationship proposed by Boucasse et al. (2014) shown using Equation 10. These values are taken from an existing ship’s stability booklet.

\[
E_{\text{Dissipation}} = \left( \left(2BM_{\text{slosh}}/L\right)^2 + 1 \right)^{3/4} \left(4M_{\text{sloshing}}gh_s\right)\theta_0^{3/2} \tag{9}
\]
**Figure 5.** Phase interface and amount of dissipation estimated using references (left) and time history of interface with time at $\omega = 0.5$ (right)

The energy dissipation is now estimated from Figure 12. of as Bouscasse et al. (2014)

$$M_{\text{fluid,slosh}} = 0.04 \cdot (4 \cdot 422.29 \cdot 28 \cdot 4.6 \cdot 9.81 \cdot 4.6)^{5/2} \cdot \frac{\pi}{180} = 10128 \text{ J per meter} \quad (10)$$

$$\Rightarrow \dot{Q}_{\text{slosh}} = 10128 \frac{\omega}{2\pi} = 806 \text{ W per meter} \quad (11)$$

4.2. Interface sensible heat transfer $\dot{Q}_{\text{interface}}$

The sensible heat transfer between the phases is estimated using the heat transfer correlation from Klimenko (1990). Nusselt number is evaluated at the phase interface and tank wall intersection region and it is assumed that the heat transfer coefficient found is uniform across the boundary. For calculating the value a boundary layer of 29mm is assumed. Nusselt number $Nu_c$ is calculated to be 56.0636. Heat transfer coefficient is

$$h = \frac{Nu_c \kappa_v}{4.6} = 0.14126W/m^2K \quad (12)$$

**Figure 6.** Velocity vectors in the top liquid layer under sloshing. At $\omega = 0.5$ the time history of the interface generated is provided in the Figure 5.

5. Conclusions

The papers demonstrates a method to predict BoR of LNG with dissipation of heat due to sloshing with a small rolling motion of the ship. The following are the findings for IGC warm conditions:

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1 Measurement of Boundary Layer on a flat plate, Kay Gemba (2007), California State University
Table 4. Properties evaluated from sloshing to calculate interface heat transfer coefficient in section 4.2

| Description                                    | Value                      |
|------------------------------------------------|----------------------------|
| Velocity                                       | 24.84 m/s                  |
| Characteristic length                          | 4.6 m                      |
| Density of liquid                              | 422.29 kg/m³               |
| Density of Vapor                               | 1.8228 kg/m³               |
| Mass flow rate                                 | 278.31 kg/s                |
| Thermal conductivity of tank wall primary membrane | 9.5 W/m K                  |
| Thermal conductivity of Liquid                 | 0.18381                    |
| Quality (assumed)                              | 0.9                        |
| Prandtl Number Liquid                          | 0.002209                   |
| Mixture Reynolds number                        | 893196                     |

Figure 7. Simulated results for pressure rise at 81.8% filling without sloshing dissipation (left) and with sloshing dissipation (right) for IGC cold conditions

(i) The BoR increased to about 0.139 % volume per day with a sloshing dissipation of about 806 W from 0.083% volume per day without dissipation.

(ii) The interface surface area is found to impact the BoR marginally, increasing the BoR with increasing surface area. There is a small enhancement to 30.9 from 28 m² per m length for the case considered.
The following are the findings for IGC cold conditions:

(i) The simulated results show pressure rise in the ullage at a filling depth of 18m corresponding to 81.8% filling in the tank with time. The BoR calculated was 0.069% volume per day without sloshing dissipation.

(ii) The BoR increased to about 0.127% volume per day with a sloshing dissipation of about 806 W when simulated for IGC cold condition.

(iii) It should be noted that the guaranteed BoR by the maker for the tank is 0.07% volume per day.

We can note that neglecting the effect of heat dissipation due to sloshing can introduce significant error in BoR computation for shipboard application. However, the interfacial surface area increases asymptotically with circular frequency of roll and presents difficulty in this approach. Such roll motions are not uncommon for LNG carriers in rough weather. The ullage height, frequency and amplitude of roll further complicates calculation of liquid free surface area or the heat and mass transfer phenomena. The approach adopted in this paper suits accounting for heat dissipation with all types of ship motions for small amplitudes and frequency. Further research is required to study sloshing with regard to estimating heat dissipation for larger vessel motions.

6. Notations

\( m_{boil} \) is the rate of boiling of liquid

\( m_L \) is the mass of the liquid

\( m_V \) is the mass of the vapor

\( m_{vent} \) is the mass rate of BoG venting

\( T_L \) is the liquid temperature

\( Q_{in\ leak,\ L} \) is the total heat in-leak into the liquid

\( \Delta H_{vap} \) is the enthalpy of vaporization

\( Q_{dosh} \) is the dissipation of kinetic energy in the liquid

\( Q_{interface} \) is the sensible heat loss to liquid

\( Q_{in\ leak,\ V} \) is the total heat in-leak into the ullage

\( T_V \) is the uniform temperature of the vapor in ullage space

\( h_L \) is the specific enthalpy of the vapor at a temperature of

\( h_V \) is the specific enthalpy of the vapor at a temperature of \( T_V \)

\( N_{uc} \) is the Nusselt number

\( Re_m \) Reynold's number of the mixture

\( \rho_L \) is the density of the liquid

\( \rho_V \) is the density of the vapor

\( \kappa_{relative} \) Relative thermal conductivity

\( \omega \) Roll motion excitation circular frequency

\( \theta_0 = 5 \text{ deg.} \) Initial roll angle for excitation

7. References

[1] Bouscasse, B., Colagrossi, A., Souto-Iglesias, A. & Cercos-Pita, J. (2014), ‘Mechanical energy dissipation induced by sloshing and wave breaking in a fully coupled angular motion system. i. theoretical formulation and numerical investigation’, *Physics of Fluids* 26(3), 033103.

[2] Demirbilek, Z. (1983), ‘Energy dissipation in sloshing waves in a rolling rectangular tank—i. mathematical theory’, *Ocean Engineering* 10(5), 347–358.

[3] Faltinsen, O. & Timokha, A. (2014), Sloshing, Cambridge University Press.

[4] Klimenko, V. (1990), ‘A generalized correlation for two-phase forced flow heat transfer—second assessment’, *International Journal of Heat and Mass Transfer* 33(10), 2073–2088.

[5] Korean Register (2020), *Guidance of Heat Transfer Analysis for Ships Carrying Liquefied Gases in Bulk/Ships Using Liquefied Gases as Fuels*, Korean Register of Shipping, 36, Myeongji ocean city 9-ro, Gangseo-gu, Busan, 46762 Republic of Korea.
[6] Qu, Y., Noba, I., Xu, X., Privat, R. & Jaubert, J.-N. (2019), ‘A thermal and thermodynamic code for the computation of boil-off gas – industrial applications of lng carrier’, Cryogenics 99, 105–113.

[7] Saha, P. & Sandilya, P. (2020), ‘A novel perspective on the performance analysis and design of an injection cooling system for liquid storage’, International Communications in Heat and Mass Transfer 117, 104794.

[8] Se-Yun-H & Jang-Hyun-L (2016), ‘Comparative study on the thermal insulation of membrane lng ccs by heat transfer analysis’, Journal of the Computational Structural Engineering Institute of Korea 29(1), 53–60.

[9] Setzmann, U. & Wagner, W. (1991), ‘A new equation of state and tables of thermodynamic properties for methane covering the range from the melting line to 625 k at pressures up to 100 mpa’, Journal of Physical and Chemical Reference Data 20, 1061–1155.

[10] Solaas, F. (1995), Analytical and numerical studies of sloshing in tanks, dr.ing thesis, Department of Marine Hydrodynamics, Norges Teknisk-Naturvitenskapelige Universitet, Trondheim Norway, pp. ON: DE97753136; ISBN 82–7119–854–8; TRN: NO9705215.