PREDICTION OF BOIL-OFF LNG IN CRYOGENIC STORAGE TANK BY NUMERICAL MODELING

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Abstract

Boil-off LNG is a phenomenon occuring in cryogenic storage tank affected by ambient heat and loading/unloading operation. During this moment, volume stays constant and pressure increases, otherwise pressure will be constant and fluid boils released from the vessel. Dangerous effect due to pressure build up to tank structure or economical losses and environmental pollution caused by venting to the atmosphere shall be avoided. Predicting the boil-off rate properly will be a key factor to determine the amount of flammable gas removed. This is essential for risk assesment purposes to estimate the consequences of such incidents. Moreover, this is primarily due to the vigorous boiling exhibited by cryogens with very low boiling points (e.g. LNG: -163 ^{O}C) upon being released on land or water at ambient temperature.

In this paper, a density based predictive source term model for estimating the rate of vaporization is presented. The model is validated to experimental data from field. Thermodynamic and heat transfer analysis will be conducted. The heat, mass and momentum balance equations are derived for different scenarios and more complex phenomena are incorporated using a simplified statistical mechanics approach. Time averaged local void fraction for different regimes are used to estimate more relevant density model.

Keyword : *Boil-off, CFD, LNG, cryogenic liquid, heat conduction, boiling, source term model, vaporization*

Introduction

Liquefied Natural Gas (LNG) is in the cryogenic temperatures area. The range for the saturated boiling temperature is -163 ^{O}C. When it is in the vapor phase due to solar heat and loading / unloading operation, there will be a build-up of pressure in the LNG storage tanks. In terms of avoiding the danger of an explosion, the LNG vapor must be removed out of the tank. Discharges to the atmosphere will impact economic losses and environmental pollution, so that the necessary effort to keep the total volume of LNG in the tank by reducing LNG boil-off. Prediction amount of LNG boil-off happens needed in terms of knowing the extent of the losses incurred.

In this paper, we need a way of right modeling in predicting the number of LNG boil- off that occurred in the tank. It's expected later on to help researchers and engineers to establish the proper way of doing conservation LNG volume, so not much is wasted and reduce losses.

Validation

The model is validated by comparing with experimental data from field. It's compared with the result from work done by [1]. There are several parameters used in this paper and by [1] are slightly different in order to prove that the simplified model and assumption are applicable to the benchmark result done by [1]. Figure 1 shows the difference between both.

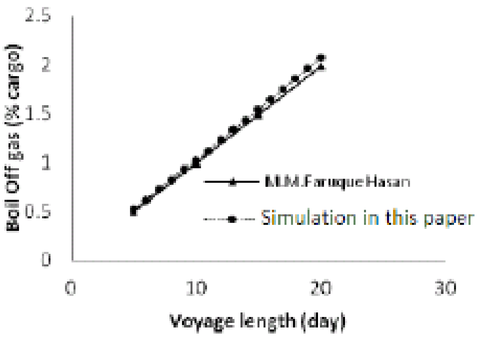


Fig. 1. Slight difference between the results

Modeling Boundary

Membrane-type LNG tanker will be used as a reference analysis, because more than half of the tanker industry wear this type [3]. 2-dimensional geometry to be dealt is presented in Figure 2. The width of the tank to be simulated is in accordance with the size of the general industry. Furthermore, 3-dimensional geometry will be simulated with ANSYS software and its meshing by tetrahedral element. All sides are treated as boundary walls, while the upper side allow movement in and out of LNG either liquid or vapor. Appropriate industry practice, outlet pressure is at a pressure of 101.3 kPa, slightly higher than the atmospheric pressure.

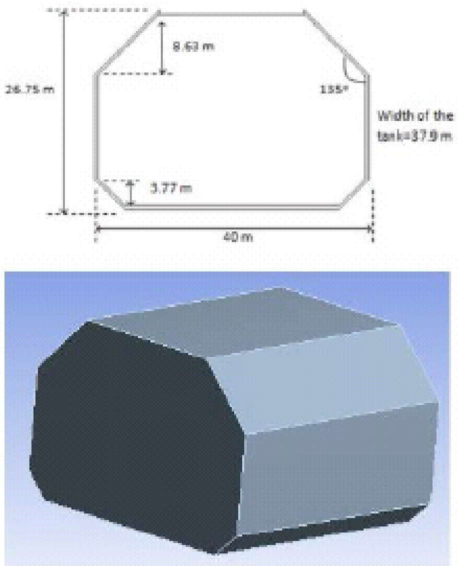


Fig. 2. Geometry modeling for 3 dimensional simulation

Material Properties

There are two defined volumes. The First is structural volume covers from outer shell to the inner shell of the tank expose to the cargo, which is represent material of main insulation, outer steel, inner steel, area of support junction, aggregate with different size, angle iron, ballast medium and so on. The Second is cargo volume represents the material of LNG. These two volumes are well presented by Table 1.

Table 1. Characterized volumes by material properties

Properties	Value
Volume 1 (LNG)	
Saturated temperature	-163 °C [7]
Liquid density	424.53 kg/m^3 [7]
Liquid Specific heat, c_p	3450 J/kg.K [7]
Liquid viscosity, μ	11781.33 kg/ms [7]
Liquid thermal conductivity, k	0.193 W/m.K [7]
Liquid Surface tension, σ_L	0.014 N/m [7]
Heat of vaporization , h_{fg}	51.03 x 10^4 J/kg [7]
Heat of Fusion, h_{sf}	58.62 x 10^3 J/kg [7]
Vapor density	1.826 kg/m^3 [7]
Volume 2 (Insulation and structural between inner to outer shell)	
Overall Heat Thermal Transmittance, U	0.411 kJ/m^2.K [3]

BOR Formula

Boil-off Gas (BOG) can be determined mainly from density and enthalpy of the LNG. Regarding to estimate the density of the natural gas vapor can be found in some literatures [4,5]. They used Benedict-Webb-Rubin (BWR) equation to predict natural gas density inside storage tank. Whilst, Boil-off Rate (BOR) is computed by energy balance equation [6]:

$$BOR = (q \times 24 \times 3600 \times 100\%) / 9\ V\ h_{fg} \quad (1)$$

The equation shows that the BOR are directly related to the variation of heat leakage, q, heat of vaporization h_{fg}, LNG density and total LNG volume inside the tank. However, in this paper, LNG BOG formation is determined purely based on saturated temperature of LNG (-163 ^{0}C).

$$\text{Mass Transfer Rate} = r \times VF_l \times \varrho_l \times (T - T_{sat}) / T_{sat} \quad (2)$$

Where r is under relaxation factor, VF_l is liquid volume fraction, ϱ_l is Liquid density, T_l is Liquid temperature and T_{sat} is saturated temperature.

The implementation of UDF in ANSYS FLUENT enables to use fundamental equation of fluid flow. The schiller-naumann drag law use for the phase interaction which is used to describe the drag between spherical vapor particle and surrounding LNG liquid condition.

Model Assumptions

Several simplifying assumption are made in order to meet the model requirement, while at the same time preserving the accuracy and reliability of computed BOG mass flow.

1). Vapor temperature is at saturated condition, so that relation of vapor-liquid is known at equilibrium condition.
2). The boiling phase on nucleate boiling regime
3). Any backflow condition occurred at the surface consider as in liquid phase
4). Representation for insulation material of polyurethane foam and ratio of support junction connecting inner and outer shell of the tank, overall heat transmittance is assumed as the value of 0.411 kJ/m^2.K [1]
5). The capacity of the single tank is 35,062 m^3 as in a real practice for 145,000 m^3 ship size
6). The ambient temperature are based on critical condition accordance with relevant requirement on the United States Cost Guard (USCG) which is 45 °C and 32 °C for air and seawater temperature

Result

In order to use equation (2), properties of each cell which are liquid density, liquid volume fraction and liquid temperature are required. Total liquid volume fraction of LNG inside LNG tank during boil-off formation can be obtained by integrating from the whole volume of the tank.

As a result, it can be seen at Fig. 3 about the relation between LNG temperature and vapor formation. Vapor formations are larger near the wall of the LNG tank due to ambient heat impacting to tank structure. In case of lighter density, vapor will buoyancy and tend to exit the surface. However, the backflow occur at the surface due to pressure acting at the outlet at the saturated condition. Only vapor pressure which is higher than zero gauge pressure setup at the pressure outlet will escape and Boil-Off considered loose.

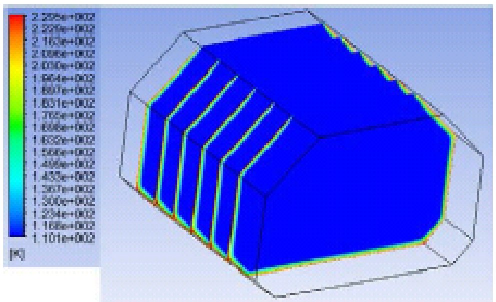
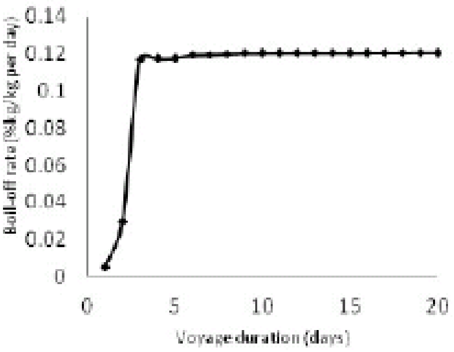


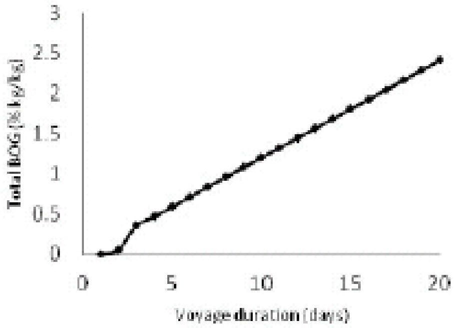
Fig. 3. Vapor temperature plot

As the heat leakage through the structural and insulation part of the tank are continuous, the LNG temperature is still maintained around the saturated temperature. The temperature of LNG became slightly higher than saturated temperature only near the wall. As the LNG far from the wall, the LNG temperature still maintain at the saturated temperature. This is the aim for LNG transportation mode for releasing boil-off gas in order to maintain LNG in liquid phase as much as possible.

Fig. 4 represents graph of the BOR value. It takes almost constant after approximately 5 days after voyage for the corresponding boundary condition. This happens due to initial temperature of LNG are set slightly below saturated temperature. It's related also with the performance of the LNG tank insulation.



(a)



(b)

Fig. 4. a) Boil-off rate and b) Total boil-off gas as a function of voyage duration

Conclusion

CFD ANSYS will help modeling the vapor behaviour of LNG inside tank in order to predict boil-off gas as an effect by ambient heat to the saturated boiling point of LNG. Nevertheless, Utilization of this software shall be applied to proper manner in order to derive right prediction compared to field data. Furthermore, the model can be developed to improve reducing boil-off gas of LNG inside tank. In this paper, the model is able to get the BOR for specific boundary condition with the value of 0.13 % per day which below standard industry range and within specification of IMO standard.

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