Boil-Off Gas: the LNG Tanks Guarantee

Sosthene Gasaba Ngenda and Angel Luis Sanchez Merino, SENER Ingeniería y Sistemas S.A., describe the role of boil-off gas in LNG tanks.

Analysing boil-off gas (BOG) is important because it is the most requested value, together with the useful capacity, as the guarantee in all refrigerated tanks. The determination of the BOG in full containment LNG tanks is generally carried out using the analytical method. In the present case, the calculation of BOG is done by both analytical and numerical (finite element method) approaches.

BOG is defined as the LNG that has been evaporated or boiled-off, producing an increase in the pressure inside the tank. This phenomenon is caused by the heat input into the LNG tank during storage and operation. There are several sources of heat input in this type of cryogenic tanks, such as: solar radiation, natural convection, and soil conduction. The outcome of this heat input into the tanks is a loss of energy – it is necessary for this to be minimised by installating the different required thermal insulations inbetween the outer and inner tank.

Whether the thermal insulation has been designed to meet the requested BOG value is usually and traditionally assessed analytically, considering 1D heat transfer calculation and other approximations and assumption, as constant thermal conductivities of the materials.

To double check and develop a more detailed calculation method of the BOG, SENER has developed the idea of carrying out an investigation based on numerical methods (finite element method) to calculate BOG in full containment LNG tanks. The used model intends to overcome the geometry simplifications and to use the thermal conductivities, depending on temperatures. In addition, the model is implemented parametrically so that it can be used for any other tank immediately getting the result.

The results obtained from the same tank using both analytical and numerical methods are compared to highlight which of the two approaches is more optimum.

Tank description

The analysis performed has been applied on the tank shown in Figure 1. This is a full containment LNG tank with the following main characteristics:

- Useful volume: 190 000 m^3.
- Diameter of inner tank: 42 m.
- Internal diameter of outer tank: 43 m.
- Total height of the tank: 52.4 m.

The tank is filled with LNG up to a level of 37.016 m, which is used for BOG calculations. The main layout of the thermal insulation used for this tank is shown in Figure 1 and detailed as:

- On the slab: Cellular glass type 'Foamglas HLB800 and HLB1200'. Other materials are used but with mechanical requirements and not as thermal insulation (concrete, sand, bituminous damp proof course, liner bottom, and secondary and primary bottom).
- Against walls: Resilient blanket, perlite powder, and cellular glass type 'Foamglas One'.
- On the suspended deck: Fibreglass insulation.

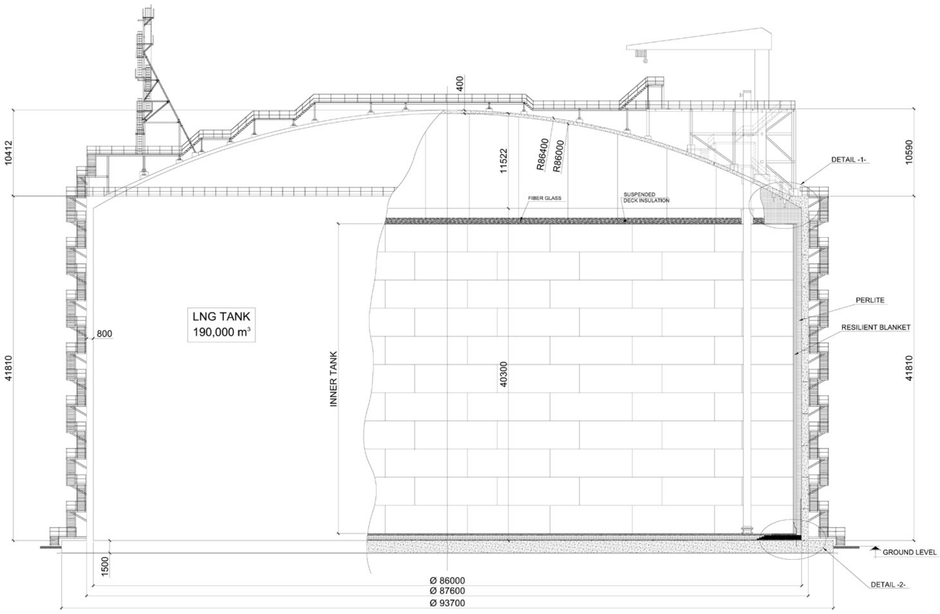

Figure 1. Full containment LNG tank general description.

Material thermal conductivities

The thermal conductivities of the different materials are critical in the BOG calculation. However, depending on the location of the thermal insulation, these materials have additional properties, including compressive strength (e.g. the cellular glass) or tensile strength (e.g. resilient blanket). The different insulation materials used in a refrigerated tank, such as an LNG full containment typology, can be split into two groups.

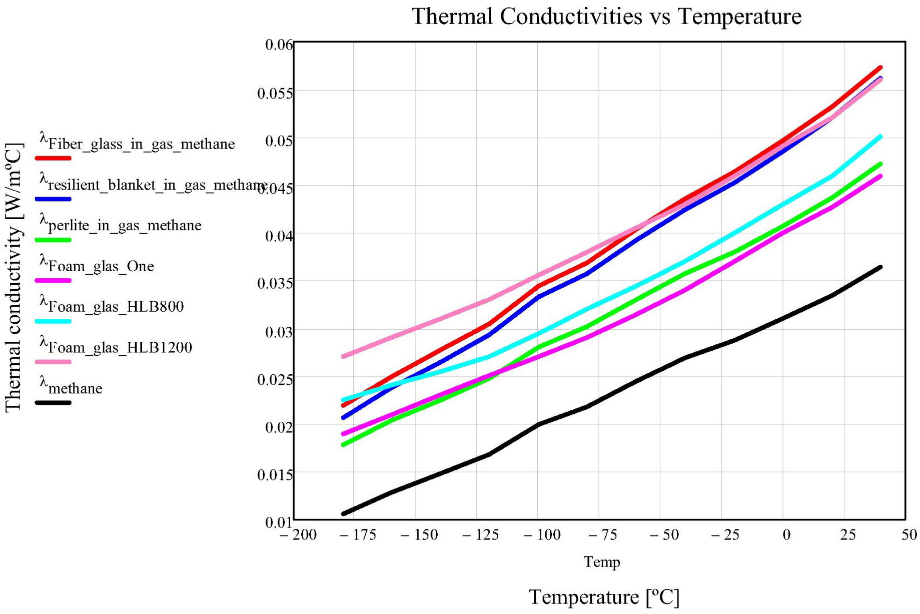

Figure 2. Thermal conductivities depending on temperature.

Materials with thermal conductivities almost independent on temperature

These materials are considered to have thermal conductivities greater than the rest of thermal insulation materials, and therefore less influence in the heat input calculation.

In addition, their dependence on temperature is very light – this means that they can be considered as a material whose thermal conductivities are independent from the temperature. Other materials, such as steel and aluminium, are not considered in the calculation due to their small thickness and high thermal conductivities in comparison to all other materials.

Materials with thermal conductivities dependent on temperature

Due to the wide range of temperatures in an LNG tank (between -170˚C and almost +70˚C), it is important to consider the dependency of thermal conductivity on the temperature of most of the thermal insulation materials. These thermal conductivities are represented in Figure 2.

The main materials involved in the finite element method calculation of the BOG are:

- Fibreglass[1] in gas methane, which comprises the material over the suspended deck, insulating the inner tank by its top.
- Resilient blanket[1] in gas methane, which comprises the material surrounding the wall of the inner tank.
- Perlite[1] in gas methane, which comprises the material surrounding the resilient blanket.
- Foamglas HLB800 and HLB1200, which comprises the material supporting and insulating the inner tank.
- Foamglas One, which comprises the material filling the space between the thermal corner protection and the outer tank.

Analytical calculation

Two of the most important hypotheses considered in the analytical calculation of the BOG are:

- All the thermal conductivities are constant at an average temperature.
- The tank geometry is zoned and simplified.

This is an iterative process that requires to use the material thermal conductivity at the estimated average temperature.

The analytical calculation is based on the well-known heat transfer theory (conduction, convection, and radiation). For that theory, the additional required data is given in Table 1.

Table 1. Technical additional data

Concept	Value
Tank liquid gross volume	205 134 m^3
Pure methane density (ρ)	422 kg/m^3
Methane latent heat	509 kJ/kg
Ambient temperature	34˚C
Soil temperature	30˚C
Heat transfer co-efficient (external face of wall)	6.34 $W/m^2 \cdot {}^\circ C$
Heat transfer co-efficient (external face of dome)	6.96 $W/m^2 \cdot {}^\circ C$
Stefan-Boltzmann	$5.675 \cdot 10^{-8}$ $W/m^2 \cdot {}^\circ C^4$
Maximum incident solar radiation	918 W/m^2
Concrete absorption co-efficient	0.60
Concrete superficial emissivity co-efficient	0.91
Ceiling aluminium superficial emissivity co-efficient	0.30
LNG superficial emissivity co-efficient	0.96
Carbon steel superficial emissivity co-efficient	0.79
Fibreglass superficial emissivity co-efficient (aluminum foil)	0.79
Porosity (fibreglass/resilient blanket/perlite)	0.965/0.965/0.850
Site latitude	17˚ 17 ft 39.3281 in.

Numerical calculation

The numerical calculation approach is aimed at avoiding the consideration of the hypotheses in the analytical calculation approach. That means:

- The thermal conductivities dependent on temperature: The numerical model can consider the thermal conductivity point by point for each material, as shown in Figure 2.
- No tank geometry simplification is considered: The calculation is more accurate since the corners and the spherical dome heat transfer are more precisely calculated by a numerical model than a 1D analytical model.

In this analysis, the numerical model is a finite element model. The commercial software used for such simulation is the ABAQUS.

Figure 3 shows the numerical axisymmetric model used to calculate the BOG. The different colours represent the different materials as per Figure 1.

Results

For both approaches, the BOG generated in one day by a refrigerated tank is given by the following relationship:

Where:

$$(BOG) = \frac{24*3600\,[s]*Q[W]}{V_{LNG}[m^3]*\rho[\frac{kg}{m^3}]*L_{heat}[\frac{J}{kg}]}\,[\%]$$

- Q[W] is the total heat input as per Table 2.

Table 2. Comparison between analytical numerical methods

Element	Heat input (Q) 'Analytical calculation' [kW]	Heat input (Q) 'Numerical calculation' [kW]
Slab	95.4	80.2
Wall	85.2	77.5
Roof	40.1	45.0
Pipes[2]	3.2	3.2
Total	223.9	205.9
BOG	0.044%	0.040%

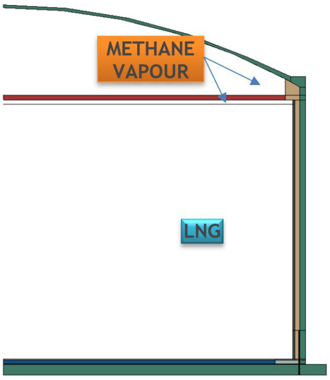

Figure 3. Numerical axisymmetric model.

- V_{LNG}[m^3] is the tank liquid gross volume as per Table 1.
- ρ[kg/m^3] is the pure methane density as per Table 1.
- L_{heat}[J/kg] is the methane latent heat as per Table 1.

To compare the results obtained by the analytical and numerical calculations, the global heat input and then the BOG are summed up in Table 2.

As can be seen in Table 2, the numerical method allows a lower estimation of the heat input to be maintained, obtaining a lower BOG value. In terms of volume, the reduction in the BOG is from 90.3 m^3/d predicted by the analytical method to 82.1 m^3/d, which is a reduction of 8.2 m^3/d.

Conclusions

Two approaches have been considered in the determination of the BOG for the same given full containment LNG tank: the 1D analytical method and axisymmetric numerical finite element method. For that, the same sources of heat inputs are considered and applied on both calculations (conduction, convection, and radiation). In addition, the same thermal boundary conditions have been considered. On the contrary, the hypotheses considered on both material properties and geometry are different.

The main conclusion obtained after this analysis is that the numerical method approach predicts a lower BOG value than the analytical method approach. This reduction is important since it leads to a thermal insulation reduction and then to an economical optimisation of the refrigerated tank.

Taking the opportunity of the parametrisation, the analysis has been carried out on numerous different refrigerated tank sizes. The conclusion has been the same: the numerical method approach leads to a lower BOG value than the analytical method approach.

This tank parametrisation allows companies, such as SENER, to carry out a quick design and an accurate proposal of the suitable and optimum thermal insulation in a competitive way and time. For SENER, this usually arduous task is definitively hereinafter turned into an easier one. **LNG**

Notes

1. This material has a porosity filled with methane gas which increases its thermal conductivity. This increment is: $(\lambda_{methane} - \lambda_{air})P_r^{1/3}$.
   Where:
   - $\lambda_{methane}$ and λ_{air} is respectively the conductivity of methane and air.
   - P_r is the porosity of the considered insulation material.
2. The heat input through the pipes is estimated by means the analytical method.