NUMERICAL SIMULATION OF LNG EVAPORATION INSIDE SEMI-TRAILER TRUCKS USED FOR THE TRANSPORTATION OF LNG TO SMALL SCALE TERMINALS AND REFUELLING STATIONS: PARAMETERS AND IMPLICATIONS

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Abstract. *During the past few years a substantial increase in interest for delivering Liquefied Natural Gas (LNG) directly to the consumers has been witnessed at European Union (EU) level. Despite the instability in oil prices, this interest is anticipated to grow given the recent EU policy towards alternative fuel infrastructure. Transportation however of LNG from production (or supply) to consumption is related to a number of non-technical and technical challenges. The latter are related to the formation of the so called "boil off gas", due to the potential evaporation of LNG, making the distance between the large scale LNG import terminal and the small scale LNG facility or refueling station a critical issue for the development of a small scale LNG value chain. A large portion of LNG transportation takes place through LNG trailers which although heavily insulated, suffer from moderate regasification of LNG, due to heat transfer from the surrounding environment, leading to, increased pressures and to sloshing inside the tank. Thus a first attempt to model with CFD techniques the evaporation rate of LNG inside a typical semi-trailer tank under ambient conditions are presented in order to develop a procedure that would enhance understanding and provide quantitative estimates of the level of LNG evaporation inside a semi-trailer truck carrying LNG at conditions that are relevant to a Greek summer day.*

1 INTRODUCTION

Liquefied natural gas is an odorless, colorless, noncorrosive and non-toxic cryogenic liquid, lighter than water, at normal atmospheric pressure. LNG is a liquid form of natural gas. The phase change from gas to liquid (and in reverse from liquid to gas) occurs at a temperature of 110.15 K for a pressure of 1 bar [1].

Directive 2014/94/EU states that all Member States must ensure that an appropriate number of LNG refueling points, accessible to the public, are put in place by the end of 2025, at least along the existing TEN-T Core Network. It also indicates that the necessary average distance between refueling points should be approximately 400 km. As a consequence, it is possible to deliver smaller quantities of LNG by road using semi-trailer trucks or ISO containers, directly to end user forming a small scale LNG chain. Specialized, double-skinned vacuum insulated tank trucks transfer LNG from the receiving terminals to "satellite" stations, where it is unloaded into insulated pressurized storage tanks. This kind of direct on shore distribution, commonly now referred as "Virtual Pipeline", could potentially become a substitute to a traditional pipeline.

This paper reports on work carried out as part of a diploma thesis and comprises a first attempt to model the evaporation rate of LNG inside a typical semi-trailer tank under ambient conditions relevant to a Greek summer day. Publicly available information on the design characteristics of a typical LNG tank was used to design a model in ANSYS MODELLER [2]. The grid was created in ANSYS Meshing while CFD calculations with ANSYS FLUENT [2] were carried out in two stages. In the first stage, heat fluxes from ambient air and solar radiation were calculated using a single phase model as a function of time. Then as a second phase, the evaporation rate of LNG inside the tank was computed. The VOF model was used to model the interphase between the liquid and evaporated natural gas and user defined functions were used to import the computed heat transfer from the first phase of the calculation and to impose the mass transfer rate of equation.

2 SEMI-TRAILER TANK SPECIFICATIONS

There is a variety of available trailer models with different characteristics. However, the design concept in most cases includes an inner and an outer vessel separated by a vacuum-insulated gap. The most common type of insulation used for such applications are multilayered insulation (MLI) and evacuated perlite. The first contains multiple layers of a reflective material separated by spacers with low conductivity, while the latter is a loose granular inorganic material of volcanic origin blown up at high temperatures. Both type of insulations are considered suitable for cryogenic applications due to their low thermal conductivity and excellent thermal properties. Especially perlite, provides a superior insulation with thermal conductivity up to 40 times less than extruded polystyrene foam (0.029 W/mK) depending on vacuum and temperature [3].

LNG semi-trailer manufacturers offer tanks at various dimensions, working pressures and capacities. In addition, all trailers are equipped with additional pipework and operational fittings for safety and regulation reasons. Figure 1 presents the drawing of the 53.000 LNG model offered by OHS, according to which the simulation geometry is designed at ANSYS MODELLER.

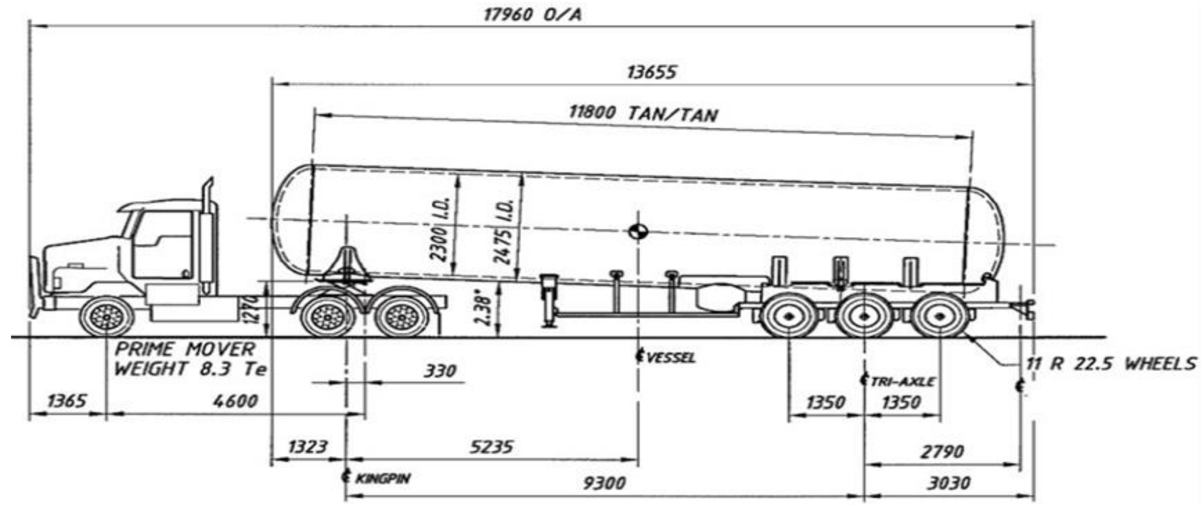

Figure 1.OHS trailer dimensions

3 BOIL-OFF GAS

One of the challenges in transporting and storing LNG is maintaining the liquid phase of natural gas inside the tanks as heat leakage to LNG through the tank shell results in LNG evaporation. The created vapor phase, which is usually called "Boil off Gas" (BOG), is a significant problem especially when no external refrigeration action takes place [4]. Although publicly available information on the boil-off of LNG in semi-trailers is scarce, it follows from studies in large import terminals that the boil off LNG if not released can cause excessive pressure buildup inside tanks [5]. On the other hand, release of BOG into the atmosphere can have significant financial implications as well as a non-negligible environmental impact as methane, which is the most important constituent of natural gas, is a greenhouse gas. Liquefying BOG, a common practice in land-based terminals, and also in LNG carrying vessels remains a non-practical solution for semi-trailers.

It is clear that estimation of the BOG rate is a crucial process for the design of LNG infrastructure, considering that heat leakage can occur through the whole LNG chain. Most of the previous approaches in literature examine the BOG rate in maritime transportation, LNG terminals and non-mobile tanks [4], [6], [7], [8]. Many approaches are based on assumptions solely for surface evaporation of the liquid with BOG rate calculated as a percentage of the original LNG volume [4], [5]:

$$BOR = \frac{Q \cdot 360 \cdot 24}{\Delta H \cdot V_{LNG} \cdot \rho} \cdot 100 \tag{1}$$

where BOR is the daily percentage of BOG (%/day), V_{LNG} the volume of LNG in cargo tanks in m^3, ρ the LNG density in kg/m^3, Q the heat exchange in W and ΔH the latent heat of evaporation in J/kg. However, equation (1) does not account for vapor movement inside the tank and includes several simplifications concerning heat transfer to the tank [7]. Zakaria et al. [8] modelled the mass transfer rate of LNG from liquid to gaseous phase, coupled their model with ANSYS FLUENT and provided a comprehensive characterisation of the temperature and BOG formation to predict the overall evaporation rate in stationary large-scale LNG tanks. As proposed by Zakaria et al [8] the mass transfer rate was calculated from:

$$Mass\_Transfer\_Rate = \frac{r \cdot VF_l \cdot \rho_l \cdot (T_l - T_{sat})}{T_{sat}} \tag{2}$$

r is the under relaxation factor, VF_l is the liquid volume fraction, ρ_l is the liquid density, T_l is the liquid temperature and T_{sat} is the saturated temperature. The implementation of a User Define Function (UDF) in ANSYS FLUENT enabled them to model the complete heat and mass inside the stationary tanks. The present work uses the work and methods of mentioned above [8] to calculate the evaporation of LNG inside a semi-trailer truck.

4 SIMULATION SET UP

The main assumption of the model is that a truck similar to the one in Figure 1 is travelling in a typical summer day in the vicinity of Thessaloniki. For modelling purposes, we assume that the tank is inside a large air container with dimensions 35,4x9x10m, large enough to account for a typical turbulent flow around the tank. In this work there are two regions of fluid flows, one region with single phase flow (air outside the tank) and another one with multiphase flow (inside the tank). Nevertheless, initial work showed that it was not possible to model concurrently both regions as well as heat transfer due to solar radiation. As a consequence, the proposed strategy to simulate evaporation included dividing the problem into two sequential sub-cases. As a first step heat fluxes from ambient air and solar radiation were calculated using a single phase model as a function of time. Then as a second phase, the evaporation rate of LNG inside the tank was computed. UDFs were used to import the computed heat transfer from the first phase of the calculation and to impose the mass transfer rate of equation (2).

The model was created using ANSYS Design Modeler, as shown in Figure 2. Three regions were created; the region inside the tank, the tank and the region of the surrounding air. Mesh generation and parts designation was done using ANSYS Meshing. Fluent solver preference and medium relevance center were selected for mesh generation. Moreover, the initial small rectangle of the box is assumed to be the velocity inlet, while the opposite one is the pressure outlet. The lateral faces are considered as asphalt walls due to air backflow problems. However, only the bottom face corresponds to the road characteristics, while for the others emissivity is set equal to one unit in order to permit solar radiation to reach the tank and distinguish these walls from the road.

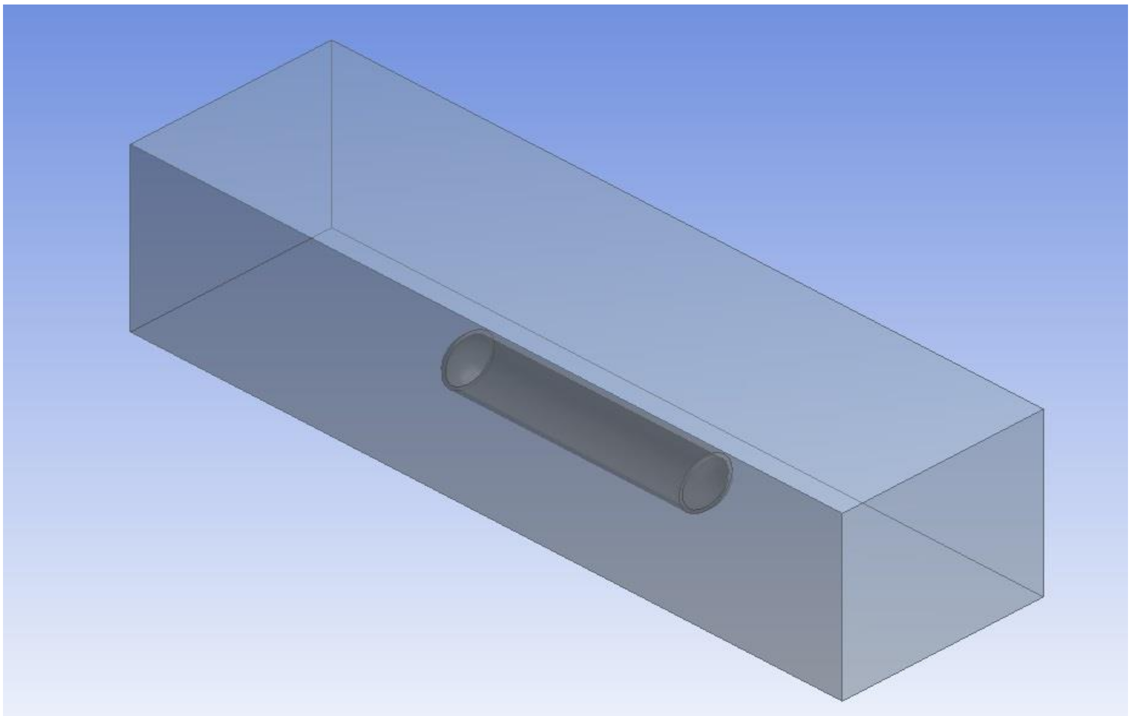

Figure 2. ANSYS Modeler geometry

The first sub-case is used to calculate the heat fluxes that reach the tank. For this purpose, all heat transfer mechanisms and materials used must be defined. Gravitational acceleration and the Boussinesq approximation were used to account for natural convection. The standard k-e model was used to account for the turbulent air flow and the surface to surface model was activated to include radiation heat fluxes. The FLUENT solar calculator provides information about the solar irradiation at Earth's surface in Thessaloniki (longitude $22^0 58'$, latitude $40^0 31'$). The time of the simulation chosen corresponds to the 21th day of June at 13:00 with good weather conditions.

The content of the tank is LNG, while the insulation used is perlite under vacuum. The properties of the materials used are given in Table 1. As, perlite thermal conductivity is not constant but temperature-depended, Hofmann suggested the following empirical equation (3) to relate thermal conductivity with temperature for a perlite density of 50 kg/m^3 y [9]. As a consequence, a UDF was used in order to express this correlation.

$$\lambda = a + bT^c (a = 1{,}911210^{-4};\ b = 3{,}475710^{-12};\ c = 3{,}6783) \tag{3}$$

	Cp (J kg^{-1} K^{-1})	μ (Pa s)	K (Wm^{-1}K^{-1})	ρ (kg m^3)	Emissivity
Air	1006,43	1,79e^{-5}	0,0242	1,225	-
Asphalt	920	-	0,75	2360	0,88
LNG	3450	1,46e^{-4}	0,193	424,53	-
Methane	2222	1,09e^{-5}	0,0332	0,6679	-
Perlite	UDF	-	387	50	0,55

Table 1: Materials used properties [3], [8], [9]

Air temperature is assumed to be 313 K and as a result inlet velocity is set at 313 K with 2% turbulent intensity and 9m hydraulic turbulence diameter. Insulation and LNG temperature are initialized at 110,99 K, while the tank pressure equals 800kPa. Vehicle speed is supposed to be around 80 km/h (approximately 22 m/s) and as a result this is the velocity magnitude at the inlet. The tank heating is simulated for 5 hours or 18.000 seconds which corresponds to a trip of 400 km.

5 RESULTS

The area-weighted average heat fluxes at the surface of the tank are recorded for the 18.000 seconds of the simulation. These values are presented in Figure 3 with blue color.

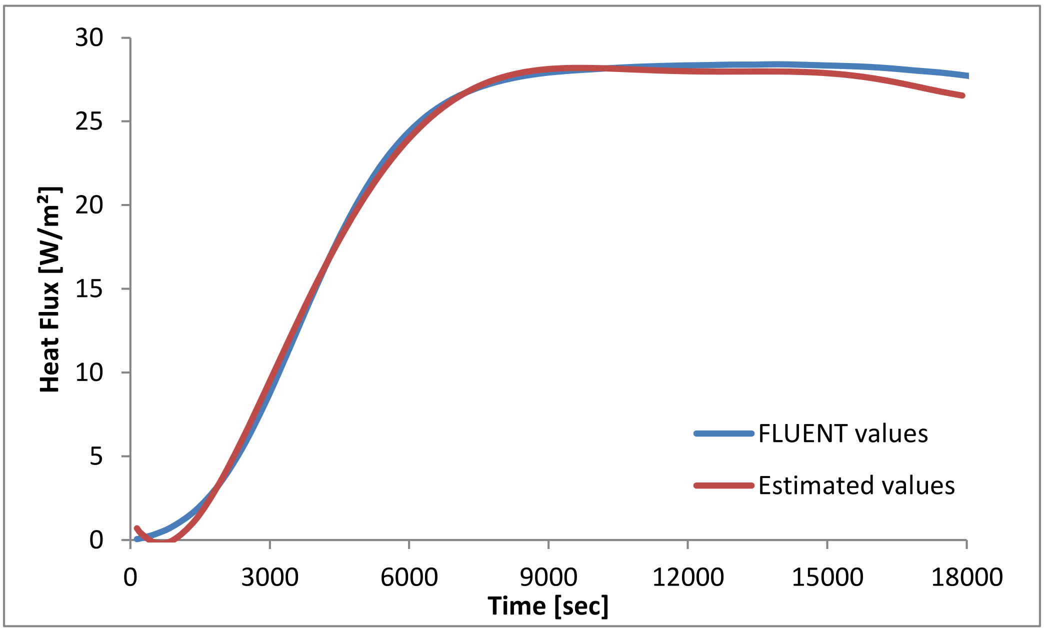

Figure 3. FLUENT and estimated heat fluxes

However, there is a need to express the correlation between heat fluxes and time in a mathematic equation in order to use it in a second UDF at the second sub-case and for this reason, equation (4) is used. The graph of the latter with respect to time is depicted in Figure 3 with red color, in order to compare the effectiveness of this approach.

$$Q = 3{,}97e^{-23}t^6 - 2{,}63e^{-18}t^5 + 6{,}74e^{-14}t^4 - 8{,}21e^{-10}t^3 + 4{,}46e^{-6}t^2 - 0{,}0049t + 1{,}292 \quad (4)$$

The second sub-case for the calculation of the boil-off gas rate is based on the above data. As a consequence, a second UDF is written to define the heat fluxes at the tank wall. In addition, the surrounding air is removed in contrast to the tank and its content. The tank is supposed to be filled with LNG, which evaporates to methane based on the UDF written according to equation (2). The "Volume of Fluid" model is used, while the flow inside the tank is considered laminar. Moreover, the tank is heated according to equation (4) and the initial temperature is set at 110,99K. Gravitational acceleration is set at y axis and Boussinesq approximation is also enabled. Finally, perlite is the insulation material with temperature dependent thermal conductivity according to equation (3).

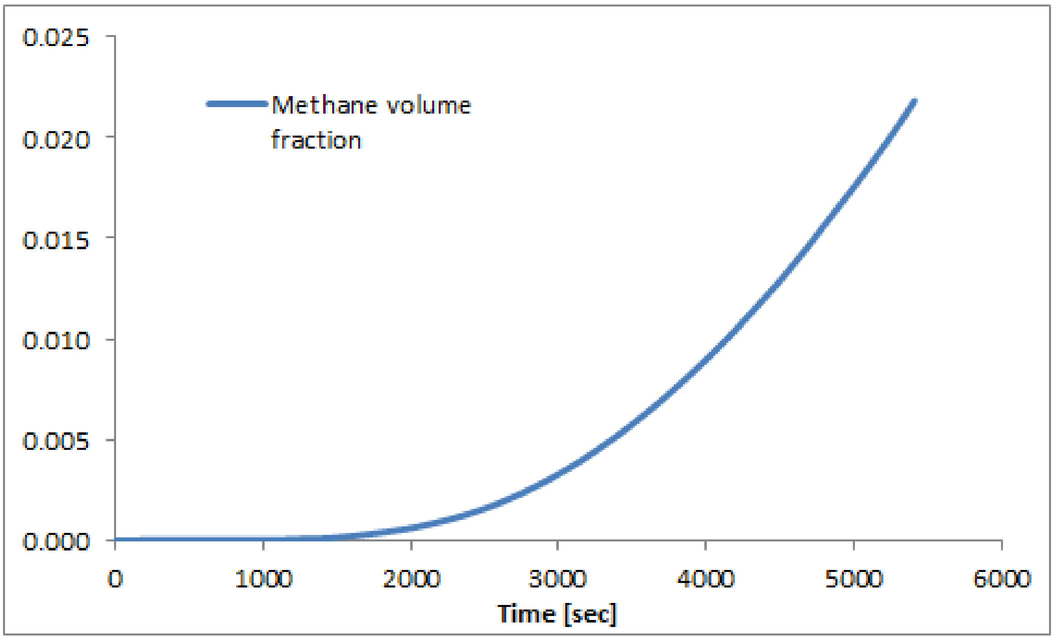

Figure 4. Methane volume fraction

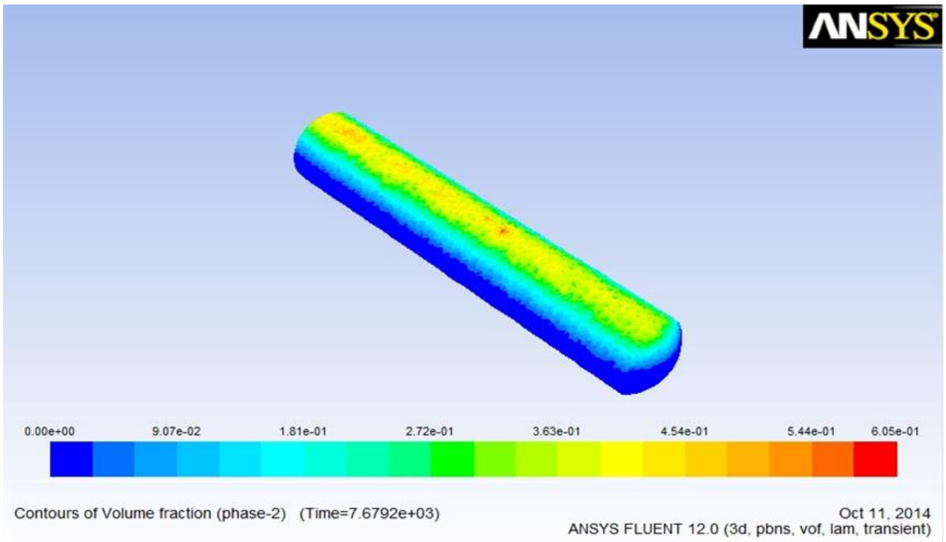

Figure 5. Methane allocation inside tank

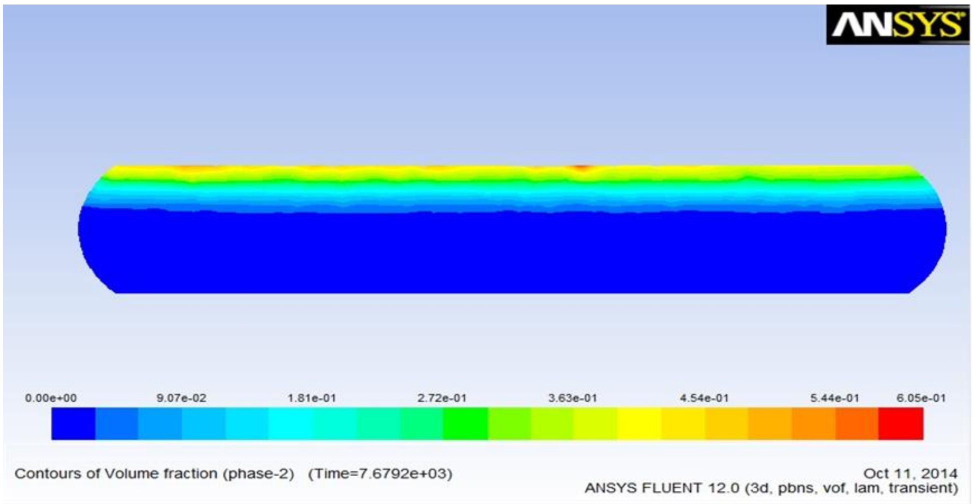

Figure 6. Methane allocation at x-axis symmetric plane

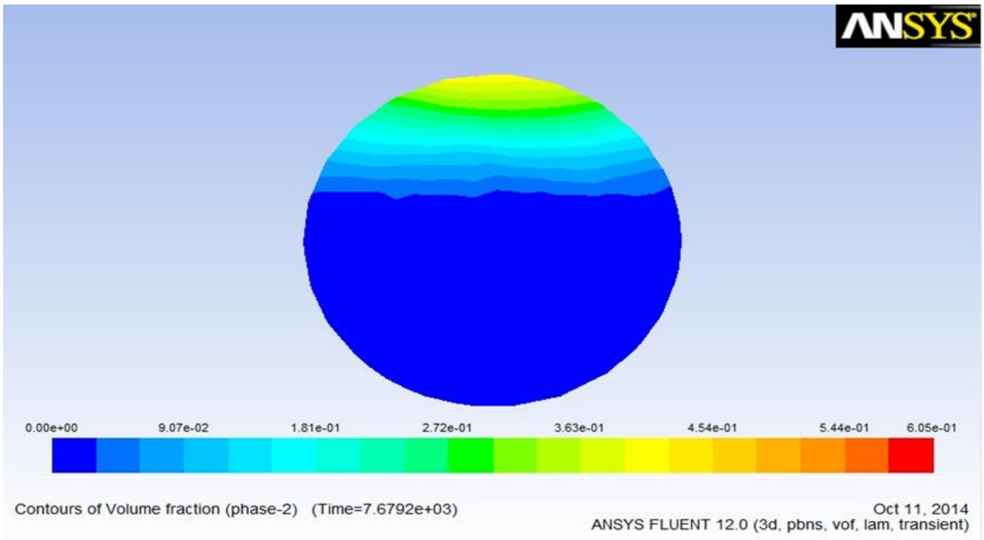

Figure 7. Methane allocation at z-axis symmetric plane

The area-weighted volume fraction of the created methane is recorded with respect to time and is depicted in Figure 4. The allocation of methane inside the tank is shown in Figure 5, while the same results are depicted in Figures 6 and 7 for the two symmetric planes of the tank for the same time point.

6 CONCLUSIONS

The importance of these results is obvious when the cost of the released natural gas is taken into consideration. For this reason, all the evaporated LNG is assumed as lost to the environment and that no re-liquefaction system is installed on the truck. The average European Energy Exchange (EEX) spot price for Title Transfer Facility (TTF) natural gas at April 2015 was approximately 23,5 €/MWh. The truck capacity is 53 m^3 and the evaporated LNG is 1,166 m^3, which corresponds to 699,6 m^3 of natural gas. As a consequence, there is a loss of 157€ after a trip of only one hour and a half.

It is clear that the insulation material and the surrounding weather conditions are crucial aspects for the road transport of LNG. Although, evacuated perlite has excellent insulating properties there are considerable natural gas losses when LNG is transported in hot countries like Greece. Nevertheless, it must be stated that in this simulation no re-liquefaction system is added to the tank, while it is assumed that LNG evaporates to methane.

Additional work including a detailed parametric analysis, application of a full Eulerian approach and evaluation of the results by comparison to experimental data is essential to validate the approach used in the present work.

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