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A Dynamic Model for Liquefied Natural Gas Evaporation During Marine Transportation

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Abstract

Marine transport of natural gas, predominately in the form of Liquefied Natural Gas (LNG), is of growing importance in the global energy markets. LNG is transported with vessels having cryogenic tanks without any means of external refrigeration. Hence, a significant fraction of the cargo LNG volume evaporates during voyage, which is usually called Boil-Off Gas (BOG). According to the type of the energy system, BOG can be utilized as fuel, reliquefied or burned in an oxidizer. The handling of the boil-off gas during the LNG vessel operation and the assessment of its thermodynamic properties are key issues in the technical and economic assessment of the complete marine energy systems of LNG vessels. A detailed dynamic boil-off model has been developed, which accounts for the variation of BOG mass flow, composition and thermodynamic properties during voyage. The model employs coupled non-linear vapor – liquid phase equilibrium thermodynamic equations and differential conservation equations describing the evolution of LNG quantity and composition with time. Various solution and time discretization schemes have been tested to assess the solution accuracy and stability. The model has been used to investigate the variation of the LNG and BOG quantity, composition and thermodynamic properties during typical voyage profiles of a case study LNG vessel. Variations of the thermodynamic properties and of the quantity of BOG in the range of 6 to 10% during voyage have been found, having a significant impact in operation modes and fuel consumption of the energy system. Results have been also compared with the traditional approaches used in the marine technical practice.

Keywords: Liquefied natural gas, boil-off gas, vapor-liquid equilibrium, dynamic simulation.

1. Introduction

Marine transport of natural gas is in the form of Liquefied Natural Gas (LNG). LNG is transported with vessels having cryogenic tanks without any means of external refrigeration. Therefore, a significant fraction of the cargo LNG volume evaporates during voyage, which is usually called Boil-Off Gas (BOG). According to the type of the propulsion system of the vessel, BOG can be utilized as fuel, reliquefied or burned in a gasification unit as depicted in *Figure 1*.

The assessment of the BOG quantity, composition and thermodynamic properties during voyage is of key importance for the technical and economic assessment of the complete marine energy systems of LNG vessels.

In this study a detailed dynamic boil-off model has been developed, which accounts for the variation of BOG mass flow, composition and thermodynamic properties during voyage. The model employs vapor-liquid equilibrium calculations of the LNG mixture coupled with dynamic species conservation over time.

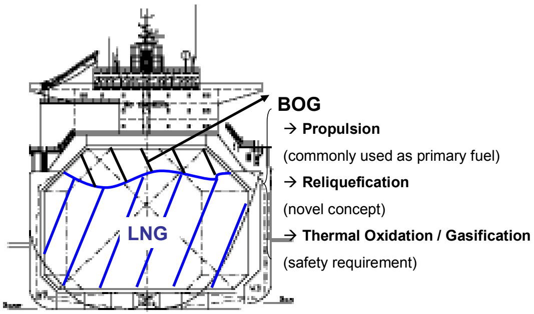

Figure 1. Utilization of Boil – Off Gas onboard LNG vessels.

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This model is intended to be used in an overall thermoeconomic optimization algorithm for the complete energy system of LNG vessels. Therefore, several simplifying assumptions have been made in order to reduce the computing time, while at the same time, preserving the accuracy of the estimates of BOG mass flow, composition and thermodynamic properties during voyage.

2. Vapor-liquid Equilibrium

Liquefied natural gas is a multi-component mixture, consisting of highly volatile organic and inorganic species. Therefore, the coexistence of both vapor and liquid phases of the LNG mixture has to be considered. The equilibrium conditions between vapor and liquid phase of a mixture of n_S species, are determined via a set of equality conditions of the Gibbs free energy of each species in each phase (Gyftopoulos and Beretta, 1991; Smith, et al., 1996):

$$G_{g_i} = G_{\ell_i} \quad , \quad i = 1,\ldots,n_S \tag{1}$$

A more convenient, yet equivalent, set of Vapor-Liquid Equilibrium (VLE) conditions is derived by the use of fugacity of the species, which is directly related to Gibbs free energy (Gyftopoulos and Beretta, 1991). The use of fugacity results in a significant simplification of the VLE calculations and equilibrium conditions are now described by equality of fugacity between phases (Gyftopoulos and Beretta, 1991; Smith, et al., 1996):

$$\hat{f}_{g_i} = \hat{f}_{\ell_i} \quad , \quad i = 1,\ldots,n_S \tag{2}$$

In the general case, when considering real gas or liquid behavior, fugacity of each species is a function of both pressure and temperature. In addition, fugacity of pure species is usually expressed with the aid of fugacity coefficient, according to the definition:

$$f(P,T) = \phi(P,T)\cdot P \tag{3}$$

Fugacity coefficients are calculated from the Equation Of State (EOS):

$$\ln\phi = \int_{P_0}^{P} \left(Z(P,T)-1\right)\cdot\frac{dP}{P} \tag{4}$$

The explicit expression of the compressibility factor Z depends on the selected EOS used to describe the pure species and mixture behavior (Gyftopoulos and Beretta, 1991).

It is noted that the coefficients of all non-ideal EOS for pure species are, in general, different from those describing the behavior of a mixture (Nasrifar and Bolland, 2006). In that respect, based on Eq. (4), the fugacity coefficient of a species i in its pure form has a different form and value than the one when considering the same species as a constituent of a mixture:

$$\phi_i \neq \hat{\phi}_i \tag{5}$$

The fugacity of a species i in a vapor mixture is given (Smith, et al., 1996):

$$\hat{f}_{g_i}(P,T) = \hat{\phi}_{g_i}(P,T)\cdot x_{g_i}\cdot P \tag{6}$$

The fugacity of a species i in a liquid solution is given by (Smith, et al., 1996):

$$\hat{f}_{\ell_i}(P,T) = \gamma_i\cdot\phi_{\ell_i}\left(P_{sat_i},T\right)\cdot x_{\ell_i}\cdot P_{sat_i}\cdot C_i \tag{7}$$

where C_i is the Poynting correction factor, which is defined by:

$$C_i = \exp\left[\frac{v_{\ell_i}\cdot\left(P-P_{sat_i}\right)}{RT}\right] \tag{8}$$

By inserting Eqs. (6), (7) and (8) in Eq. (2), the general expression of the VLE conditions is transformed to:

$$\begin{gathered}\hat{\phi}_{g_i}\cdot x_{g_i}\cdot P = \gamma_i\cdot\phi_{\ell_i}\cdot x_{\ell_i}\cdot P_{sat_i}\cdot C_i \\ i = 1,\ldots,n_S\end{gathered} \tag{9}$$

Molar compositions of both the vapor phase mixture and the liquid phase solution can be determined by solving the system of VLE conditions of Eq. (9) coupled with the necessary molar conservation equations for a given pressure and temperature of the thermodynamic system.

For moderate pressures the Poynting correction factor is close to unity (Gyftopoulos and Beretta, 1991). In addition, under the assumption of ideal gas behavior of the vapor phase mixture, Eq. (6) is simplified to:

$$\hat{f}_{g_i} = x_{g_i}\cdot P \tag{10}$$

Furthermore, if ideal behavior of the liquid phase solution is assumed, Eq. (7) is simplified to:

$$\hat{f}_{\ell_i} = x_{\ell_i}\cdot P_{sat_i}(T) \tag{11}$$

Therefore, under these ideal behavior assumptions of both the vapor and liquid phase mixtures, the VLE conditions are simplified to the ideal Raoult's law (Gyftopoulos and Beretta, 1991):

$$\begin{gathered}x_{g_i}\cdot P = x_{\ell_i}\cdot P_{sat_i}(T) \\ i = 1,\ldots,n_S\end{gathered} \tag{12}$$

The VLE conditions of Eq. (9), combined with appropriate equations of state suitable for natural gas mixtures, have been extensively used for the accurate determination of natural gas thermodynamic properties (Morch, et al., 2006; Nasrifar and Bolland, 2006; Nasrifar, et al., 2005; Ratanapisit and Ely, 1999). These studies are more focused on providing methodology and thermodynamic data for natural gas production, processing, storage and pipeline transportation.

The marine transportation of LNG is characterized by low (near atmospheric) storage pressures and cryogenic temperatures (about $-160^{\circ}\mathrm{C}$). In addition, the LNG mixture is also characterized by the significantly higher concentration of methane (above 80%) than the concentration of all other constituents. In these conditions, the assumptions of ideal gas for the vapor phase mixture and of ideal solution for the liquid phase are good approximations of the behavior of the mixture (Gyftopoulos and Beretta, 1991) and a good starting point for modeling the multi-component mixture VLE.

In this study assumptions of ideal behavior have been used, in order to assess the VLE behavior of the complete LNG mixture. However, the methodology and modeling approach presented in Section 3 can be readily extended to be used for real gas and liquid behavior, with the aid of a suitable equation of state for LNG constituent species and mixture (Nasrifar and Bolland, 2006).

In addition, the developed model, presented in Section 3, is a bulk evaporation model that neglects surface evaporation effects. Complex and detailed surface evaporation models of LNG mixtures inside cryogenic tanks are widely applied for the prediction of LNG roll-over, sloshing motion and spill phenomena both in land storage and marine transportation (Heestand, et al., 1983; Munakata, et al., 1995; Oestvold, 2006). However, these models require a finite element analysis of the LNG storage tank and therefore, are time consuming requiring a large number of inputs. The purpose of this study was to produce a simple model, with short execution time capable of giving an accurate estimate of the quantity and thermodynamic properties of boil-off gas over time. Such a model, of course, cannot be used in order to simulate complex evaporation phenomena such as rollover and sloshing inside LNG tanks.

3. Lng Evaporation Model

3.1. Traditional Approach

In the majority of LNG propulsion studies appearing in the literature (Andrianos, 2006; Levander and Hannula, 2004; MAN-B&W, 2004), certain drastic simplifying assumptions are made regarding the available BOG quantity and composition. Namely, the daily boil-off rate is considered constant and the thermodynamic properties of BOG are equal to those of pure methane, which is the main constituent of natural gas.

These assumptions may be acceptable for preliminary evaluation of systems, but for detailed thermoeconomic simulation and optimization studies they have to be reconsidered. This issue is empirically acknowledged by the LNG propulsion system designers (Kuver, et al., 2002; Laurilehto, 2000).

3.2. Boil-off gas Production

A detailed boil-off model is proposed in this study. The developed model is based on the solution of the VLE system of equations for the LNG mixture within the cargo tanks of the vessel.

The VLE is considered under the assumptions of ideal behavior of both the gaseous phase mixture and the liquid phase solution. The model also takes into account that the mass of BOG depends on the heat transfer between the external environment and the LNG through the cargo tank insulation (Chen, et al., 2004).

At any instant of time (t) of the voyage of the vessel the VLE equations, which correspond to a given LNG volume, composition and cargo tank temperature, are:

$$\begin{gathered}\left(x_{g_i}\cdot P_g = x_{\ell_i}\cdot P_{sat_i}\right)^t \\ i=1,\ldots,n_S \;\wedge\; t\in[0,\tau]\end{gathered} \tag{13}$$

By definition the molar composition of a mixture or solution is:

$$x_i=\frac{N_i}{N_{tot}}\ ,\quad i=1,\ldots,n_S \tag{14}$$

Introducing Eq. (14) to Eq. (13) yields:

$$\left(\frac{N_{g_i}}{N_{g_{tot}}}\cdot P_g=\frac{N_{\ell_i}}{N_{\ell_{tot}}}\cdot P_{sat_i}\right)^t \tag{15}$$

The saturation pressure of each LNG constituent is calculated by a generalization of the Clausius – Clapeyron relation called Antoine equation (Smith, et al., 1996). Antoine equation is a statistical three parameter fit of experimental saturation pressure data:

$$\log_{10}\left(P_{sat_i}{}^t\right)=a_i-\frac{b_i}{T_V{}^t-c_i} \tag{16}$$

The values of the experimentally derived equation parameters a, b and c are depicted in

TABLE I, for certain typical LNG constituents used in this study (NIST, 2007).

The number of moles of each species is conserved within the overall LNG mixture. The total number of moles of each LNG species is equal to the sum of the number of moles in the vapor and liquid phase.

$$N_{LNG_i}{}^t = N_{g_i}{}^t + N_{\ell_i}{}^t \quad , \ i = 1,\dots,n_S \ \wedge \ \forall t \qquad (17)$$

The energy required for the LNG vaporization process is provided by the heat transferred from the cargo tank to the liquid (Chen, et al., 2004). At any instant of time, the thermal energy entering the LNG volume is:

$$dE_{HT}{}^t = \dot{Q}_{HT} \cdot dt \qquad (18)$$

The molar quantity of produced BOG is:

$$N_{g_{tot}}{}^t = \frac{dE_{HT}{}^t}{\Delta\tilde{h}_{vap_{LNG}}{}^t} \quad , \forall t \qquad (19)$$

The value of the heat transfer rate $\dot{Q}_{HT}$ can be either analytically calculated by detailed heat transfer analysis of the tank structure with its insulation or, as used in this case, by empirical estimation based on the average boil-off rate of typical LNG vessels (Kuver, et al., 2002).

The enthalpy of vaporization of each species (i) in the LNG mixture is calculated by an experimentally derived equation (Somayajulu, 1988) of the form:

$$\begin{aligned} \Delta\tilde{h}_{vap_i}{}^t &= A_i \cdot \left(X_i{}^t\right)^m + B_i \cdot \left(X_i{}^t\right)^{1+m} \\ &+ C_i \cdot \left(X_i{}^t\right)^{2+m} + D_i \cdot \left(X_i{}^t\right)^{3+m} \qquad (20) \\ \text{where: } \ X_i{}^t &= \frac{T_{cr_i} - T_V{}^t}{T_{cr_i} - T_{tr_i}} \end{aligned}$$

and A, B, C, D and m are substance dependent parameters.

The total enthalpy of vaporization for the LNG is:

$$\Delta\tilde{h}_{vap_{LNG}}{}^t = \sum_{i=1}^{n_S} x_{LNG_i}{}^t \cdot \Delta\tilde{h}_{vap_i}{}^t \qquad (21)$$

The values of the coefficients appearing in Eq. (20) for various substances can be found in (Somayajulu, 1988) and those used in this study are given in TABLE I.

Equations (15), (17) and (19) constitute a non linear system of $2 \cdot n_S + 1$ equations. The main parameters of this system are the cargo tank temperature and the LNG mixture molar quantity of each species (N_{LNG_i}). Equations (18), (21) and (20) are auxiliary parameter equations for the aforementioned system. The unknown quantities of this system are the vapor phase (BOG) molar quantities (N_{g_i}), the liquid phase molar quantities (N_{ℓ_i}) and the gas pressure (P_g). The number of unknowns is also $2 \cdot n_S + 1$, thus the system can be solved with an appropriate non linear method.

Once the system of equations is solved, the molar compositions of liquid phase and BOG are evaluated with Eq. (14). In addition, the lower heating value and the molecular weight of BOG are evaluated with the following equations:

$$MW_g{}^t = \sum_{i=1}^{n_S} x_{g_i}{}^t \cdot MW_i \qquad (22)$$

$$\begin{aligned} \tilde{H}_{u_g}{}^t &= \sum_{i=1}^{n_S} x_{g_i}{}^t \cdot \tilde{H}_{u_i} \\ H_{u_g}{}^t &= \frac{\tilde{H}_{u_g}{}^t}{MW_g{}^t} \end{aligned} \qquad (23)$$

3.3. Dynamic Model

The variation of BOG quantity and thermodynamic properties is assessed by a set of differential equations modeling the dynamic species conservation over time.

The rate of change of the molar quantity of a given LNG species depends on BOG evaporation rate, the need of additional boil-off gas which is forcedly evaporated to cover the propulsion needs of the vessel and the existence of a reliquefication plant onboard the vessel.

Forced boil-off and reliquefication rates are what are usually called in dynamic systems terminology "external disturbances" of the dynamic system, due to the fact that they are time dependent functions the form of which is determined by factors independent of the system under study, i.e. the LNG evaporation process.

The set of differential equations describing the dynamic species conservation is:

$$\frac{dN_{LNG_i}}{dt} = -\dot{N}_{g_i} - \dot{N}_{frc_i} + \dot{N}_{rlq_i} \quad , \quad \forall i = 1 \dots n_s \qquad (24)$$

The BOG rate is calculated with the procedure described in subsection 3.2 while the forced boil-off and reliquefication rates are functions of the LNG mixture composition, time, ship design and voyage propulsion requirements:

$$\dot{N}_{frq_i} = f_{frq}\left(N_{LNG_{i=1\dots n_s}}, t, \mathbf{u_1}\right) \ , \quad \forall i = 1 \dots n_s \qquad (25)$$

$$\dot{N}_{rlc_i} = f_{rlc}\left(N_{g_{i=1\dots n_s}}, t, \mathbf{u_2}\right) \ , \quad \forall i = 1 \dots n_s \qquad (26)$$

where u_1 and u_2 are variables representing other influences such as required BOG flow for propulsion and auxiliary power, existence and capacity of reliquefication plant, etc.

To account for temperature changes in the LNG tanks during voyage due to heat transfer, the dynamic model is supplemented with a temperature rate of change equation:

$$\frac{dT_V}{dt} = c(t) \tag{27}$$

where c(t) is an empirical function or constant, derived from experimental observations on LNG vessels (Kuver, 2005; Kuver, et al., 2002).

TABLE I. VALUES OF PARAMETERS FOR EVALUATION OF THE SATURATION PRESSURE AND ENTHALPY OF VAPORIZATION (NIST, 2007; Somayajulu, 1988).

Species	Antoine equation Eq. (16)			Enthalpy of vaporization equation Eq. (20), $m = 0.375$					
	a_i	b_i	c_i	A_i	B_i	C_i	D_i	$T_{tr,i}$ (K)	$T_{cr,i}$ (K)
CH_4	3.98950	443.028	-0.490	9.06452	1.52	-3.0519	1.18854	90.68	190.55
C_2H_6	4.50706	791.300	-6.422	18.00355	4.43633	-10.2366	5.66822	90.348	305.33
C_3H_8	4.01158	834.260	-22.763	23.97875	5.87352	-13.7851	8.79046	85.47	369.8
C_4H_{10}	4.70812	1200.475	-13.013	27.75109	6.80611	-14.8685	9.12374	134.86	425.16
N_2	3.73620	264.651	-6.788	6.15835	0.77101	-1.59378	0.69579	63.15	126.2

4. Simulation Model

4.1. Model Description

The detailed dynamic BOG production model, described in Subsections 3.2 and 3.3, has been implemented in the MATLAB/Simulink graphical simulation environment.

The model consists of three major groups of sub-models (modules): The thermodynamic calculations sub-models, the vapor-liquid equilibrium non-linear algebraic solver module, and the differential equations dynamic sub-models. The main parts of the simulation model structure in the MATLAB/Simulink environment are depicted in *Figure 2*.

4.2. Numerical Solution

Various differential equation solvers and time discretization schemes have been tested to assess the solution accuracy and stability.

Three ordinary differential equation (ODE) solvers have been tested: The Euler (ODE1), the Runge-Kutta (ODE4) and the Dormand-Price (ODE5) solver (Forsythe, et al., 1977). The effect of the solver choice on solution accuracy has been assessed. The calculated mass of BOG, as a function of time, for solving the dynamic model with each one of the three ODE solvers is depicted in *Figure 3*.

The results indicate that ODE4 and ODE5 solvers yield exactly the same results, while ODE1 solver yields only slightly different results compared with the other two solvers. However, the differences in results obtained with the ODE1 solver compared to the results from the other two solvers are very small. Therefore, the Euler scheme (ODE1 solver) has been used in this study due to its simplicity and short execution time.

A voyage of an LNG vessel and thus the boil-off of gas last from 5 to 20 days at a maximum. Therefore, the duration of the dynamic boil-off phenomenon is of the same order of magnitude.

Two time discretization schemes have been considered: time intervals of one hour and time intervals of one day. The effect of the discretization schemes choice on the solution accuracy has been assessed. The calculated mass of BOG, as a function of time, obtained with each one of the two discretization schemes is depicted in *Figure 4*.

The results indicate that there is a small difference in the results produced with the two discretization schemes. By integration of the instantaneous mass of BOG, the total mass of BOG during a voyage has been calculated. The total mass of BOG during voyage with one hour time intervals is 2316.6 tons, while with one day time intervals is 2315.9 tons. The difference between the two values is 0.03%. Therefore, the coarse one day time intervals have been used in this study.

The aforementioned analysis indicated that the proposed model can be implemented on a computer code using a very simple ODE solver, like the Euler scheme, and a coarse discretization of time intervals up to 24 hours. These features make the proposed model easy to implement with a very short execution time.

Thus this model is particularly suitable to be integrated in wider thermoeconomic simulation and optimization studies of energy systems of LNG vessels.

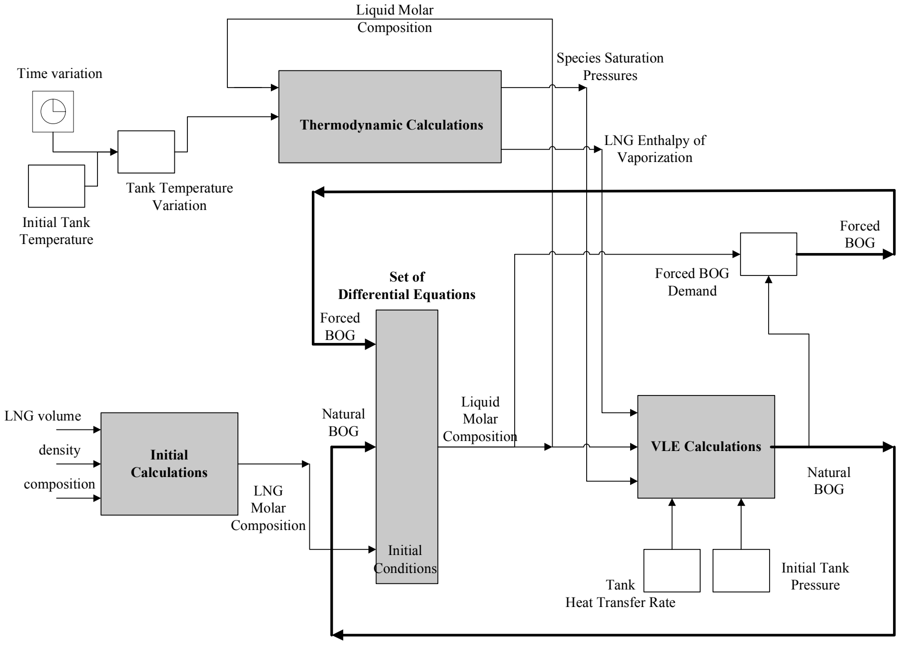


Figure 2. BOG simulation model structure in the MATLAB/Simulink environment.

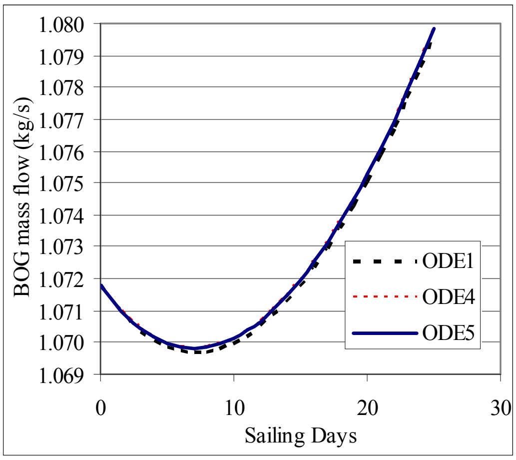


Figure 3. BOG mass flow derived with each one of the ODE solvers.

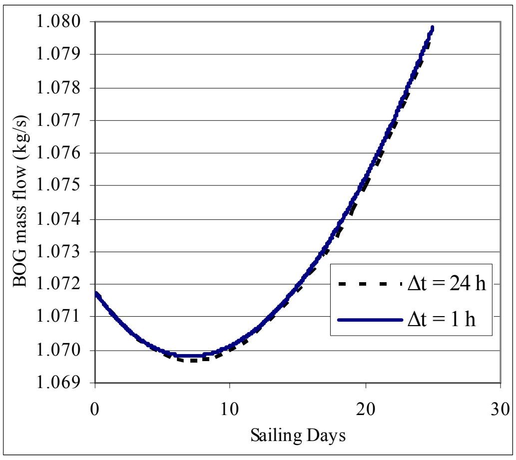


Figure 4. Variation of solution with respect to the choice of the discretization interval.

5. Results

5.1. Case Study

The model has been used to investigate the variation of the LNG and BOG quantity, composition and thermodynamic properties during typical voyage profiles of a case study LNG vessel.

The initial composition of a typical Arab gulf LNG, as well as typical values of the tank heat transfer rate (see Eq. (18)) and temperature rise rate (see Eq. (27)) are given in TABLE III. The value of the heat transfer rate has been calculated based on empirical estimation of the average boil-off rate of typical LNG vessels (Kuver, et al., 2002). The temperature rise rate has been also derived from experimental data from typical LNG vessels (Kuver, 2005; Kuver, et al., 2002).

TABLE II. TYPICAL LNG COMPOSITION AND CARGO PARAMETERS.

Substance	Composition (% molar)
Methane CH_4	89.90
Ethane C_2H_6	6.00
Propane C_3H_8	2.20
Butane C_4H_{10}	1.50
Nitrogen N_2	0.40

$$\dot{Q}_{HT} = 600 \text{ kW}$$

$$T_V^{@\,terminal} = -163^{\circ}\text{C}\,, \quad dT_V = 0.5 \text{ K / day}$$

$$V = 150000 \text{ m}^3$$

5.2. Investigations

The first investigation has been the study of the variation of BOG production rate and LHV of a fully loaded LNG vessel of 150000 m^3 capacity for a 25 day voyage, without any forced boil-off or reliquefication onboard. The results are depicted in *Figure 5*.

From *Figure 5* it can be readily deduced that there is a significant variation of both BOG mass and LHV, and consequently the assumption of constant boil-off rate and pure methane LHV, which is usually used in various studies, is not correct.

The BOG mass flow rate decreases at the begining of the voyage, reaches a minimum value and then increases again. This behavior is due to the fact that at the begining of the voyage, when the tank temperature is the lowest, only the more volatile components evaporate (methane and nitrogen). These components have lower molecular weights than the less volatile components (ethane, propane and butane) and cause a reduction of the MW of the BOG mixture. The nitrogen content in BOG is higher at the beginning of the voyage yielding low LHV values. The nitrogen content decreases during voyage and the LHV of BOG increases. As the temperature increases during voyage, the heavier components begin to evaporate and contribute to the MW of the BOG mixture, thus increasing the BOG mass flow rate. The LNG and BOG compositions at the start and the end of the voyage are presented in TABLE III.

The second investigation has been the simulation of the BOG behavior with simultaneous forced boil-off of LNG during voyage. Forced boil-off is often necessary in LNG vessel operation in order to cover the fuel requirements of the propulsion plant.

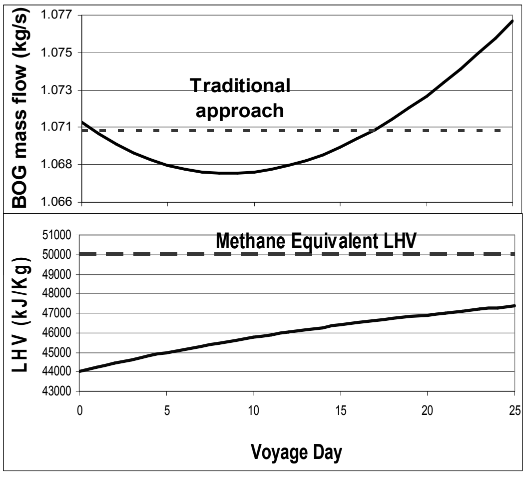


Figure 5. Variation of BOG mass flow and LHV during voyage.

TABLE III. INITIAL AND FINAL MOLAR COMPOSITIONS OF LNG AND BOG.

	LNG (%)		BOG (%)	
	Initial	Final	Initial	Final
Methane	89.9	89.7	92.65	96.8
Ethane	6	6.24	0	0.01
Propane	2.2	2.29	0	0
Butane	1.5	1.56	0	0
Nitrogen	0.4	0.22	7.34	3.15

For the purpose of this study, a typical propulsion unit of nominal power 25MW and a thermal efficiency of 40% have been considered. This assumption results in a required fuel heat power input to the propulsion plant of 62.5MW. In addition, the speed of the vessel, and consequently the propulsion power, have been considered constant throughout the voyage. Therefore, at any instant of time the required fuel heat power input has been the sum of the heat input of the natural and the forced BOG.

Forced boil-off of LNG is performed by extracting a small amount of the liquid from a specially controlled cargo tank. Therefore, the composition of the forced boil-off is that of the LNG in the cargo tanks.

In the set of graphs of *Figure 6*, the variation of the BOG (forced and natural) mass flow, LHV and the volume of BOG that is consumed from the propulsion power plant are depicted. Forced boil-off is decreasing during voyage due to the fact that the heating value of the natural BOG increases and therefore, less quantity of forced boil-off is needed to cover the required heat input. The heating value of the forced BOG is almost constant, since it is the heating value of the LNG which has a small variation with time due to the relatively small quantity of LNG that is evaporated.

The natural BOG mass flow and LHV variation through voyage, depicted in *Figure. 6* have the same trends as those in the case with no forced boil-off present *Figure 5*. This is due to the fact that the same thermodynamic mechanisms of VLE are also dominant in this scenario. However, there are quantitative differences in the amount of BOG mass flow and the value of LHV. The variations of methane and nitrogen compositions of BOG during voyage are also depicted in *Figure 7*.

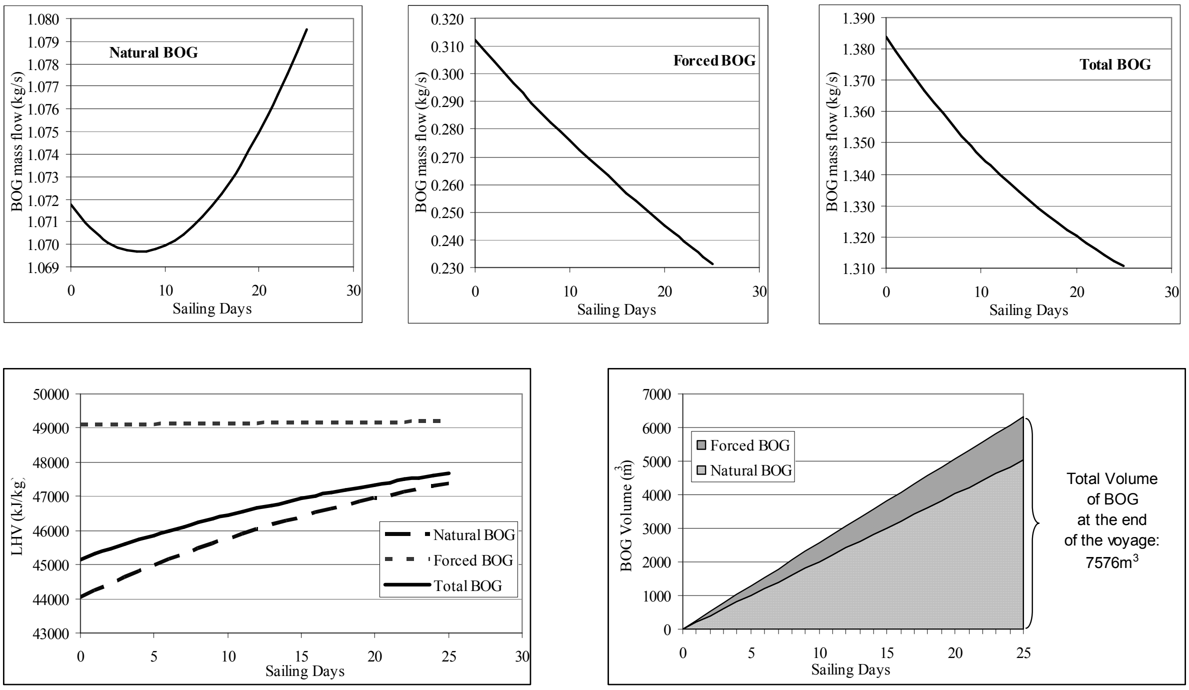
It must be noted that the forced boil-off has a significant effect on both the quantity and the heating value of the total BOG. If the BOG is used as a fuel of the propulsion plant of the LNG vessel, then the interrelation of the required fuel input with the boil-off process becomes a key issue in the thermoeconomic assessment of the complete propulsion system.

6. Conclusion

A dynamic model for the evaporation of LNG has been developed. The properties of the boil-off gas during voyage have been assessed and rough simplifying assumptions usually employed in previous studies have been removed. This model is a first step in the simulation of the evaporation of LNG during marine transportation and the thermodynamic approach will be enhanced in subsequent studies.

The main benefit of this model is that it is easy to implement, can be easily solved and has a very short execution time. These features allow for this model to be integrated in the thermoeconomic simulation and optimization of marine energy systems of LNG vessels.

The investigations performed in this study indicated that the boil-off gas quantity and quality significantly vary during a voyage and therefore this variation must be taken into account in the thermoeconomic assessment of marine energy systems of LNG vessels.



Total Volume of BOG at the end of the voyage: 7576m^3

Figure 6. Variation of natural, forced and total BOG quantity and LHV value during voyage.

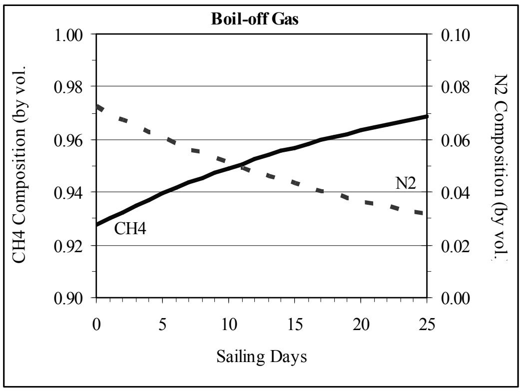


Figure 7. Variation of BOG methane and nitrogen compositions during voyage.

Nomenclature

BOG	Boil-off Gas
C	Poynting correction factor
EOS	Equation of state
f	Fugacity
G	Gibbs free energy
H_u	Lower heating value
LNG	Liquefied Natural Gas
MW	Molecular weight
n	Number of intervals, species, etc.
N	Number of moles of a substance
P	Pressure
Q	Heat
R	Universal gas constant
T	Temperature
x	Molar composition
v	Specific volume

V	Volume
VLE	Vapor-Liquid Equilibrium
u	External variable
Z	Compressibility factor

Greek letters

γ	Activity coefficient
Δh_{vap}	Enthalpy of vaporization
τ	Time duration
ϕ	Fugacity coefficient

Subscripts

cr	Critical Point
frc	Forced boil-off
g	Gas, Vapor
HT	Heat transfer
ℓ	Liquid
rlq	Reliquefication
S	Species
sat	Saturation
tot	Total
tr	Triple point
V	Cargo tank

Superscripts

^	Constituent of a mixture
~	Molar quantity
t	Time

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