STUDIES OF THE NEW GENERATION LNG SHIPS

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SOMMAIRE

TOTAL SA, Le Chantier Coréen SAMSUNG HEAVY INDUSTRY et le BUREAU VERITAS se sont associés dans le cadre d'un « Joint Development Projet» (JIP) pour étudier une nouvelle génération de navires méthaniers de 180000m3 à rendement énergétique optimisé, en prenant en compte l'évolution supposée des routes commerciales ainsi que l'utilisation commerciale du navire tout en vérifiant la conformité aux règlements environnementaux futurs.

Dans ce but, une nouvelle forme de coque, l'optimisation de la propulsion et de la production électrique ont été réalisés sur la base d'un profil opérationnel prédéfini du navire.

Les lignes de coque ont été optimisées par HydroOcean, filiale du BUREAU VERITAS en utilisant des outils de simulation numérique, basés sur la théorie de Navier-Stoke, par des calculs en eau calme comme sur houle (régulière et irrégulière).

Les résultats numériques en eau calme comme sur houle, ont été comparés à des essais en bassin.

SUMMARY

TOTAL SA, the Korean Shipyard SAMSUNG HEAVY INDUSTRIES and BUREAU VERITAS have teamed up, within the scope of a Joint Industry Project, to design a new generation of 180000m3LNG carrier with high energy efficiency considering future LNG trading patterns, new trading route and compliance with future environmental regulations.

In this purpose, a full hull form, propulsion and power generation optimisation has been performed for a pre-defined complete operational profile of the ship (i.e. full voyage including loading and unloading operations, manoeuvring, channeling, etc.).

The hull lines have been optimised by BV subsidiary HydrOcean using state-of-the-art Navier–Stokes Computational Fluid Dynamics (CFD tools), considering both calm water performance and ship behaviour in waves.

The performance of the final design has been validated by calm water and seakeeping model tests.

1. INTRODUCTION

In 2014, TOTAL, SHI and BV have agreed to join their knowledge and resources to design a new generation of LNG carrier with high energy efficiency. The main aims of this agreement were:

- to design the most optimized and economical LNG carrier with high energy efficiency considering the future LNG trading patterns, new trading route and compliance with future environmental regulations;
- to study the feasibility of possible designs and technologies in technical, operational and economical points of view in order to optimize the design.

The optimization work started from a “traditional”, yet modern, design. The cargo containment was standard, the propulsion was a dual fuel diesel electric, and the hull optimized for laden condition. The first optimization was to choose a more efficient cargo containment from GTT manufacturer which promised to reduce boil-off. To optimize the propulsion, new generation two stroke, large bore, slow speed, and dual fuel main engines, promising lower fuel consumption, have been evaluated using holistic ship energy modelling. Finally, an advanced CFD hull optimisation for both laden and ballast conditions have been made. In the end, the final design reduces significantly (boil-off) gas consumption compared to the initial one, making it possible to sell more cargo at each travel. It also saves money with lower maintenance costs. The major developments and conclusions of this project are presented hereafter.

2. OPTIMISATION DE LA PROPULSION

Several years ago, when dual fuel engines did not exist, LNG carriers were powered by steam turbines powered by gas boilers burning the natural boil-off. At some point in time it was found more economical to use main diesel engines, running on fuel oil. The major raisons were the improved LNG tank insulation reducing amounts of boil off available, the higher efficiency of diesel engines, the lower prices of crude oil and the lack of skilled crew trained in using high pressure steam boilers. The inevitable remaining gas surplus from boil off was either burned of reliquefied, reliquefaction being a big energy consumer process. In the 2000s, the development of dual fuel engines (gas and fuel), and new air emission regulations (Tier II and Tier III in Emission Control Area (ECA) zones) convinced ship owners to switch back to gas for LNG propulsion. The first dual fuel engines available were medium speed engines and diesel electric (or hybrid) propulsion architecture became a standard amongst LNG carriers. The very recent developments and production of large bore, two stroke, and dual fuel engines change the deal once again.

In this section, the potential energy saved by modern dual fuel two stroke diesel engines will be assessed. Three propulsive architectures will be compared:

- A 4-stroke dual fuel diesel electric (DFDE)
- A 2-strokedual fuel, low pressure and low speed engine(LPLS)
- A 2-stroke dual fuel, high pressure and low speed engine with EGR* (HPLS)

The comparison will be made using the Bureau Veritas holistic energy simulation platform SEECAT[1]

2.1 Holistic ship energy model

SEECAT stands for Ship Energy Efficiency Calculation and Analysis Tool. It is a simulation platform dedicated to model, calculate and optimize ship’s energy efficiency. It is able to track energy used all along the different energy process that occur in a ship (hull resistance, propeller thrust, engine propulsion, steam production, exhaust gas heat transfer, electricity generation, HVAC, etc.). Calculation are made over a realistic operational profile with given speed and loading conditions (see Figure 1). In this case, it represents a roundtrip between Sabine Pass (USA) and Incheon (South Korea), through Panama Canal.

During navigation three speeds are mainly used 12, 17.5 and 19.5 knots. Figure 2 shows the speed profile for one round trip. Five navigation modes are defined over a round trip. As represented in Figure 2, each navigation mode is associated to one number: 1 for seagoing, 2 for maneuvering, 3 for unloading, 4 for loading and 5 for port. During a round trip there are two loading conditions: laden condition from Sabine Pass to Incheon and ballast condition from Incheon to Sabine Pass. In addition, the North American NOx Emission Control Area (NECA) (see green part in Figure 2) is defined in the operational profile. In this area the Exhaust Gas Recirculation (EGR) is activated with the HPLS architecture to comply with Tier III regulation of MARPOL Annex VI. Gas mode is used all time for main engines, auxiliaries and oil fired boiler. Two-stroke main engines (HPLS and LPLS) are "off" (i.e. not consuming gas) during loading, and unloading.

Over this roundtrip, five key performance indicators (KPI) were calculated by SEECAT:

- FBOG: Forced boil-off gas mass
- NBOG: Natural boil-off gas mass
- GCU: Boil-off gas burnt in the gas combustion unit
- Total gas consumption: gas consumption from all consumers (gas boilers, main engines and gensets).
- Pilot fuel: pilot fuel consumption in dual fuel engines

Figure 1: Map of vessel's route between Sabine Pass (USA) and Incheon (South Korea)

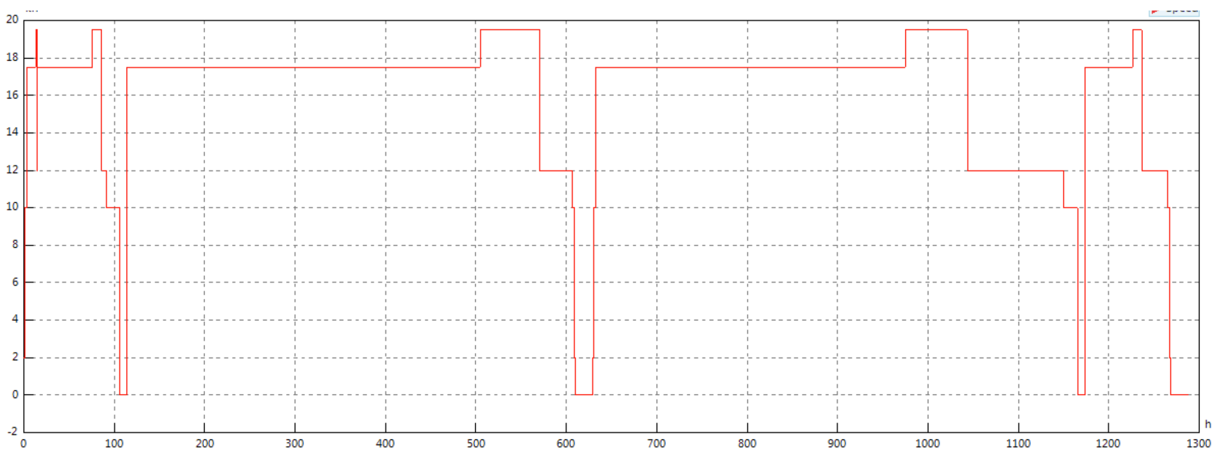


Figure 2a: Ship speed Profile considered

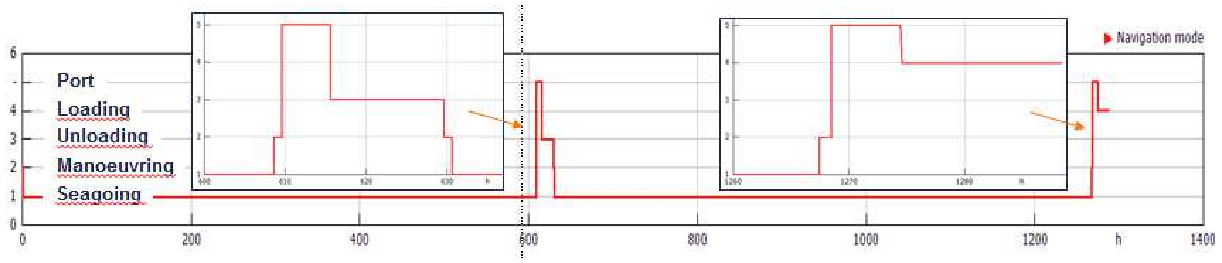


Figure 2b: Navigation mode Profile

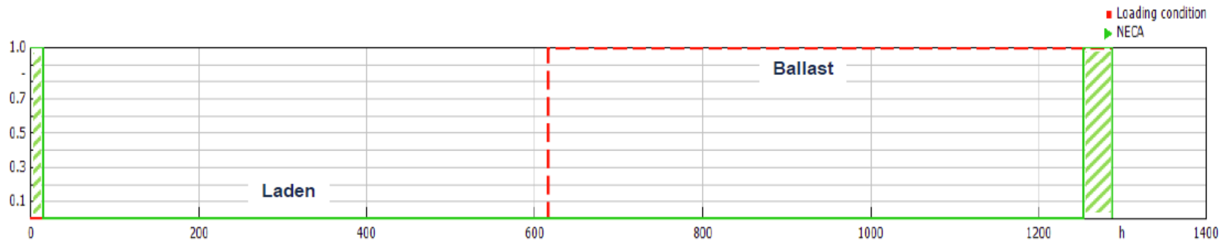
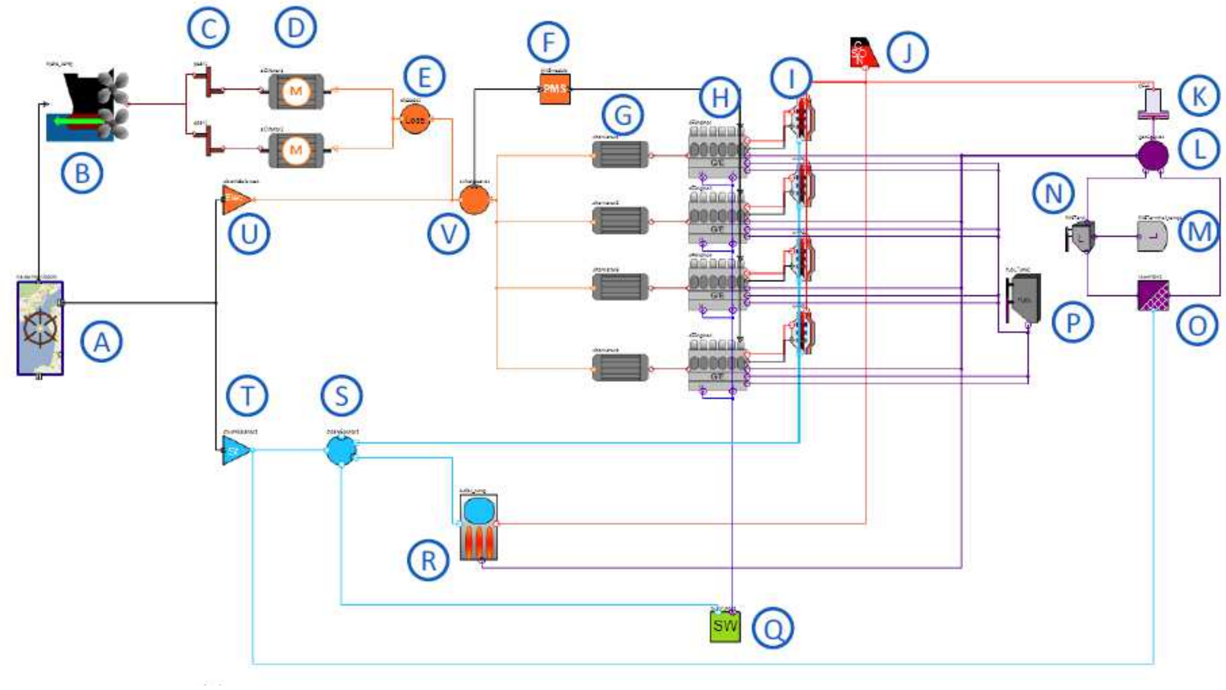


Figure 2c: Loading condition (interrupted line) and NECA profile (green area)



A : Navigation module that defines the operational profile
B : Hydrodynamic model that defines hull and propeller behaviour
C : Gearbox
D : Electric propulsion engine
E : Electrical losses
F : Power management system
G : Alternator
H : Diesel generators
I : Waste heat recovery boilers
J : Emission meter
K : Gas combustion unit
L : Gas distribution system
M : Land gas terminal
N : LNG tank
O : LNG evaporator
P : Oil fuel tank
Q : Sea water
R : Oil or gas boiler
S : Steam distribution system
T : Steam balance
U : Electrical balance
V : Electrical distribution system

Figure 3: SEECAT Modeling

2.2 Propulsion architecture

Nowadays, the DFDE architecture can be considered as a traditional propulsive architecture for LNG carriers. It is composed of four dual fuel diesel generators (see Figure 3).Propellers are powered by medium speed synchronous motor with a gear box. Steam is produced by 4 waste heat recovery boilers mounted on the four engines and one oil fired boiler.

The LPLS (Figure 4) and HPLS(Figure 5) configurations are mechanical propulsion. The prime movers are two 2-stroke dual fuel engines. Steam is produced by two waste heat recovery mounted on the two main engines exhausts and one oil fired boiler. Electricity is generated by three gen sets.

Prime movers of DFDE and LPLS configurations can run all the time in gas mode, and comply with Tier III NOx regulations in this mode. HPLS configuration, that uses high pressure gas system, needs an additional device to comply with Tier III regulations. Exhaust Gas Recirculation (EGR) has been added, and is activated only when the ship is in a NECA zone.

In addition to the 2-stroke engine and the EGR, differences between the HPL Sand LPLS configurations are the high pressure pumps and compressors as well as the corresponding electrical balance

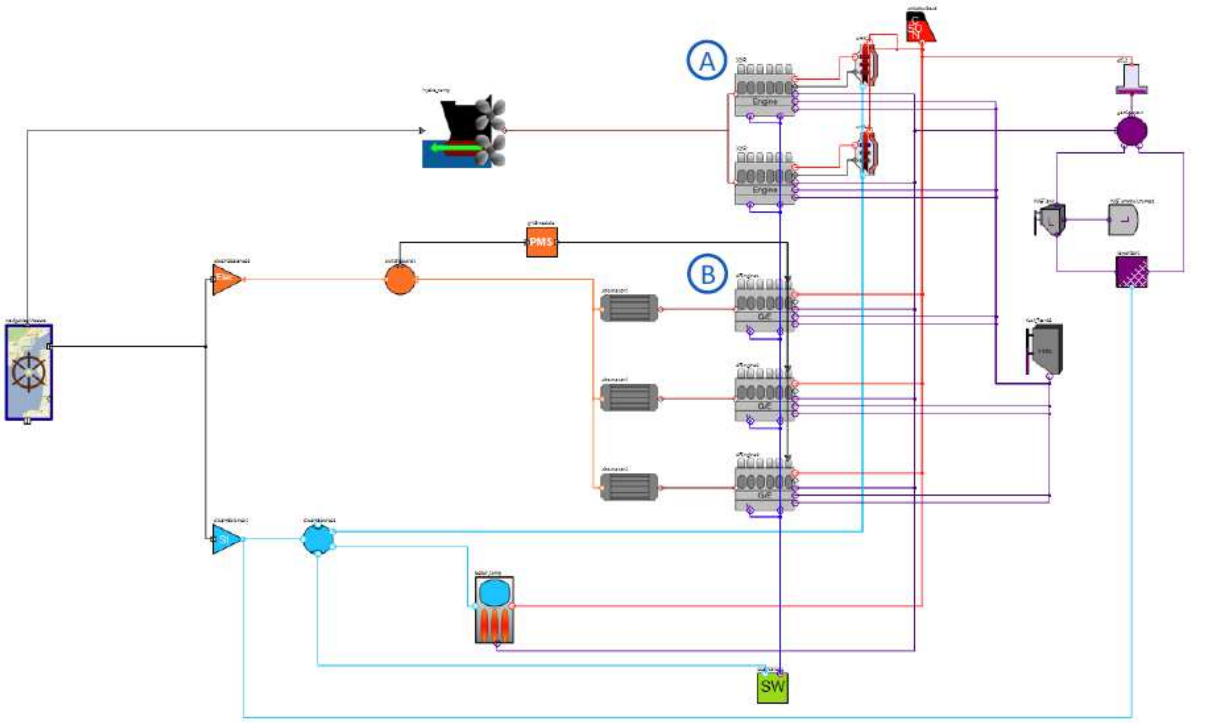


Figure 4: SEECAT Modeling with LPLS architecture of the tanker

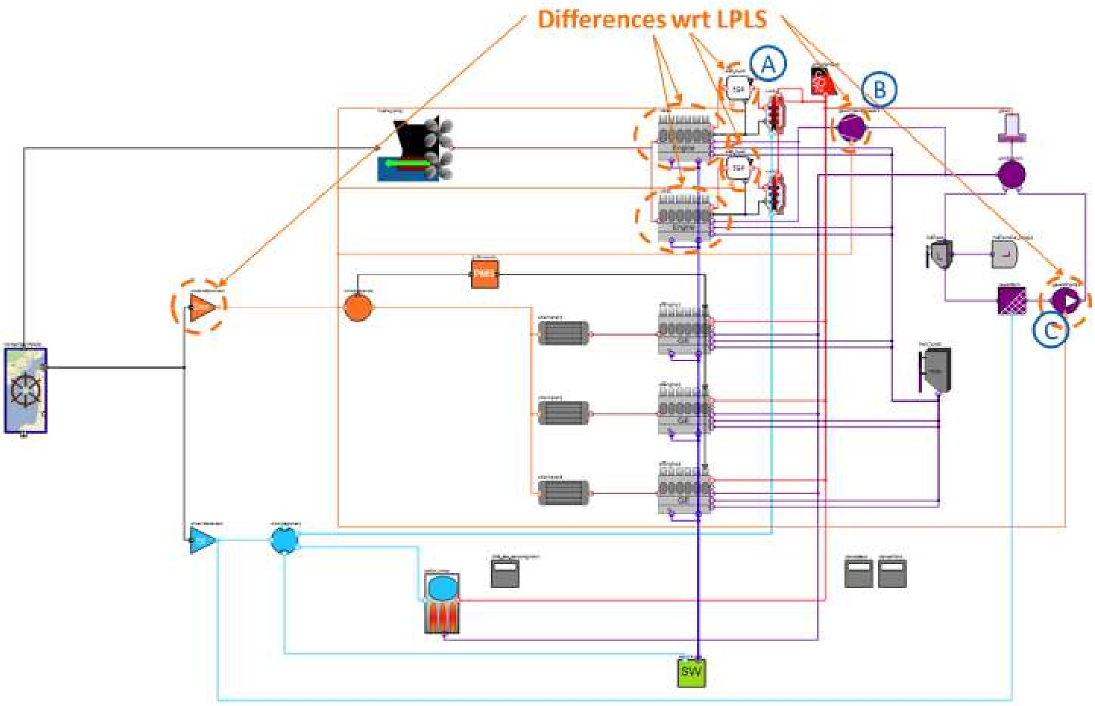


Figure 5: SEECAT Modeling with HPLS architecture of the tanker

2.3 Advanced boil-off gas model

Natural gas is transported on board ships under liquid form (LNG) to save up space. To do so, LNG is kept at very low temperature (around –160 °C) in insulated tanks. As insulation is never perfect, thermal heat from the outside eventually penetrates the tank and makes LNG boil. This natural boil-off gas (NBOG) is then used as fuel in engines for propulsion and electricity production. If there is too much NBOG, the remaining gas can be either burned or re-liquefied. If gas consumption is too high and there is not enough NBOG, boil-off can be forced, using an evaporator (heat exchanger). This later operation is called forced boil-off gas (FBOG) in opposition to NBOG.

As being as energy efficient and economical as possible are the two main objectives of this project, determining the mass flow of NBOG accurately is of crucial importance. Classically, NBOG calculations are made using a static BOG rate according to the following equation:

$$\dot{m}_{NBOG} = V_{LNG} \times BORrate \times \rho$$

This equation is simple and effective when roughly calculating the remaining volume of LNG at the end of a journey. But it is not accurate enough for advanced comparisons between engines. The evaporation of LNG is a dynamic and complex process which depends also on the LNG nitrogen (N_2) content. With the help of TOTAL, BV has built a new model of LNG tank that calculates the NBOG mass flow more accurately than traditionally.

The amount of nitrogen in LNG can vary from almost zero to a few percent. Despite this small fraction it can have a big influence on the quality of the boil-off. As nitrogen is lighter than LNG it will evaporate in priority, reaching high percentages in boil-off. For example, just after loading, for a LNG containing just 1% of nitrogen, the molar fraction of nitrogen in boil-off can reach up to 21 %.This has great impact on the engines behavior as it dilutes the methane and reduces the boil-off's energy content (see Figure 6.

The engine hence requires more boil-off mass flow to produce the same amount of power. If methane is diluted too much the engine can be de-rated, i. e., it can no longer guarantee its maximum power due to very low boil-off energy content and produces less power. If this phenomenon did not occur in these simulations it can nevertheless be simulated in SEECAT. Static boil-off gas models cannot reproduce these behaviors.

As nitrogen evaporates first, its fraction in LNG reduces with time as it can be observed in Figure 7.

As nitrogen evaporates first and it is a light gas, the boil-off's molar mass and hence the mass flow increases over time (see Figure 8) instead of reducing has calculated with a static model.

Finally, this new advanced boil-off model makes it possible to reproduces important physical phenomenon during boil-off, increasing in the end the overall accuracy of the model. The mass flow of LNG consumed is determined more precisely as well as the engine's consumption. It also makes it possible to change the LNG composition and see its influence over engine ranking and later hull ranking

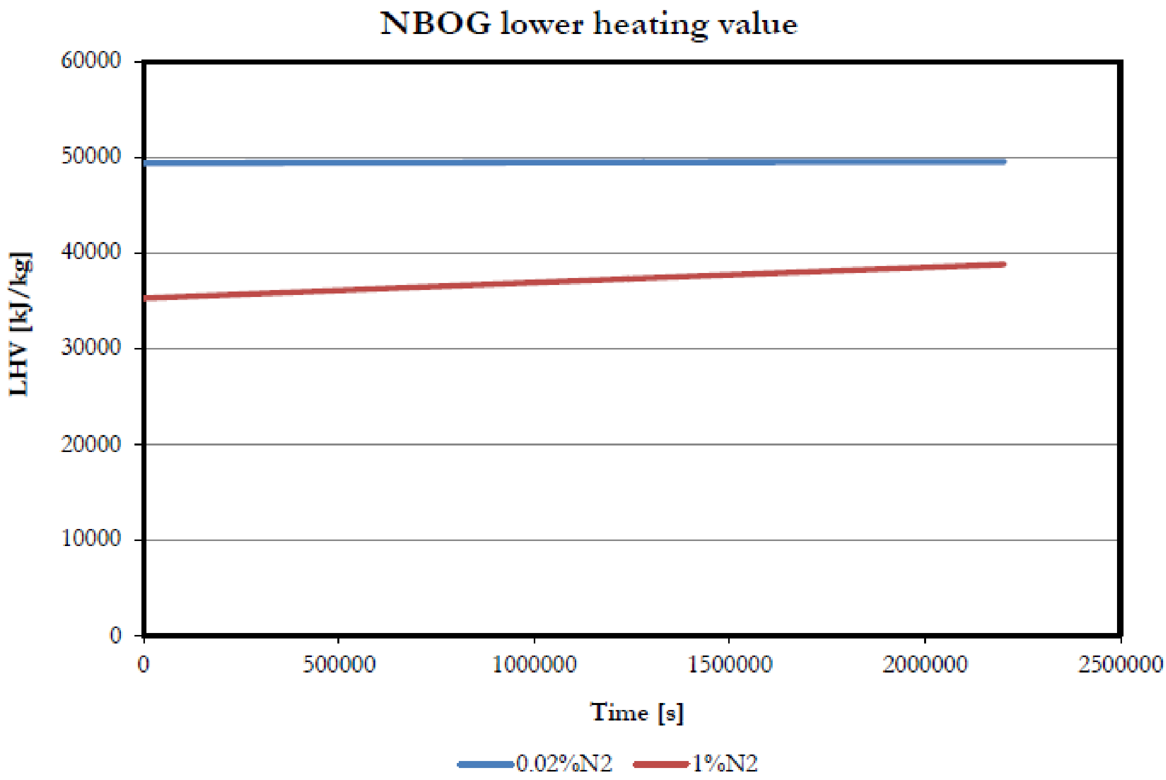


Figure 6 : Boil Off rate Comparison for 2 different LNG

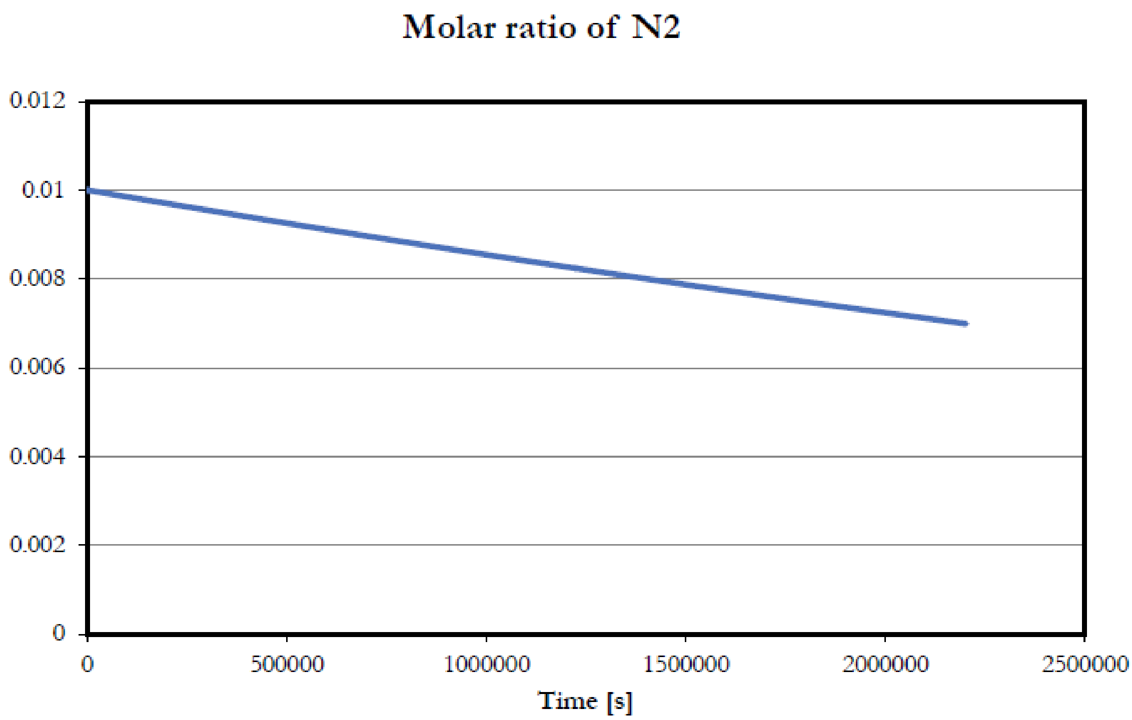


Figure 7 : Evolution of Nitrogen content in LNG versus time

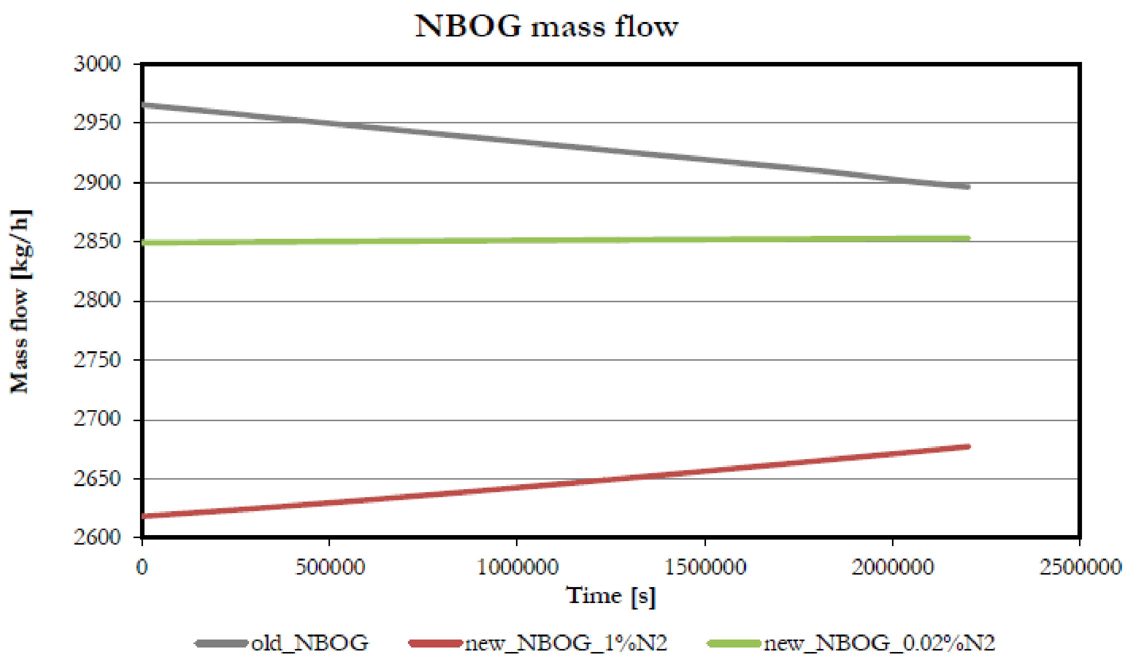


Figure 8: Natural Boil Off rate mass flow comparison between static and BOG model

2.4 Results

Six simulations were made, one for each architecture and for two different LNG compositions. Main results are presented in Table 1.

2.5 Analysis

First of all, it can be observed that LNG composition highly influences fuel consumption which is crucial for economic analysis.

Secondly, the total amount of NBOG does not change with engine architecture, but only with gas composition, which was expected.

For each architecture, the fuel consumption is higher than the NBOG amount, hence requiring forced boil-off (FBOG).In each case, some of the NBOG is burned in the GCU. This happens at low speeds when NBOG is higher than the gas consumption.

In terms of gas consumption, the DFDE is by far the highest consumer. Both two stroke architectures are close but HPLS has the lowest consumption. However ,it is offset by the pilot consumption which is much higher in HPLS than LPLS. DFDE has the lowest pilot consumption of the three.

One way of adding up pilot and gas consumption is to look at CO2emissions. In this respect, DFDE is by far the least environmentally friendly architecture. Again, LPLS and HPLS are very close. In the 0.02%mol N2LNG, the LPLS is the cleanest architecture saving up to 5.7% CO2, but it is the HPLS which is the cleanest in the 1%mol N2LNGwith a CO2reduction of 6.3%.

In the end, if the two two-stroke architecture present some differences, they are clearly more efficient than the traditional diesel electric architecture.

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	LNG compo: 0.02%$_{molar}$ N_2			LNG compo: 1%$_{molar}$ N_2		
Conso. [tons]	DFDE	HPLS	LPLS	DFDE	HPLS	LPLS
GCU	187	290	228	151	153	150
FBOG	978	690	738	1452	1069	1165
NBOG	2633	2633	2633	2539	2539	2539
Total Gas	3424	3032	3143	3839	3455	3554
Pilot	32	150	65	32	150	65
Total CO2	10019	9549	9449	11063	10334	10366

Tableau 1 : Résultats principaux pour 2 différentes compositions de gaz

3. HULL OPTIMISATION

One of the main axis of research for energy saving is hull form optimization. The project started with a hull already optimized by SHI for laden condition. BV subsidiary Hydrocean*, did the optimisation of the hull form for laden and ballast condition, as ballast condition represents half of each voyage. First of all the hull form optimisation started by the evaluation of the initial hull form, secondly a first set of optimisation in calm water was carried out, thirdly an evaluation in waves has been done and finally the final hull form has been evaluated. The computations were performed using CFD solver and hull modeler software.

3.1 Initial hull form evaluation

The hydrodynamic performances of the initial hull optimisation were assessed using ISIS-CFD. Simulations have been carried out at full scale and model scale.

Resistance and self-propulsion simulations results at full scale are shown in Figure 9 and Figure 10 respectively.

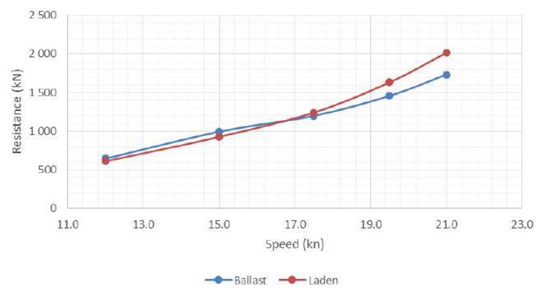

Figure 9: Total resistance versus speed

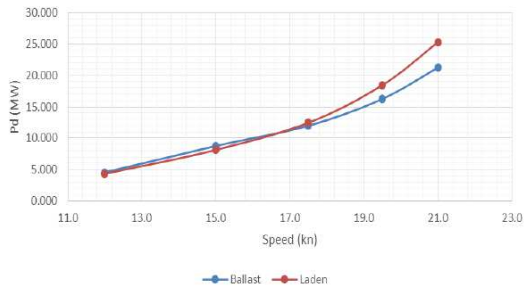

Figure 10: Ship delivered power vs speed

One can observe that for speed below 17 knots resistance and power are higher for ballast than for laden condition.

Figure 11 presents a comparison for the initial hull between full scale resistance and resistance extrapolated at full scale from model scale computations. There is a very good agreement between the full scale resistance and resistance extrapolated at full scale from model scale computations.

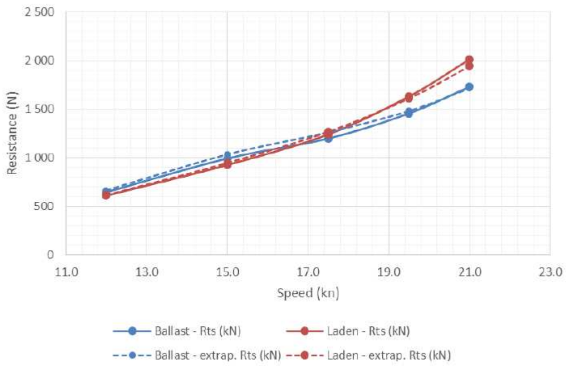

Figure 11: Comparison model test/CFD

3.2 Calm water Evaluation

After presenting the optimisation constraints, the first step of the optimisation, that consists in the evaluation of the impact of each deformation taken separately on the resistance and/or the ship power, is shown. Best deformations regarding ship power reduction are then combined in order to obtain the optimum hull shape regarding ship power in calm water. Computations have been performed for the 6 main operating conditions defined for the target operational profile (see section 2.1): 2 loading conditions (laden and ballast) and 3 speeds.

The optimization was performed while respecting the constraints provided by SHI, mainly concerning:

- Engine boundary,
- Cargo boundary in order to fulfil New IGC code,
- Flat of side constraints,
- Propeller characteristics.

A first set of self-propulsion calculations was first performed for elementary variations of:

- Bulbous bow length, width and height,
- Bow design,
- Entrance angle, fore sections shape,
- Transom immersion and width,
- Skeg distance and angle,
- Longitudinal centre of buoyancy,

As illustrated on figure 12.

Combinations of the best deformations were then investigated in order to find the best hull form regarding ship power reduction. An intermediate step corresponding to the combination of deformations applied on the forebody separately from combination of deformations applied on the aftbody was performed before the final evaluation of the last candidates. All new designs were evaluated on the 6 operating conditions.

In total, more than 100 hull forms have been evaluated in self-propulsion for 6 operating conditions which represented more than 600 free surfaces Navier-Stokes computations.

Figure 13 shows the differences on the weighted average of the delivered power with respect to the initial design of the ballast part of the operating profile versus the one of the laden part of the operating profile.

The hull form offering the lowest total weighted average delivered power over the full operating profile

3.3 Design evaluation in waves

Hull performance in waves was then considered in the optimisation process. First, the added resistance on has been calculated for the 12 best hull forms issued from the calm water optimisation process. In this purpose, resistance calculations have been conducted at full scale using aNavier-Stokes free surface

CFD solver with SWENSE method for wave modelling in the following conditions:

- One ship speed (17.5 knots)
- One regular head wave chosen with regards to the most probable sea state along the selected route (Hs=1.5m and Tz=6.5s)

The obtained reductions with respect to the initial hull in weighted average added resistance over ballast and laden conditions versus reductions in calm water resistance are presented in Figure 14.

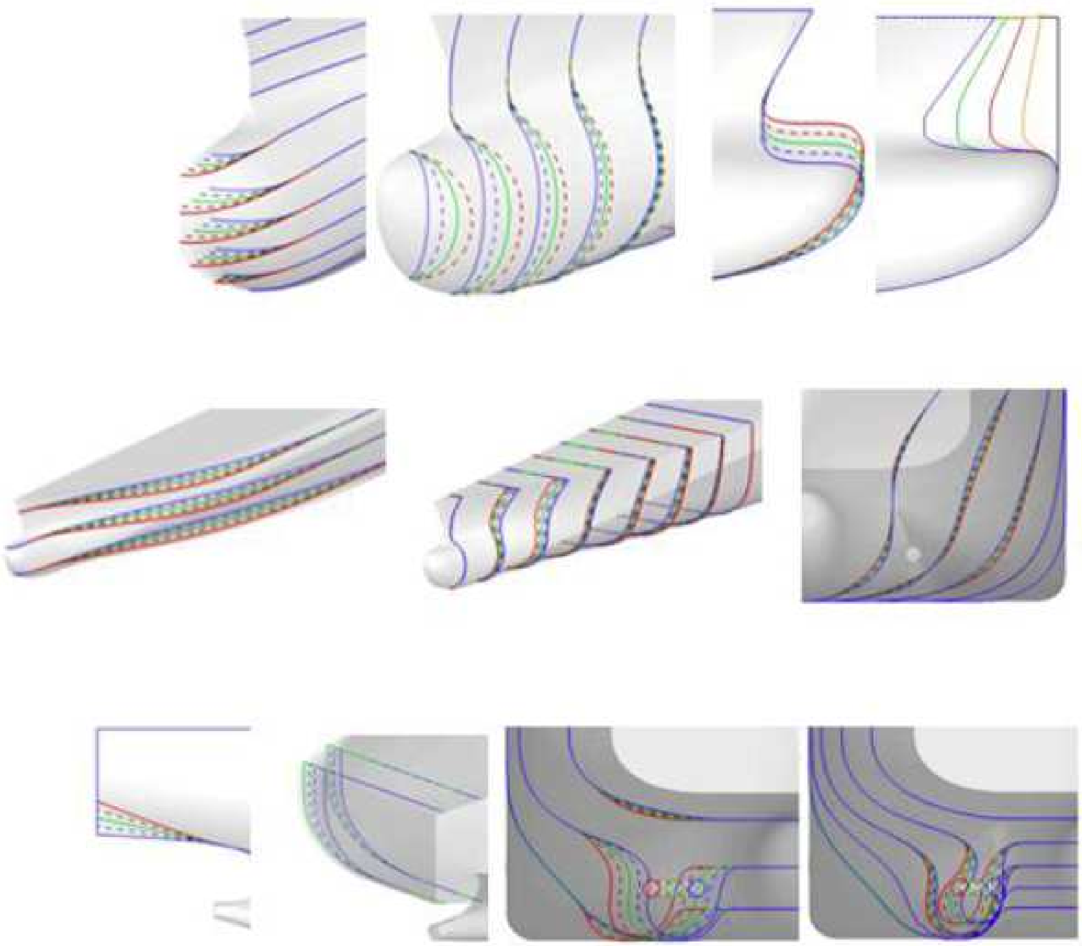

Figure 12: Elementary hull deformation

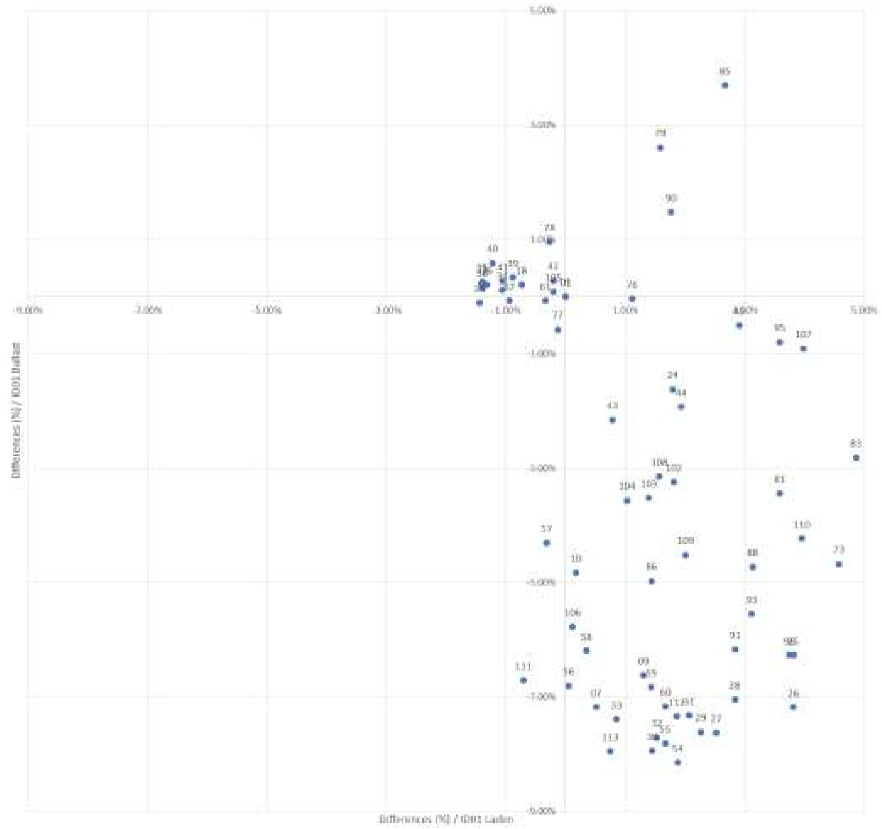

Figure 13: Weighted average of the delivered power with respect to the initial design of the ballast part of the operating delivered power with respect to the initial design of the ballast part of the operating profile versus the one of the laden part of the operating profile

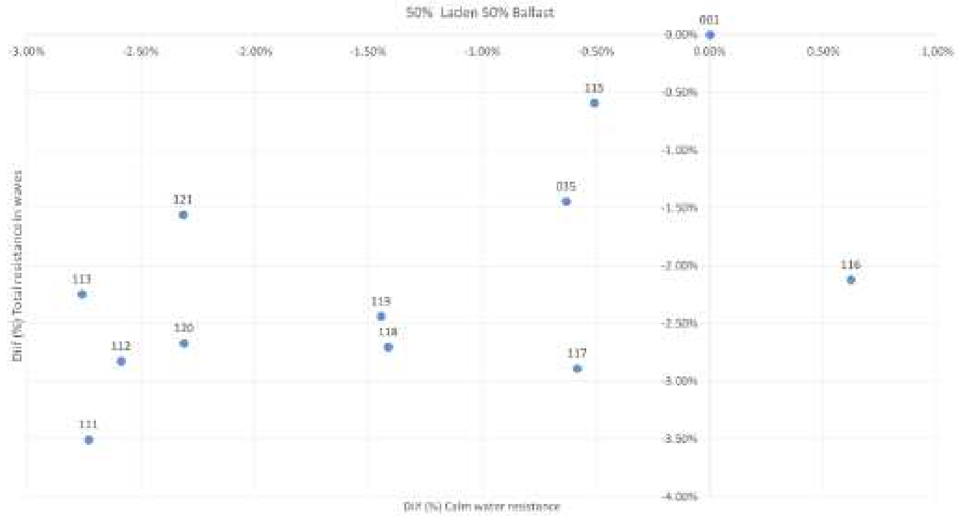

Figure 14 : Differences with the initial design regarding the total resistance in waves as a function of the differences with the initial design regarding the calm water resistance

The hull shape presenting the best compromise between weighted average added resistance and weighted average calm water resistance was then selected to optimize the upper part of the bow, above the laden waterline, in order to not affect the calm water performance. The added resistance variations obtained for the different selected deformations of the bow upper part are presented in Figure 15, with a maximum additional gain of 1.13%.

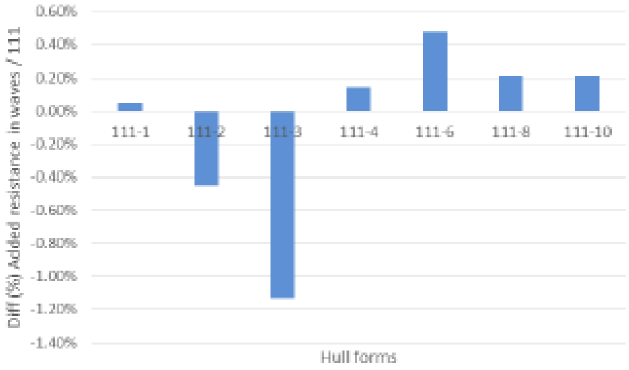

Figure 15: Gain obtained on added resistance

3.3 Final Hull form evaluation

The hydrodynamic performances of hull form resulting from the above described optimization process were finally evaluated in self-propulsion in calm water and in waves, using ISIS-CFD, and compared to model tests conducted by SHI.

Figure 16 shows a good agreement between the delivered power at model scale obtained from model tests and from CFD simulations, acknowledging that rudders and bow thruster that were modelled in the basin were not modelled in the CFD computations.

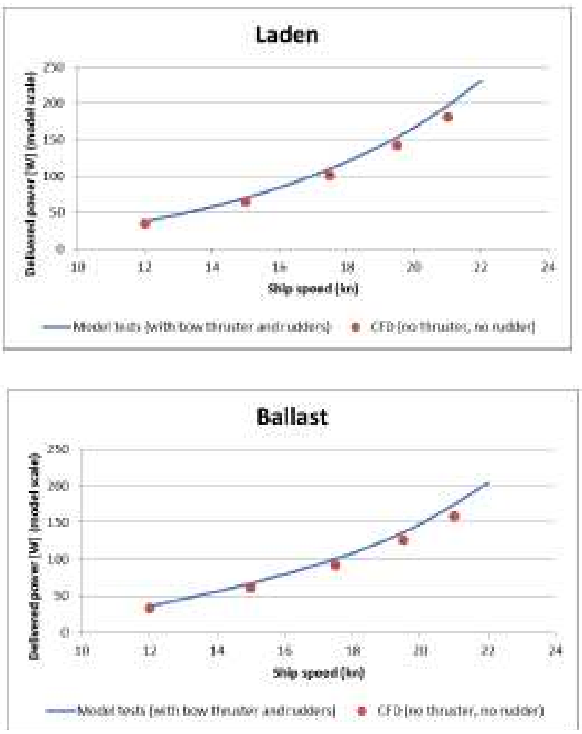

Figure 16: Comparison of power between CFD and model tests

Figure 17 shows the comparison between the delivered power computed at full scale for the initial and the final hull form for both loading conditions (ballast and laden). If slightly larger powers are needed at speeds larger than 19.5kn, significant gains are obtained at lower speed and in particular in ballast condition where the bump visible at 15 knots was completely reduced by the optimisation.

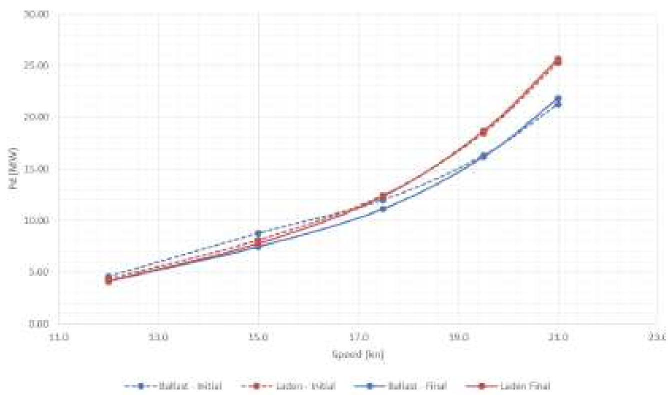

Figure 17: Ship delivered power function of speed

When considering the full operational profile of the ship, as illustrated in Figure 18, the hull optimisation enabled a reduction of weighted average delivered power of 8% in ballast condition, for an increase of 0.3% in laden condition, **resulting in a global reduction of 3.8% over a round trip.**

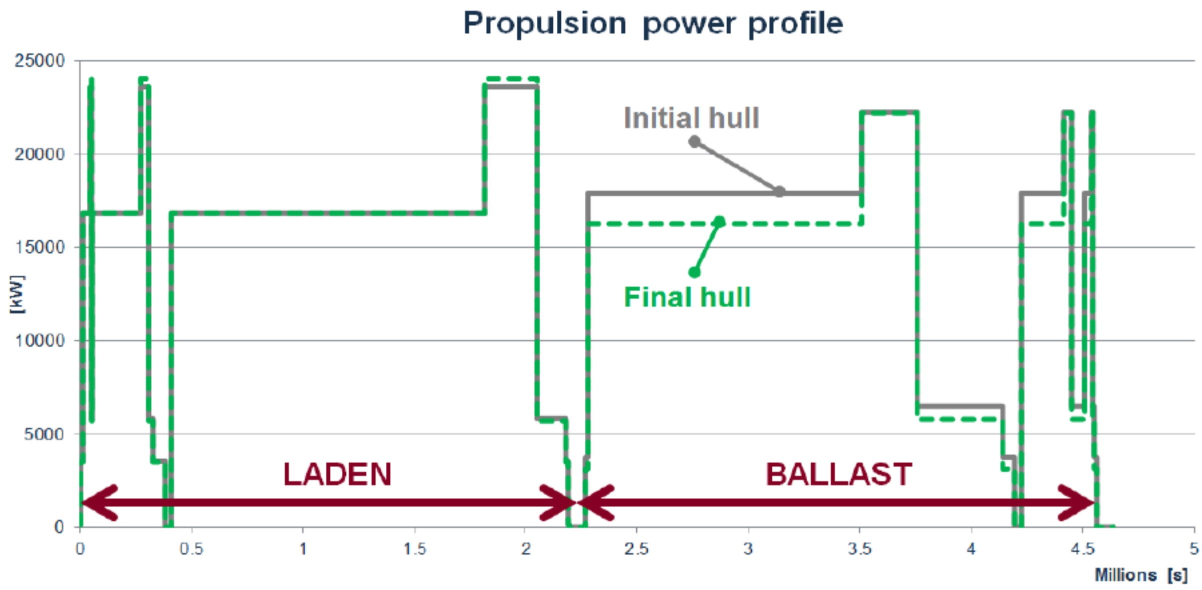

Figure 18: Consumption Profile during a rotation

Finally, the final hull was evaluated in irregular waves for two sea states (4 and 5) in head waves and the results were compared to seakeeping tests performed by SHI.

The quadratic transfer functions(QTF) of added resistance in waves were first computed in laden and ballast conditions by using Navier-Stokes free surface CFD solver with SWENSE method for wave modelling. Then the QTF were combined with wave spectra to obtain the mean added resistance for each sea state. The latter was then combined with wind force and calm water resistance. Delivered powers were finally derived from the total resistance in BV SEECAT tool.

The calculated delivered power (CFD) at full scale is compared to the one obtained from seakeeping model tests (EFD) performed on the selected irregular sea states in Figure 19for sea state 4 and Figure 20for sea state 5. For both sea states, the agreement is very satisfactory.

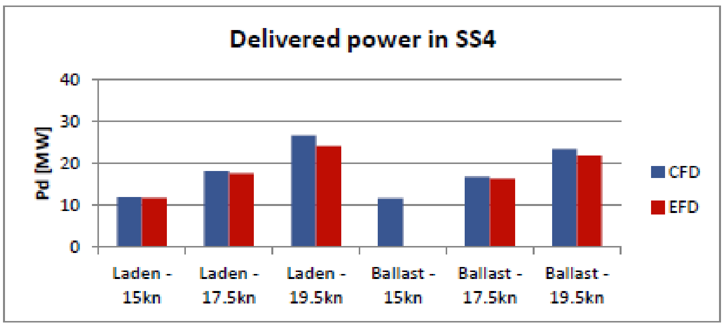

Figure 19: Delivered power

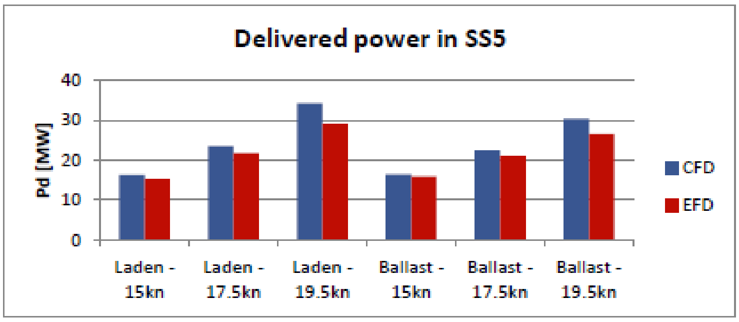

Figure 20 : Delivered power

4. ECONOMICAL ANALYSIS

To evaluate the most profitable engine architecture, economical simulations were evaluated. They compared capital costs, maintenance costs as well as fuel and gas consumption. They were based on new SEECAT simulations done with the final hull design and with the updated two stroke propulsion architecture (for the LPL Sand HPLS architectures, the engines maximum continuous rating power and specific fuel and gas consumption have been adapted to the latest hull along with their respective waste heat recovery boilers and EGR systems).Comparison was hence made between initial hull(DFDE)and final hull (two stroke dual fuel architecture).

4.1 Consumption cost

Consumption costs add up LNG consumed in engines and boilers, lubricating oil and pilot fuel. Lubricating oil consumption has been calculated by Total "Lub Marine" services. Whereas gas and fuel consumption figures come from SEECAT simulations. The total consumption cost over a round trip is presented in Figure 21. HPLS and LPLS (with final hull) are very close to each other (1.6 % difference) and show significant improvement (8.3 % savings) over DFDE (initial hull).

Moreover, the new design makes it possible to deliver 491 additional tons of LNG at each roundtrip, which represents 12% savings (see Figure 22).

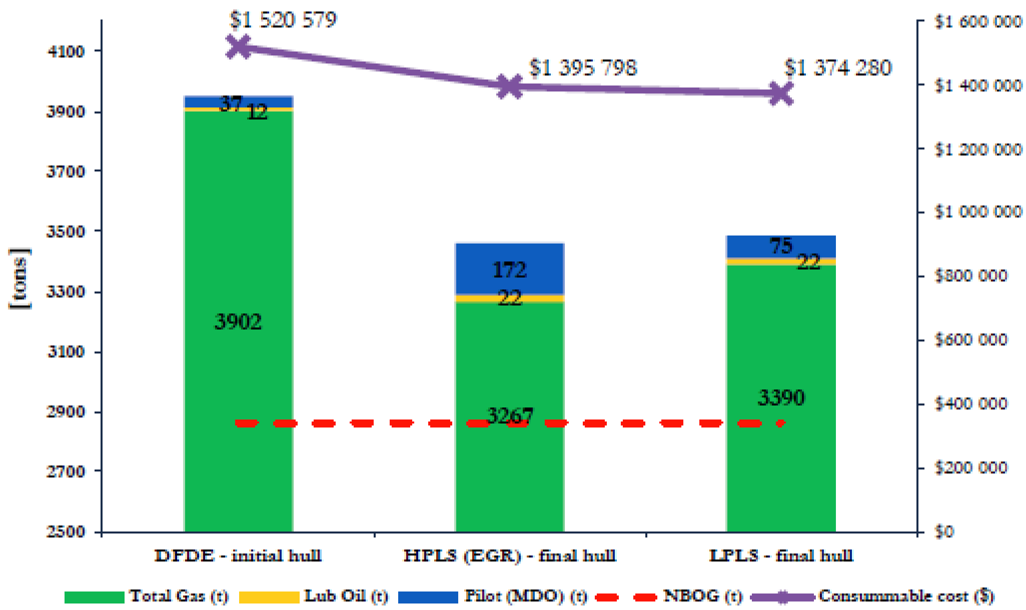

Figure 21 : Cost comparison

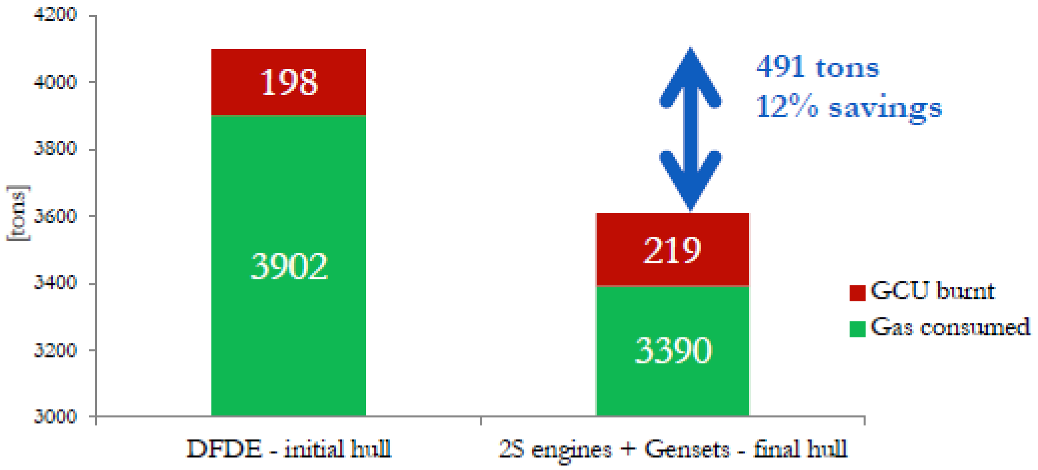

Figure 22: Cargo consumed during one round trip. Comparison DFDE 2 strokes

4.2 Maintenance costs

Maintenance costs depend on many factors (ship-owner, crew behavior, running hours, fuel quality, maintenance contract commercial agreement, unpredictable events, etc.). For engines they are roughly function of the total number of cylinders, which explains the gains possible with two-stroke engines (see Figure 23).For DFDE architecture, estimations are an average between manufacturers' data and effective feedback from current TOTAL LNGC chartered fleet. For the two stroke architectures, estimations rely only on manufacturer's data. As these architectures are recent on the market, a 30 % security margin has been added for two-stroke engine maintenance costs.

Looking at daily maintenance costs, the two-stroke architectures help save $1547 which represents a 43% reduction over DFDE (see Figure 24).

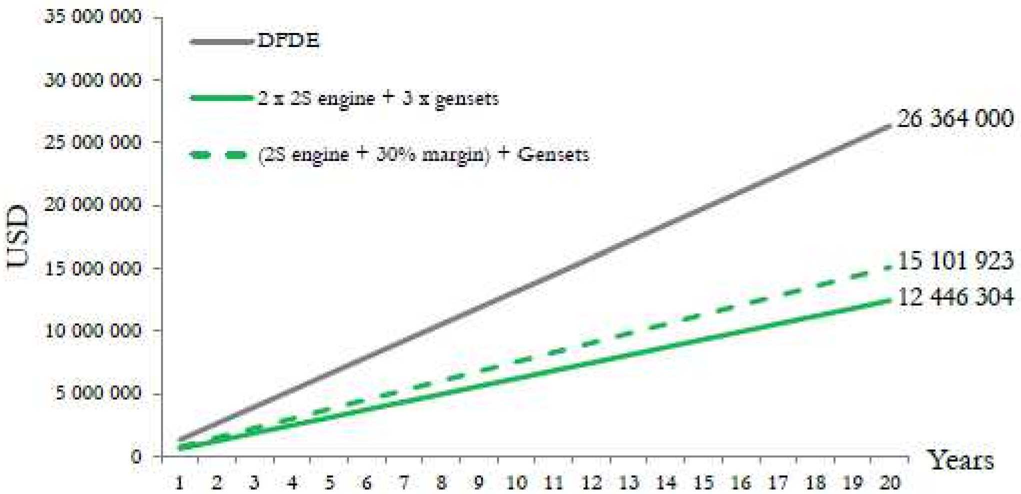

Figure 23 : Average maintenance cost over 20 years. Comparison between average two-stroke architecture and diesel electric architecture.

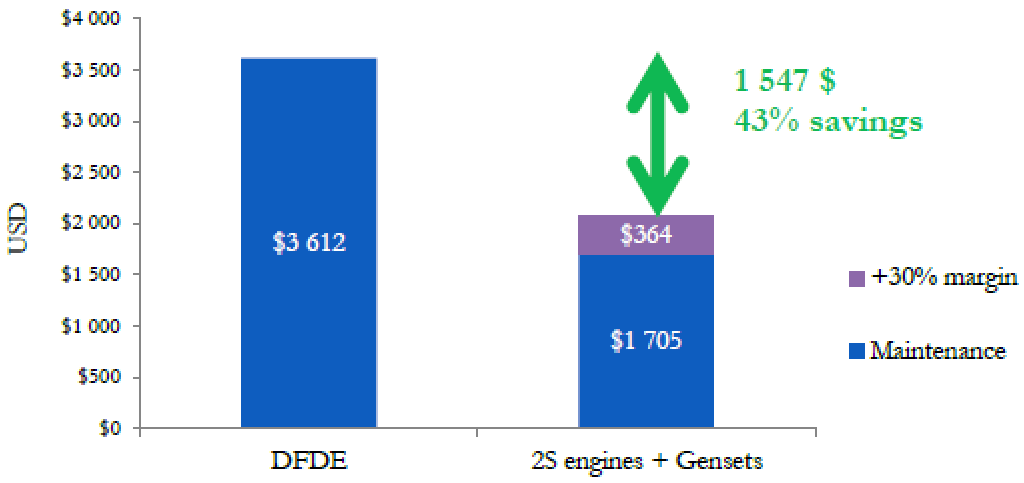

Figure 24 : Daily averaged maintenance costs. . Comparison between DFDE architecture and average two-stroke architecture.

4.3 Overall OPEX Cost

In the end, the two stroke architectures help save 13.5 % of maintenance and consumption costs. The final choice between HPLS and LPLS was made over capital costs*.

5. CONCLUSION

TOTAL, SAMSUNG HEAVY INDUSTRIES and BUREAU VERITAS have teamed up to design a new generation of 180000m3LNG carrier with high energy efficiency considering future LNG trading patterns, new trading route and compliance with future environmental regulations. In this purpose, a full hull form, propulsion and power generation optimisation has been performed for a pre-defined complete operational profile of the ship (i.e. full voyage including loading and unloading operations, manoeuvring, channelling, etc.).The hull lines have been optimised by BV subsidiary HydrOcean using state-of-the-art Navier–Stokes Computational Fluid Dynamics (CFD) tools, considering both calm water performance and ship behavior in waves and the performance of the final design has been validated by calm water and seakeeping model tests. The results of hull optimisation had shown gain of 3.8% in average delivered power over a round trip, mainly coming from amajor gain on ballast loading condition.

Various dual fuel propulsion and power generation architectures have been defined and their performances have been assessed using a holistic energy modelling of the ship. Moreover afine Boil-Off gas model, predicting the evolution in time of the Boil-Off gas rate and Lower Heating Value has been developed and integrated in the simulations. The results of simulations showed the importance of the composition of the gas on the prediction of the boil-off.

Several Key Performance Indicators have been defined and used to compare the design and select the optimal one. They included CAPEX costs as well as OPEX costs where predicted gas and fuel consumptions were considered together with forced Boil-Off gas quantity and mass of gas burnt at the Gas Combustion Unit per voyage. In general the two stroke dual fuel engines architectures were performing better than the DFDE architecture.

6. REFERENCES

[1] P. Marty, P. Corrignan, A. Gondet, R. Chenouard, and J.-F. Hétet, “Modelling of energy flows and fuel consumption on board ships: application to a large modern cruise vessel and comparison with sea monitoring data,” presented at the 11th International Marine Design Conference, University of Strathclyde, Glasgow, Scotland, 2012, vol. 3, pp. 545–563

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