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An analysis of the energy efficiency of LNG ships powering options using the EEDI

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ABSTRACT

This paper presents analyses future powering options for LNG carriers when considering the Energy Efficiency Design Index (EEDI). The IMO has recently approved amendments to MARPOL Annex 6 to extend the application of the EEDI to include LNG Carriers (LNGCs). This paper investigates the impacts of this upcoming EEDI regulation, due to be enforced from September 2015, will have on the design of future LNGCs. The study found that the current EEDI reference baseline is insufficient to stimulate improvements in the design of future LNGCs because the current Dual Fuel Diesel Electric (DFDE) propulsion proposed to be installed on majority of future LNGCs orders already achieves EEDI values that are compliant with the EEDI baseline. Analysis of EEDI values for LNGCs employing the new two-stroke gas injection diesel propulsion system also displayed similar results. However when considering unburnt methane emissions of the DFDE it was seen that the GHG emission index value could potentially rise by up to 115% meaning the EEDI is limited in its value to reduce global warming. This paper also proposes and analyses amendments to the EEDI baseline values for LNGCs as well as suggesting methods to include methane slip emissions into the current EEDI calculations.

1. Introduction

The use of natural gas as a fuel for energy production has been gathering momentum over the past decade the reasons for which are mainly due to the fact that it is available in abundance, it is cheaper, and produces lower emissions than other established fossil fuels. For ease of storage and/or transport, Natural Gas (NG) is converted to its liquid form (LNG – Liquefied Natural Gas) by cooling the natural gas to −160 °C, taking 600 times less volume than when in its gaseous state, and it can then be transported to its markets by sea using specially designed cryogenic vessels – LNG Carriers (LNGC). Use of these LNGCs is a cost effective way of transporting NG over long distances, where pipelines do not exist, to specially designed terminals, from where the LNG is re-gasified and distributed by NG pipeline. As of July 2014, there are 335 LNGCs in operation (Clarksons Shipping Intelligence Network, 2014a), with these LNGCs utilising three different propulsion types the predominant being steam turbine propulsion (STPS), while the others are the diesel electric (DFDE) and the traditional slow speed two-stroke diesel engine with re-liquefaction plant (SSDR).

As LNG is transported at −160 °C and near atmospheric pressure, inevitably the LNG boils off due to imperfect insulation and sloshing in the tanks, and it is the need to handle this boil off gas on-board the vessel that has led to these vessels employing a steam power and propulsion plant which has enjoyed a 40 year-long dominance in LNG carriers. Steam boilers burn natural gas as easily as fuel oil whilst other power plant options traditionally could not quite do so. While steam turbines have proved extremely reliable within this period, compared to other propulsion alternatives, they are inefficient in terms of fuel consumption due to the inherent properties and limitations of the Rankine Cycle. The fuel consumption on steam ships compared to diesel ships is too high to bear for non-LNG ship applications hence steam propulsion plant has all but disappeared being replaced by others such as slow speed two-stroke diesels. For LNG vessels built 10–30 years ago however there was little or no motivation to develop alternative propulsion plants as the state of the cargo insulation was such that on a loaded voyage, the natural boil off flow was sufficient to provide 100% of the fuel requirement. Even assuming there were more efficient gas burning plants available at the time

Abbreviations: BOG, boil off gas; CO_2, carbon dioxide; CPP, controllable pitch propeller; DC, direct current; DDD, direct drive diesel; DFDE, Dual Fuel Diesel Electric; DNV, Det Norske Veritas; FBO, forced boil off; FPP, Fixed Pitch Propeller; GCU, gas combustion unit; GHG, Green House Gases; GI, gas injection; GWP, global warming potential; HFO, heavy fuel oil; HRSG, Heat Recovery Steam Generator; IMO, International Maritime Organisation; LNG, Liquefied Natural Gas; MARPOL, marine pollution; MDO, marine diesel oil; ME-GI, M-type electronically controlled gas injection; MEPC, Marine Environment Protection Committee; MPP, Maximum Propulsive Power; SSDR, Slow Speed Diesel with Re-liquefaction plant; STPS, Steam Turbine Propulsion System.

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Nomenclature

$\eta_{electrical}$	electrical efficiency
BOR	boil off rate (%)
C_f	carbon factor
COP	coefficient of design performance
COP_{comp}	design power of compressor (kWh/kg)
DWT	deadweight (tonnes)
EEDI	energy efficiency design index (gCO_2/tNM)
EEOI	energy efficiency operational indicator (tCO_2/tNM)
MCR	maximum continuous rating (kW)
P_{AE}	auxiliary engine power (kW)
P_{ME}	main engine power (kW)
R_{Reliq}	ratio of boil of gas to re-liquefied boil off gas
SFC	specific fuel consumption (g/kWh)
V_{ref}	reference speed (knots)

of LNGC development, it is likely they could not have been used without having an alternative solution for the significant boil off gas (BOG) that was experienced around that time. Wayne and Hogson (2006). However, the development in insulation technologies have resulted in significantly lower LNG cargo boil off rates in modern LNGC designs which has resulted in insufficient natural gas boil off to fuel the propulsion plant therefore supplementing with either the use of forced boil off gas or use of heavy fuel oil (HFO). This has led to the development of alternative more fuel efficient propulsion systems and/or re-liquefaction (converting boil-off back to LNG) systems offering economic advantages compared to the conventional steam plant. Furthermore over this period IMO began to introduce regulations to govern the emissions of exhaust gases from ships including NOx and more recently CO_2. This led to a shift in propulsion plant design for LNGCs from the STPS towards the DFDE and SSDR as can be seen upon analysing data from Clarkson's World Fleet Register (Clarksons Shipping Intelligence Network, 2014b)

From the 1960s to 1990s, the STPS was employed by almost all LNG carriers with few exceptions. By the 2000s, the proportion had fallen to 69% and in the current decade to 21%. The future order book presently stands at 12% (Clarksons Shipping Intelligence Network, 2014b).

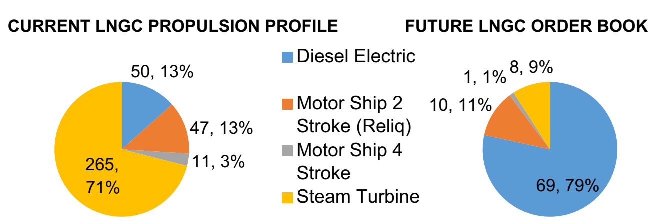

Fig. 1. Current LNG fleet and Order book (Barend Thijssen, 2005).

This paper assesses the energy efficiency of the different LNG shipping powering options over two key themes; (a) To review the energy efficiency of different LNGC designs over time and comparing them with today's designs having different types of propulsion systems through analytical study (b) To examine the potential impact of this propulsion change coupled with upcoming emissions regulations, with regards to achieving a reduction in CO_2 emissions (Fig. 1).

2. Description of the different LNGC propulsion technologies

2.1. Steam turbine propulsion system

STPS are currently is found in 71% of the current LNG fleet (Clarksons Shipping Intelligence Network, 2014a), and this majority is due its domination over the past decades due to its easy handling of BOG, simple operation and intrinsic safety. When the cargo tank pressure is elevated, the steam boilers burn the BOG to produce high pressure steam which drives the turbines connected to the propeller. During periods where the power and propulsion load is not sufficient to handle the BOG capacity, the steam generated is dumped in the main condenser. It is this simple philosophy that eliminates the need for a gas combustion unit (GCU) which is a requirement for the other two propulsion systems – the SSDR and DFDEs (Chang et al., 2008a).

The outline of the STPS plant is shown in Fig. 2 and normally consists of two gas/HFO fuelled boilers supplying steam to a cross compounded double reduction geared steam turbine plant driving the propeller. This generated steam is also used to supply auxiliary services including turbo generators which provide electricity and feed pumps. The total electrical capacity of the turbo generator is dictated by the total electrical load required during full rate cargo discharge i.e. when using the electrical cargo pumps, and it is for this reason as well as the need for redundancy, that two turbo generators are usually installed. Older steam LNG carriers have installed one 100% capacity auxiliary diesel generator, having capacity equal to one of the turbo generator sets, as a safety requirement, to supply sufficient power during black outs or periods where the steam system is not available to power the turbo generators. Newer steam LNG ships however have two 50% capacity diesel generators to give increased protection against single point failures leading to difficulty in recovering the plant after a black out. The described outline of the plant is similar on every steam powered LNG ship in service remaining largely unchanged since the first steam LNG ships entered service in 1964 (Wayne and Hogson, 2006).

2.2. Slow Speed Diesel with Re-liquefaction plant

The SSDR is a single fuelled (IFO) diesel mechanical propulsion system with a re-liquefaction system where the BOG is liquefied and returned to the cargo tanks, instead of being burnt in the engine. The slow speed diesel propulsion configuration on these systems are usually the twin screw format with two slow speed diesels connected directly to two propeller shafts (Wayne and Hogson, 2006) as seen in Fig. 3. This propulsion unit is also equipped with a GCU to dispose the BOG in instances where the BOG capacity is larger than the capacity of the re-liquefaction plant.

The BOG re-liquefaction concept is based on a closed nitrogen cycle, extracting heat from the BOG. In this cycle, cargo boil off is evacuated from the LNG tanks by a Low Duty compressor, the vapour is then compressed to 5 bar and then cooled to −160 °C in a cryogenic heat exchanger. This ensures condensation of all hydrocarbons in the gas so they are converted back to LNG, while the nitrogen and other non-condensable remain as gas bubbles in the LNG. These bubbles are however removed in a liquid separator where the LNG is separated and pumped back to the cargo tanks with the nitrogen-rich non-condensable gases either discharged to the atmosphere or burnt in the GCU (MAN B&W, 2004). For current sized LNG carriers this additional re-liquefaction system would impose an additional electrical power of between 3 and 4 MW, although some current LNGCs with slow speed diesel configurations have capacities

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