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Dynamic process simulation promotes energy efficient ship design

Vesa Lepistö [a,*], Jari Lappalainen [b], Kari Sillanpää [a], Pekka Ahtila [c]

[a] Meyer Turku Oy, FI-2101 Turku, Finland
[b] VTT Technical Research Centre of Finland Ltd., FI-02044 VTT, Finland
[c] Aalto University, Department of Energy Technology, FI-00076 Aalto, Finland

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ABSTRACT

Energy efficiency has become increasingly important to ship owners and builders, due to fuel costs and tightening environmental regulations, but also due to public opinion and expectation for green technology. Improved energy efficiency and significant savings are achievable by increasing waste heat utilization. A probable side effect of commissioning new technology is increased system complexity. This makes it more difficult to make design decisions between alternative technologies; also, the operation of the system needs more attention. Dynamic system level simulation has been used for energy systems analysis already for decades in onshore energy industry; now it is increasingly applied in marine engineering. In this study a commercial simulator Apros was used to model and simulate energy systems of a cruise ferry Viking Grace, which features novel energy saving solutions, such as a waste heat accumulator system and cooling options by liquefied natural gas (LNG) vaporizing, and by seawater. Dynamic models of these systems were developed and validated against available measurement data. The study showed that modelling and dynamic system level simulation can provide substantial benefits in the design of energy efficient ship in new buildings, and in existing ships.

1. Introduction

Ship engineering has played a major role in maritime history meeting a great variety of challenges for transportation and enjoyment. For last decades, the awareness of fossil fuels limitedness and environmental aspects has led the technology towards higher energy efficiency and lower emissions of pollutants. The challenge set by the global warming, thus considering also carbon dioxide (CO_2) as a pollutant, has further raised the role of energy efficiency. Significant progress has been shown, but on the other hand, it is easy to find topics for further development.

In the last few years, both international and national legal requirements regarding the exhaust emissions have become much stricter. The marine industry is now facing the challenges of adopting new technologies and/or operational practices to comply these requirements. Fig. 1 shows the timeline for existing and planned environmental regulations for shipping. In January 2013, the Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP) entered into force. In setting increasingly stringent requirements to the energy efficiency of new ships, the EEDI is intended to stimulate development of more energy efficient ship design, indirectly leading to reduce operational CO_2 emissions. The SEEMP is intended to directly stimulate more energy efficient operational practices. (Nyhus, 2013).

For marine diesel engines, the emission requirements focus primarily on the reduction of nitrogen oxides (NO_x) and sulphur oxides (SO_x). Most critical amongst these regulations are the measures to reduce the SO_x emissions inherent with the relatively high sulphur content of marine fuels (MAN Diesel, 2014). Since January 2015, the maximum allowed sulphur content has been 0.1% in emission control areas (ECA). Outside ECAs, it is allowed to use fuels with 3.5% sulphur concentrations until January 2020, except for passenger ships operating on regular service in the EU waters the limit is 1.5%. Finally, in 2020 (or 2025 outside the EU depending on IMO decision in 2018) the regulation of global maximum sulphur content of 0.5% will enter into force that will present even bigger challenges (MotorShip, 2011).

Realistically, use of low sulphur fuel (LSF) means expensive distillates like MDO, MGO or liquefied natural gas (LNG). The increasing use of LSF might lead to higher price of these fuels. In the future, more ships will most likely be powered by LNG. For cruise ships one problem is even three times larger bunker volume

Abbreviations: AC, air conditioning; CFD, Computational Fluid Dynamics; COP, coefficient of performance; CWS, chilled water system; ECA, emission control area; EEDI, energy efficiency design index; EGB, exhaust gas boiler; EGC, exhaust gas cleaning; HFO, heavy fuel oil; HT, high temperature; IAS, integrated automation system; IMO, International Maritime Organization; LNG, liquefied natural gas; LSF, low sulphur fuel; LT, low temperature; MDO, marine diesel oil; MGO, marine gas oil; NO_x, nitrogen oxides; SEEMP, Ship Energy Efficiency Management Plan; SO_x, sulphur oxides; VFD, variable frequency drive; WHRS, waste heat recovery system

* Corresponding author.

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Nomenclature

F	friction force (N/m^3)
$\vec{g}, g$	acceleration of gravity (m/s^2)
h	enthalpy of the fluid (J/kg)
k	pressure loss coefficient
p	pressure (Pa)
ΔP	pump head (Pa)
Q	heat transfer rate ($J/(m^3\ s)$)
t	time (s)
v	fluid flow velocity (m/s)
z	spatial coordinate (m)

Greek symbols

α	gas volume fraction
Γ	mass transfer rate ($kg/(m^3\ s)$)
ρ	fluid density (kg/m^3)

Subscripts

fl	friction loss
i	interface
k	phase (liquid or gas)
p	pump
w	wall

LNG needs compared to HFO or MGO. Moreover, availability and infrastructure for a large-scale use of LNG is not yet ready (Passenger Ship Technology Summer, 2012). To meet the regulatory requirements for emissions of SO_x instead of using LSF, ship owners can install an exhaust gas cleaning (EGC) after treatment system, typically known as a scrubber.

The ship route and operation area set important boundaries for the ship design. An optimized design for a ship with certain operation profile can significantly vary depending on the targeted operation area. On the other hand, a single route may include a wide variety of different conditions. This all raise a question how tight an optimization is reasonable for certain specific conditions. Too optimized design certainly reduces system's flexibility in possible future changes in the operation profile and conditions.

A typical cruise ship has seasonal variations in sailing area with transit journeys in between. In each sailing area the hotel load, and especially the speed of the ship, varies greatly. The operation profile includes port visits, sea sailing at different speeds and daily processes like food preparation and laundry, which all cause large changes to the energy balance. The design must take into account the annual edge conditions, yet the emphasis is on the typical, seasonally changing, conditions (Lepistö, 2014).

Even for a very efficient marine engine, less than 50% fuel energy is converted to useful work as shown in Fig. 2. The rest, over 50% of fuel energy, is mainly taken away as waste heat by engine exhaust gas, engine high temperature (HT) cooling water, engine low temperature (LT) cooling water and finally emitted into air and sea (Zou et al., 2013). Waste heat is mainly utilized from the exhaust gases and the HT cooling water. Significant savings are achievable by improving the waste heat utilization.

To economically fulfil all the energy challenges marine engineering is facing, there is an urgent demand for proper tools to examine and verify alternative solutions within the ship energy management. When compared to process engineering and plant design within conventional power industry, ship design has numerous specific features and constraints to cope with. Ships needs to operate on large load range and the load variations are much more frequent than in power plants. One inherent restriction comes from the limited space for equipment placing and service. Moreover, the solutions installed will most often be carried over on every cruise for the vessel's lifetime, which must be taken into account in the design and investment decisions.

This study focuses on computational dynamic simulation, which generally represents – using mathematical modelling – how system's state evolves over time. Contrary to focusing on rather limited domains, such as an engine, or a piece of equipment, this study deals with a substantially larger part of the process, and thus is often called system-wide simulation. The number of system-wide modelling literature in marine engineering is still rather limited, but the situation is rapidly changing, as the need for holistic approach in marine simulation has been broadly recognized during the last few years

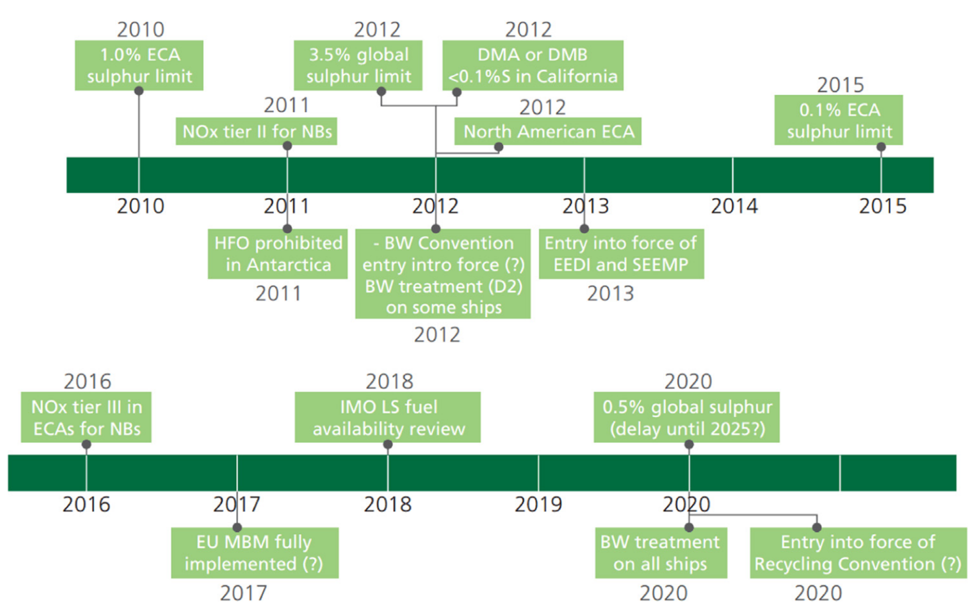

Fig. 1. Timeline for environmental regulations for shipping (SDARI, 2014). Acronym DMA is used for marine gas oil (MGO) and DMB is marine diesel oil (MDO).