Energy Conversion and Management 79 (2014) 640–651

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Techno-economic investigation of alternative propulsion plants for Ferries and RoRo ships

George A. Livanos [a,*], Gerasimos Theotokatos [b], Dimitrios-Nikolaos Pagonis [a]

[a] Department of Naval Architecture, Technological Educational Institution of Athens, Ag. Spyridonos Street, Egaleo GR 12210, Greece
[b] Department of Naval Architecture & Marine Engineering, University of Strathclyde, 100 Montrose Street, Glasgow G4 0LZ, UK

ARTICLE INFO

Article history:
Received 13 November 2012
Accepted 23 December 2013
Available online 31 January 2014

Keywords:
Ferries propulsion plant
Dual fuel engines
Waste heat recovery systems
EEDI
Techno-economic assessment

ABSTRACT

In this paper, the main alternative propulsion plants based on reciprocating internal combustion engines of a ferry or RoRo ship operating in routes that include Emission Control Areas (ECAs) are comparatively assessed. Specifically, a dual fuel engine propulsion plant is compared with a conventional Diesel engine plant. For both cases, the installation of a waste heat recovery system, which covers a part of the ship electric energy demand, is also considered. The ship main DF engines are assumed to operate using LNG and a small amount of MDO for initiating combustion, whereas low sulphur MDO was regarded as the fuel for the case of the Diesel engine plant. The installation of Selective Catalytic Reduction (SCR) after-treatment unit for reducing the NOx emissions for the case of Diesel engines plant is also taken into account. The propulsion plants were modelled under steady state conditions, and the simulation results were analysed in order to compare the alternative configurations. Furthermore, the Energy Efficiency Design Index (EEDI) values were calculated and the two examined propulsion system cases were compared on EEDI basis. Finally, the Life Cycle Cost for each alternative propulsion plant was calculated and used for completing an economic evaluation of the Dual fuel propulsion plant versus the conventional designs applied in ferries.

1. Introduction

The increased pressure for greener shipping resulted in an updated legislation framework set by the International Maritime Organization (IMO), for constraining the greenhouse gaseous emissions, mainly the carbon dioxide, as well as the nitrogen oxides (NOx) and sulphur oxides (SOx). Thus, in the recent amendment of IMO rules [1–3], the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) were introduced focusing on the reduction of CO_2 emissions and fuel consumption throughout the ship lifetime. For reducing SOx emissions, the IMO [4] defines the upper limits of the sulphur content for the fuels used onboard ships sailing inside and outside Emission Control Areas (ECA). Presently, the use of marine fuels with up to 1% sulphur content is only permitted inside ECAs, whereas the allowed fuel sulphur content value will be drastically reduced reaching 0.1% from 2015 onwards. For the NOx emissions, the three tier program [5] has been established according to which, Tier II that requires 15% reduction of NOx compared to Tier I is currently in effect, whereas Tier III imposes 80% reduction in NOx (also compared to Tier I) and will come into effect possibly in 2016.

To cope with the continuously increasing environmental demands, a number of measures for the ship propulsion system can be taken; these comprise the induction of more optimised propulsor designs including wing thrusters and contra rotating propellers, as well as the replacement of the conventional mechanical system by the more flexible Diesel-Electric propulsion system or combined Diesel mechanical/electric propulsion systems [6]. However, in order for the ship propulsion engines running on Heavy Fuel Oil (HFO) or Marine Diesel Oil (MDO) to comply with the future environmental regulations [7], techniques such as Selective Catalytic Reduction (SCR) or Exhaust Gas Recirculation (EGR) might be required for reducing the NOx emissions, whereas exhaust scrubbers or alternatively separate low sulphur fuel systems have to be installed onboard for addressing the SOx emissions reduction issue [8,9]. These measures deteriorate the ship propulsion plant efficiency and as a result increase the CO_2 emissions as well as the ship operational cost. All the above, in conjunction with the unprecedented rising of fuel oil prices throughout the last years and the continuously increasing availability of natural gas resources around the globe [10] render the use of Liquefied Natural Gas (LNG) as an alternative marine fuel attractive. LNG fuel is presently established as a clean and reliable fuel for propulsion and auxiliary power generation and its usage forms a very efficient way for reducing emissions [11]. Indeed, the SOx emissions are totally eliminated owing to the fact that sulphur is not contained in

* Corresponding author.
E-mail address: glivanos@teiath.gr (G.A. Livanos).

0196-8904/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.enconman.2013.12.050

Nomenclature

AE	specific available energy (J/kg)
AFC	annual costs for fuel consumption (€)
AK	annual machinery cost (€)
ALOC	Annual Lubricating Oil consumption Costs (€)
AMC	Annual Maintenance Cost (€)
AUC	Annual Urea solution consumption Cost (€)
c_p	specific heat at constant pressure (J/kg/K)
c_u	urea concentration (%)
C_F	conversion factor (g CO_2/g fuel)
CAPEX	Capital Expenditure (€)
DWT	deadweight (t)
EEDI	Energy Efficiency Design Index (g CO_2/t/NM)
FP	fuel price (€/g)
f	correction factors (–)
h	specific enthalpy (J/kg)
H_L	lower heating value (J/kg)
IC	investment cost (€)
IRR	internal rate of return (%)
LOP	lube oil price (€/g)
$\dot{m}$	mass flow rate (kg/s)
n	lifetime of investment (years)
OPEX	Operation Expenditure (€)
P	power (W)
$\dot{Q}$	heat transfer rate (W)
R	discount rate (–, %)
RH	running hours
SFOC	brake specific fuel consumption (g/kW h)
SLOC	brake specific lubricating oil consumption (g/kW h)
SMC	specific maintenance cost (€/kW h)
SUC	specific urea consumption (g/kW h)
T	temperature (K)
UP	urea price (€/g)
V_{ref}	reference ship speed (kn)
V	volumetric flow rate (W)
ε	heat exchanger effectiveness (–)
η	efficiency (–)
ΔNOx	specific NOx emissions reduction (g/kW h)
Δp	pressure drop, pressure increase (Pa)
ΔT	temperature difference (K)
$\Delta\eta$	efficiency increase (–)
ρ	density (kg/m^3)

Subscripts

a	air
ac	air cooler
AE	auxiliary engine
b	boiler
bv	baseline value
c	condensate water
cw	circulating water
d	drum
ec	economizer
el	electric
ev	evaporator
f	fuel
fw	feed water
g	exhaust gas
G	generator
hfw	heating of feed water
HT	high temperature
i	inlet
is	isentropic
m	mechanical
ME	main engine
o	outlet
pd	pump downstream
pp	pinch point
pu	pump upstream
s	saturated steam
sh	superheater, superheated steam
ST	steam turbine
sw	sea water
TG	turbogenerator
u	urea
w	saturated water

Abbreviations

AE	auxiliary engine(s)
CO_2	carbon dioxide
EIAPP	Engine International Air Pollution Prevention
HFO	Heavy Fuel Oil
IMO	International Maritime Organization
LNG	Liquefied Natural Gas
LPG	liquefied petroleum gas
MCR	maximum continuous rating
MDO	Marine Diesel Oil
ME	main engine(s)
MGO	Marine Gas Oil
NOx	nitrogen oxides
SCR	selective catalytic reactor
SOx	sulphur oxides
WACC	weighted average cost of capital
WHR	waste heat recovery

LNG, whereas the NOx emissions can be reduced up to 85% owing to the fact that the combustion takes place at air–fuel ratio values around 2.1–2.3 (lean burn combustion concept). In addition, the reduction of CO_2 emissions can reach 25–30% thanks to the low carbon to hydrogen ratio of fuel. On top of the above, the DF engines exhibit very low particulate emissions level, no visible smoke and no sludge deposits [12]. The LNG infrastructure has been developed in the last years [13], particularly in Norway, to the extent that other ship types, like Ro-Ro and smaller ferryboats can be bunkered.

The use of liquefied fuels (LNG/LPG) for the ship propulsion is not a new idea; these fuels have been used for many years onboard liquefied gas carriers equipped with steam turbine propulsion systems. Recently, four-stroke diesel mechanical or diesel-electric propulsion systems [14] have been also used. The former provide greater increase of the propulsion plant efficiency, whereas the latter combine the high efficiency with the increased flexibility. In all these cases, the boil-off gas produced due to evaporation inside the ship cargo tanks has been used as the main fuel in the ship propulsion system.

Nowadays, the commercial available gas engine portfolio includes three main technologies [15]: Gas, Gas–Diesel (GD), and Dual-Fuel (DF) engines. Gas engines are of the four-stroke type and run exclusively on gas. The combustion of the gas-air mixture takes place based on the Otto cycle triggered by spark plug ignition, whereas the gas is injected into the engine cylinder ports upstream the engine valves at low pressure (4–6 bar). The GD engines can operate on different mixtures of gas and diesel fuels or alternatively on diesel fuel only. The engine cylinder processes follow the Diesel cycle (compression–ignition) and the gas is injected into the