Applied Energy 211 (2018) 306–317

Contents lists available at ScienceDirect

Applied Energy

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

Evaluation of gas turbines as alternative energy production systems for a large cruise ship to meet new maritime regulations

A. Armellini[a], S. Daniotti[a], P. Pinamonti[a], M. Reini[b,*]

[a] Polytechnic Department of Engineering and Architecture, University of Udine, via delle Scienze, 208, 33100 Udine, UD, Italy
[b] Department of Engineering and Architecture, University of Trieste, via Valerio, 10, 34128 Trieste, TS, Italy

HIGHLIGHTS

- Optimization of a cruise ship energy system configuration and operation.
- Effects of the new environmental pollution limits on cruise ship energy systems.
- GTs allow environmental, weight, and volume benefits.
- The relevant amount of heat recovered by GTs may partially compensate the efficiency gap with respect to ICE.

ARTICLE INFO

Keywords:
IMO
Cruise ship
Emissions
Optimization
Gas Turbines

ABSTRACT

As a consequence of the new and up-coming regulations imposed by the International Maritime Organization (IMO), polluting emissions produced by large ships are now under strict control. Moreover, specific areas called "Emission Controlled Area" (ECA), which request even lower pollutant emissions, will be extended.

To face up to this issue, ships propelled by Internal Combustion Engines (ICEs) burning Heavy Fuel Oil (HFO) can be equipped with abatement devices such as scrubbers and Selective Catalytic Reactor systems. Along with these solutions, which seem to be the route ship-owners will prefer, other methods can be considered, such as the use of Marine Gas Oil (MGO): a more expensive fuel, but with lower sulphur content. The use of MGO allows users to consider a further and more drastic modification of the power system, namely the use of Gas Turbines (GTs) in place of ICEs. GTs, despite being less efficient, are much lighter, more compact, and can more easily reach low NO_x emissions than ICEs. Even if these aspects are theoretically well known, there are still difficulties in finding studies reporting quantitative analysis (weight, dimensions, fuel consumption) that compare GT and ICE power systems employed on board.

The present paper aims to provide these data by analyzing different solutions applied to a real case. Unlike other studies, the work is focused on a cruise ship rather than on a cargo ship, because a cruise ship's operation profile is more variable during the trip.

1. Introduction

The Maritime Transport sector consists of a heterogeneous group of vessels, which can be divided into two major classes: "goods transport" and "passenger transport". The first class accounts for 90% of the overall worldwide transportation [1], but the second has doubled its market in the last decade [2]. Vessel engines have to burn fossil fuels to conduct their activities, causing both Green House Gases (GHGs) and non-GHGs emissions. The former are responsible for climate change; the latter for acid rain, the decrease of agricultural yields, water contamination, modification of soil biology, deforestation and for damaging monuments. Emissions trading, financial incentives, emission monitoring obligations, and emissions (or energy efficiency) standards are the most used regulation mechanisms to reduce the environmental impact connected to the shipping industry. The most noteworthy regulator in the shipping industry is a specific branch of the United Nations, namely International Maritime Organization (IMO), which, in 2013, introduced two new policy mechanisms aiming to cut down GHG emissions: the Energy Efficiency Design Index (*EEDI*) and the Ship Energy Efficiency Management Plan (SEEMP). According to Anderson and Bows [3], the target of keeping the global temperature increase below 2 °C, compared to preindustrial level will imply a reduction of carbon emissions from shipping by more than 80% compared to 2010 levels.

IMO regulates non-GHG emissions too. The most prominent

* Corresponding author.
E-mail address: reini@units.it (M. Reini).

https://doi.org/10.1016/j.apenergy.2017.11.057
Received 23 January 2017; Received in revised form 24 October 2017; Accepted 8 November 2017
Available online 14 November 2017

Nomenclature

%MCR	Maximum Continuous Rating [%]
DWT	Dead Weight Tonnage [ton]
EEDI	Energy Efficiency Design Index [gCO_2/ton/miles]
$E_{el.}$	global electric load [kJ]
EF_h	h-th pollutants Emission factor [$g_{h\text{-th,pollutants}}/kg_{fuel}$]
EF_{ICE_NOx}	ICE's NO_x emission factor [g_{NOx}/kg_{fuel}]
EF_{ICE_SOx}	ICE's SO_x emission factor [g_{SOx}/kg_{fuel}]
E_{fuel}	single cruise time interval fuel energy [kJ]
$E_{fuel,big,ICEs}$	single cruise time interval fuel energy for "big" internal combustion engines [kJ]
$E_{fuel,OFBs}$	single cruise time interval fuel energy for Oil Fired Boilers [kJ]
$E_{fuel,PMs}$	single cruise time interval fuel energy for Prime Movers [kJ]
$E_{fuel,small,ICEs}$	single cruise time interval fuel energy for "small" internal combustion engines [kJ]
$E_{fuel.global}$ (=FE)	global cruise fuel energy [kJ]
$E_{fuel.global\_OFBs}$	global cruise fuel energy for Oil Fired Boilers [kJ]
$E_{fuel.global\_PMs}$	global cruise fuel energy for Prime Movers [kJ]
EL	total electric loads [kW]
EL_prop.	propulsive electric loads [kW]
$E_{TH,ACC.}$	ship global accommodation thermal load [kJ]
$E_{TH,ACC.\text{-}EGBs}$	accommodation thermal loads recovered in Exhaust gas boilers [kJ]
$E_{TH,ACC.\text{-}OFBs}$	accommodation thermal loads supplied by Oil Fired Boilers [kJ]
$E_{TH,FW.}$	ship global thermal load for fresh water production [kJ]
$E_{TH,FW.\text{-}Cogen}$	fresh water production thermal load covered by co-generation [kJ]
$E_{TH,FW.\text{-}OFBs}$	fresh water production thermal load covered by Oil Fired Boilers [kJ]
FE	fuel energy content [kJ]
Fuel	fuel burned [ton]
h	h-th pollutants
k	single cruise time interval
LHV	lower Heating Values [kJ/kg]
npep	non-propulsive electric loads [kW]
PE_h	h-th pollutants emissions [ton]
t	integer Number of ICE type "small" operating in the k-th cruise time interval (0, 1 or 2)
T_g OUT EGB	exhaust gas temperature of EGB [°C]
TIT	GT Turbine Inlet Temperature [°C]
TOT	GT Turbine Outlet Temperature [°C]
u	Integer Number of ICE type "big" operating in the k-th cruise time interval (0, 1 or 2)
η	efficiency
η_{OFB}	oil fired burners efficiency
η_{SCR}	selective catalytic reactor efficiency
$\eta_{scrubber}$	scrubber efficiency
$\eta_{ship,global}$	global ship's energy efficiency

Acronyms

A	Autumn
ACC	Accommodation
COP	Coefficient of Performance
ECA	Emission Controlled Area
EGBs	Exhaust Gas Boilers
ER	Engine Room
FW	Fresh Water
GHG	Green House Gas
GT	Gas Turbine
HFO	Heavy Fuel Oil
ICE	Internal Combustion Engine
ICE_eco	Internal Combustion Engine in "ecofriendly" mode with SCR and scrubber installed on board
IMO	International Maritime Organization
LNG	Liquefied Natural Gas
MARPOL	Maritime Pollution policies
MGO	Marine Gas Oil
MINLP	Mixed Integer Non Linear Programming
MSF	Multi Stage Flash evaporator
MVDC	Medium Voltage Direct Current
OFBs	Oil Fired Burners
ORC	Orgnic Rankine Cycle
PMs	Prime Movers
RPM	Rated Engine Speed
S	Summer
SCR	Selective Catalytic Reactor
SECA	SOx Environmental Controlled Area
SEEMP	Ship Energy Efficiency Management Plan
TH	Tanks Heating
W	Winter

convention, the International Convention for the Prevention of Ship's Pollution (MARPOL), was adopted in 1973 and it targeted several aspects of air pollution. "Annex VI," which was added to the convention in 1997, addresses exhaust gas emissions such as SO_x, NO_x, and particulates [4]. Since NO_x and SO_x emissions have been increasing in these years [5], IMO is setting a lower threshold values. Particular attention has been given to SO_x Emission Controlled Areas (SECAs), regarded as needing an immediate intervention.

MARPOL addresses NO_x pollutants with three "tiers": each tier consisting of a description of limits imposed on ships in relation to ICE engine RPM, as can be seen in Fig. 1. Nowadays only ships travelling in the Emission Controlled Areas (ECAs) have to observe emission limits of Tier III, but starting from January 1st 2016 every ship has to [6].

Regarding SO_x emissions, MARPOL currently sets limits on the fuel sulphur content, differentiating from SECA and not-SECA areas. From 2015, ships travelling in the SECA seas had to use fuel with less than 0.1% sulphur content. Outside SECA areas the limit imposed is set at 3.5%, but starting from 2020 also non-SECA areas will be subjected to a drastic reduction of the sulphur threshold value of the fuel employed at 0.5% (Fig. 2) [6].

As a consequence of the cited limits and regulations, ship-owners will have to adopt new strategies and solutions in order to be IMO compliant. In order to respect *EEDI* and SEEMP, ships have to be more

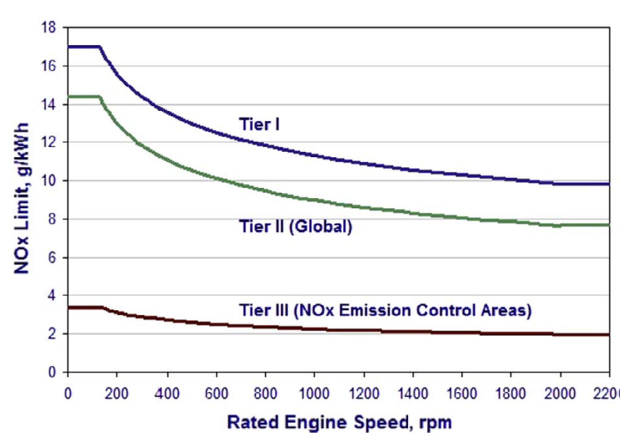

Fig. 1. MARPOL NO_x's threshold limits values [6].