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Modeling and optimization of integrated exhaust gas recirculation and multi-stage waste heat recovery in marine engines

Fotis Kyriakidis, Kim Sørensen*, Shobhana Singh, Thomas Condra

Department of Energy Technology, Aalborg University, Pontoppidanstræde 111, 9220 Aalborg East, Denmark

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ABSTRACT

Waste heat recovery combined with exhaust gas recirculation is a promising technology that can address both the issue of NO_x (nitrogen oxides) reduction and fuel savings by including a pressurized boiler. In the present study, a theoretical optimization of the performance of two different configurations of steam Rankine cycles, with integrated exhaust gas recirculation for a marine diesel engine, is presented. The first configuration employs two pressure levels and the second is configured with three-pressure levels. The models are developed in MATLAB based on the typical data of a large two-stroke marine diesel engine. A turbocharger model together with a blower, a pre-scrubber and a cooler for the exhaust gas recirculation line, are included. The steam turbine, depending on the configuration, is modeled as either a dual or triple pressure level turbine. The condensation and pre-heating process is optimized to utilize the maximum waste heat recovery. The Genetic algorithm and fmincon active-set algorithm are used to optimize the design and operation parameters for the two steam cycles. The optimization aims to find the theoretically optimal combination of the pressure levels and pinch-point temperatures to maximize the power production. Results show that the two-pressure level steam cycle produces 1577 kW of net power; whereas the three-pressure level cycle produces 1641 kW at full load operation. The optimum pressure levels for the two-pressure level configuration are found to be 33.4/4.7 bar_a. For the three-pressure level configuration, the optimum pressure levels are found to be 33.5/10.5/4.7 bar_a. The amount of waste heat recovery from the pressurized boiler is significantly higher than from the main boiler for both cycles. It is, therefore, concluded that the three-pressure level steam cycle (configuration 2) is more efficient than the two pressure level cycle (configuration 1). At the same time, the engine equipped with waste heat recovery with a three-pressure level steam cycle is simpler to operate in Tier II operation. However, the two-pressure level steam cycle is a simpler configuration.

1. Introduction

In recent years, ship owners have been facing stricter directives for lowering emissions from ship engines [1] and at the same time the maritime industry has been put under financial pressure derived from multiple factors. The Tier III directive from International Maritime Organization (IMO) imposes regulations of lower NO_x emissions from ships operating in emission-controlled areas (ECAs) [2]. Furthermore, the world's seaborne trade has been facing multiple challenges with respect to the considerable reduction of chartered ship rates as well as the oversupply of shipping transport capacity [3]. Large container ships, which are the dominant carrier for transporting goods around the world, mostly use two-stroke engines for propulsion. The maximum efficiency of such engines is roughly around 50% [4], which means approximately 50% of the fuel energy did not convert into shaft work and is considered as waste heat. Therefore, designing and optimizing waste heat recovery (WHR) systems that recover waste heat energy and reduce the level of emissions at the same time have become attractive investments for ship owners.

There are a number of means of recovering the waste heat from engines, such as turbocharging [5,6], thermoelectric generators [7], organic Rankine cycles (ORCs) [8–10], exhaust gas recirculation (EGR) [11,12] and exhaust heat exchangers [13–16]. The large volume of exhaust gas leaving the ship engine can be utilized to recover the useful heat. Exhaust gas recirculation (EGR) that recirculates a part of the exhaust gas back to the engine is a promising technology. The installation of an EGR system in a marine engine is the most common and cost-effective solution to fulfill current and future NO_x emission regulations [17–19]. Depending on the engine load, a certain percentage of the exhaust gas is recirculated back to the engine in order to reduce NO_x formation after a significant part of its energy content is recovered in the high pressure boiler (HPB). The HPB operates together with the

* Corresponding author.
E-mail address: kso@et.aau.dk (K. Sørensen).

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Nomenclature

Symbols

$\dot{m}$	mass flow rate, kg/s
η	efficiency, %
h	enthalpy, kJ/kg
P	absolute pressure, bar_a
Q	heat, kW
s	specific entropy, kJ/kg K
T	temperature, K or °C
W	work, kW
$\dot{W}$	power, W/s

Subscripts

HP	high pressure
HPB	high pressure boiler
LP	low pressure
MB	main boiler
bl	blower
cd	condenser
eg	exhaust gas
eV	evaporator
is	isentropic
mix	mixing point
pu	pump
sat	saturated
st	steam turbine

Abbreviations

ECA	Emission Controlled Area
EGR	Exhaust Gas Recirculation
GA	Genetic Algorithm
HP	High Pressure
HPB	High Pressure Boiler
IMO	International Maritime Organization
LP	Low Pressure
MB	Main Boiler
MOGA	Multi-objective Genetic Algorithm
MP	Medium Pressure
MVEM	Mean Value Engine Model
NLPQL	Non-linear Programming by Quadratic Lagrangian
PP	Pinch Point
RC	Rankine Cycle
RSM	Response Surface Method
SFOC	Specific Fuel Oil Consumption
ST	Steam turbine
TC	Turbocharger
WHR	Waste Heat Recovery

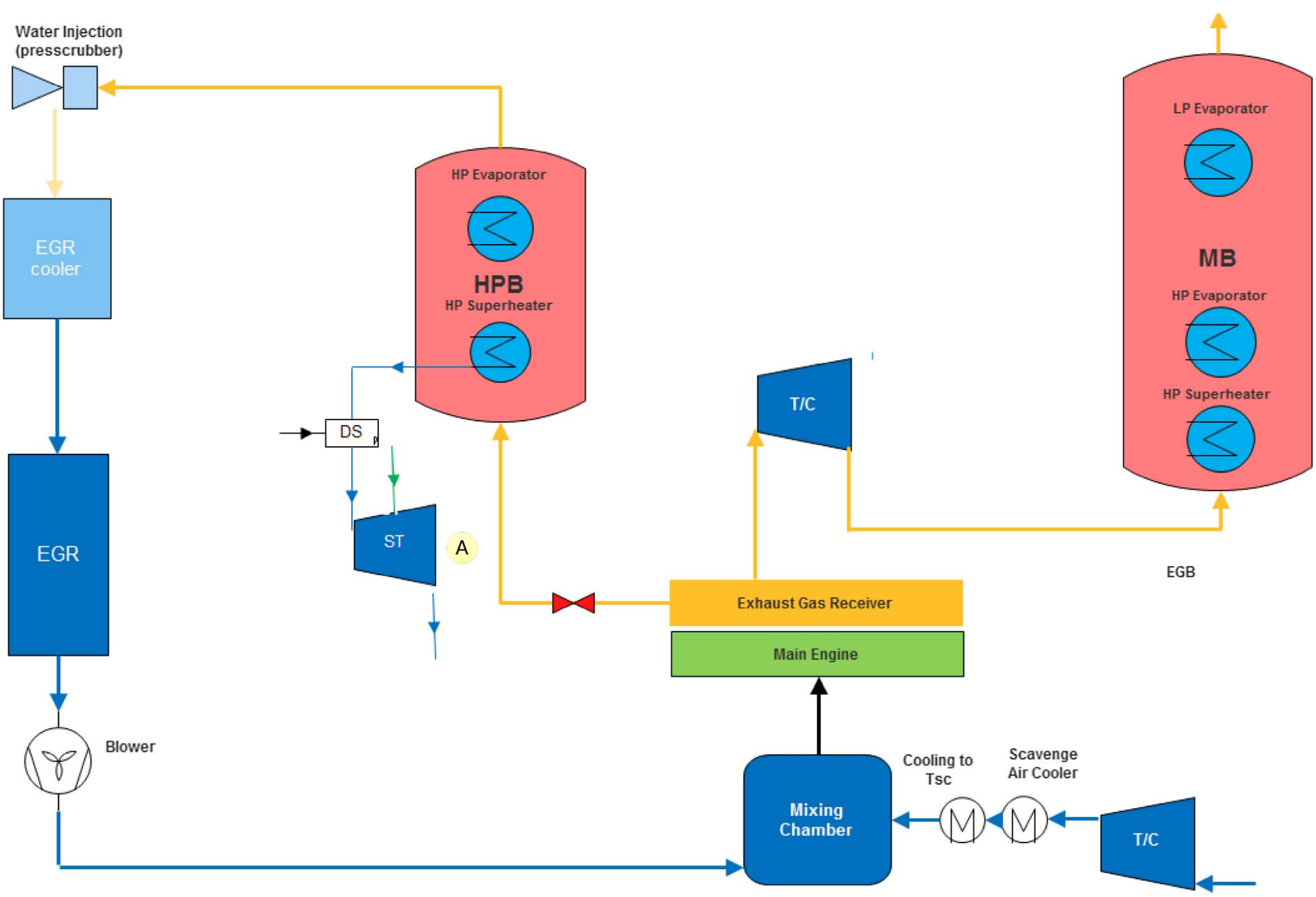

Fig. 1. Schematic process flow diagram of WHR system with EGR.