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Utilizing the scavenge air cooling in improving the performance of marine diesel engine waste heat recovery systems

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ABSTRACT

This paper aims at improving power generation efficiency of marine diesel engine waste heat recovery systems. It presents a novel technique of integrating the heat rejected in the scavenge air cooling process and the exhaust gas in operating a single and dual pressure steam power generation cycles. Moreover, a thermodynamic analysis of proposed systems was performed to identify the optimum operating parameters for achieving an overall efficiency improvement. The analysis considered the exergy destruction in each component and the energy/exergy efficiencies. A performance analysis was conducted to assess applicability and power output at off design conditions. An evaluation of achieved improvements by suggested designs was presented from both an economical and environmental standpoint. In conclusion, results show that, the recommended cycle increased overall efficiency improvement from 2.8% for the conventional system to 5.1%, with an additional power output of 1210 kW, representing 9.7% of the engine's power. Also, exergy efficiency increased significantly by 6.6% when using the presented system. Furthermore, the waste heat recovery system attained a reduction in fuel consumption of 1538 Ton/year, reducing carbon dioxide emission by 4790 Ton/year.

1. Introduction

Maritime transport, an essential contributor to world trade, has risen over the last decades where total transported payload increased from 2.6 billion tons in 1970 to 9.5 billion tons in 2013 [1]. Lately, due to current climate change and CO_2 emissions reduction efforts for environmental protection, a need emerged to enhance diesel engines power generation efficiency using waste heat recovery for energy utilization [1–3]. The IMO estimate the total maritime shipping CO_2 emissions in 2012 at 938 million tons; expected to rise to 250% by 2050 [1]. On the other hand, the new ships' design efficiency has dropped 10% since 1990, due to less hydrodynamic hull design as a need to maximize cargo capacity [4]. Diesel engines currently dominate the field of marine propulsion due to its high thermal efficiency compared to other prime movers as it can exceed 50% [5]. Different waste heat recovery techniques have been used, such as; turbocharging, turbo-compounding, Brayton cycle, Rankine engine cycle and thermoelectric generators (TEG) [6,7]; such techniques have increased engine thermal efficiency from 2% to 20%, depending on system design, quality of energy recovery, component efficiency, and implementation [8].

Accordingly, the ideal technique available for emissions reduction is to utilize the waste heat from fuel combustion that nearly reaches 50% for additional power generation. Hence, an efficient approach to increase power generation efficiency is through employing a power cycle driven by diesel engine waste heat. Main engine exhaust gas energy is the most attractive amongst waste heat sources due to its high mass flow rate and high temperature. This will result in fuel consumption and CO_2 emissions reduction [5,9]. The benefits of applying waste heat recovery (WHR) systems are not only constrained to environmental benefits, but also provide a commercial aspect for shipping companies constituting in a lower annual fuel bill as well as lower emission of CO_2 and NO_X which results in the 'green' ship image improving their position in freight competition [9,10].

The waste heat energy from a diesel engine mainly resides in the exhaust gas where, about 25.4% of fuel energy is still available for use [9]. However, due to adiabatic compression of the scavenge air

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Nomenclature

A	Surface area, m^2
C	Cost, $
C_p	Specific heat capacity, kJ/kg °C
d_f	Fin diameter, m
$\dot{E}$	Exergy rate, kW
e	Specific exergy, kJ/kg
F	Correction factor
g	Gravitational acceleration, m/s^2
HV	Heating value of fuel, kJ/kg °C
H	Heat transfer coefficient, W/m^2 °C
h	Specific enthalpy, kJ/kg
K	Thermal conductivity, W/m °C
l	Fin length, m
m	Mass flow rate, kg/s
Nu_o	Nusselt number
P	Pressure, bar
P_t	Tube pitch, m
Pr	Prandtl number
$\dot{Q}$	Heat transfer rate, kW
Re	Reynolds number
R_{th}	Thermal resistance, °C/W
S	Fin spacing, m
T	Temperature, °C
U_o	Overall heat transfer coefficient, W/m^2 °C
$\dot{W}$	Power input or output, kW

Greek symbol

δ	Fin thickness
η	Efficiency
ψ	Exergy efficiency
λ	Exergy destruction ratio
λ_c	Taylor instability

Subscripts

0	Dead state
cogen	Cogeneration
cond	Condenser
dest	Destruction
e	Exit
eco	Economizer
engine	Engine related parameter
eva	Evaporator
f	Fuel
g	Exhaust gas
heat	Heat added
i	Inlet
OV	Overall
PP	Pump
Pinch	Pinch point
rej	Heat rejected
s	Water-steam
SG	Steam generator
SU	Superheater
Turb	Turbine
WH	Waste heat

Acronyms

CEPCI	Chemical engineering plant cost index
HFO	Heavy fuel oil
HP	High pressure
IMO	International Maritime Organization
LP	Low pressure
ORC	Organic Rankine cycle
RPM	Revolution per minute
WHR	Waste heat recovery
WHRS	Waste heat recovery system

in the turbocharger; an increase in temperature occurs. Hence, cooling the scavenge air is required to enhance the engine volumetric efficiency. The reduction of scavenge air temperature is done by the charge air cooler, where a significant amount of fuel energy (nearly 14.1%) is wasted [9]. A promising contributor for waste heat recovery applications other than exhaust gas is heat available in the scavenge air which can be used to operate a Rankine cycle. The scavenge air offers nearly the same mass flow rate as the exhaust gas and a relatively high temperature. Additionally, the exhaust gas has a minimum temperature that needs to be avoided; to evade its dew point temperature caused by high HFO sulfur content. The scavenge air is not associated with this technical problem, thus its temperature can be decreased without interrupting engine's performance, which offers full heat utilization and enhanced management of waste heat sources.

Numerous scientific studies targeted improvement in power generation efficiency and emission reduction of diesel engines by mainly using waste heat from exhaust gas for additional power generation. In reference to these, different approaches and systems were considered for achieving such objective. Macian et al. [11] introduced a methodology for design optimization of WHR bottoming Rankine cycle from heavy-duty diesel engines. The methodology was based on considering different heating and working fluids. Bonilla et al. [12] discussed the potential of different WHR technologies to use waste heat from industry located in Basque Country in Spain. Zheshu ma et al. [13] performed an analysis for WHR from the exhaust of a container ship's diesel engine at variable engine load and exhaust gas boiler operating pressure. Bari and Hossain [14] studied numerically the effect of using a shell and tube heat exchanger in WHR from a diesel engine using a CFD program. The effect of different parameters such as shell diameter, number of shells, and tubes diameter have been studied to obtain the optimum WHR unit performance. Butcher and Reddy [15] presented a performance analysis for a WHRS operating on a Rankine cycle. The main focus was on the effect of pinch point on the power output, second law efficiency and outlet temperature of exhaust gas. Various cogeneration schemes were studied in previous literature where Abusoglu and Kanoglu [16] performed a first and second law performance analysis of a diesel engine powered cogeneration system. The study was based on characteristics of an existing diesel powered cogeneration plant in which thermodynamic performance and efficiency were studied at full engine-load range. Furthermore, Yilmaz [17] analyzed the performance of a cogeneration system operating on a reversible Carnot cycle while investigating variable operating conditions. It was concluded that all performance criteria increases when the ratio between temperature of heating fluid and cooling fluid increases. Different tri-generation systems were presented including a novel tri-generation scheme that was introduced by Mohan et al. [18]. Based on the exhaust supplied by the gas turbine operating Al-Hamra power plant. The tri-generation involved power generation by a steam Rankine cycle, water treatment by an air gap