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Waste heat recovery from diesel engines based on Organic Rankine Cycle

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HIGHLIGHTS

- Waste heat recovery from diesel engines by Organic Rankine Cycle is mentioned.
- Working fluids are aggregated and classified to meet the requirement of each system.
- Thermodynamic and economic analysis of engine-Organic Rankine Cycle is reported.
- Main components of engine-Organic Rankine Cycle are presented for each selection.

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ABSTRACT

Diesel engines play an important role in transport, small medium-size stationary generator, agriculture, as well as generate the biggest CO_2 emission and environmental pollution. However, in fact, more than 60% of energy from air-fuel mixture combustion is not used to produce the mechanical work and is released into the environment as waste heat. Therefore, the conversion of waste heat from diesel engines into useful work along with engine development is to improve the efficiency and thermal management strategies. This review paper is to aim at giving an overview of the latest technology of the engine-Organic Rankine Cycle system in the applications of waste heat recovery from the heat sources with different temperatures, with particular concentration on diesel engines. About 25% of maximum thermal efficiency is found from the literature as using conventional standalone engine-Organic Rankine Cycle system. However, about 90% of overall thermal efficiency is reported from combined recovery system of waste heat sources. Moreover, the reports of working fluid selection, thermodynamic analysis, main components selection, and Organic Rankine Cycle system design/architecture based on the technology, economic and environmental aspects are gathered and presented to give the most suitable design point for the selected applications.

1. Introduction

Nowadays, a modern society usually desires to have the non-polluted fresh air, and to use the fuel sources efficiently. However, in daily life, the internal combustion engines, especially diesel engines (DE), are widely used in transport sectors, agricultural production, and stationary generator. The innovation for continuous development of these engines is to reduce the fuel consumption and emissions, and to increase the thermal efficiency. In 2014, around eight billion metric tons of CO_2, equivalent 24% of total greenhouse gas (GHG) emissions, which were generated by the transport sector, was reported by the US EPA [1]. The key task aiming to reduce the toxic pollutants has been really challenging to the reduction of fuel consumption without modifying the driving cycle. The rapid increase in CO_2 emission promotes more and more advanced and perfect technologies [2]. Apart from the urgent requirements of low cost (USD/g saved CO_2) and minor modifications, the powertrain optimization and engine efficiency improvement have been not yet solved, the solutions of thermal management [3], and waste heat recovery have been mentioned because the energy in the waste heat is almost equal to the mechanical energy [4]. Thus, it is compulsory for the engine researchers and manufacturers to look for a way of increasing the efficient use of energy compared to the challenges of emission reduction [5]. To achieve this purpose, there are two classifications including engine-improved-technologies and engine-bottoming-technologies [6].

Several examples of engine technologies such as combustion improvement, specially shaped combustion chambers, advanced injection solutions [7], reduction of engine friction and powertrain, reasonable use of lubricating oil or coolants, reduction of engine mass by light alloys were conducted with broad and in-depth studies. Besides,

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Nomenclature

A	heat transfer area
AT	after-treatment
C	compressor
CA	compressed air
CAC	charge air cooler
CFC	chlorofluorocarbon
CRF	capital recovery factor
CO	carbon monoxide
CO_2	carbon dioxide
DE	diesel engine
DEE	di-ethyl-ether
DEF	diesel exhaust fluid
DME	di-methyl-ether
DOC	diesel oxidation catalyst
DPF	diesel particulate filters
DWF	dry working fluid
EG	exhaust gas
EGR	exhaust gas recirculation
EPC	electricity production cost
Ex	exergy
EXP	expander
g_e	specific fuel consumption
GWP	global warming potential
HC	hydrocarbons
HCCI	homogenous charge compression ignition
HCFC	hydrochlorofluorocarbon
HDDE	heavy duty diesel engine
HD-REHER	heavy duty roots expander heat energy recovery
HE	heat exchanger
HFC	hydrofluorocarbon
HFE	hydrofluoroether
HFO	hydrofluoroolefine
HPC	high-pressure compressor
HPT	high-pressure turbine
HT	high temperature
HP-CAC	high-pressure charge air cooler
ICE	internal combustion engine
IMO	international maritime organization
IWF	isentropic working fluid
LDDE	light duty diesel engines
LNG	liquefied natural gas
LNT	lean NO_x traps
LP-CAC	low pressure charge air cooler
LPC	low pressure compressor
LPT	low pressure turbine
LT	low temperature
LTC	low temperature combustion
NO_x	nitric oxide
Nu	nusselt number
RCCI	reactivity controlled compression ignition
Re	reynolds number
ODP	ozone depletion potential
ORC	Organic Rankine Cycles
P_c	critical pressure
PFC	perfluorocarbon
PM	particular matter
PN	particulate number
PPCI	premixed charge compression ignition
Pr	Prandl number
SCR	selective catalytic reduction
SF	safety factor
SO_x	sulphur oxide
T	turbine
T_{boi}	boiling temperature
T_c	critical temperature
T_{ex}	exhaust gas temperature
TE	thermal efficiency
TEG	thermo-electric generators
TIC	total investment cost
WF	working fluid
WH	waste heat
WWF	wet working fluid

advanced turbocharging technologies, Diesel Oxidation Catalysts (DOC), Diesel Particulate Filters (DPF), Exhaust Gas Recirculation (EGR), Selective Catalytic Reduction (SCR) [8], Lean NO_x Traps (LNT), advanced Miller timing [9], Organic Rankine Cycles (ORC) have been applied to recover waste heat [10], and reduce emissions [11] of the ICE. Turbo-compounding [12], Thermo-Electric Generators (TEG) [13], and advanced tires [14] are also considered as technologies for engine-bottoming without meddling the engine structure.

Recently, several researchers have reported their study results on fuel-cell [15], hybrid, hybrid-electrical or mild hybrid-engine [16], recovery system of vehicle kinetic energy from brake or flywheels [17]. Many advanced combustion technologies such as Homogenous Charge Compression Ignition (HCCI) [18], Premixed Charge Compression Ignition (PCCI) [19], Reactivity Controlled Compression Ignition (RCCI) [20], low-temperature combustion engine (LTC) [21] were also studied and developed. Considerations and interests have been given to a resumption of investigation into alternative fuels such as LNG (Liquefied Natural Gas) [22], dimethyl ether (DME), diethyl ether (DEE) [23], n-alkanes, biogas [24], biodiesel, bio-oils [25] or fuel additives [26] aiming at reducing the emissions for diesel engines, although these fuels were almost not considered using for diesel engines previously. The reduction tendency of emission substances including particular matter (PM), particulate number (PN), unburned hydrocarbons (HC), smoke, carbon monoxide (CO), thermal efficiency (TE) and power were reported by [27]. Otherwise, a slight increase in specific fuel consumption (g_e), exhaust gas temperature (T_{ex}), emissions of nitric oxide (NO_x) of diesel engines running on B100 (100% of biodiesel) or fossil diesel fuel-biodiesel blends were presented by [28]. A dramatic reduction in soot emission as using DME was also denoted by [29].

The waste heat of exhaust gas from engines containing around 30–35% of total energy from air-fuel mixture combustion could be recovered and utilized by using several novel solutions or devices such as TEG [30], compressor-exhaust gas turbine group based on some typical cycles like Kalina, Rankine [31], ORC system [32] or Brayton [33]. Although the TEG was the simplest system and technology, its efficiency was also the lowest (< 4%), thus it could not meet the requirements of bottoming-cycle as unavailable thermoelectric materials [34]. Meanwhile, the efficiency of the turbo-compound system under certain situations was8%higher than that of TEG, but it could not recover the waste heat (WH) from low-temperature sources [35].

In fact, ORC was shown exceptional and effective features for the possibility at both high temperatures (exhaust gas, EG) [36], and low temperature (cooling water, cooling oil, Charge Air Cooler (CAC), lubricating oil) [37]. The positive characteristics of ORC-based WH recovery system were presented that small volume, light weight, low cost, no invasive property compared with turbo-compounding, energy efficiency improvement, environmental protection [38] or typical applications like seawater desalination and electricity production [39]. The viewpoints about eco-technical aspects, the applicability in the market of ORC technologies were also given a countenance by Velez et al. [40]. Much experimental and theoretical in-depth research aiming at implementing the application of ORC technologies has been conducted