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Technical and economic analyses of waste heat energy recovery from internal combustion engines by the Organic Rankine Cycle

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ABSTRACT

Due to its low complexity, the Organic Rankine Cycle can be considered as one of the best options for waste heat recovery at low (at most 230 °C) and average (230–650 °C) temperatures. A technical and economic study has been conducted in this work in order to increase the efficiency of electricity production, and thus reduce fuel consumption and polluting gas emission from Internal Combustion Engines. For such a purpose, two Organic Rankine Cycle sets were suggested. The first one is facing deployment in water shortage areas (Organic Rankine Cycle using a cooling tower for the condensing system) and another one with the water supply condenser being made by the urban water net. Both simulated systems were able to increase electricity production by almost 20% when toluene was the working fluid. The economic analysis was based on the Engineering Chemical Cost Plant Index model which showed that the financial return from the implementation of the Organic Rankine Cycle system can occur in six years. Thus, it is noted that the Organic Rankine Cycle system can be installed in areas where there is no water abundance and without much yield loss. Despite being an appropriate technological solution to recover the waste heat present in Internal Combustion Engines exhaust gas, it still lacks in governmental incentives for a wide application of the system.

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1. Introduction

Due to current environmental protection policies, technological advances are on the rise regarding energy efficiency increase. Among possible solutions to this issue, the ORC is the most used [1]. According to [2], gases such as carbon dioxide and sulphur dioxide may have their emissions reduced with ORC implementation, since the cycle theoretically does not require additional fuel for operation. It was also mentioned by Quoilin et al. [3] and by other authors, thus there is a higher energy production for the same amount of pollutants.

According to [4], the ORC has been considered the main procedure to convert heat from low-temperature sources into electricity. There are many possible ORC heat sources, e.g. exhaust gas from biomass combustion (400 °C), which was used as heat source for the current ORC system [5]. In some cases, the exhaust gas from biomass combustion has been used, but by using heat from sunlight as support, thus obtaining a trigeneration power plant [6]. The use of geothermal energy has also been studied (130–170 °C) as heat source for an ORC plant which obtained a 55% improvement in the net electricity output [7]. Another heat source for an ORC power plant is ICEs exhaust gases, as it is the aim of this study.

Heat released in the ICE exhaust gas from thermal power plants correspond to more than half of the calorific power provided to them. This number is equivalent to approximately 55% of the heat which is possible to be removed from the fuel [8]. Pollutants are released along with this reject (carbon dioxide – CO_2, sulphur oxide – SO_x, nitrogen oxide – NO_x, etc.), which are harmful to the environment. The heat released is classified among three gas temperature categories: low (at most 230 °C), average (230–650 °C), and high (up to 650 °C). Since ORC have a low system complexity, it can be considered as one of the best options for employment of low and medium temperature tailings, such as in the case of ICEs' exhaust gas [9].

According to [10], the ICE heat recovery system is targeted in most research papers regarding the ORC cycle subject. This organic cycle shows an efficiency between 7 and 10%, providing fuel economy of around 10%, in other words, it is aimed at producing the same amount of energy from the ICE without the ORC, the plant was equipped with the organic power system studied by Sprouse and Depcik [10], which requires about 10% less fuel. Then, it allows the system to achieve payback in the short-to-medium term (2–5 years), depending on the plant size.

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Nomenclature

$\dot{m}$	mass flow [kg/s]
A	annuity
AR	area [m^2]
B	type equipment (or device) constant
C	investment cost/sorting equipment constant (pressure based)
Cost	real total investment cost
$\dot{E}$	energy [W]
e	specific exergy [J/kg]
F	factor
f	factor cost with operation, maintenance, and installation insurance
G	financial gain [R$/kW h or US$/kW h]
h	specific enthalpy [J/kg]
H	working hours during the year [h/year]
i	annual interest rate
K	correlation between equipment and ability (or size) constant
PP	pinch point
P	pressure [Pa]
Price	selling price of electricity
Q	heat [J]
s	specific entropy [J/(kg·K)]
T	temperature [K]
t	plant operating time [year]
V	volume [m^3]
W	power [W]

Abbreviations

ANEEL	Brazilian Electricity Regulatory Agency (Agência Nacional de Energia Elétrica)
CEPCI	Chemical Engineering Plant Cost Index
EPC	Electricity Production Cost
ICE	Internal Combustion Engine
ORC	Organic Rankine Cycle
PPI	Producer Price Indexes
PRSV	Penge Robinson – Stryjeke – Vera

Greek letters

Δ	variation
η	efficiency

Subscriptions

0	reference
2001	2001 year
w	condensation water
pu	pump
BM	module or equipment
cond	condenser
i	input
evap	evaporator
f	working fluid
gas	exhaust gas
I	thermodynamics first law
II	thermodynamics second law
net	net or useful
M	material
P	pressure
p	ambient pressure
rev	reversible
o	output
Sep/2014	2014 september
sup	superheater
t	turbine
tow	cooling tower
total	total value

Superscript

0	standard

Authors from Ref. [11] performed the simulation with an internal combustion diesel engine and used only R245fa as a working fluid, for both primary and secondary ORCs. Operating range varied from 900 to 1900 rpm and the load reached 247 kW. Primary and secondary ORC systems produced 10 kW and 17.85 kW of energy at the ideal operational point, respectively. Heat recovery efficiency was 5.4% for the integrated system. A 13% fuel economy was also observed, and it might increase if the engine operates under medium and high loading conditions.

Another heat recovery option based on ORC technology was analyzed under Ref. [12], in which approximately one third of the total fuel energy was released by the exhaust system as a 590 °C gas. ICE itself produced 235.8 kW of power and had 943 kg/h fuel consumption. These authors analyzed 20 different types of working fluids (moist and isentropic), system thermal efficiency, electrical energy produced, and electricity production cost, among other parameters. The system consisted of a combined cycle diesel – ORC. The exhaust gas was made up of: 15.1% CO_2, 5.37% H_2O (water), 73.03% N_2 (nitrogen), and 6.49% O_2 (oxygen), which passed through three heat exchangers that supplied thermal energy to the organic fluid to generate the required electricity. Fluids which best met the authors' requirements were: R141b, R123, and R245fa, in this order. These fluids presented the highest values for thermal efficiency and power produced, as well as the lowest prices for electricity produced, 16.6–13.3% for R141b, 60–49 kJ/kg for R123, and 0.3–0.35$/kW h for R245f, respectively.

Efficiency is between 30 and 40% for diesel fueled ICE (Diesel Cycle). The rest of the energy is dropped by different paths: exhaust gases, cooling system, lubrication system, and radiation; in which only the first three are viable for energy recovery. However, in order to take advantage of the ORC technology [13], there are some restrictions as mentioned below:

- Maximum and minimum temperatures which the working fluid can reach, without extra fuel burning, are equivalent to the heat source and the condensation fluid, respectively;
- The minimum temperature difference within the evaporator, between the organic fluid and the heat source, must be greater than 10 K to ensure heat transfer;
- If there is one superheater in the system, the maximum temperature that can be reached by the organic fluid should not promote its decomposition;
- In order to avoid leaks from the condenser, the maximum pressure at the equipment entrance should be of approximately 1 bar. A maximum of 35 bar must be set for the evaporator, otherwise equipment costs for the system would increase above the limit. These values depend on the ORC system size.
- The fluid title at the end of expansion must be greater than or equal to 0.9. This would prevent formation of droplets on turbine blades, which could damage them. In addition, in order to preserve the expansion device, the pressure ratio inside the equipment must not exceed a value of 10.

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