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Research Paper

# Cascade utilization of exhaust gas and jacket water waste heat from an Internal Combustion Engine by a single loop Organic Rankine Cycle system

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## HIGHLIGHTS

- A single loop ORC is proposed to recover the waste heat of exhaust and jacket water.
- Energy analysis are conducted for establish the mathematical model.
- System performance based on three working fluids is evaluated.
- Heat exchanger performance under different part-load conditions is validated.

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## ABSTRACT

This work presents the methodology of Internal Combustion Engine (ICE) waste heat recovery by an Organic Rankine Cycle (ORC) system. Though jacket waster heat is usually ignored due to its low temperature, the contained thermal energy is roughly the same as that of exhaust gas from an ICE with certain rated loads, which makes the recovery of this energy a subject of interest. The cascade utilization of exhaust gas and jacket water heat by single loop ORC systems is here investigated and compared with a system which only recovers exhaust gas heat. System performances are evaluated through thermal efficiency, waste heat recovery efficiency and improvement of ICE efficiency. Then the calculated heat exchanger capacity is validated under different ICE load conditions. Results show that the highest thermal efficiency (21.82%) can be reached by using R141b. The full recovery of exhaust gas heat yields the highest waste heat recovery efficiency (10.19%) and improvement of the ICE efficiency (14.23%). Preheaters and evaporators operated at high evaporating pressure may have a heat exchanger capacity which is lower than the calculated heat amount under ICE part-load conditions. It is therefore essential to validate the calculated heat exchanger capacity in real operating conditions.

## 1. Introduction

Internal Combustion Engines (ICEs) are broadly used as the prime mover in power units. However, only about 40% of the energy deriving from fuel combustion can be converted into useful work, and the remaining part is generally dismissed into the environment in the form of waste heat, which is mainly dispersed in the exhaust gas and in the jacket water. The exhaust gas temperature mainly depends on the rated power of the ICE while the jacket water temperature is virtually the same for every engine. Usually the exhaust gas temperature is above 673 K [1], while for the jacket water the outlet temperature is between 363 K and 368 K and the return temperature is between 343 K and 358 K [2]. It is generally acknowledged that the recovery of waste heat from the exhaust gas and the jacket water provides valuable opportunities, which can significantly enhance the engine efficiency and bring significant economic and environmental benefits [3].

In Combined Cooling, Heating and Power (CCHP) systems, an ICE with rated power ranging from 500 to 2000 kW is normally adopted to generate electricity due to its running stability and low initial investment costs [4,5]. Meanwhile, the large amount of waste heat from ICEs is generally employed to meet the heating and cooling needs from users. Unfortunately, when CCHP systems are operated in transition seasons like spring and autumn, the production of thermal energy always exceeds the heating and cooling demands, thus resulting in a low energy efficiency. Organic Rankine Cycle (ORC) systems have been widely proposed as bottoming

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**Nomenclature**

| | |
|---|---|
| A | area [$m^2$] |
| c | specific heat [kJ/kg K] |
| de | equivalent diameter [m] |
| F | total heat transfer area of cross section [$m^2$] |
| h | enthalpy [kJ/kg] |
| K | the overall heat transfer coefficient [$W/m^2$ K] |
| m | mass flow rate [kg/s] |
| $Nu_f$ | Nusselt number [–] |
| *Pr* | Prandtl number [–] |
| q | heat flux density [$W/m^2$] |
| Q | thermal energy [kW] |
| r | latent heat [kJ/kg] |
| R | fouling resistance [$m^2$ K/W] |
| *Re* | Reynolds number [–] |
| T | temperature [K] |
| u | velocity [m/s] |
| W | power [kW] |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | convective heat transfer coefficient [$W/m^2$ K] |
| $\delta_p$ | thickness of the plate [m] |
| $\eta$ | efficiency [–] |
| $\lambda$ | thermal conductivity [W/m K] |
| $\mu$ | viscosity [Pa s] |
| $\rho$ | density [$kg/m^3$] |
| $\sigma$ | surface tension [N/m] |

*Subscripts*

| | |
|---|---|
| ab | absorbed heat |
| c | channel |
| Crit | critical |
| e | electricity |
| ex | exhaust gas |
| exp | expander |
| f | fluid |
| fu | fuel |
| g | generator |
| in | inlet |
| jw | jacket water |
| me | mechanical efficiency |
| out | outlet |
| p | pinch point |
| pu | pump |
| re | recovery efficiency |
| s | saturated vapor |
| th | thermal efficiency |
| the | theoretical value |
| tr | transferred heat |
| w | wall |

power cycles to recover waste heat from ICEs and consequently improve the comprehensive performance of CCHP systems in transition seasons [6–8].

Exhaust gas is usually considered as a suitable heat source for ORCs [9]. Therefore, a number of research works have been published which focus on heat recovery from the exhaust gas of ICEs because of its high temperature and large amount of power. Tian et al. [10] have evaluated 20 candidate working fluids with different critical temperature, demonstrating that R141b, R123 and R245fa showed a better performance as working fluids. Yang et al. [11] studied the impact of superheating on the performance of ORC systems for the recovery of exhaust heat from diesel engines. Their results showed that the increasing degree of superheating can reduce the required working fluid mass flow rate, and thus decrease the risk of environmental pollution. Koelsch et al. [12] investigated methanol, toluene and Solkatherm SES36 as potential working fluids for ORCs. Shu et al. [13] investigated the performance of ORCs by using blends of hydrocarbons and refrigerant retardants as working fluids. Bombarda et al. [14] compared the thermodynamic performances of a Kalina cycle and an ORC cycle to recover exhaust gas heat from diesel engines. Since the obtained useful powers from both cycles were equal, the ORC cycle was recommended because of its scheme simplicity.

On the contrary, the waste heat of the jacket water attracts less attention due to its low temperature. Fig. 1 displays the trends of thermal energy of exhaust gas and jacket water from a series of widely employed ICEs in industry, as a function of rated power in a range from 125 kW to 2000 kW [15]. The discharged thermal energy amount is approximately the same for exhaust gas and jacket water from ICEs with rated power between 500 kW and 2000 kW, which is the most suitable range for CCHP systems. This fact clearly indicates that the massive amount of thermal energy from the jacket water is also potentially valuable for recovery by ORCs [16]. Peris et al. [2] investigated six different configurations of ORCs to recover jacket water heat in ICEs, showing that the Double Regenerative ORC using SES36 as a working fluid can achieve the maximum net efficiency of 7.15%. Yang et al. [17] investigated the suitable working fluids and operating temperatures for the recovery of jacket water waste heat of large marine diesel engines by an ORC. R600a was identified as the working fluid which yields the best performance at evaporation temperatures ranging from 331 K to 341 K and condensation temperatures ranging from 308 K to 318 K.

However, using ORC techniques to merely recover jacket water heat is not a realistic goal at present, since it can obtain limited improvements in the ICE efficiency at the expense of dramatically increasing the investment cost. Other studies concerning the heat recovery of the jacket water often suggested the cascade utilization of energy from exhaust gas and jacket water in order to further improve the efficiency of ICE due to their different temperatures [18]. He et al. [19] proposed a combined thermodynamic cycle which employed an ORC to recover waste heat from the high-temperature exhaust gas and a Kalina cycle to recover waste heat from the low-temperature jacket water. Compared with traditional cycle configurations, a larger amount of waste heat can be recovered by this combined cycle. Yang et al. [20] examined the performance of a dual loop ORC consisting of two systems with different temperature levels for the separate recovery of exhaust energy and waste heat from the coolant system. Their results showed that the maximum waste heat recovery efficiency can reach 5.4% by using R245fa as working fluid. Shu et al. [21] conducted an energy and exergy analysis of a dual-loop ORC for the recovery of waste heat from the exhaust and the engine coolant. Their results showed that the highest performance is obtained with R1234yf as a working fluid, by setting the evaporating temperature of the high temperature and low temperature loops to 570 K and 343 K, respectively. However, the complex configuration and the high investment costs pose limitations to the application of this system in the fields of industry and manufacture. The combined cycle or dual loop cycle can be expected to achieve a higher degree of waste heat recovery