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# Thermodynamic analysis of an in-cylinder waste heat recovery system for internal combustion engines

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ABSTRACT

In this paper, an in-cylinder waste heat recovery system especially for turbocharged engines is proposed to improve the thermal efficiencies of internal combustion engines. Simplified recovery processes can be described as follows: superheated steam generated by engine waste heat is injected into the pipe before the turbine to increase the boost pressure of the fresh air; intake valve close timing is adjusted to control the amount of fresh air as the original level, and thus the higher pressure charged air expands in the intake stroke and transfers the pressure energy directly to the crankshaft. In this way, the increased turbine output by the pre-turbine steam injection is finally recovered in the cylinder, which is different from the traditional Rankine cycle. The whole energy transfer processes are studied with thermodynamic analyses and numerical simulations. The results show that the mass flow rate of the injected steam has the biggest influence on the energy transfer processes followed by the temperature of the injected steam. With this in-cylinder waste heat recovery system, the fuel economy of a selected turbocharged diesel engine can be improved by 3.2% at the rated operating point when the injected mass flow ratio is set to be 0.1.



## 1. Introduction

With the problems of energy and environment becoming more and more serious, depending solely on improving the combustion process in the cylinder cannot fulfill people's higher requirement for the thermal efficiency of the ICE (internal combustion engine). Since more than half of the fuel energy is taken away by the exhaust gas and cooling water, WHR (waste heat recovery) technologies show great potentialities of improving the fuel economy and reducing the $CO_2$ emissions.

There are mainly three kinds of WHR techniques including the thermoelectrical generator, compounding turbo and Rankine cycle, which have their own advantages and disadvantages. Hussain et al. [1] and Yu et al. [2] conducted simulation and experimental researches on exhaust heat recovery with thermoelectric generators, which demonstrated the potential of this technique for automotive industry. Hountalas et al. [3] examined effects of the mechanical and electrical compounding turbo on the fuel economy, power output, and pollutant emissions. Arias et al. [4] and Boretti [5] showed interests in applying the Rankine cycle on hybrid cars due to the flexible energy management system. Ringler et al. [6] confirmed the Rankine cycle can provide an additional power output of about 10% on a gasoline engine. Briggs et al. [7] demonstrated a thermal efficiency of 45% on a light duty diesel engine with the organic Rankine cycle. Yu et al. [8] indicated that the organic Rankine cycle can improve the thermal efficiency of a diesel engine by 6.1% with the exhaust gas and jacket water as waste heat sources. Gao et al. [9] proposed that the Rankine cycle system with a reciprocating piston expander can increase the engine power output by 12% when a high speed turbocharged diesel engine operates at 80 kW/2590 r/min. In general, the thermoelectrical generator has the advantages of free maintenance, silent operation, high reliability and involving no moving and complex mechanical parts, while its high cost of thermoelectrical materials and the low recovery efficiency (normally lower than 4%) restrict the application on ICEs [10]. The compounding turbo transfers the surplus pressure energy of the exhaust gas into mechanical power, which adds the pumping loss and has limited operating conditions [11]. For the Rankine cycle, a potential fuel economy improvement around 10% has been demonstrated by many manufacturers [12], but its high cost, big size and complicated configuration still need to be improved.

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**Nomenclature**

| | |
|---|---|
| $cp$ | specific heat capacity [kJ/kg K] |
| $D$ | Mass flow ratio [−] |
| $h$ | specific enthalpy [kJ/kg] |
| $\dot{I}$ | exergy destruction rate [kW] |
| $\dot{m}$ | mass flow rate [kg/s] |
| $P$ | pressure [bar] |
| $\dot{Q}$ | heat flow [kW] |
| $s$ | specific entropy [kJ/kg K] |
| $T$ | temperature [K] |
| $\Delta T$ | temperature difference [K] |
| $\dot{W}$ | power [kW] |
| $x$ | mole ratio [−] |

*Greek symbols*

| | |
|---|---|
| $\pi$ | pressure ratio [−] |
| $\eta$ | efficiency [%] |

*Subscripts*

| | |
|---|---|
| $c$ | compressor |
| exh | exhaust gas |
| eva | evaporation |
| max | maximum |
| $p$ | pump |
| $t$ | turbine |
| $w$ | water |
| 0–5, 0′–6′ | state points in waste heat recovery system |

*Abbreviation*

| | |
|---|---|
| BMEP | brake mean effective pressure |
| BSFC | brake specific fuel consumption |
| CA | crank angle |
| IVC | intake valve close |
| NOx | nitride oxides |

Different from those typical WHR techniques, many new recovery strategies have been reported in recent years [13–20]. Conklin and Szybist [13] presented a concept of adding two additional strokes to the Otto or Diesel engine cycle to increase the fuel efficiency. The research results showed that the two-stroke steam cycle can add an additional power stroke by recovering waste heat from the engine coolant and exhaust gas with water injection and expansion. Fu et al. [14] designed an open steam power cycle for exhaust gas energy recovery on a four-cylinder naturally aspirated engine with the last cylinder used for steam expansion, which made the Otto or Diesel cycle couple with the open Rankine cycle on ICEs. The outcomes indicated that the maximum bottoming cycle power can reach 19.2 kW and the thermal efficiency can be improved by 6.3% at 6000 r/min. Serrano et al. [15] performed a theoretical investigation on coupling the Rankine cycle WHR system with a two-stage turbocharged diesel engine. New alternative solutions that the Rankine cycle supplied the recovered energy directly to the low pressure compressor were studied, and the results showed that those alternative layouts produce lower benefits in fuel consumption compared to that obtained in the conventional Rankine cycle. Fu et al. [16] continued to propose a steam turbocharging system to boost the engine intake pressure instead of the traditional exhaust turbocharging system. The results indicated that the engine power can be improved by as much as 7.2%, and thermal efficiencies can be improved by 2 percent points or more in the high speed range. Liu et al. [17]compared various means of bottoming cycles for exhaust gas energy recovery including direct secondary expansion, over-heated and standard Rankine steam cycles and Brayton cycles with or without regeneration. Shu et al. [18] analyzed the combined thermoelectric generator and organic Rankine cycle used in exhaust heat recovery of the ICE theoretically. Yamada and Mohamad [19] proposed an open Rankine cycle subsystem on a hydrogen ICE which produces nearly three times more water than a conventional engine. He et al. [20] demonstrated more waste heat can be recovered with combined thermodynamic cycles, which consist of an organic Rankine cycle for recovering waste heat of lubricant and exhaust gas and a Kalina cycle for recovering waste heat of cooling water.

To transfer the Rankine cycle expander output into useful power, there are two typical alternatives including directly linking the expander shaft with the crankshaft and converting the mechanical power into electrical power [11]. Both of those two alternatives are not easy to be achieved, which has become a main obstacle for the Rankine cycle utilization. Thus Serrano et al. [15] and Fu et al. [16] tried to connected the Rankine cycle turbine shaft directly to the compressor shaft and replaced the traditional turbocharging system to boost the charge air as mentioned above.

In this paper, a novel concept is proposed to reintroduce the waste heat of the exhaust gas into the cylinder with the pre-turbine steam injection and the adjustment of IVC (intake valve close) timing. The main purpose of this study is to verify the feasibility and the potential benefits of this new in-cylinder WHR system. The structure and principles of the new system are presented first, and then the whole recovery system is divided into two subsystems for theoretical analyses. Thermodynamic models based on the first and second laws of thermodynamics are built in Matlab software to analyze the energy and exergy transfer processes and effects of injected parameters on the recovery efficiency. The main operating parameters of a selected diesel engine equipped with this new WHR system are evaluated under full load operating conditions with a calibrated model in GT-power software.

## 2. System description and thermodynamic analysis

### 2.1. System description

Fig. 1 shows the layout of the in-cylinder WHR system for a turbocharged engine. The main working processes can be described as follows. As the working fluid, water is compressed to a certain

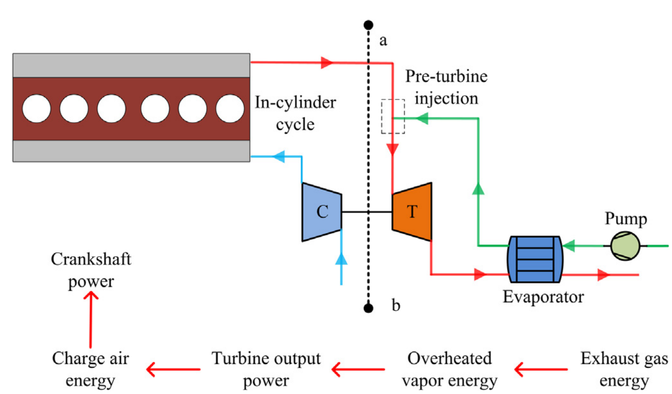


**Fig. 1.** Layout and principle of the in-cylinder waste heat recovery system.