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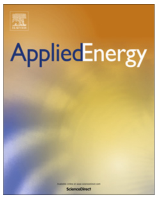

A comparative study between a Rankine cycle and a novel intra-cycle based waste heat recovery concepts applied to an internal combustion engine

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HIGHLIGHTS

- Concept of intra-cycle waste heat recovery (ICWHR) is proposed.
- ICWHR is compared to Rankine cycle based WHR.
- Key advantages of ICWHR are analysed.

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ABSTRACT

A novel intra-cycle waste heat recovery (ICWHR) methodology, applied to an internal combustion engine is presented in this study. Through a split type thermodynamic cycle design, quasi-isothermal compression of the charge air and isobaric combustion of the air/fuel mixture can be performed separately in two chambers. Within such a design, the exhaust heat can be recovered to the intake air flow between the compression chamber and combustion chamber. Consequently, the recovered energy can be re-utilized in the combustor directly, and an intra-cycle waste heat recovery process can be achieved. To investigate the fundamental aspects of this new methodology, a comparative study between the conventional Rankine based WHR and the new ICWHR was undertaken. Both theoretical and numerical analysis were applied to evaluate the performance characteristics of these two technologies. The ICWHR cycle differs from the Rankine cycle in that an energy conversion subsystem is not necessary since the recovered energy is sent back to the combustion chamber directly, and then the system efficiency is improved significantly. Furthermore, the theoretical results indicate that the full cycle efficiency of ICWHR system is determined by the regeneration effectiveness, the compression ratio and the fuel equivalence ratio, then the limitations of Rankine cycle, such as working fluid selection and system parameter calibration can be avoided mechanically. Finally, through a one dimensional system model, analysis of optimal operation range, system efficiency and the heat transfer behaviours of ICWHR system are discussed in this paper and comparisons made with a Rankine cycle WHR system.

1. Introduction

The internal combustion (IC) engine remains the powertrain of major choice for road transport applications globally [1–3]. Concerning the energy balance of IC engines, up to 55% of the input energy is lost to the environment through the exhaust and various heat exchange processes between the engine structure, charge air and lubricating oil [4,5]. Therefore, recovering this waste heat and converting it to useful work is an obvious method of improving the overall efficiency of the combustion engine [6,7]. However, although the quantity of energy available for recovery is significant, the quality of much of the available thermal energy is low [8]. Fig. 1 shows the energy balance for a typical heavy duty diesel engine, of the type installed in a commercial vehicle. It can be seen that about 1/3 of the total energy is emitted out through the exhaust system and more than 20% is emitted out through the cooling system. Table 1 presents the typical quantities and qualities of available heat relative to ambient conditions (15 °C) normalised by the break power of the engine based on a 12.8 l Euro 6 engine described in [9]. From the table it is apparent that the heat from the vehicle cooling system and charge air cooler is of

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Nomenclature

atdc	after top dead center
AFR	air fuel ratio
BSFC	brake specific fuel consumption (g/kW h)
C	isothermal index
CA	crank angle
CR	compression ratio
c_p	specific heat under constant pressure
c_v	specific heat under constant volume
ER	expansion ratio
h	enthalpy (kJ/kg)
int	intake
k	isentropic exponent
m	mass
Q_{LH}	fuel heat release amount (kJ)
Q_{RE}	recuperated heat (kJ)
Q_{REJC}	heat rejected during compression stage
Q_{REJC}	heat rejected during expansion stage
T	temperature (K)
tri	trilateral cycle
S	entropy
u	heat transfer coefficient

Greek symbols

γ	specific heat ratio
δ	regenerator effectiveness
η	thermal efficiency

Subscripts

1–4, 2′	stage point
Exh	exhaust
wf	working fluid
he	heat exchanger
cov	conversion efficiency
source	heat source

insufficient quality to merit effective recovery. As such, only heat from the exhaust will be considered.

Today, the thermal energy rejected to the environment from the vehicle exhaust can be recovered by a range of methods including:

- Expansion of hot exhaust gases through turbo-compounding [10].
- Recovery of heat through thermo-electric generation [11].
- Recovery of heat through a separate Rankine/organic Rankine cycle loop [12–14].

These and other methods were reviewed by Sprouse and Depcik [15] and the merits and de-merits for vehicle applications were thoroughly discussed. The review indicated that these approaches have a common feature when they are applied for IC engine waste heat recovery in that an additional energy conversion facility, such as a turbine, an expander or a thermo-electric generator (TEG) is normally to convert the thermal energy into the dynamic energy or electricity. Such a feature leads to a poor efficiency when applied on IC engines. For example, Organic Rankine Cycle (ORC), which has been proven to be one of the most effective solutions for engine waste heat recovery [16], will only provide a 3–6% engine efficiency improvement on a practical heavy duty diesel engine. This is mainly because of the mismatch of the working fluid and the highly variable exhaust temperature conditions. For the turbo-compounding system, the exhaust back pressure can be increased when the turbine is installed in the exhaust pipe. Then the waste heat recovery efficiency could be undermined because of the pumping losses and the underutilisation of the exhaust heat. Concerning the TEG system, the thermal efficiency is low because of the ineffective thermal-electrical energy conversion process [17].

Rather than using an additional system to achieve the energy conversion, directly recovering the thermal energy back into the internal combustion engine cycle, such as in a recuperated Brayton cycle, will potentially offer a higher thermal efficiency and a simpler system [18]. Roux et al. [19] reported that an 8–15% efficiency improvement can be achieved when the recuperation is applied in a Brayton cycle based gas turbine. However, a further efficiency improvement is difficult to achieve since the temperature difference between the after-compression and the after-expansion temperature of the working fluid is normally small and the amount of the recuperated heat is reduced [20].

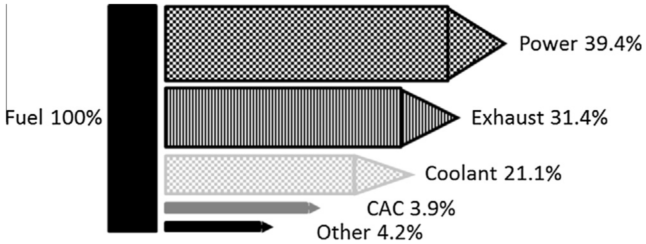

Fig. 1. Typical energy balance of a Euro 6 diesel engine [9].

Table 1
Quantities and qualities normalised to the break power.

	Quantity	Quality (exergy)
Radiator	53.5%	12.8%
Charge air cooler	9.8%	3.3%
Exhaust post turbine and aftertreatment	79.5%	59.3%

Recently, the isothermal compression technique was extensively investigated by several academic/research groups [21,22]. Isothermal compression has the potential to reduce the after-compression temperature of the working fluid. By injecting the coolant media (such as liquid nitrogen or water) into the working fluid, the temperature of the compressed working fluid can be decreased significantly, much lower than the after-expansion temperature of the working fluid. Accordingly, the amount of the recuperated heat will increase.

Applying the isothermal compression on the Diesel engines, the concept of intra-cycle waste heat recovery (ICWHR) is developed in the present work. Through a split cycle engine structure design, the compression and expansion processes are conducted in separate chambers [21,23], and then a heat recuperation is achieved through a recuperator installed between the two chambers. Due to the isothermal compression of the charge air, the temperature difference between the compression and expansion chamber is enlarged. Consequently, a significant engine efficiency improvement is achieved.

In this paper, a comparative study between the conventional Rankine cycle based WHR and the above mentioned intra-cycle waste heat recovery is conducted. For the first time, the ICWHR, which potentially leads to a step engine efficiency improvement, is demonstrated. Additionally, the application of a bottoming cycle to a conventional diesel powertrain – or 'combined cycle' is also described. Such an approach has been presented by others [24], but here, a theoretical analysis is presented together with full cycle