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Review of organic Rankine cycles for internal combustion engine exhaust waste heat recovery

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HIGHLIGHTS

► This review article focuses on engine exhaust waste heat recovery works.
► The organic Rankine cycle is superior for low to medium exergy heat sources.
► Working fluid and expander selection strongly influence efficiency.
► Several authors demonstrate viable systems for vehicle installation.

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ABSTRACT

Escalating fuel prices and future carbon dioxide emission limits are creating a renewed interest in methods to increase the thermal efficiency of engines beyond the limit of in-cylinder techniques. One promising mechanism that accomplishes both objectives is the conversion of engine waste heat to a more useful form of energy, either mechanical or electrical. This paper reviews the history of internal combustion engine exhaust waste heat recovery focusing on Organic Rankine Cycles since this thermodynamic cycle works well with the medium-grade energy of the exhaust. Selection of the cycle expander and working fluid are the primary focus of the review, since they are regarded as having the largest impact on system performance. Results demonstrate a potential fuel economy improvement around 10% with modern refrigerants and advancements in expander technology.

1. Introduction

The Internal Combustion Engine (ICE) has been a primary power source for automobiles, long-haul trucks, locomotives, and ships over the past century. Over this time, periods of high fuel costs and concerns about foreign oil dependence have resulted in increasingly complex engine designs to decrease fuel consumption. For example, engine manufacturers have implemented techniques such as enhanced fuel/air mixing, turbocharging, and variable valve timing in order to increase thermal efficiency. However, around 60–70% of the fuel energy is still lost as waste heat through the coolant or the exhaust [1]. Moreover, increasingly stringent emissions regulations are causing engine manufacturers to limit combustion temperatures and pressures lowering potential efficiency gains.

To date, legislation of exhaust emission levels has focused on carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), and particulate matter (PM). Manufacturers of Spark Ignition (SI) engines have met these standards by using the Three Way Catalyst (TWC), while Compression Ignition (CI) engines have been fitted with a 4-way aftertreatment system [2]. In both cases, catalytic devices convert harmful emissions to nitrogen gas (N_2), carbon dioxide (CO_2), and water (H_2O). Through modification of injection timing and rate shaping, CI engines often operate with reduced combustion temperatures to prevent the formation of NO_x as its conversion in a 4-way aftertreatment system is relatively difficult. SI engines often accomplish a similar tactic by retarding the spark timing; however, TWC devices have the inherent advantage of using CO and HC to reduce NO_x. Therefore, there is less of a need to adjust the combustion timing. As mentioned previously, these strategies reduce engine efficiency by achieving less combustion at prime crank angles.

It appears that future regulations will focus more on CO_2 emissions, which require increasing the efficiency of the ICE or moving to more costly hybrid drivetrains [3]. Of interest, many researchers recognize that Waste Heat Recovery (WHR) from engine exhaust has the potential to decrease fuel consumption without increasing emissions, and recent technological advancements have made these systems viable and cost effective [4].

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The two primary sources of waste heat from an ICE are the engine exhaust (medium-grade) and engine coolant (low-grade). Other options for heat recovery include the relatively smaller amounts available from an Exhaust Gas Recirculation (EGR) cooler and Charge Air Cooler (CAC) [2]. Despite both primary sources having similar energy content, the higher temperature of the engine's exhaust makes it more thermodynamically attractive when viewed from the perspective of exergy. This results in a higher theoretical efficiency gain when coupled to a heat engine [1]. Previous research in this field involves the recovery of each source, as well as the potential for simultaneous heat recovery from both the engine coolant and exhaust. Most studies choose a Rankine cycle for WHR due to its simplicity and ability to operate with low to moderate temperature differences [5].

1.1. Rankine cycle

A Rankine cycle is a closed-loop system where a working fluid repeatedly circulates through four components to transform waste heat into mechanical or electrical power. If the selected working fluid is organic in nature, researchers often refer to this system as an Organic Rankine Cycle (ORC). The first step in this cycle uses engine exhaust to heat the fluid in an evaporator in order to capture waste heat available (process 2–3 in Fig. 1a). Selection of the evaporation process as the first step has been made in order to illustrate the conversion of waste heat to usable energy; however, the choice is otherwise arbitrary since the system is cyclic (thermodynamic textbooks primarily indicate the beginning of this process with the "2" nomenclature). The superheated vapor then passes through an expander to generate mechanical or electrical power; this device can be either a displacement or a turbomachine (process 3–4 in Fig. 1a). After the fluid undergoes expansion, it flows through a condenser in order to discharge low-grade thermal energy to the atmosphere (process 4–1 in Fig. 1a). Finally, a pump compresses the working fluid back to its original state (process 1–2 in Fig. 1a). To note, there are two variations of the traditional Rankine cycle; reheat and regenerative.

In the reheat version, the working fluid does not expand fully to the condenser pressure in a single stage (process 3–4 in Fig. 1b). Instead, the cycle sends the partially expanded working fluid back to the evaporator for reheating (process 4–5 in Fig. 1b) with a subsequent a second expansion resulting in the working fluid ending at the condenser pressure (process 5–6 in Fig. 1b). The principle advantage of the reheat Rankine cycle is an increased quality at the expander exit [6]. A higher working fluid quality indicates a reduction in moisture content, which increases the lifetime of turbine expanders. In the regenerative variation, a portion of partially expanded working fluid (process 5–6 in Fig. 1c) preheats the condensed liquid before it enters the boiler (process 2–3 in Fig. 1c). Preheating in this manner decreases the amount of heat added at low temperatures, increasing the mean effective temperature of heat addition while enhancing cycle efficiency [7]. Of pertinence, these explanations only apply to traditional steam Rankine cycles, not to ORC's; however, it is important to understand the fundamentals of these cycles before expansion to ICE utilization. Fig. 1 provides a comparison of the three Rankine cycle variants for clarity of description.

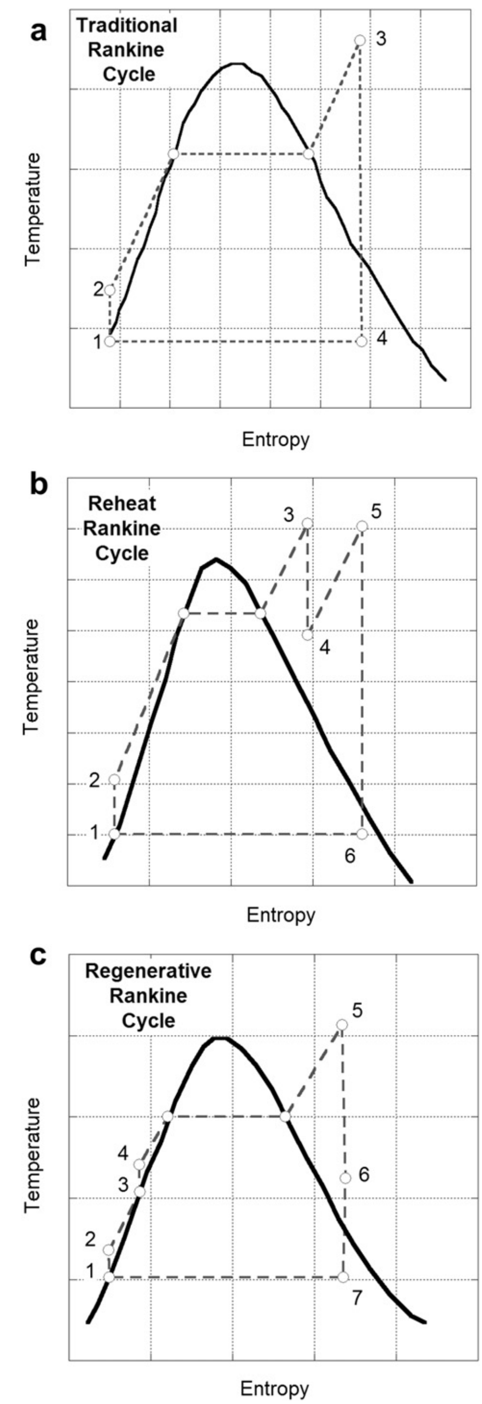

Fig. 1. Variations of Rankine cycle: (a) Traditional, (b) reheat, and (c) regenerative [7].

1.2. Alternative WHR methods

It is also possible to achieve WHR using other unique thermodynamic cycles. One such method is the open Brayton cycle, which requires only three components. Another common option is the Stirling cycle engine that includes a closed system comprised of a regenerator and a cylinder, which contains both a displacement and power piston [8]. More recently, increased focus has been placed on the development of Kalina cycle systems, which parallels an ORC in configuration with the addition of an absorber and flash tank [9]. This cycle uses a variable composition mixture of ammonia and water as the working fluid. Similarly, supercritical carbon-dioxide systems have drawn attention in various WHR applications. While most WHR research focuses on thermodynamic cycles, thermoelectric (TE) devices offer a unique alternative, since they directly convert thermal energy into electrical energy.