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A technical review on waste heat recovery from compression ignition engines using organic Rankine cycle

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ABSTRACT

The study deals with the utilization of organic Rankine cycle (ORC) to recover waste heat from compression ignition (CI) engines and produce additional power output. A review on the potential of waste heat recovery from exhaust gas, water jackets and intake charge air of CI engines was carried out. Research challenges associated with engine-ORC technology such as selection of organic working fluid, type of evaporator/condenser, back pressure due to additional ORC components in the exhaust line are discussed. The evaporator for the engine-ORC needs to be designed by keeping a view of variable exhaust gas heat source (variable temperature and mass flow rate profiles). It is explored from the literature study that engine-ORC system could operate with the maximum thermal efficiency range about 10–25%. The main reason for low thermal efficiency could be due to lower operating temperatures in the ORC. However, the overall efficiency of combined system (engine and engine-ORC with exhaust gas/water jackets/intake air/use of hot water from condenser for heating/refrigeration application) is significantly higher (60–90%) than the conventional standalone ORC system (10–25%). It is also found that R245fa is the better organic working fluid for engine-ORC application based on better performance, availability, economic and environmental aspects.

1. Introduction

Internal combustion (IC) engines are widely used in small scale electrical power generation (especially in the power range of hundreds of kW to few MW) due to their reliability, high thermal efficiency and low maintenance. In IC engines, about 30–45% of fuel energy is converted into useful power output whereas the remaining fuel energy is being wasted mainly through exhaust gas, exhaust gas recirculation (EGR), and heat losses [1–3]. Conklin and Szybist reported about 28% fuel energy is being lost through exhaust gases of a compression ignition (CI) engine [4]. Wang et al., in their experimental investigation on a CI engine mentioned that the energy lost through exhaust gas was about 19% of total combustion energy [5]. Galindo et al. stated about 26% of total fuel energy is being wasted through exhaust flue gases of a 32 kW CI engine as shown in Fig. 1 [6]. In addition, a significant amount of energy (about 42%) is being wasted through cooling water of the engine. The waste energy could be recovered using a number of novel strategies such as Kalina Rankine Cycle [7–10], organic Rankine cycle (ORC) [7,11–13], Brayton cycle [14] and thermoelectric generator [4,13]. Among all these strategies ORC is a promising and effective strategy for residual high and low temperature heat resources (High temperature sources: Exhaust gas and EGR, Low temperature sources: Water jackets and charge air) [4,5,13,15–17]. Velez et al. presented an overview of technical and economic aspects, as well as the market evolution of ORC technologies [18]. They stated that the ORC technology is a promising candidate for conversion of thermal energy, at low and medium temperatures, into electrical and/or mechanical energy on a small scale [18]. As the ORC system utilizes of its energy source intensively, this technology could facilitate an electricity supply to remote areas/hill areas, the self-production of energy, the desalination of seawater for human consumption, or even to increase the energy efficiency in the industrial sector respecting the environment [18]. Much research effort has been expended so far towards implementation of the ORC technology in the real market [4,12,13,16,19]. The ORC technology is best suitable for waste heat recovery applications of low temperatures (≤ 350 °C) and the low heat content [19,20]. Larjola

Abbreviations: A/C, Air conditioning; CHP, Combined heat and power; CI, Compression ignition; CO, Carbon monoxide; CO_2, Carbon dioxide; EGR, Exhaust gas recirculation; GWP, Global warming potential; H_2, Hydrogen; H_2O, Water; HC, Hydrocarbon; HT, High temperature; IC, Internal combustion; LT, Low temperature; N_2, Nitrogen; NG, Natural gas; NO_x, Oxides of nitrogen; O_2, Oxygen; ODP, Ozone depletion potential; ORC, organic Rankine cycle; P, Brake power; SO_2, Sulphur dioxide

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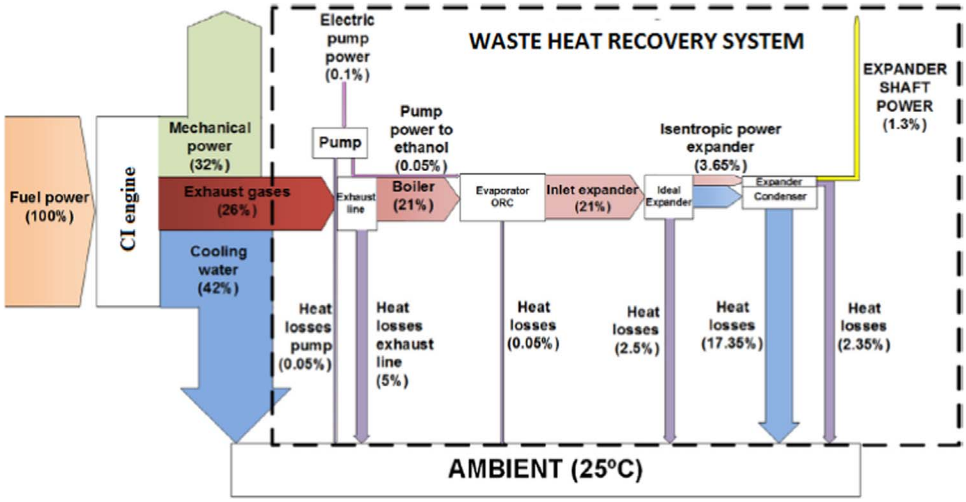

Fig. 1. Energy distribution of a 30 kW CI engine with waste heat recovery system [6].

also supports the utilization of ORC technology with the highest overall efficiency in conversion of low temperature heat energy to electrical energy [21]. Benato and Macor integrated the ORC system to a conventional biogas fueled engine for improving the net electrical power output [22]. They found that a recuperative ORC designed using real data guarantees a 30% higher net electric power output [22].

The operation of ORC is similar to the conventional steam Rankine cycle, except the fact that the former uses an organic working fluid while the latter uses steam. These organic fluids have a lower boiling points and higher vapor pressures than water or steam. This allows the ORC system to operate at exceedingly lower temperatures than conventional systems [23]. In comparison to water/steam that are used in the conventional stem Rankine cycles, the organic working fluids used in ORCs have higher molecular masses enabling compact designs, higher mass flow rates, and higher turbine efficiencies (as high as 80–85%) [24–26]. An instance of a recent successful installation in India was by M/s Ultra Tech Cements India Ltd. in Andhra Pradesh, India, where the installed ORC plant recovers waste heat energy from the clinker cooler that has an exhaust gas temperature of about 320 °C. The ORC installation can generate 4 MW of electrical power, thereby reducing carbon dioxide (CO_2) emissions about 16,871 tons per annum [24]. The main objectives of the present review study are to understand the potential of heat energy from different sources of CI engine such as exhaust gas and water jackets. Research challenges associated with implementation of engine-ORC system are also discussed in detail. The scattered information of engine-ORC system available in literature are compiled together and presented in a coherent manner. The compiled results could be a reference source for development of engine-ORC systems by original engine manufacturers (OEM), researchers and policy makers.

Higher mass flow rate and temperature of exhaust gases from IC engines could provide substantial potential of thermal energy sources. The ORC could be used to recover the waste heat energy from IC engines, thereby improving the thermal efficiency of the engines. For example, Galindo et al. found the engine thermal efficiency enhancement about 1.2–3.7% with the combined engine-ORC system [6]. The other significant advantage of ORC employment in IC engines is reduction of specific emissions [27] due to additional power output without using extra fuel for the engine operation. For example, the CO_2 emission would decrease drastically with reduction in fuel consumption for the same power output. Conversion of exhaust waste heat into useful power would not just bring measurable advantages for improving fuel consumption but also increase engine power output (power density) or downsizing, further reduction of CO_2 and other harmful exhaust emissions correspondingly [13]. However, a trade-off between waste energy recovered and energy lost due to the engine back pressure, vehicle weight increase, discharge energy at the condenser, and the management of the strong off-design operating conditions are the major research challenges for effective implementation of this ORC technology in real life applications.

It may be noted that as the temperature of engine-out exhaust gases is about 500–650 °C, there could be a high potential to recover the exhaust gas waste heat energy using an additional ORC system [28]. Similarly, the research work of Daghigh and Shafieian revealed a high potential of heat recovery in submarine CI engines as the engine out exhaust gas temperature is about 650 °C and high mass flowrates of 6116–14611 m^3/h [29]. They worked on combined cooling, heating and power generation with thermal recovery of the marine CI engine with integration of ORC system. They found the maximum heat recovery with exhaust gas mass ratio of 0.23–0.29 and working fluid mass flow rate of 0.45–0.57 kg/s from the engine [29]. A few other investigations have been carried out to assess the waste heat energy potential from engines, engine-ORC operational and performance characteristics, and research challenges associated with the system which are explained in the following sections.

2. Waste heat energy potential from CI engines

Literature information on energy available with exhaust gases from CI engines is given in Table 1. From the table, it could be concluded that the potential of exhaust gas energy from conventional CI engines is about 24–38%. It may be noted that the waste heat energy recovery potential from any fluid (exhaust gas/EGR/intake air etc.) is a strong function of its temperature. The recovery potential from high temperature fluids (exhaust gas/EGR) would be high as the whole system works at high operating temperatures. Exhaust gas temperatures increases substantially with dual fuel (diesel-hydrogen) CI engines as compared to conventional single fuel (diesel) CI engines [30–33]. For example, Chintala and Subramanian reported that the exhaust gas temperature increased from 364 °C with convention CI mode to 427 °C with dual fuel CI mode (10.1% hydrogen energy share) as shown in Fig. 2 [1,33–35]. The research findings of Sivabalakrishnan et al. also stated that the exhaust gas temperature increased from about 200–550 °C with increasing load on a hydrogen dual-fuel CI engine [36]. The experimental tests conducted by Nguyen et al. also revealed the similar results of increasing trend of the exhaust gas temperature from about 250–650 °C in a CI engine under hydrogen dual fuel mode [37]. It was also reported that brake thermal efficiency of a CI engine increases with addition of hydrogen [34,35]. Electrical efficiency of dual fuel CI engine coupled ORC system may increase as compared to the conventional diesel engine