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The Development and Application of Organic Rankine Cycle for Vehicle Waste Heat Recovery

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Abstract

The development of engine waste heat recovery (WHR) technologies attracts ever increasing interests due to the rising strict policy requirements and environmental concerns. Organic Rankine Cycle (ORC) can convert low medium grade heat into electrical or mechanical power and has been widely recognized as the most promising heat-driven technologies. A typical internal combustion engine (ICE) converts around 30% of the overall fuel energy into effective mechanical power and the rest of fuel energy is dumped through the engine exhaust system and cooling system. Integrating a well-designed ORC system to ICE can effectively improve the overall energy efficiency and reduce emissions with around 2–5 years payback period through fuel saving. This book chapter is meant to provide an overview of the technical development and application of ORC technology to recover wasted thermal energy from the ICE with a particular focus on vehicle applications.

Keywords: internal combustion engine, vehicle application, organic Rankine cycle, engine waste heat recovery

1. Introduction

Over the last century, the internal combustion engine (ICE) as one of the main power sources has been widely adopted in the vehicle and marine propulsion systems such as automobiles, trains, trucks, boats, and ships. The increasing concerns on the environmental problems caused by burning fossil fuels promote the technology development of more efficient, more compact, and more cost-effective ICE, which can potentially improve the overall energy efficiency, reduce the emissions and generate more effective engine shaft power by burning fossil

fuels [1]. Moreover, the increasingly strict emission legislations are focusing on the nitrogen oxides (NO_x), particulate matter (PM), carbon monoxide (CO), and hydrocarbon (HC).

Engine manufacturers have developed and adopted the technologies such as turbocharging, variable valve timing [2], Miller timing strategies [3], advanced injection strategies, and engine friction reduction technologies in order to improve the system thermal efficiency. However, adopting the stated technologies the ICE is still difficult to convert more than 40% of the fuel energy into effective mechanical power [4, 5]. And there is around 60–70% of fuel energy is wasted from the exhaust system and cooling system of ICE [4, 5]. Other approaches such as burning alternative fuels [6] and the development of hybrid pneumatic system [7] to recover the engine kinetic energy were also considered. Recent research attentions are focusing on the development of engine bottoming technologies such as advanced after treatment systems or engine waste heat recovery (WHR) technologies [8]. The Organic Rankine Cycle (ORC) is one of the most promising heat-driven technologies converting heat into mechanical power or electricity [9, 10]. ORC system can recover various heat sources such as biomass combustion heat, solar energy, geothermal heat, and industry wasted heat and heat from Internal Combustion Engine (ICE) [9]. Adopting ORC technology for engine waste heat recovery can effectively improve the overall system efficiency and reduce the emissions. A well-designed ORC system can potentially achieve around 2–5 years payback period through fuel saving [4, 5, 10]. However, Velez et al. [10] pointed out the market available ORC system with the power ranges of 0.2–2 MWe under the cost around 1 and 4×10^3 €/kWe, and lower powers are in pre-commercial status because of the relatively long payback period using small-scale ORC system. The technical development, main research barriers, and potential solutions of the technology are summarized in this chapter, which aims to have an overview of the ORC technology and promote its applications.

1.1. Emerging applications of the technology for vehicles

The applications and extensively research interests of waste heat recovery technologies started in the 1970s during the oil crisis [11]. The first application of ORC for engine waste heat recovery was reported by Patel and Dogle in 1976 [12]. The research project conducted by Mack Trucks and the Thermo Electron Corporation was sponsored by US Department of Energy (DOE). The first prototype ORC machine was installed on a Mack 676 diesel engine to recover the exhaust waste heat. The system adopted Fluorinol-50 as the ORC working fluid and a three-stage axial flow turbine expander. The mechanical power of the expander was transferred to the power take-off device coupled with a speed reduction gearbox. They demonstrated the technical feasibility of the system and its economic interests. The optimal performance of the system could achieve a 13% increase in maximum power with around 15% reduction of fuel consumption. Follow on progress reported by Pate et al. [13] announced a 1 year test program of an ORC bottoming system coupled on a Mack diesel engine in 1979 and they declared a plan of expanding the ORC system on 10 trucks in 1981–1982. In 1983, the research group reported the testing results of the program [14], which demonstrated 12.5% improvement of the average fuel consumption on high-way vehicle fuel economy tests. However, no follow on progress for the expanding plan can be found from the literature. The ORC systems developed nowadays can achieve much higher efficiency because of the broad choice of advanced working fluids and the development of system components, such as expansion devices and heat exchangers. However,

the commercial ORC system for vehicle application is still not available from the market. One of the possible reasons is the concern on the substantial capital cost due to the complexity of the system and complicated control strategies required for vehicle application.

1.2. Representative prototypes developed by vehicle manufactures

The application of steam Rankine cycle for vehicle waste heat recovery has been reported by BMW in 2005 [15], who later announced the proposed system can achieve 15% improvement for engine performance [16, 17]. **Figure 1** is the schematic diagram of the BMW turbosteamer concept, who converts both engine coolant and exhaust energy into engine mechanical power. The system adopts two-stage turbine machines, which is similar as large-scale stationary power generation system.

In 2008, Honda has reported the project exploring the application of steam Rankine cycle for engine exhaust heat recovery as illustrated in **Figure 2** [18]. The system adopts an axial piston swash plate type expander as the expansion machine under the controlled steam operational conditions ranging from 400 to 500°C at the pressure ranging from 7 to 9 MPa in order to optimize the Rankine cycle performance in engine transient driving conditions. The expander was directly connected to an electric generator producing electricity to recharge the battery pack. The maximum thermal efficiency of the system is 13% at 23 kW and the maximum power from the expander is 32 kW. Results are shown in 62 miles/h constant speed driving tests; the overall thermal efficiency can be improved by 3.8%. However, Honda announced the system will not be considered for production unless higher efficiencies can be achieved [18].

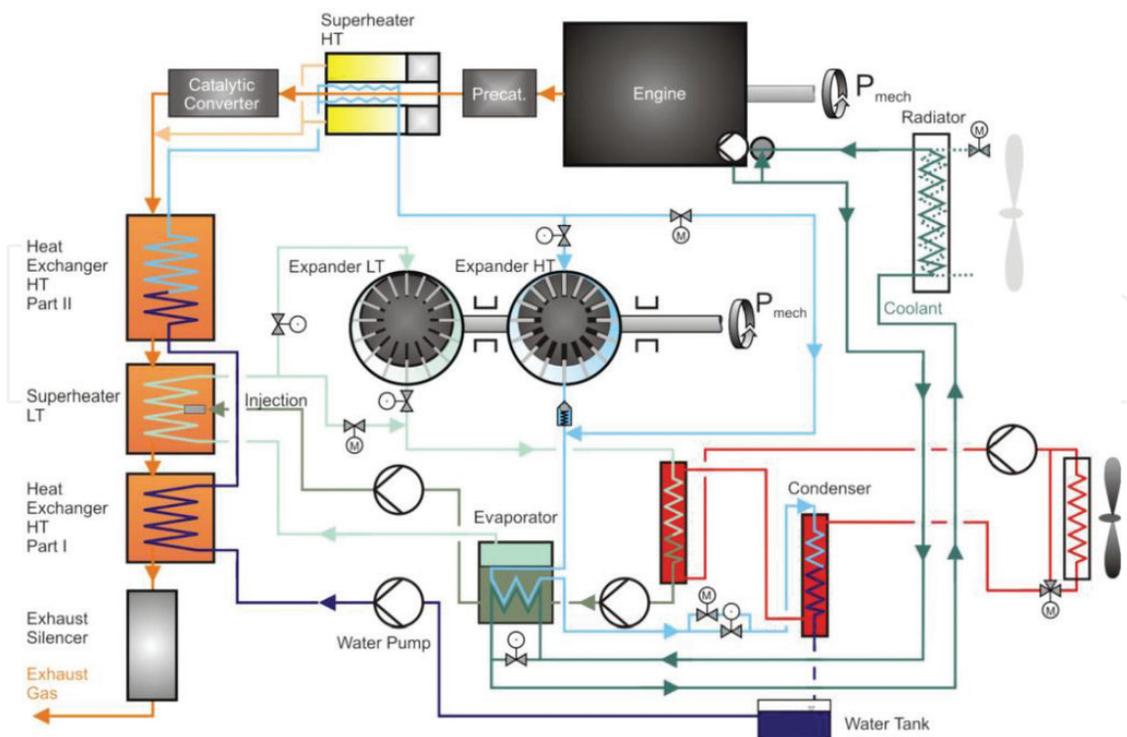


Figure 1. Schematic diagram of BMW-Turbosteamer concept [16].

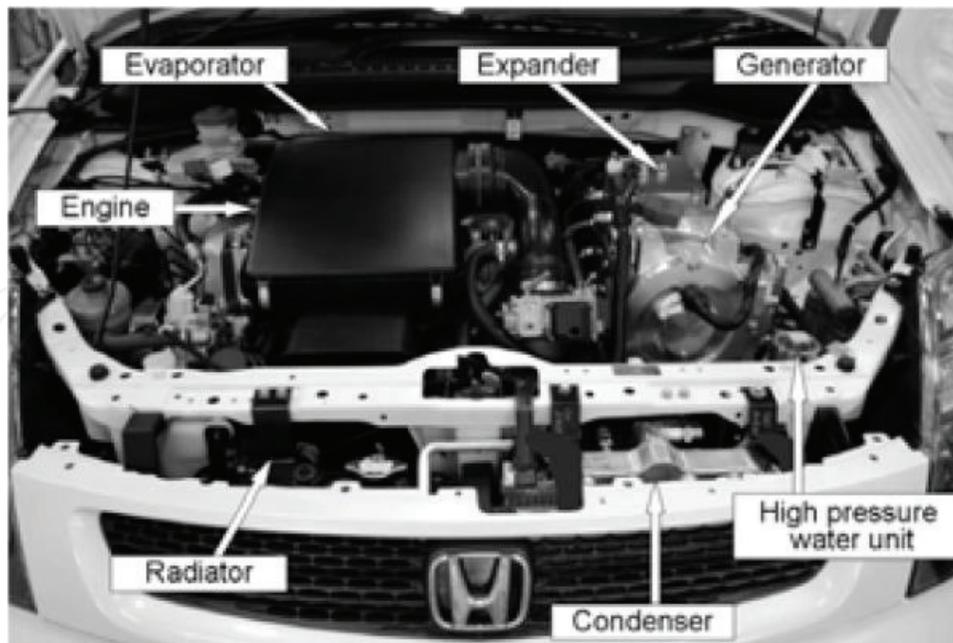


Figure 2. Layout of the Honda Rankine cycle prototype [18].

Cummins has conducted a project funded by U.S. Department of Energy to study an advanced engine waste heat recovery system using ORC technology since 2005 [19]. Cummins announced the developed ORC system can potentially improve the engine total efficiency by 5–8% [19]. The company further developed the waste heat recovery system and integrated with other advanced engine technologies aiming to boost the heavy-duty diesel engine to as high as 55% efficiency as reported in 2013 [20].

2. Organic Rankine cycle (OCR) for vehicle waste heat recovery (WHR)

2.1. Heat sources from ICEs

The designed temperature difference between evaporation and condensation temperature determines the overall efficiency of a typical ORC. For on-road vehicle application, the condensation temperature is controlled by the radiator and the capability of engine radiator determines the lowest condensation temperature. Therefore, the majority studies of Waste Heat Recovery (WHR) from ICE focus on the engine exhaust energy [21], because the exhaust temperature of ICE is various from 200 to 700°C, which is much higher than the coolant temperature ranging from 80 to 100°C [4, 5]. The other two heat sources are the charge air (50–70°C) and engine oil (80–120°C) [22]. The maximum ratio of utilization the fuel energy converting into engine brake power for propulsion is about 40–45%. The rest of fuel energy is dumped through engine exhaust, wasted because of friction losses and heat transfer losses. It is, therefore, necessary to study the heat sources from ICE to design and evaluate an ORC system for engine waste heat recovery.

The heat sources from the engine are usually calculated under engine steady state points from either experimental tests or simulation results. Although it is theoretically feasible and potentially worthwhile to recover the heat from charger air cooler and engine lube oil as reported in the literature [23], the practical applications of ORC system for engine waste heat recovery are mainly focusing on the exhaust energy and engine coolant energy. These two heat sources contain the majority of wasted heat energy from the engine. The maximizing utilization of these two heat sources can benefit for the overall vehicle thermal management and improve the cooling circuit impact.

Rather than the engine used in stationary power generation system, who usually operated under fixed rotational speed for an electrical generation [24], the engine used for vehicle application operates under variable speed and torque conditions. Therefore, the full engine operational map analysis method is popularly used to evaluate the heat sources from the engine for vehicle application. For example, Zhang et al. [25] used similar analysis methods and conducted the analysis of a 105 kW light-duty diesel engine. In order to conduct the parametric performance study of engine waste heat recovery system, the following four parameters are critical to being identified: the temperature and mass flow rate of exhaust and coolant energy under variable engine operational conditions. Another alternative method to evaluate the recoverable waste heat from the engine coolant and exhaust energy was introduced by Ringler et al. [17], who pointed out that the ratio of the recoverable heat from the coolant and exhaust energy of ICE ranges from 1.5 to 0.5. The results from the reported work also supported the conclusion [26–28]. Similar analysis method to evaluate the recoverable coolant and exhaust energy from a single cylinder engine was used and reported by Lu et al. as illustrated in **Figure 3** [30].

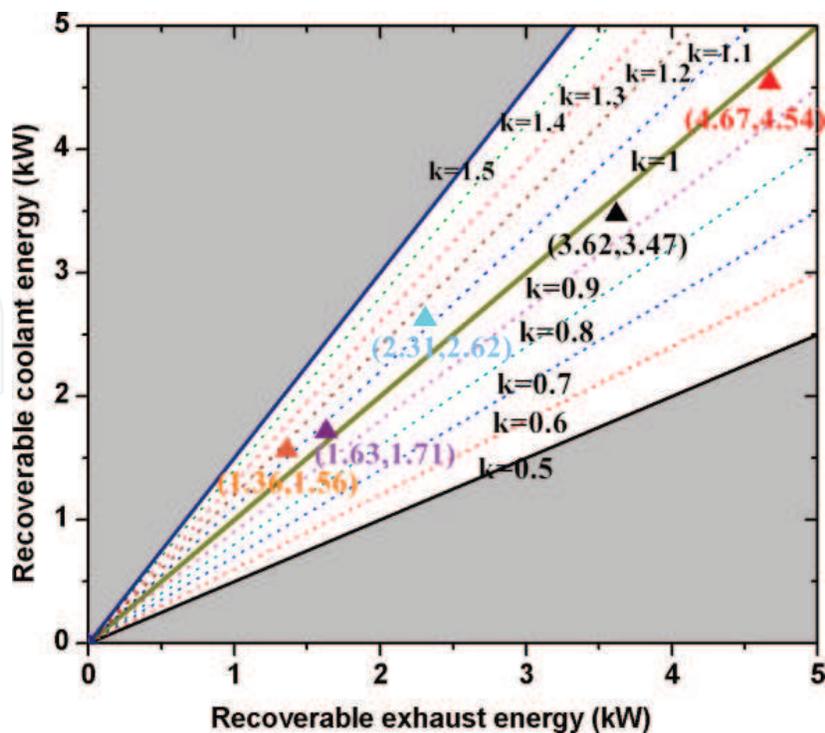


Figure 3. Recoverable coolant and exhaust energy from a single cylinder ICE [29].

2.2. Working principle of Rankine-based power generation systems

2.2.1. Rankine cycle

Steam Rankine cycle has been widely employed in large-scale power plants in the industry. This technology has been recognized as the most popular energy conversion systems, which mainly consists of four components, a pump, an evaporator, a turbine, and a condenser shown in **Figure 4**. The working principle of steam Rankine cycle can be described as follows. The liquid-phase water is first compressed to high-pressure state and flows into the evaporator, where the heat is provided from the heat sources to change the water from the liquid phase into the gas phase. The high-temperature and high-pressure steam then flow through an expansion machine where the power can be retrieved or converted into electricity. In the final step, the condenser rejects the heat from the expander steam and condenses the steam into the liquid phase.

Rankine cycle applies water as the working fluid, which has the advantages of high specific heat capacity, broad ranges of working conditions, non-toxic, and safe to use and environmentally friendly. However, steam Rankine system requires very high driven temperature in order to keep the steam in the gas phase at the exit of the expander. Because the exiting of liquid phase of fluid requires being prevented otherwise the blades of the turbine will be gradually damaged resulting in the reduction of lifetime and decrease of the expander efficiency [31].

2.2.2. Organic Rankine cycle (OCR)

As mentioned before, steam Rankine cycle requires very high heat source temperature. The Organic Rankine Cycles have been widely investigated since the 1880s. Instead of using water in Rankine cycle, the Organic Rankine Cycles employ organic working fluids such as refrigerants and hydrocarbons to recover the low-grade heat from biomass power plant, geothermal power and solar ponds [32]. The selection of working fluid plays a key role in ORC performance [33–36].

The working fluids used in Organic Rankine Cycle can be classified as wet, dry and isentropic types, who have different slopes of the vapor saturation curves in the T - s diagram as shown

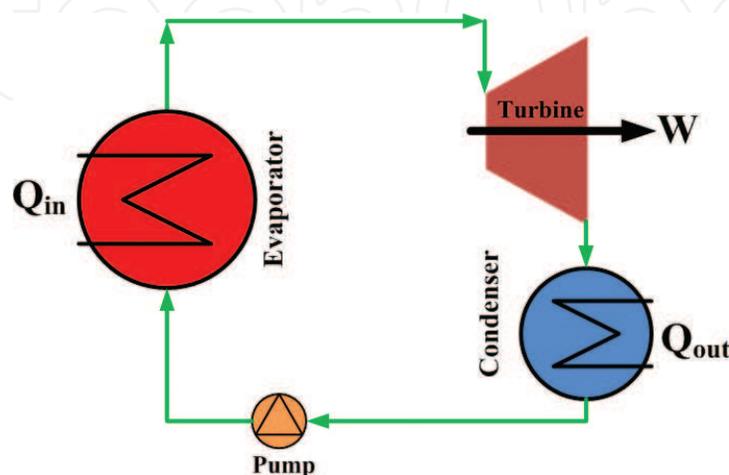


Figure 4. Schematic diagram of steam Rankine cycle.

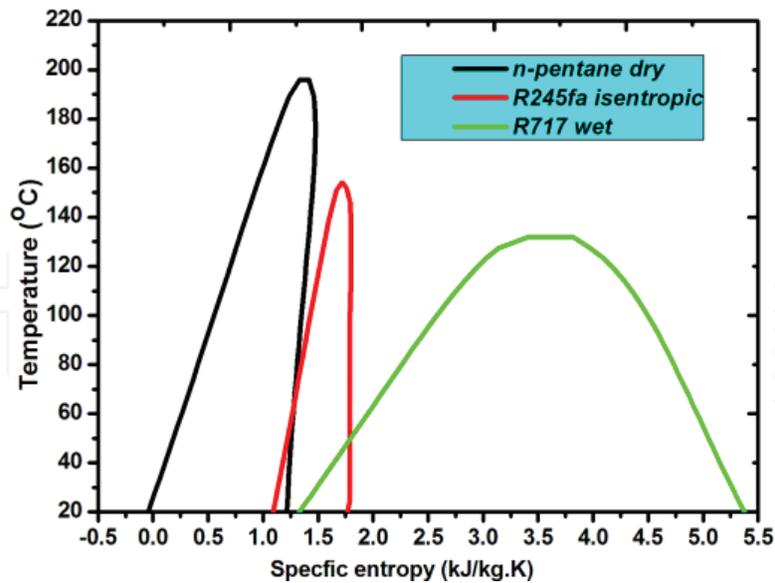


Figure 5. Three types of ORC working fluids: dry, isentropic, and wet.

in **Figure 5**. The wet fluids such as R717 have a negative slope of the vapor saturation curve. On the other hand, the dry fluids have a positive slope. The isentropic fluids have a vertical slope of the vapor saturation curve such as R134a.

A wrong choice of working fluid could lead to a low-efficient and expensive plant of ORC system. Tchanche et al. [37] assessed the thermodynamic and environmental properties of 20 different fluids for solar Organic Rankine Cycle by comparing the system efficiency, irreversibility, flow rate, pressure ratio, toxicity, flammability, ozone depletion potential (ODP), and global warming potential (GWP). The influence of fluid properties on an ORC and a supercritical Rankine cycle with 35 different working fluids was assessed by Chen et al. [36] considering the latent heat, density, specific heat, and the effectiveness of superheating. An exergy-based study of fluid selection for geothermal generated ORC system was conducted by Heberle et al. [38]. The exergy analysis indicated in a series circuit, working fluids with high critical temperatures such as isopentane are more favorable to be used. The working fluids with low critical temperatures, such as R227ea, are favored in parallel circuits and power generation under the heat source temperature below 450 K. The author investigated a small-scale solar-powered regenerative ORC system using six different refrigerants. The first and second law analysis suggested that R600 and R600a have the best performance under the temperature ranges from 70 to 120°C [31]. Wang et al. [33] report a study to compare the performance of 10 kW net power output ORC system using different working fluids for engine exhaust heat recovery. Results indicate R11, R141b, R113, and R123 manifest slightly higher thermodynamic performances than other working fluids [33]. The system performance study of a geothermal ORC system using 31 pure working fluids has been conducted by Saleh et al. [34]. The maximum thermal efficiency is 0.13 with n-butane as working fluid under 120°C heat source temperature [34]. There is no working fluid can be recognized as the best to be used in any ORC systems. The section of optimal working fluid needs to consider the system thermodynamic performance, the economics of the system, designed system parameters such as maximum and minimum temperature and pressure conditions, environmental, and safety aspects.

2.3. Expander candidates

The expansion machines can be divided into two types: turbine machine using the kinetic energy of the working fluid to drive the expander and positive displace expander producing power by changing the volume of working chamber.

2.3.1. Turbines

Turbines have been widely applied as the expansion machine to replace the piston type of expander in steam Rankine cycle since the nineteenth century and have been acknowledged as the optimal expander for large-scale power plants. It consumes the internal energy of vapor into kinetic energy, which results the velocity of the flow are relatively high but the pressure and forces between the supply and exhaust point are rather small [39]. The mechanical power is then been obtained from the shaft of the turbine by turning the rotor blades when the high-velocity fluid passes through the turbine. There are mainly two types of turbines: axial flow turbines and radial flow turbines [40]. The axial flow turbines are driven by the flow in the parallel direction to the shaft, while the radial flow turbines are rotated by the flow traveling through the hub to the tip of the turbine as indicated in **Figure 6**. However, the application of turbines for small-scale power generation system has not been widely accepted as the best expansion machine, especially in the power plants lower than 100 kW. Radial flow turbines are one of the exceptions, which have been recently used for small-scale application in Organic Rankine Cycle (ORC) [42–47]. Kang reports the design and experimental investigation of an ORC using R245fa as the working fluid and radial flow turbine as the expansion machine [42]. The radial turbine

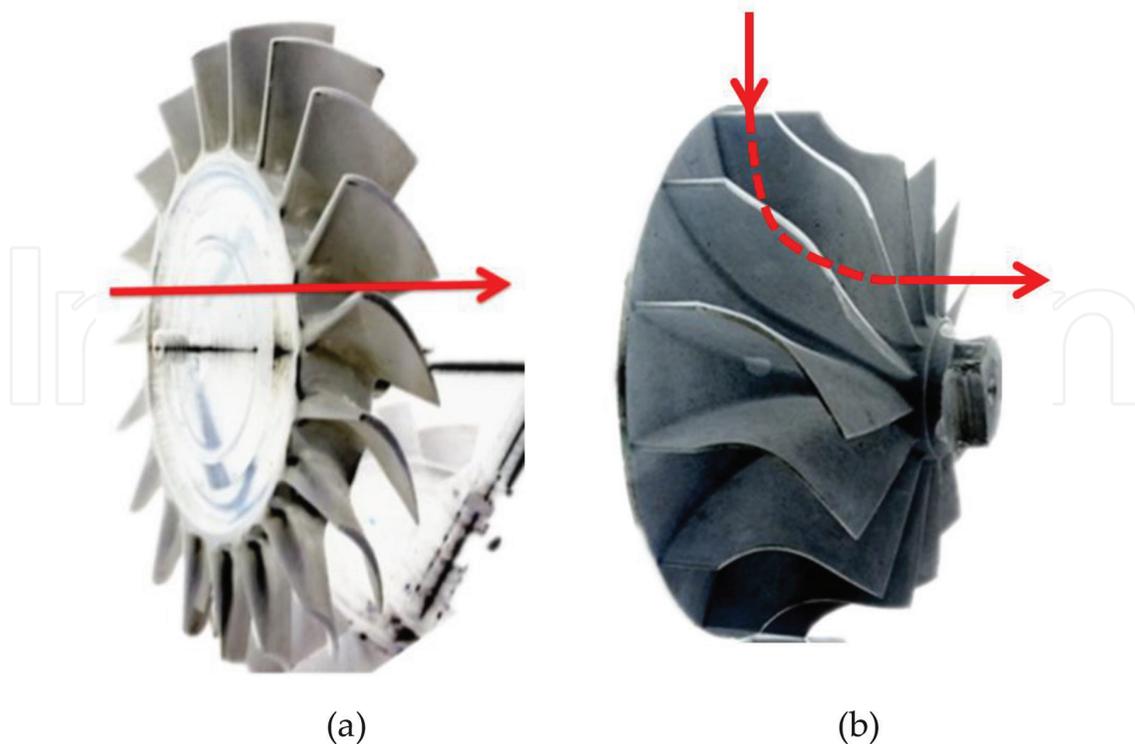


Figure 6. Working principle of turbine machines. (a) Axial flow turbine and (b) radial flow turbine [41].

was directly connected to a high-speed generator to produce electricity and results indicated the maximum cycle efficiency, the isentropic turbine efficiency, and electricity power obtained from the testing rig is 5.22%, 78.7%, and 32.7 kW, respectively [42]. Pei et al. [47, 48] carried out an experimental investigation on a 1–2 kW ORC system using a special designed and constructed radial flow turbine. The reported study achieves the isentropic efficiency of the radial flow turbine at 65–68% with the rotational speed around 20,000–40,000 using R123 as the organic working fluid in the ORC system [46, 47]. Compared with positive displacement expander, turbines are easier to be designed with relatively less required parts. A single stage turbine only requires two bearings to be mounted to the generator on the shaft. Furthermore, there is no contact seal existing in the turbines, which means no lubrication oil is necessary to be adapted to the system. The application of turbine for small-scale application is still not successful because the turbine is designed under rather low-expansion ratios and high-volume flows. The rotational speed of conventional turbines ranges from 10,000 to 100,000 rpm because of the physical design of this type of expansion machine, which results to a limited or hard sourcing of proper generator for electricity production. One of the solutions to adapt the turbine machine directly with the generator is to use a high-speed generator, which will lead to high initial cost and increase the overall cost of electricity generation system. The other method to obtain the mechanical work from the turbine and convert it into electricity is by using gear. This method can effectively solve the high initial cost of the system but will require larger space for the turbine unit and reduce the efficiency of the turbine machine due to mechanical losses in the gear. Furthermore, the availability of small-scale turbine machine is still limited. The currently used radial flow turbines in small-scale power generation system are either from specially designed by the researcher or modified from a conventional turbine from an automotive turbocharger.

2.3.2. Positive displacement expanders

Different from the working principle turbine machines, positive displacement expanders use the expansion power by changing the volume inside the expansion chambers, which can also be named volumetric expanders. The most commonly used positive displacement expanders include piston type expander, screw expander, and scroll expander and vane expander. The positive displacement expanders can be classified into two types reciprocating piston expanders and rotary expanders. Screw expander, scroll expander, and vane expander are three main types of rotary expanders.

The piston type of machines attracts extensive intentions since it was invented and has been widely applied in different areas to meet various requirements such as the most commonly used as an Internal Combustion Engine. In the past 30 years, piston expander has been adopted and developed as the expander into steam Rankine system integrating with the internal combustion engine to recover the exhaust energy [4]. The piston type of expander can be designed and constructed with one valve version and two valve version in order to allow the expansion process starting and ending inside the piston volume chamber. The working principle of these two types of reciprocating piston expanders is illustrated in **Figure 7**. Piston type of expansion machine requires precisely controlled methods for the intake and exhaust valves, which will result to the requirement of a complex control system although this type of expander can potentially reach very high-expansion efficiency [50]. Moreover, piston

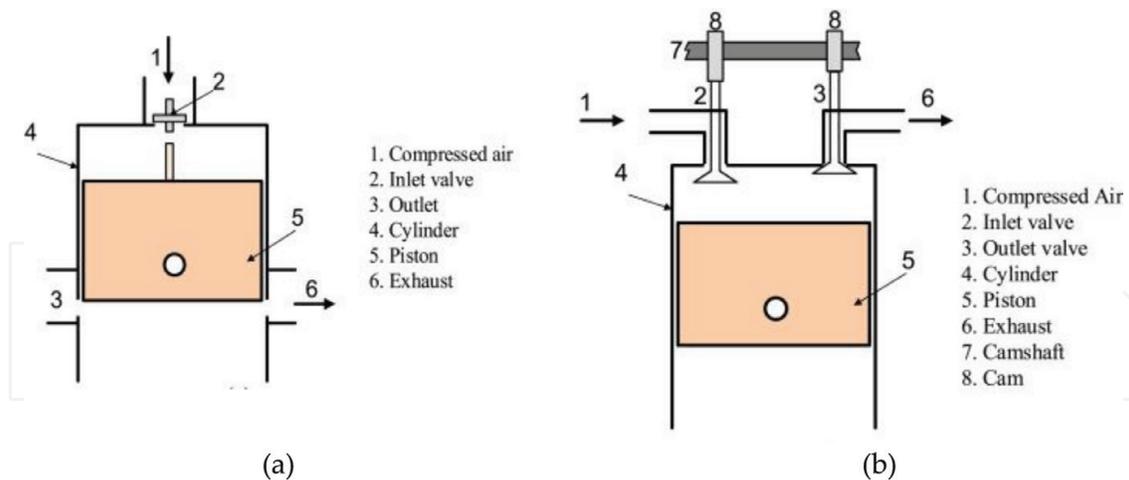


Figure 7. Working principle of reciprocating piston expander. (a) Single valve piston expander and (b) two valve piston expander [49].

expander requires a lot of bearings, a great number of moving parts, and balancing setting up, which results in a relatively complex and costly system.

Screw expander is composed of two meshing helical rotors a male and a female rotor, which requires at least four bearings for the two rotors as shown in **Figure 8**. This type of expansion machine has been widely applied in steam Rankine cycle plants for geothermal waste heat recovery system [52]. Lubrication oil is commonly used in the screw machine to seal the expanded working fluid inside the expansion chamber, which can effectively reduce the internal leakage losses during the expansion process. Screw expander has a relatively high rotational speed in positive displacement expanders and the rotation speed of this machine can reach as high as 6000 rpm [52]. The electricity production from screw expander, therefore, requires a specially designed high-speed generator or adding a gearbox to convert the mechanical power from the screw machine into electricity. This type of expansion devices has the advantages such as medium internal frictions, medium leakage losses, low vibration noise, wide ranges of power output, and long lifetime. The power produced from this expansion machine as reported by previous researchers ranging from 1.5 kW to 1 MW with the expansion ratio of 2–8 [53]. Leibowitz et al. developed an ORC power generation system using screw expander in a demonstration unit to cost-effectively recover the waste heat into power. Results indicated that screw expander is a good candidate expansion machine for the ORC system with the power output at 20 kW with installation cost in the range of \$1500–\$2000/kWe [54]. However, there is

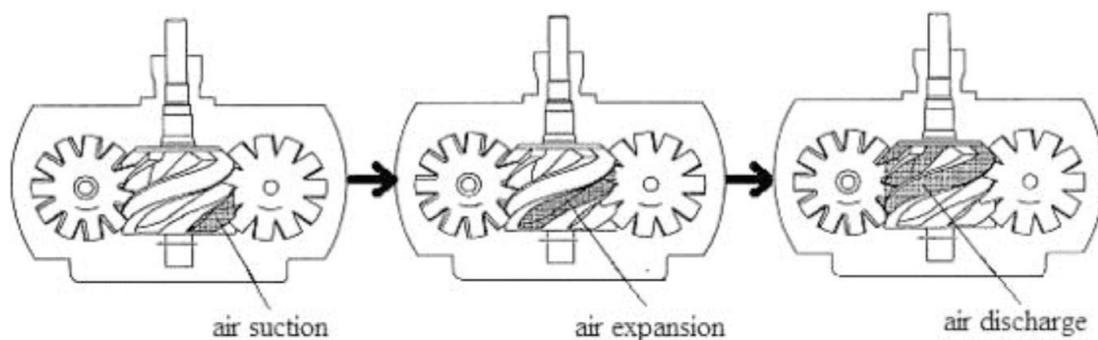


Figure 8. Working principle of screw expander [51].

no commercially available product under the power output lower than 10 kW from the market as reported by Ian et al. [55]. Because small size of screw expander needs extremely precise machining requirements to make the rotors and internal leakages of small size screw expander are relatively higher than that of the large-scale device [51, 56].

Scroll type of machine was first developed by a French inventor in 1905 and then the scroll machine starts to attract attention to be applied in Air condition system as a compressor to produce refrigeration since the mid of 1980s [57]. The most of the available scroll expanders from the market are modified from scroll compressor by swapping the inlet and outlet ports to change the device working mode from compressor to the expander. Scroll device is relatively simple equipment, which mainly includes two scrolls. The scroll expander has the advantages of little vibration, low-noise, a limited number of moving parts, broad availability, high-reliability and low initial cost [58, 59]. Scroll device has two scrolls and one of the scrolls is fixed on the shell, which is called situational scroll, while the other scroll orbiting eccentrically without rotating is named orbiting scroll. During the expansion process, high-pressure vapor enters and expands centrally of two scrolls pushing the orbiting scroll to start orbit as illustrated in **Figure 9**. The mechanical work can be continually obtained from the orbiting scroll through the shaft. Likewise the other positive displacement expanders, scroll expander has a fixed built-in expansion ratio. The optimal performance of scroll expander can be obtained when the specific volume ratio of the designed system equal to the built-in expansion ratio. Quoilin et al. pointed out the losses appearing when scroll type of expansion machine is working under and over expansion processes [9]. For example, 1 kW

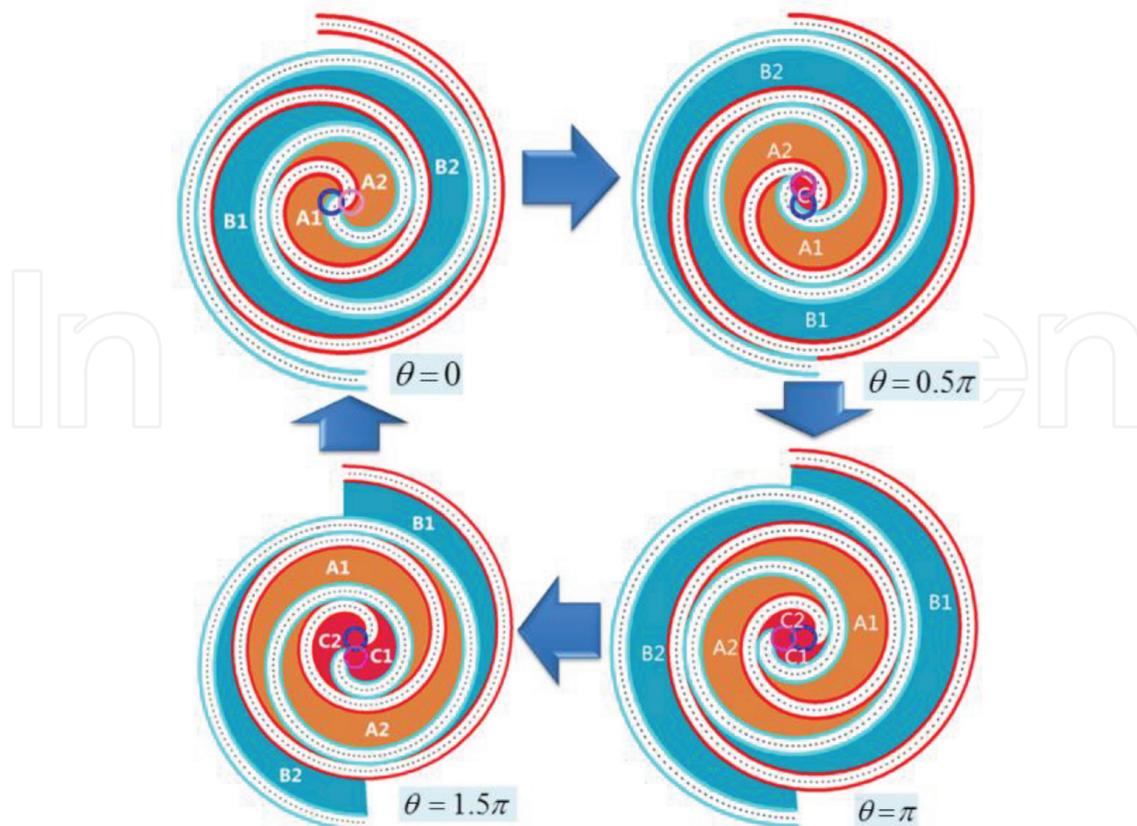


Figure 9. Expansion process of the scroll device under different crank angles [60].

oil-free scroll expander was used in an ORC system to recover the exhaust gas heat from a 30 kW gas turbine as reported by June et al. [61]. The ORC system used a zeotropic mixture with 48.5% R245fa and 51.5% R365mfc as the working fluid and the experimental results indicated the overall efficiency of the ORC system was about 3.9% [61]. The scroll expander was operated in the over-expansion region, which can therefore only achieve the efficiency of 28.4% under the tested condition. The overall ORC efficiency can be much higher than 3.9% if the expansion machine has been operated within the optimal conditions [61]. A prototype of ORC system using an open-drive oil-free scroll expander with R123 as the working fluid was experimentally investigated by Lemort et al. [62]. Results indicated the maximum isentropic efficiency of the scroll expander could be as high as 68% [62]. Muhammad et al. [63] reported the experimental study of a small-scale ORC system recovering the heat from hot steam. An oil-free scroll expander was used in the system to produce electrical power. Results show the maximum electrical power from the system was 1.016 kW when the system thermal efficiency was 5.64% and the isentropic efficiency of the expander was 58.3% [63]. During the experiment, the maximum ORC thermal efficiency was achieved at 5.75% and the scroll expander achieved the maximum isentropic efficiency as high as 77.74% [63]. A hermetic type refrigerant scroll compressor with built-in volume ratio at 3.24 was modified as an expander and used in an ORC system as reported by Yang et al. [64]. The experimental results indicated the maximum shaft power was 2.64 kW when the ORC thermal efficiency was 5.92% [64]. The majority of scroll expanders available from the market are modified from scroll compressors, which are not designed to be used for expansion applications. A separate lubrication system is normally required to lubricate the contact seals of two scrolls and reduce the radial leakage. The other function of the oil is to seal the working fluid inside the expansion chambers during the expansion process to prevent and reduce the flank leakage of the scroll type machine.

Vane expanders have the advantages of simple construction, easy manufacture, low-cost, self-start under load and smooth torque production [35, 65]. The expansion process happens between the cylinder wall and the sliding vanes. When the high-pressure working fluid flows into the inlet port and fills chamber A, the spinning power from the rotor can be gathered as illustrated in **Figure 10**. The pressure differences among the chambers resulted by expansion process driver the rotor. Qiu et al. [56, 66] investigated a vane expander in a biomass fire CHP system with ORC and achieved the isentropic efficiency of 54.5% at the speed of 824 RPM (mechanical work of 1.552 kW). The electricity generated by the vane expander was 792 W, which lighted seventeen 50 W bulbs. The efficiencies of several vane expanders using different working fluids at different working temperatures and pressures were summarized by Aoun [67]. Results showed that the maximum efficiency of 80% was achieved by a vane expander using R-11 at 800 RPM. The rotational speed of vane type of expanders is relatively lower than other expansion machines with commonly from 1500 to 3000 rpm, which can be directly installed to the generator without requiring of gear box [35]. However, the average isentropic efficiency of vane expanders is with the range of 15–55%, which is not that competitive compared with other volumetric expansion machines, as reported by Muhammad et al. [53]. Moreover, this type of expander requires a lubrication system to lubricate the contact surface of the rotor and vane. The existing of lubricate oil will contaminate the working fluid and flow back to the system.

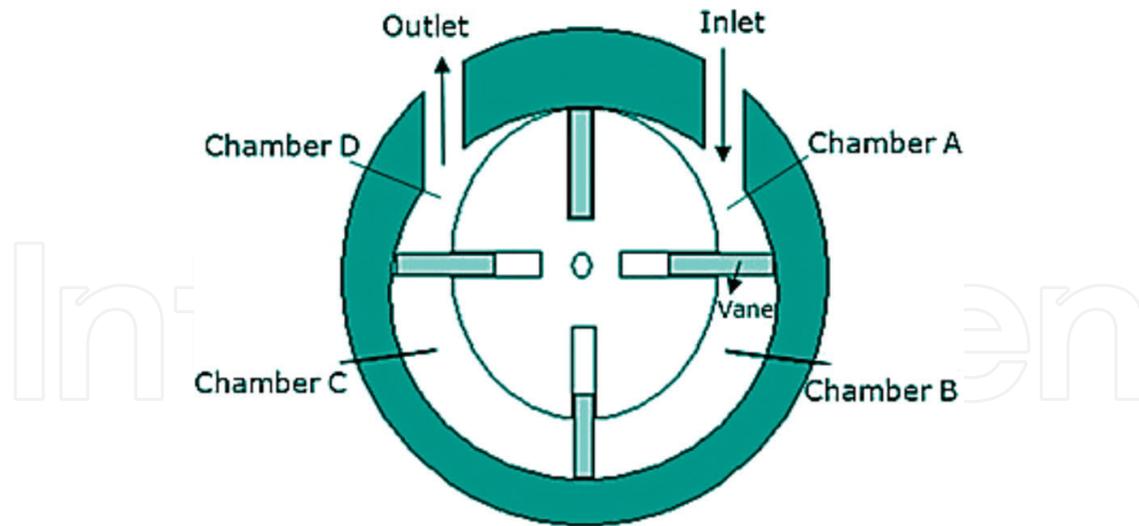


Figure 10. Working principle of vane-type expander [56].

2.4. Cycle investigations

Due to the limited space, the demand of high-power to weight ratio for ORC system and complicated control strategies for vehicle application, the ORC systems are still under technical development and testing stages. The current commercialization status of ORC technology for engine waste heat recovery is mainly for stationary power generation applications because of their desirable stable operating profiles [11]. A representative study on ORC system recovering exhaust energy from a stationary compressed natural gas (CNG) engine was reported by Song et al. [24]. The results showed the electric efficiency of the CNG engine could be potentially improved by a maximum 6.0% and the overall engine brake specific fuel consumption (BSFC) can be reduced by a maximum of 5.0% [24].

The two primary heat sources from ICE systems are engine cooling system and exhaust gases, which almost contain 60–70% of the fuel energy. Engine coolant energy is normally recognized as a heat source that is not worth to recover because the coolant temperature is about 80–100°C. However, the coolant energy contains about 30% of the fuel energy. The effective utilization of engine coolant energy for ORC waste heat recovery of the ICE could potentially improve the overall system efficiency and reduce the pay-back period of the overall cost with a properly designed system [9, 10]. A typical single-loop ORC system recovering both engine coolant and exhaust energy can be shown in Figure 11. A recuperator can be used to recover unused heat at the exit of expansion machine to preheat the working. The coolant energy can either be used as preheating source or main heat source for ORC systems. Only part of the coolant energy can be recovered if it was used as preheating source. For example, a study conducted by Yu et al. [69] investigated the potential of using engine coolant energy as ORC preheating source. The simulation results indicated there is around 75% exhaust heat and 9.5% coolant energy can be recovered from a diesel engine [69]. Tian et al. [70] deeply investigated the effects of fluids and parameters of the ORC system for engine exhaust heat recovery. The performance ORC system using 20 working fluids (boiling point range from -51.6 to 32.05°C) was studied to evaluate the

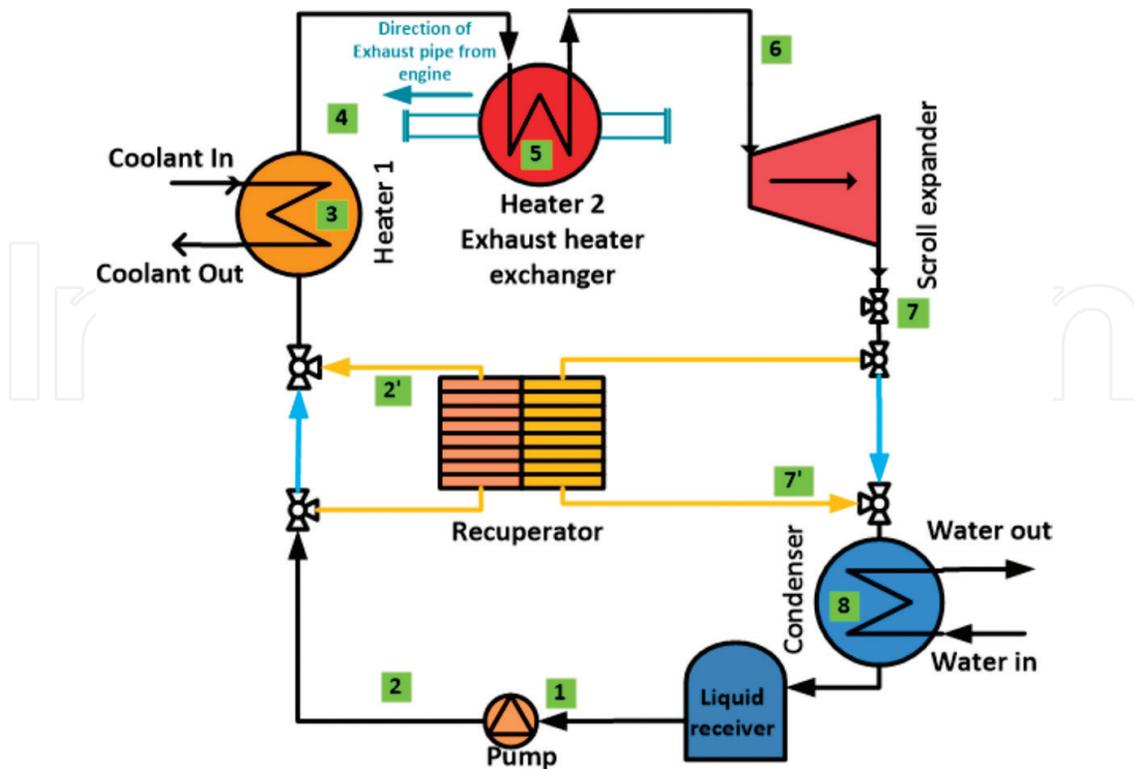


Figure 11. Single-loop ORC for engine coolant and exhaust recovery [68].

cycle parameters such as the overall thermal efficiency, expansion ratio, effective power output and electricity production cost [70]. R141b, R123, and R245fa were identified as the optimal working fluids. The highest thermal efficiency of these three working fluids ranges from 16.6% to 13.3% with the electricity production cost various from 0.30 to 0.35 €/kWh [70]. A simulation study of an ORC system for diesel engine exhaust heat recovery was reported by Zhao et al. [71]. Results indicated the BSFC reduction and the overall thermal efficiency of the engine integrated with ORC unit is 3.61 g/(kWh)–0.66% [71]. Shu et al. [72] recommended to use alkane-based working fluids for diesel engine exhaust heat recovery from the technical and economic point of view [72].

Another potential approach for engine coolant and exhaust recovery is using dual-loop ORC, which adopts two separately ORC systems to regenerate multi-heat sources from ICE [28, 73, 74]. The schematic system diagram and T - s diagram of dual loop ORC system can be found in **Figure 12**. Wang et al. [28, 73] conducted the study on a dual loop ORC to evaluate the performance of a gasoline engine and a light-duty diesel engine. The dual loop ORC system contains a high-temperature loop recovering engine exhaust heat and a low-temperature loop for coolant heat recovery. The proposed concept has the potential to comprehensively reuse all the recoverable heat from engine coolant and exhaust sources [73]. The investigations of using dual loop ORC system were also conducted on a selected gasoline engine and a diesel engine. For the selected gasoline engine, the results showed the dual loop ORC system can effectively improve the overall system efficiency by 3–6% throughout the engine operating region [73]. When the system was used on a light-duty diesel engine, the evaluation results indicated the thermal efficiency can be improved by 8% compared to that of the original engine [28]. At the engine rated power condition, the power output of the combined system can be improved by 26.63% [28]. Further study of the dual-loop ORC for engine coolant and exhaust recovery

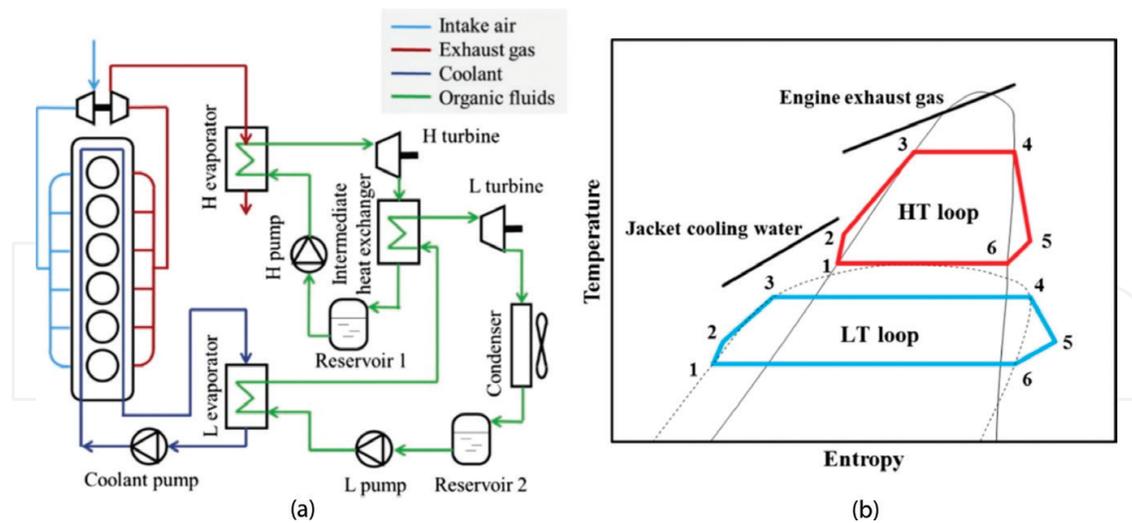


Figure 12. Dual-loop ORC system (a) schematic diagram and (b) T - s diagram [26, 75].

was reported by Shu et al. [74], who investigated the influence of using different working fluids. The high-temperature loop adopted water to recover the exhaust energy and six working fluids have been selected for the low-temperature [74]. The dual-loop ORC system can achieve the maximum overall exergy efficiency as high as 55.05% using R1234yf as working fluid [74]. The dual-loop ORC requires two sets of ORC system components and advanced controlling strategies to balance the different heat sources, which will increase the capital cost of the system and result in high payback period.

2.5. Technical barriers

The power output from the ORC system can be either mechanical or electrical. As introduced in the previous section, the expansion machines can be divided into two types turbine machine using the kinetic energy of the working fluid to drive the expander and positively displace expander producing power by changing the volume of working chamber. When the mechanical configuration is used, the expander shaft is connected to the engine drive belt or a gear. Alternatively, an alternator is used to convert the mechanical work from the ORC expander to electricity. The generated electricity can be used to power the vehicle battery or supply auxiliary utilities. One of the main drawbacks of the solution is the efficiency of available vehicle alternators, which is around 50–60% [5, 9].

The designed evaporation and condensation temperature determines the overall efficiency of ORC system. A higher temperature difference between evaporation and condensation can result in a higher overall ORC efficiency. The engine front radiator is therefore required to reject high-load of heat in order to maintain the low condensation temperature. The limited space for vehicle application restricts the size of engine cooling system. An electrically driven cooling fan is generally not recommended to achieve low condensation temperature because it would sharply reduce the overall system performance.

Another main technical constraint is the dynamic/transient heat sources. In order to maintain the ORC system within the optimal operating region, the control of pump speed, and expander speed are required. Therefore, the complex control strategies are critical to being

developed or advanced ORC systems should be investigated. Using variable speed pump, adding control valves and integrating thermal energy storage system to manage fluctuation waste heat are some common strategies as reported by Manuel et al. [76].

3. Conclusions

Vehicle waste heat recovery technologies are currently under enormous interests for the purpose of reducing emissions and improving overall efficiency. Organic Rankine Cycle is one of the best solutions to recover engine waste heat into mechanical or electrical power. Key conclusions of this chapter can be summarized as follows.

It is critical to characterize the recoverable heat from the engine before designing the ORC system. A broad range of working fluids are available to be selected but there is no working fluid can be recognized as the best to be used in any ORC systems. A high-efficiency alternator to be coupled with ORC expander is in high-demand in order to promote the application of electrical version engine waste heat recovery system. For vehicle application, a compact system is desirable because of the limitation of space. A well-designed engine thermal management system should be considered. The transient heat source performance is the major technical obstacle to use ORC system for engine waste heat recovery and it can be expected either advanced control strategies or thermal energy storage technology should be used to solve the problem and promote the practical application of the ORC system for the vehicle.

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