
Alok Manas Dubey
Professor, Department of Mechanical Engineering,
Raj Kumar Goel Institute of Technology,
Ghaziabad, Uttar Pradesh- 201003, India.

Abstract

Recently waste heat recovery of engines has fascinated ever more concerns. It can elevate engine thermal efficiency and help truck manufacturers meet the limitations of CO₂ emission. Heat available in the exhaust gas of a diesel engine can be a vital heat source to supply extra power using separate organic Rankine cycle (ORC). The organic Rankine cycle (ORC) has been well thought-out as the most prospective technology of WHR. To take full benefit of waste heat energy, the waste heat in both exhaust gases and the coolant need to be recovered. This paper is a comprehensive review of literature about the novel ORC systems used to recover heat from diesel engines. Various advanced configurations such as confluent cascade expansion (CCE) system, organic split cycle (OSC), ORC with an ejector and a regenerator and a dual-loop organic Rankine cycle with and without regeneration have been investigated and reviewed extensively.

Keywords
Regeneration, Split cycle, Dual loop, Ejector, Configuration

Introduction

Engine exhaust and engine coolant are the two primary sources of waste heat from an ICE. Other alternatives for heat recovery comprise of the relatively lesser amounts obtainable from an Exhaust Gas Recirculation cooler and Charge Air Cooler. Although both primary sources have comparable energy content, the higher temperature of the engine’s exhaust makes it thermodynamically more prominent when considered from the viewpoint of exergy. This results in an elevated theoretical efficiency gain when coupled to a heat engine. Previous research in this field involves the recovery from each source, in addition to the ability for synchronized heat recovery from both the engine coolant and exhaust. Literature is full of studies which prefer a Rankine cycle for WHR due to its simplicity and potential to operate with low to medium temperature differences.

ICE-ORC system description

In the system shown in Fig.1, the exhaust gas rejects heat in the evaporator and is subsequently released to the atmosphere whereas the jacket water initially discards heat in the preheater and then returns back to the ICE(2). The working fluid is initially pumped to high pressure and after that preheated by the jacket water and then heated by the exhaust gas in the evaporator. Subsequently the formed vapor enters the expander to produce useful work. Next the low pressure vapor goes into the condenser, where it condenses into saturated liquid by exchanging heat with cooling water. The thermal energy is completely recovered from the exhaust gas. This lowers the temperature of the exhaust gas at the exit of the evaporator to the least value allowed. On the contrary, the thermal energy of the jacket water is fully recovered, and the temperature of the jacket water at the exit of the preheater is the same as the return temperature.

Fig.1. Schematic representation of the ICE Organic Rankine Cycle(2)
Confluent Cascade Expansion CCE-ORC system description

Schematic of the CCE-ORC (6) system is shown in Fig.2. This system comprises of a low temperature loop and a high temperature loop. A fraction of working fluid is compressed to an elevated pressure in order that high evaporating temperature can be obtained to equal the exhaust temperature. Next this working fluid is superheated by exhaust gases and flows into the HT turbine. In the low temperature circuit, the left fraction of the working fluid is pumped to lower pressure in order that the evaporating temperature in this loop is lowered in comparison to the coolant temperature. After that the compressed working fluid exchanges waste heat energy of coolant and is converted to saturated vapor in the low temperature evaporator. The working fluid following the low temperature evaporator and the high temperature turbine combine together, and subsequently flows into the LT turbine. After that the working fluid flows into the condenser and is condensed into saturated liquid by air.

Fig.2. Schematic representation of the Confluent Cascade Expansion Organic Rankine Cycle (6)

Organic split-cycle (OSC)

The Organic split cycle (1) is a result of the execution of a thermodynamically useful split stream evaporation process as shown in Fig.3. The split streams are produced in the separator which then enters into the boiler section in the preheater and the evaporators 1 in a simple manner, like any other simple split cycle. The Organic split cycle consists of the same components as the conventional recuperated cycle between the states 4 to 3. The working fluid partly evaporates in the recuperator and then enters in a two-phase state to the separator. Here the liquid and vapour phases are separated in a liquid and vapour stream. The liquid stream has a lower concentration of the vapour and is named as the lean stream while the vapour stream has a higher concentration of vapour and is called the rich stream.

Fig.3. Schematic representation of the Organic Split Cycle (1)

The lean stream is pumped to the boiler pressure and the rich stream is initially condensed and after that pumped to the boiler pressure and subsequently preheated to a temperature equivalent to the pressurized lean stream. The two streams combine at the outlet of the evaporator 1 and the remaining heating and boiling process is accomplished in evaporator 2 and the superheater. The superheated vapour proceeds to enter the turbine or a scroll expander to produce mechanical work.

ORC with an ejector and a regenerator (ERORC)

The cycle configuration of the EORC (3) with an ejector and a regenerator are shown in Fig.4. EORC consists of a regenerator along with the ejector in an organic Rankine cycle. A portion of the turbine exhaust energy is recovered with the help of the regenerator and consequently the load on the evaporator is reduced. This cycle comprises of two loops. In the first loop (6-8-9-10-11-3-5-6) a fraction of the condensed liquid coming from the condenser is
pumped to the regenerator. Next this liquid is heated in the first-stage evaporator and is subsequently vaporized to saturated steam. The saturated steam further expands in the turbine to produce external work. The exhaust steam from the turbine subsequently enters the regenerator and serves as a secondary fluid for the ejector.

**Fig. 4. Schematic representation of the ORC with an ejector and a regenerator (1)**

In the second loop (6-7-1-3-5-6) the remaining portion of the condenser exhaust fluid is pumped into the second-stage evaporator where it is heated to saturated steam. Lastly, this saturated steam goes into the ejector as the primary working fluid and induces the secondary fluid into the ejector.

**Dual loop Organic Rankine cycle (DORC)**

The configuration diagram of DORC (5) system is shown in Fig. 5. There are two branches high-temperature branch and low-temperature branch both of which adopt sub-critical systems. An organic working fluid and water are used as the working fluids because of water’s good chemical stability and organic working fluids superior performance. To obtain maximum thermal efficiency it is desirable to superheat water in the HT circuit to the maximum as possible limit considering the limitations of the exhaust heat exchanger design, whereas superheating should be avoided to maximum possible extent for organic working fluids in the low temperature circuit. The thermodynamic process of the HT loop is identified as 1–3–4–5–1 which is detailed described as follows. The HT loop consists of a pump (P_{HT}), an evaporator (E_{HT}), a turbine (T_{HT}) and a condenser (C_{HT}). The evaporator is driven by the high-temperature exhaust. The LT loop consists of a pump (P_{LT}), three evaporators (E_{ILT}, E_{2LT} and E_{3LT}), a turbine (T_{LT}) and a condenser (C_{LT}). These three evaporators are driven by the engine coolant, residual heat of the HT loop and low-temperature exhaust, respectively. E_{ILT} and E_{2LT} are liquid–liquid heat exchangers and E_{3LT} is a gas–liquid heat exchanger. These two loops are coupled through condenser C_{HT}, which is also evaporator E_{2LT} of the LT loop, in which the residual heat of the HT loop is the heat source and the organic refrigerant of the LT loop is the working fluid.

**Fig. 5. Schematic representation of the Dual loop Organic Rankine Cycle (5)**

The high-pressure liquid (point 1) flows into the evaporator (E_{HT}) and is heated into a high-pressure superheated vapor by the high-temperature exhaust. The superheated vapor (point 3) then flows into the turbine (T_{HT}) to convert thermal energy into mechanical work through expansion and the pressure of the working fluid lowers. The low pressure vapor (point 4) exits from the turbine (T_{HT}) and flows into the condenser (C_{HT}) to release heat to the organic refrigerant of the LT loop, where the low pressure vapor (point 4) is completely liquefied and condensed into a saturated liquid (point 5). Then it flows into the pump (P_{HT}) to be pumped into a high pressure liquid (point 1), a next loop begins. The thermodynamic process of the LT loop is identified as 6–7–8–9–10–11–6, as shown in Fig. 4. The generated high-pressure liquid (point 6) continuously flows into evaporators (E_{ILT}, E_{2LT}, E_{3LT}) to be heated by the engine coolant, residual heat of the HT loop and low-temperature exhaust. After each heating, the working fluid reaches point 7, point 8 and point 9, respectively. The non-isentropic expansion process in turbine T_{LT},
condensation process in condenser $C_{LT}$ and non-isentropic compression process in pump $P_{LT}$ are similar to those in the HT loop.

**Regenerative Dual loop Organic Rankine Cycle (RDORC)**

The schematic of the RDORC (4) with an ejector and a dual loop cycle are shown in Fig.6. The HT loop comprises of a condenser ($C_{HT}$), an exhaust evaporator ($E_{HT}$), a regenerator ($R_{HT}$), a turbine ($T_{HT}$), and a pump ($P_{HT}$). The LT loop consists of three evaporators ($E_{1LT}$, $E_{2LT}$ and $E_{3LT}$), a condenser ($C_{LT}$), a turbine ($T_{LT}$), a regenerator ($R_{LT}$), and a pump ($P_{LT}$). $E_{1LT}$ is driven by the engine coolant, $E_{2LT}$ by residual heat of the high temperature circuit and $E_{3LT}$ by low temperature exhaust. The condenser of the HT loop which is also the second evaporator of the LT loop couples the two loops. These two loops include five typical thermodynamic processes: expansion process, pumping process, constant pressure heating process, regeneration process and constant pressure condensing process. There are three evaporation processes (6s–7, 7–8, 8–9) in the low temperature circuit.

![Fig.6. Schematic representation of the Regenerative Dual loop Organic Rankine Cycle (4)](image)

In the HT loop the low-pressure saturated liquid is pressurized by the pump and subsequently flows into the regenerator and heated by the low pressure vapor coming out of the turbine. Afterwards the working fluid flows into the evaporator to be heated into a superheated or saturated vapor. The fluid is heated thrice in the three evaporators $E_{1LT}$, $E_{2LT}$ and $E_{3LT}$. The working fluid of the HT loop is condensed by the working fluid of the LT loop, while, in the condenser of the LT loop ($C_{LT}$), the working fluid is condensed by supplied cooling water.

**Conclusion**

A review of the open literature with respect to WHR finds that IC engine exhaust and cooling water contains heat with sufficient exergy to justify implementation of a secondary cycle. The corresponding researchers have presented an improvement in the efficiency of the ORC by the above explained modifications.

**References**