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Performance Analysis of Modified Organic Rankine Cycles: A Literature review

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ABSTRACT

The organic Rankine cycle (ORC) is generally accepted as a feasible technology for conversion of low temperature heat into electricity. A more intensive use of energy source, through this technology could facilitate an increase in the energy efficiency in the industrial sector without any harm to the environment. Several ORC waste heat recovery plants are already in operation. The basic ORC is slowly being adopted into industry; however modifications are required to increase its performance and efficiency. Thus, a next reasonable step is the introduction of novel ORC architectures. An overview of the research papers in this area shows a considerable gap namely the modifications in the configurations of the existing systems. At present there is none that covers all aspects that must be taken into account in ORCs. This paper is a comprehensive review of literature about the ORC that contains the ORC configurations, applications, modeling and optimization. Various important modifications, such as internal regeneration, solution circuit, vapor liquid ejector, two stage evaporation and double pressure on the organic Rankine cycle performance and optimization have been investigated and reviewed extensively.

Keywords:Regeneration, Ejector, Double pressure, Heat recovery, Efficiency, Performance

I.INTRODUCTION

The Rankine cycle is considered the most common and competitive power generation cycle that is used to produce electricity from solar thermal energy. The four main components of a Rankine cycle are (1) a boiler, which evaporates the working fluid; (2) a turbine, in which the working fluid expands and generates power; (3) a condenser, in which the fluid condenses at lower pressure; and (4) a pump, which pressurizes the condensed fluid. ORCs employ organic fluids, such as hydrocarbons, refrigerants and siloxanes and are considered to be a better solution to utilize heat from low and medium temperature sources due to the low boiling points of organic fluids. ORCs utilize energy from different energy sources such as geothermal, ocean thermal, biomass, waste heat recovery and solar thermal.

Several modifications were suggested and performed to increase the overall efficiency of Rankine cycles. Modifications could be in the Rankine cycle itself by recuperation, also called regeneration, which includes the use of an internal heat exchanger to utilize the heat from the working fluid stream leaving the turbine in preheating the high pressure cold stream entering the evaporator or the boiler. Also the modification could be by a reheating process which includes reheating the working fluid leaving the high pressure turbine in the boiler to enter again a low pressure turbine to generate additional power.

II.ORGANIC RANKINE CYCLE WITH LIQUID-FLOODED EXPANSION AND INTERNAL REGENERATION (ORCLFE)

The concept of flooded expansion has been firstly investigated by Hugenroth et al. [1] in an Ericsson cycle. A secondary fluid or flooding medium, for example lubricant oil, being in thermal equilibrium with the working fluid at the inlet of the expander, acts as thermal buffer in the working chamber limiting the temperature drop during the expansion process. Theoretically, the working fluid exiting the expander is still at a significantly high temperature and superheated, at least in case of dry/isentropic working fluids. Thus, it can be used to preheat the working fluid exiting the pump by means of an internal regenerator, which increases the thermodynamic cycle efficiency. Achieving a quasi-isothermal expansion and the internal regeneration contribute to improving the overall efficiency of the ORC. These improvements can be related to reheat stages or feed-water heaters in traditional steam cycles but at reduced costs and complexity.

Woodland et al. [17] analyzed the benefits of flooded expansion and internal regeneration in an ORC by considering different working fluids (CO2, n-pentane, R134a, R245fa, acetone and R717) and two flooding media (water and lubricant oil Zerol 60). The liquid-flooded ORC running with wet fluids, such as water, acetone and R717, showed significant improvements because the more isothermal expansion process led to a superheated vapor at the expander outlet which allowed employing internal regeneration, normally not feasible without flooded expansion. Overall, the flooded-expansion improved the efficiency of all working fluids when an optimal amount of flooding liquid was used. The main challenges raised from practical considerations were the need of properly designed positive displacement expanders and the impact on the exergetic heat conversion efficiency due to the presence of a secondary heater for the flooding loop. The enhancements of the flooded expansion are directly linked to the ability of the volumetric expander to accept large amounts of liquid within the working chamber. In oil-injected expanders the oil mass fraction is typically below 5% of the total flow rate and it serves for the purposes of sealing and reduction of friction losses. The term flooding implies having significantly higher oil mass fraction percentages. Up to now, oil-flooded scroll expanders have been investigated both numerically and experimentally.

Hugenroth et al. [1, 2] utilized an automotive open-drive scroll compressor (Sanden TRS-105) with a displacement volume of 104.8 cm3. A similar machine was also used as an expander. The main reasons behind that choice were the availability at low cost, the efficiency, the displacement requirements and the ability to handle the flooding medium without any damage after several hours of testing. Screw machines were also considered but the available displacement volumes were too large. The overall expander efficiency was a strong function of the pressure ratio due to under- and over-expansion losses. In particular, the built-in volume ratio of the expander was smaller than the pressure ratio required by the system. The expander power decreased with the increase of the amount of oil. Furthermore, the higher the pressure ratio imposed, the lower was the detrimental effect of having oil in the expander. Still, the maximum overall isentropic efficiency obtained was approximately 67.5% for the flooded compressor (the rated scroll compressor efficiency was 84%). These effects were attributed to the fact that the expander was not designed for liquid-flooding operation. Bell et al. [3] optimized the geometry of the same scroll compressor for liquid-flooding. In particular, the internal volume ratio, suction and discharge ports were the main parameters of influence. The simulations results showed that for the same displacement and with an internal volume ratio of 2.7, the maximum overall efficiency achievable was approximately 73%. Georges [4] characterized the performance of the same compressor employed as an expander in an ORC system with liquid-flooded expansion. The experimental data revealed that there exists an optimum amount of oil that maximizes the power output. It was concluded that high built-in volume ratios (above 4) are necessary to benefit from flooding the expander. Similar conclusions were also drawn by James et al. [5] while investigating the possibility of using flooded expansion for a high-temperature Ericsson cycle. Pressure drops and drag resistance due to the presence of oil were detrimental to the performance of the machine.

Ziviani et al. [6] demonstrated that Organic Rankine cycle with liquid-flooded expansion and internal regeneration (ORCLFE) leads to improvements in system efficiency with respect to conventional ORC with internal regeneration in the heat input temperature range from 80^o C to 200^o C. A detailed thermodynamic cycle model was developed to include a physical-based expander model to evaluate the impact of built-in volume ratio, flooding ratio, mechanical losses and the solubility of the working fluid into the lubricant oil. As waste heat recovery from 100^o C to 150^o C was the main application of the ORCLFE under investigation, low-GWP refrigerants such as R1234ze (Z), R1233zd (E) and R1336mzz (Z) were considered as potential replacements of R245fa. A single-screw expander, which has been previously characterized, was employed to optimize the ORCLFE at three heat source temperatures (100^o C, 120^o C and 150^o C) for each refrigerant, in order to obtain more realistic performance predictions.

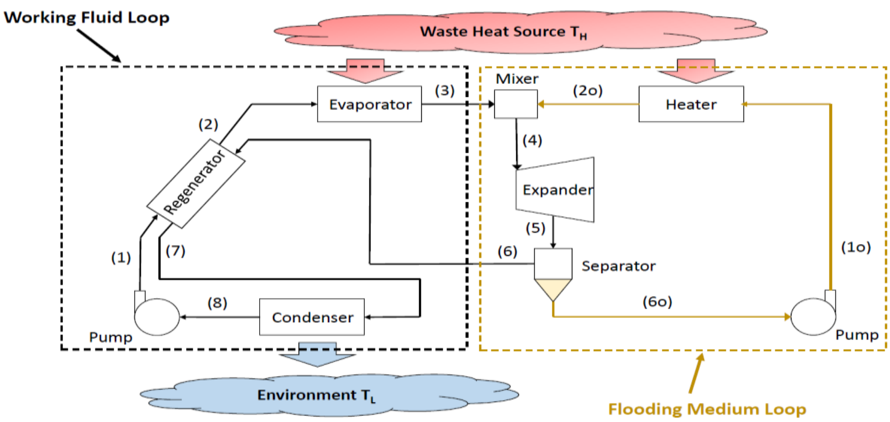

Fig.1Schematic representation of the Organic Rankine Cycle with liquid flooded expansion and internal regeneration [6]

The cycle schematic of ORCLFE is proposed in Fig. 1. Both the primary working fluid (1) and the flooding medium (1o) are pumped to the high system pressure. While the flooding medium is heated up directly by the heater (2o), the working fluid is first preheated inside the internal regenerator (2) and then vaporized and superheated by the evaporator (3). The finite heat source is used to heat up the primary working fluid and the flooding medium. State (3) and state (2o) are assumed to be at the same temperature and pressure conditions. The two fluids undergo a mixing process (4) prior to entering the expander. In the mixing section, a homogeneous mixture is ideally achieved. After the expansion process occurs (5), the vapor phase of the working fluid is separated from the flooding medium inside a single or multiple liquid separators. The flooded expansion, guarantees a significant degree of superheating of the working fluid at the expander outlet which represents a favorable condition for the internal regeneration. The working fluid vapor phase (6) is used to regenerate (7) before it is condensed in the condenser (8). The portion of flooding medium separated is then pumped back to the high pressure side and the cycle is repeated.

By employing a single-screw expander with an internal volume ratio of 5.3, the ORCLFE leads to improve the thermodynamic cycle efficiency up to approximately 8% in the case of R1233zd (E) at 150^{o} C. Although the benefits of the flooded expansion in term of increased power output are limited to few percentage points, if the flooding medium is able to mitigate frictional losses, the potential improvements on both net power output and cycle efficiency can be significant, i.e., above 20%. Furthermore, the simulation results showed that it is possible to achieve up to 50% of the Carnot efficiency. Due to the fact that screw expanders often require a dedicated lubrication system, the flooded loop with internal regeneration can be implemented with limited cycle adjustments. The selection of the lubricant oil as the flooding medium plays an important role. In the case of R245fa and ACD100FY, the solubility effect yielded an increase in oil pump specific work of up to three times, which reduced the net power output of the system.

III.ORGANIC RANKINE CYCLE WITH SOLUTION CIRCUIT

Mago et al. [7] presented that RORC could not only produces higher efficiency but also reduces the heat absorption of the system to produce the same amount of power with a lower irreversibility. Pei et al. [8] designed an innovative of low temperature solar thermal electric generation with RORC. They found that RORC increases the thermal efficiency by about 4.9%. Xi et al. [9] investigated ORC, RORC, and the double-stage regenerative organic Rankine cycle (DRORC). The results indicate that the DRORC gives the highest efficiencies. Roy and Misra [10] analyzed and compared the RORC in order to select a better working fluid using the system efficiency as the objective function. Fernández et al. [11] compared the saturated and superheated, subcritical and supercritical RORCs and evaluated the influence of internal heat exchanger (IHX) on thermal efficiency. They found that the supercritical RORC is preferable for high temperatures heat source. Moreover, the thermal efficiency is directly related to the internal heat exchanger.

Franco [12] utilized two different configurations, two basic cycle configurations, and two recuperated cycles to analyze the exploitation geothermal fluids dominated by low temperature water. The system performance increased a little, but significant reduction was found in cooling system surface area (up to 20%). Li et al. [13] constructed and experimentally analyzed the RORC with a geothermal source temperature of 130 _C. They found that the RORC has a thermal efficiency of 7.98%, which is higher than that of the ORC by 1.83%. In general, RORC not only decreases the thermal load of the condenser but also reduces the irreversible loss in the evaporator, but the system performance can be improved only to a small extent. Lecompte et al. [14] studied the ORC applied to a combined heat and power system. Kevin et al. [15] presented a set of concepts to create a customized including reheat stages, multiple pressure levels and balanced recuperators. Liu et al. [16] investigated the effect of condensing temperature glide on the performance of ORC with zeotropic mixtures.

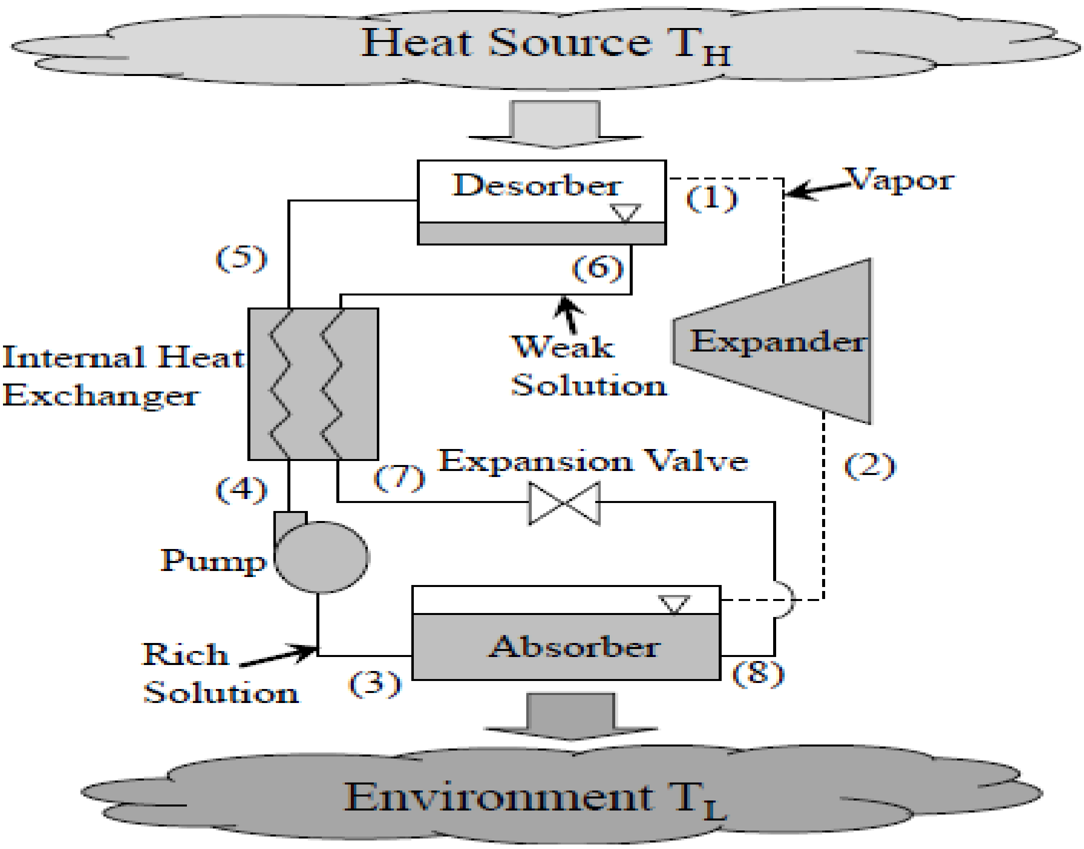

Fig.2. Schematic representation of the Organic Rankine Cycle with Solution Circuit [17]

The Organic Rankine Cycle with Solution Circuit (ORCSC), employs a zeotropic mixture of the primary working fluid and an absorbent characterized by a large boiling point difference. This enables the separation of the more volatile component (the primary working fluid) in the vapor phase from the solution in the liquid phase for a range of source temperatures. The use of a zeotropic fluid results in a temperature glide during the phase change process. As the mixture is heated or cooled at constant pressure, the saturation temperatures are not constant, and instead vary with the composition changes of the liquid and vapor phases.

State (1) represents the outlet of the desorber (note that a separator may be used to separate the vapor and liquid streams at the desorber outlet). At this state, the waste heat stream has heated the mixture, and the absorbate is desorbed from the solution. The absorbate vapor stream (which may contain a portion of absorbent vapor) then enters the expander, where it is expanded to its low-pressure state (2). State (3) represents the outlet of the absorber, where the absorbate has been resorbed into the solution to form a rich solution. Since absorption is an exothermic process, the absorber rejects heat to the environment during this process. Following this, the rich solution is pumped to the high-pressure state (4) and is subsequently preheated by an internal heat exchanger (5) before entering the desorber. State (6) represents the liquid-phase weak solution at the desorber outlet. The weak solution stream is then subcooled (7) through the internal heat exchanger, and expanded to the low-pressure state (8) by an expansion valve.

A simple ORC with water as the working fluid yielded almost 65% of the Carnot efficiency for a constant heat source temperature, and was found to be more efficient than many of the enhanced cycles. However, a range of practical considerations must be taken into account and weighed together with the thermodynamic optima. When using water in an ORC, the water expands into the vapor dome and generates a low vapor quality and low density at the expander exhaust. In addition, the ORC has a high expander pressure ratio, and vacuum pressure condensation. These issues may make water unattractive as the working fluid. The ORCSC appears to be the poorest performer, but it provides the ability to use a temperature glide to match the temperature profiles of real source and sink fluids and facilitates intrinsic capacity control. This may lead to higher overall system efficiencies when coupled with sources that have varying heat input temperatures or loads. More application-specific studies that address the nature and capacity of the source and sink streams are required to identify where this ability may be most advantageous. The ORCLFE always improves system efficiency and mitigates expander exhaust quality concerns for wet working fluids. However, it limits the choice of expander to positive displacement designs and requires the selection of a flooding medium that does not mix or react with the primary working fluid.

IV.ORGANIC RANKINE CYCLE WITH A VAPOR-LIQUID EJECTOR

To improve the ORC system efficiency, researchers have devoted their efforts to eliminate the pump. Li et al. [18] utilized gravity of the working fluid to drive ORC, and the performance was 0.9% higher, however, with a requirement of 20.9m of height. Yamada et al. [19] proposed a pumpless ORC by switching the heat source and heat sink between the evaporator and condenser. Gao et al. [20] and Jiang et al. [21] carried out further investigations on this pumpless ORC under different operating conditions and higher output power, the obtained maximum system efficiency was 2.4%. Richardson [22] introduced a bypass of high pressure vapor in the evaporator to pressurize the liquid in the condenser to replace the pump; however, it leads to the decreasing of expender output power due to reduced mass flow rate. It seems that the system improvement by eliminating the pump is limited. Xu et al. [23] introduced a regenerative ORC (RORC) by adopting the vapor-liquid ejector in a way of extracting vapor with intermediate pressure from the expender to induce the liquid from the condenser, and discharging to the pump.

Chen et al, [24] proposed a novel organic Rankine cycle with a vapor liquid ejector (EORC) to enhance the system performance. It was compared to the conventional ORC and a regenerative organic Rankine cycle (RORC), and the results showed that it had higher system efficiency when the pump had a low efficiency and the evaporating temperature is high. A parametrical study on this novel system was further carried out with three working fluids, namely, R123, R1233zd (E) and R1336mzz (Z). The ejector behavior and system performance were strongly interacted, which were elaborated and discussed. There exist optimal ejector entrainment ratios that minimize the pump work and maximizes the system efficiency. The ejector area ratio and the subcooling at the condenser outlet had great influence on the ejector pressure lift, leading to the significant variations of temperature in the evaporator I, however, their influence on the expander output power was moderate. As for the condensing temperature, it had remarkable effect on system performance except the ejector pressure lift. The three candidates had similar features of variations for the considered variables. R1233zd (E) was recommended as the good working fluid since it had higher system efficiency than R1336mzz (Z) and was more favored by the environment than R123.

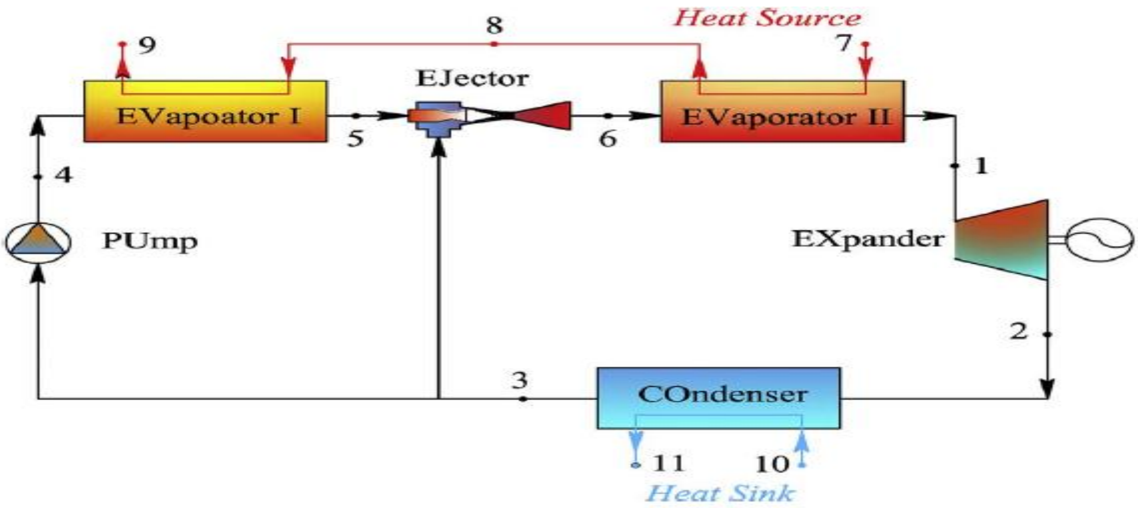

Fig.3. Schematic representation of the Organic Rankine Cycle with vapor-liquid ejector [24]

A novel arrangement of the vapor-liquid ejector in ORC, abbreviated as EORC, is shown in Fig.3. It consists of two evaporators (I and II), a vapor-liquid ejector located between the evaporators, a pump, an expander and a condenser, as shown in Fig. 3. The liquid out from the condenser is divided into two loops: one is convoyed via the pump (3–4) into the evaporator I for vaporization (4–5) and enters in the ejector nozzle as the primary flow; the rest liquid is induced into the ejector as the secondary flow. The primary vapor and the secondary liquid flows experience complex mass, momentum and heat transfer in the ejector, and become liquid at the ejector outlet with a pressure that is higher than the primary vapor (5 & 3–6). The liquid then vaporizes in the evaporator II (6–1), expands in the expander to produce power (1–2), and condenses in the condenser (2–3), to complete the cycle. It is pointed out that the EORC could use two heat sources with difference temperatures in despite of that only one heat source is illustrated in Fig. 3.

Chen et al, [24] showed that EORC has much less pump work than ORC and RORC, and has an identical expander output power to ORC which is higher than that of RORC. The performance of EORC in terms of the system efficiency was superior to that of ORC and RORC when the pump efficiency was lower than 57% and the evaporating temperature is higher than 95°C.EORC was then parametrically studied with three working fluids by varying the ejector entrainment ratio, the ejector area ratio, the condensing temperature and

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the subcooling at the condenser outlet. It was shown that there exists the optimum values of entrainment ratio for the smallest pump work and largest system efficiency, which are 3.4 and 2.5 for R123 and R1233zd (E), respectively, while for R1336mzz (Z) they are 3.5 and 3.9 where the pump work was minimized and the system efficiency was maximized. The ejector area ratio has considerable influence on the ejector pressure life, and the temperature in evaporator I, but its effect on the system efficiency was insignificant. The condensing temperature severely influenced all the discussed parameter. The subcooling had great impact on the ejector pressure lift, and it moderately effects on the system efficiency. R1336mzz (Z) had the largest pressure lift. R123 had the highest thermal efficiency, followed by R1233zd (E) and then R1336mzz (Z). It was however recommended that R1233zd (E) was a good candidate for EORC given the fact that R123 was not an environmentally friendly working fluid.

V.DOUBLE-PRESSURE ORGANIC RANKINE CYCLE SYSTEM DRIVEN BY GEOTHERMAL HEAT SOURCE

Astolfi et al. [25, 26] conducted the thermodynamic and techno-economic analysis of medium-low temperature geothermal sources organic Rankine cycle power plants. Zhai et al. [27] studied the influence of working fluid properties on system performance. Rodríguez et al. [28] compared the exergetic and economic performance between ORC and Kalina cycle for low temperature geothermal system. Zhang et al. [29] made the performance comparison between subcritical organic Rankine cycle and transcritical organic Rankine cycle for low-temperature geothermal system. Wang et al. [30] proposed a transcritical CO_2 geothermal power generation system based on the cold energy utilization of liquid nature gas (LNG) and conducted the thermodynamic analysis.

As mentioned above, the work basically focused on the single-pressure organic Rankine cycle, double-pressure organic Rankine cycle has not been discussed. The double-pressure organic Rankine cycle system can utilize energy more efficiently due to the principle of energy cascade utilization, so more research should be done in the field of double-pressure ORC system.

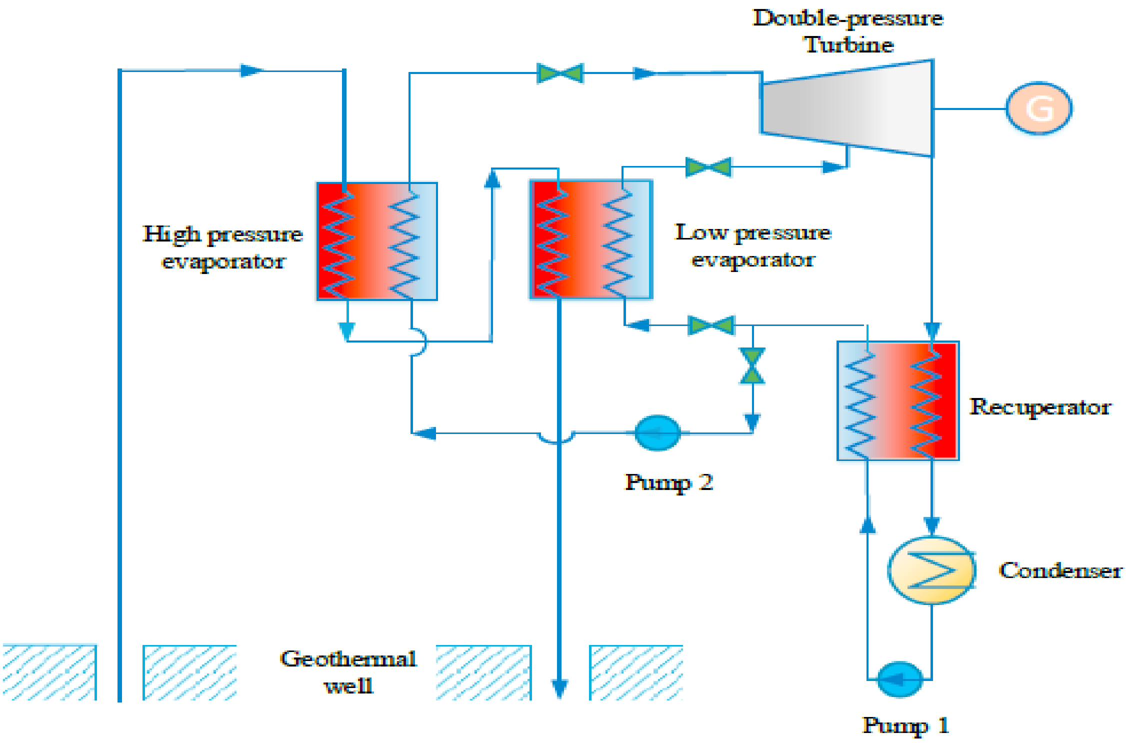

Fig.4. Schematic diagram of the double-pressure ORC system [31]

The double-pressure ORC system contains six components: double-pressure turbine, high pressure evaporator, low pressure evaporator, recuperator, condenser and generator. Geothermal water is pumped from geothermal well and then sent to evaporators to heat organic fluid. The heated organic fluid vapor from high pressure evaporator and low pressure evaporator with different temperatures and pressure are sent to turbine to produce mechanical work. The turbine exhaust is delivered to recuperator to utilize the remaining heat energy for a better system performance and then sent to condenser to be condensed to liquid by cooling water. The condensed organic fluid is pumped and divided into two parts: one is sent to low pressure evaporator and the other is pumped to a higher pressure and then sent to high pressure evaporator.

The double-pressure ORC system achieves the cascaded utilization of energy, which can improve the efficiency of energy conversion. Sun et al.[31] established a mathematical model based on thermodynamic laws, and evaluated the overall system performance. A parametric analysis was conducted to examine the effects of some key thermodynamic parameters, namely turbine high-level inlet pressure, turbine low-level inlet pressure, turbine high-level inlet temperature, on the system performance. Parametric optimization was conducted by means of genetic algorithm (GA) to find the maximum system performance. At the same time, the performances of three organic working fluids are examined. Results indicate that R245fa has a better performance among the three organic fluids. The exergy efficiency of overall system exceeded 5.8% under the supply water of 120^{o}C, and it produced more than 800kW electricity with the geothermal water at the mass flow rate of 250t/h. It was also found that the exergy efficiency had peak value under the effect of turbine high-level inlet pressure and turbine low-level inlet pressure. Increasing turbine high-level inlet temperature brought a positive effect to the system performance. Exergy analysis was also conducted and the result showed that the main exergy loss occured in high-pressure evaporator. By system optimization, the double-pressure organic rankine cycle had a better performance than a single pressure system.

VI.TWO-STAGE EVAPORATION STRATEGY TO IMPROVE SYSTEM PERFORMANCE FOR ORGANIC RANKINE CYCLE

On the premise of ensuring the temperature difference at the pinch point, the single-evaporation in the evaporator is a major factor affecting the system irreversible loss. Many literatures have studied double-loop ORC to increase the system performance. Kosmadakis et al. [32] and Kosmadakis et al. [33] presented the parametric study and economic evaluation of a two-stage solar organic Rankine cycle (SORC) for reverse osmosis desalination. It was found that the two-stage SORC significantly improves the efficiency and reduces the system cost. Wang et al. [34] analyzed the combination of a gasoline engine with a dual loop ORC. The results indicate that the thermal efficiency increases by 3–6% throughout the operating region of the engine. Liu et al. [35] proposed a two-stage Rankine cycle consisting of a water steam Rankine cycle and an ORC for power generation. Zhang et al. [36] and Shu et al. [37–39] analyzed a dual-loop organic Rankine cycle (DORC) consisting of high- and low-temperature cycles. They found that DORC with double regenerators performs better and that low condensation temperature of the high-temperature loop is beneficial to performance optimization better. Yang et al. [40] designed a set of dual-loop ORC to recover exhaust energy. The thermal efficiency is increased by 13% for the high load region and the brake specific fuel consumption can be reduced by a maximum 4%. Mohammad Khani et al. [41] utilized a gas turbine-modular helium reactor by two ORCs. Li et al. [42] presented a parallel double evaporator organic Rankine cycle (PDORC) to decrease the system irreversibility and to enhance the power output. Moreover, Stijepovic et al. [43] indicated that the multiple pressure system could have significant improvements in system performance.From the above-mentioned studies, it can be obtained that the two- or multi-stage ORC can indeed improve the system performance. However, it should be pointed out that the cycle configurations in literatures [32–43] are all parallel systems in essence, and this kind of configuration could adversely reduce the irreversible loss of the high-stage evaporator for the working fluid side. Moreover, no literature has been found to compare parallel and series two-stage organic Rankine cycles.

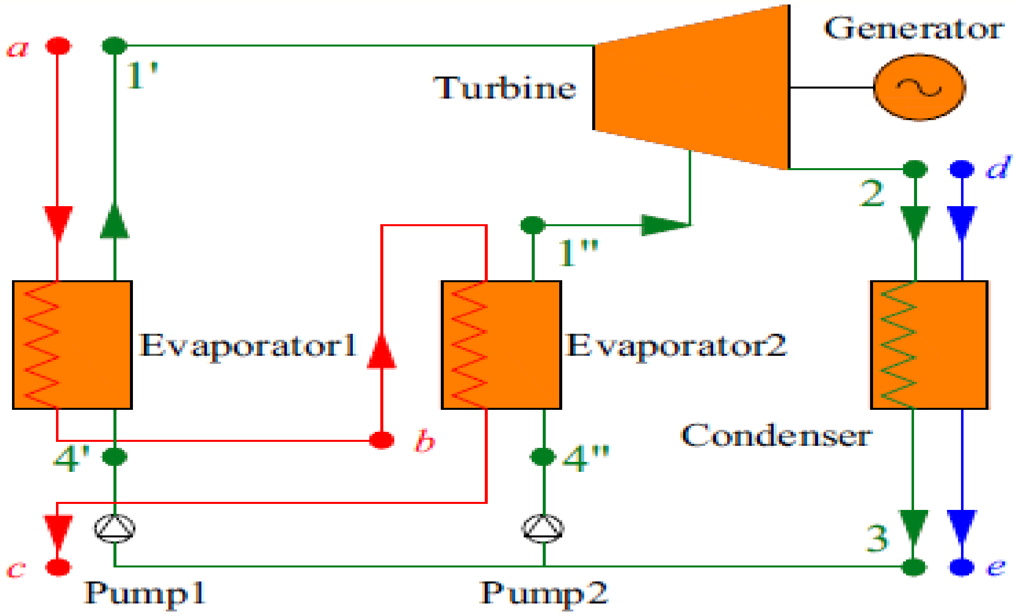

Fig.5. Schematic diagram of the parallel two-stage organic Rankine cycle [44]

Evaporator leads to the highest irreversible loss and results in reducing cycle efficiency. The heat source was segmented into two temperature ranges, which provides the possibility of two-stage evaporation. Based on cycle configuration, parallel two-stage organic Rankine cycle (PTORC) and series two-stage organic Rankine cycle (STORC) were put forward. The objective was to evaluate system performances, thereby elucidating their respective availability. Geothermal water inlet temperature (GWIT) ranges from 90 to 120^{o} C, with R245fa as the working fluid. The ratio of net power output to the total thermal conductance was chosen as the objective function. The results showed that PTORC and STORC are significantly influenced by intermediate geothermal water temperature (IGWT) and evaporating temperatures. PTORC and STORC could evidently reduce the irreversible loss, and STORC is more significant. PTORC and STORC can output more net power, depending on cycle configuration and GWIT. STORC enhances the net power output with GWIT, whereas PTORC is just the opposite. The total thermal conductance of PTORC and STORC are almost equal with that of ORC. STORC presents more excellent system performance and deserves to be popularized in engineering applications.

The PTORC shown in Fig.5 is almost the same with the basic ORC, and the main difference between them two is that the PTORC adopts double cascade- evaporating strategy whereas the basic ORC only has one. The PTORC consists of a high-pressure evaporator 1, a low-pressure evaporator 2, a high-pressure pump 1, a low-pressure pump 2, an induction turbine, a generator, a condenser, a cooling pump, and a cooling tower. The specific flowchart for the working fluid is as follows: The non-saturated liquid with a higher pressure and a lower temperature is pumped into the evaporator 1 by the pump 1, It could absorb heat from geothermal water (process a–b) coming from production wells to generate high-pressure saturated or superheated vapor (process 4'–1').

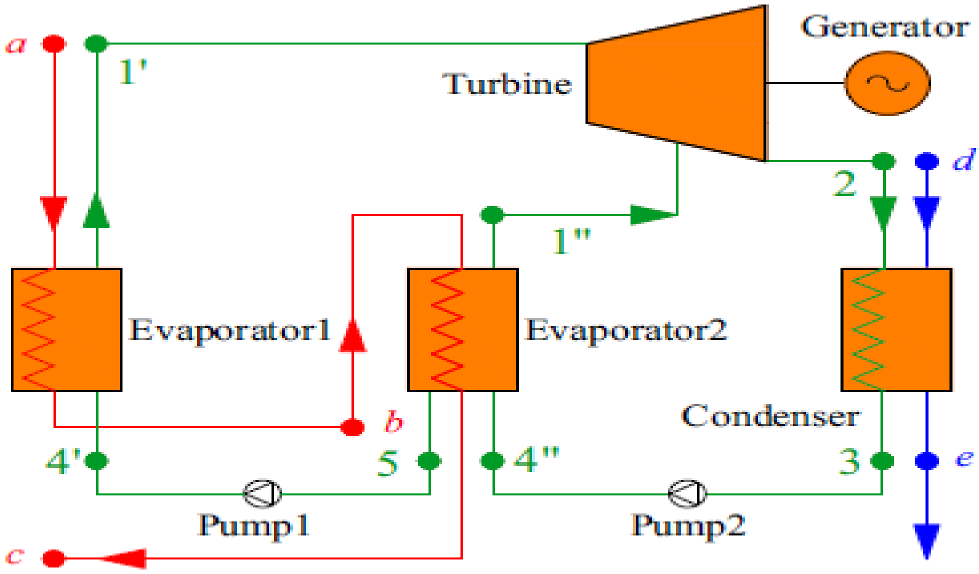

Fig.6. Schematic diagram of the series two-stage organic Rankine cycle [44]

Moreover, the non saturated liquid with relatively lower pressure temperature is pumped into the evaporator 2 by the pump 2. The heat from geothermal water (process b–c) coming from the evaporator 1 can be absorbed to generate low-pressure saturated or superheated vapor (process $4''$–$1''$). The vapor at the state points $1'$ and $1''$ flow into the corresponding stages of the induction turbine where its enthalpy is converted into mechanical energy to drive the generator to produce electricity (process $1'$ ($1''$)–2). The discharging steam from the turbine outlet would come into the condenser where it is liquefied by the cooling water (process 2–3) driven by the cooling pump. The liquid at the condenser outlet is divided into two parts, which is pressurized by the pumps 1 and 2, and then another new cycle begins. The PTORC can be identified as $1'$ ($1''$)–2–3–$4'$ ($4''$)–$1'$ ($1''$), which is shown by green lines.

The STORC shown in Fig.6 is almost the same with the PTORC, and the largest difference is that the high and low stages are connected to each other. The liquid working fluid from the condenser is first pressurized to flow into evaporator 2. This step could help to absorb heat from geothermal water (process b–c) coming from the evaporator 1 to generate low-pressure saturated or superheated vapor (process $4''$–$1''$). Then, a portion of the saturated liquid at the saturated pressure in the evaporator 2 is pumped to the evaporator 1 to absorb heat from geothermal water (process a–b) coming from production wells to generate high-pressure saturated or superheated vapor (process $4'$–$1'$).

VIII.CONCLUSION

Comparison based on second law efficiency for various cycle modifications are shown in Figs.7 to 11 for the typical organic rankine cycle. Although comparison should be made under similar operating parameters but due to scarcity of data only an approximate comparison is possible in this work. Results show that the maximum

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exergy efficiency improvement can be achieved by EORC. The performance of EORC is superior to that of RORC when the pump efficiency is lower than 57% and the evaporating temperature is higher than 95 °C. The performance of ORCLFE is better than ORCSC. The ORCLFE always improves system efficiency and mitigates expander exhaust quality concerns for wet working fluids. However, it limits the choice of expander to positive displacement designs and requires the selection of a flooding medium that does not mix or react with the primary working fluid. The exergy efficiency of two stage evaporators is partially less than both ORCLFE and ORCSC. PTORC and STORC could evidently reduce the irreversible loss, and STORC is more significant. PTORC and STORC can output more net power, depending on cycle configuration and GWIT. The double pressure ORCs however are the least performing. In the double-pressure ORC system, the turbine high-level and low-level inlet pressure have optimal values to reach the best system performance. The increase of turbine high-level inlet temperature brings a positive influence on the system performance. Through parametric optimization, the system can reach the exergy efficiency of 5.85% under the given conditions. The double-pressure ORC system has a better performance than single-pressure ORC system.

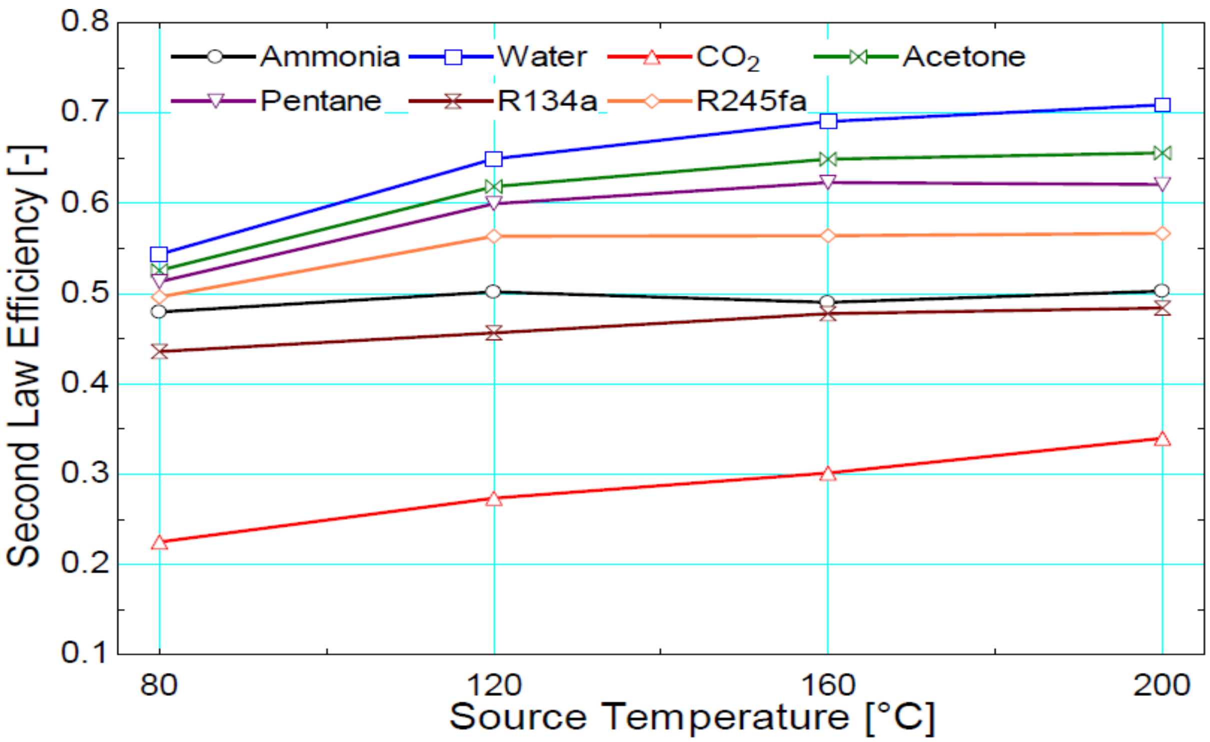

Fig.7.Second Law efficiency of ORCLFE as a function of source temperature [17]

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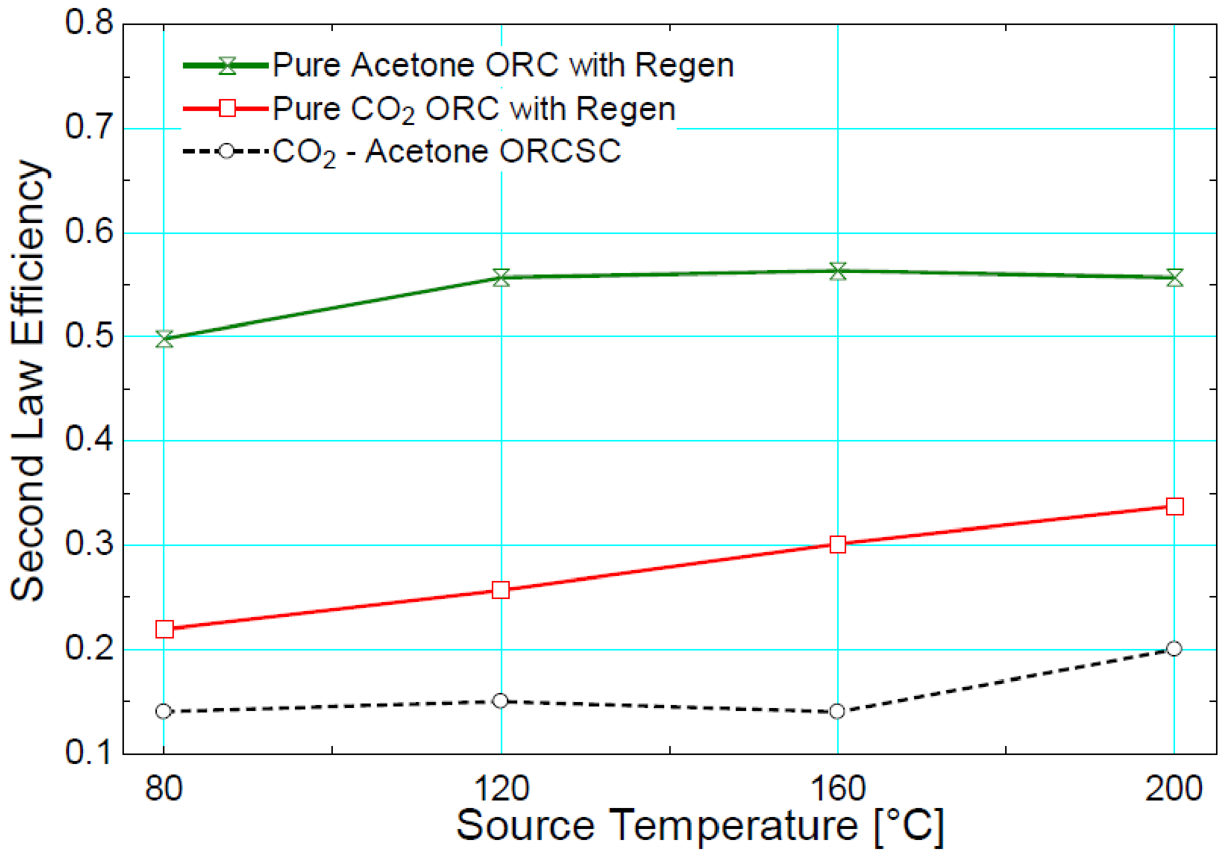

Fig.8.Second Law efficiency of ORCSC as a function of source temperature [17]

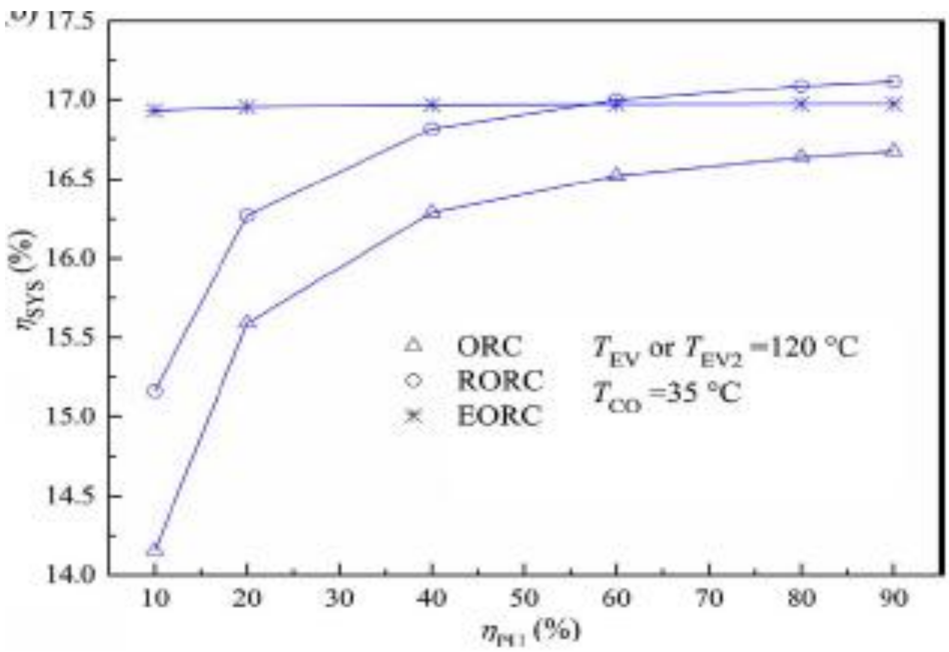

Fig.9.EORC performance comparison at different pump isentropic efficiencies [24]

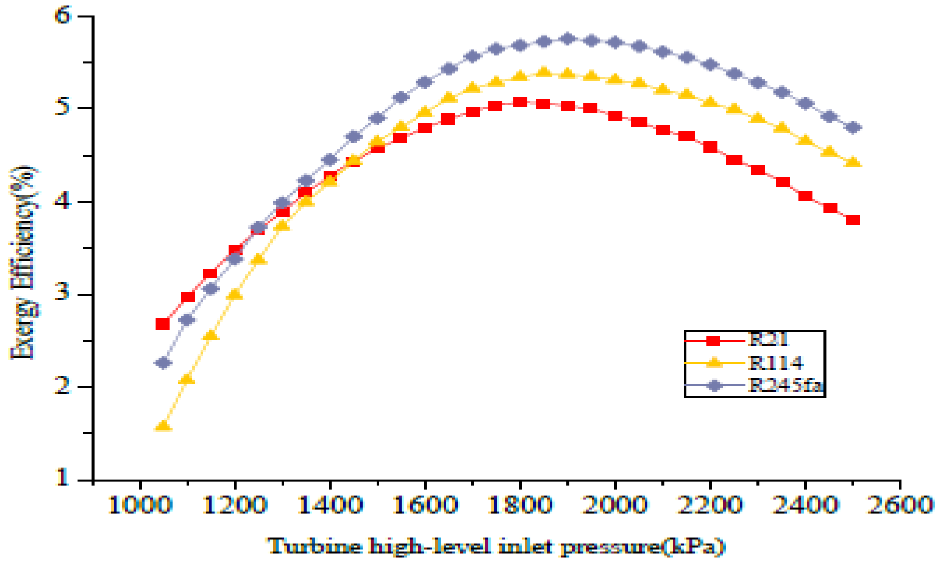

Fig.10.Second Law efficiency of double pressure ORC as a function of Turbine high-level inlet pressure [31]

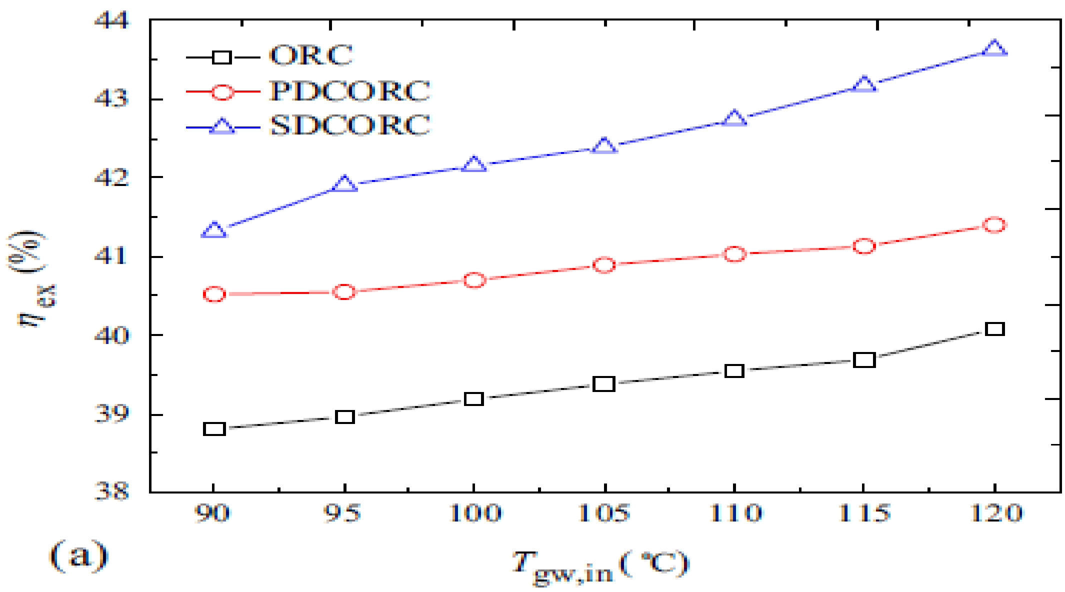

Fig.11.Second Law efficiency of two stage evaporator ORC as a geothermal water inlet temperature [44]

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