# EXERGY ANALYSIS OF ORGANIC AND AMMONIA-WATER RANKINE CYCLES WITH REGENERATION

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**Abstract -** The organic Rankine cycle (ORC) and the ammonia-water based power generating cycle are considered as the most feasible methods for recovery of low-grade finite heat sources. This paper presents a comparative exergetical performance analysis for ORC with regeneration (ORCR) and ammonia-water Rankine cycle with regeneration (AWRCR). Effects of the system parameters such as working fluid, turbine inlet pressure, and mass fraction of ammonia on the exergetical performance are parametrically investigated. Results show that AWRCR does not show higher exergy efficiency than ORCR, however, shows lower exergy destruction ratio of source heat exchanger than ORCR.

**Index Terms** -Organic Rankine cycle, ammonia-water Rankine cycle, regeneration, low-grade heat source.

## INTRODUCTION

The conventional steam Rankine cycle using water as the working fluid has lower thermal efficiency as the temperature of the heat source is lowered, and loses the economics when the temperature of the heat source is below about 370°C. Power generation cycles such as Organic Rankine Cycle (ORC) and ammonia-water based Rankine cycles have been intensively investigated and recognized as feasible and competitive power generation cycles which are able to efficiently convert low-temperature finite heat sources such as industrial waste heat and geothermal heat to useful energy of electricity [1-4].

The basic configuration of ORC is the same as the conventional steam Rankin cycle, but ORC can be operated effectively with low-temperature heat sources by using a working fluid of which boiling point is lower than water. The ORC has many advantages such as adaptability to various heat sources, lesser complexity and lesser maintenance [5-9]. The ORC is not a new concept but much research has been conducted on it, since it is important to select a proper working fluid from the many different working fluids for recovering a given low-grade source [10].

In order to identify the most suitable organic fluids, several general criterions have to be taken into consideration including thermodynamic properties, stability of the fluid and compatibility with materials in contact, safety, health and environmental aspects, availability, and costs [11]. The economics of a Rankine system is closely linked to the thermodynamic properties of the working fluid and a bad choice could lead to a low efficient and expensive plant [12]. With internal heat recovery, the thermal efficiencies averaged over all substances amount to about 70% of the Carnot efficiency and increase with the critical temperature [13].

If a zeotropic mixture is used as a working fluid in a power generation systems, the phase changes with varying temperature at constant pressure. Thus, the process of heat transfer with changing temperature reduces the imbalance of temperature difference between hot and cold streams in a heat exchanger, which is particularly effective for power cycle using a low-grade heat source in the form of sensible energy [14-15]. Roy et al. [16] investigated two ammonia-water Rankine cycles, one with and one without a regenerator, for fixed source and sink inlet temperatures. They showed that the range of evaporation pressures satisfying some basic conditions increases with the source temperature. Kim and Kim [17] carried out a thermodynamic analysis of a combined cycle consisting of an ammonia-water Rankine cycle and a LNG Rankine cycle using low-grade heat source. Kim and Kim [18] conducted a comparative analysis of the thermodynamic performances of ORC and ammonia- water Rankine cycle and reported that the component where the maximum exergy destruction occurs is the condenser in ORC but the coolant exhaust in ammonia-water Rankine cycle. Kim [19] comparatively investigated the thermodynamic performances of ORC and ammonia-water Rankine cycle with regeneration, and reported that the ammonia-water Rankine cycle does not show higher thermal efficiency than ORC, however, shows lower volumetric flow rate of working fluid than ORC.

Exergy is a measure of the departure of the state of a system from that of the environment and has been viewed as the maximum theoretical work obtainable from an overall system of system plus environment as the system passes from a given state to the dead state. The exergy analysis based on the thermodynamic second law is suitable for more effective energy resources use, since it enables the location, cause, and true magnitude of waste and lost to be determined [20-21].

This paper presents a comparative analysis of

exergetical performances for an organic Rankine cycle with regeneration (ORCR) and an ammonia-water Rankine cycle with regeneration for recovery of low-grade heat source. The effects of working fluid, turbine inlet pressure, and ammonia mass fraction on the exergetical system performance are parametrically investigated.

## SYSTEM ANALYSIS

A schematic diagram of the ORCR or AWRCR, consisting of a turbine, a pump, heat exchangers and a condenser is shown in Fig. 1.

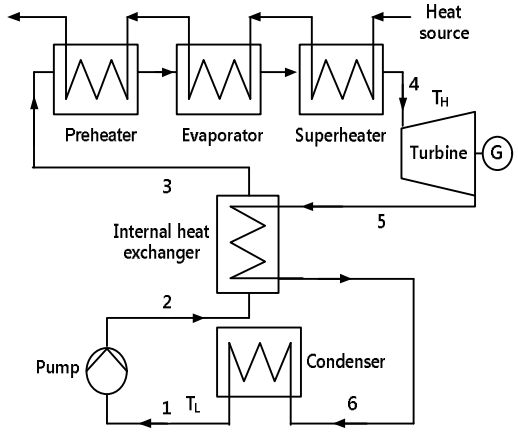



**Fig. 1. Schematic diagram of the system.**

In this work it is assumed as follows [18]:

1) The flow is steady and all components are well insulated.
2) The fluid is a pure vapor at the turbine inlet.
3) The isentropic efficiencies of the pump and turbine are constant.
4) The turbine inlet pressure is lower than the critical pressure of the working fluid, so the cycle is a subcritical one.
5) Each of the heat exchangers is assumed to be operated with a pinch point condition, which means that the minimum temperature difference between the hot and cold streams in the heat exchanger reach the prescribed value of the pinch temperature difference.

For a specified mass flow rate of the source fluid $m_s$, the mass flow rates of the working fluid $m_w$, and the coolant $m_c$ can be determined from the energy balances at the heat exchanger and condenser as follows [19]:

$$m_w = \frac{m_s c_{ps}(T_s - T_{sout})}{h_3 - h_2} \quad , \qquad (1)$$

$$m_c = \frac{m_w(h_4 - h_1)}{c_{pc}(T_{cout} - T_c)} \quad . \qquad (2)$$

Here $c_p$ denotes the specific heat, h the specific enthalpy of the working fluid, and the subscripts s and c represent the source fluid and the coolant, respectively. The heat addition rate to the system ($Q_{in}$), the net power production of the system ($W_{net}$), can then be evaluated in accordance to the following equations:

$$Q_{in} = m_w(h_3 - h_2) \quad , \qquad (3)$$

$$W_{net} = m_w(h_3 - h_4) - m_w(h_2 - h_1) \quad . \qquad (4)$$

When a system undergoes a steady state operation, the thermodynamic properties of working fluid can be arbitrarily assigned to be zero as reference values. Therefore the thermo-mechanical enthalpy, entropy, and exergy at the ambient condition or dead state can be neglected regardless of its chemical composition. The specific exergy e and the rate of exergy input to the system by source fluid can be calculated as [20]:

$$e = h - h_0 - T_0(s - s_0) \qquad (5)$$

$$E_{in} = m_s c_{ps}\{T_s - T_0 - T_0 \ln(T_s / T_0)\} \qquad (6)$$

Here s is the specific entropy and subscript 0 refers the dead state. The exergy efficiency of the system $\eta_{ex}$ is defined as the ratio of net work to exergy input, and the exergy destruction or anergy of the adiabatic system is calculated as the difference of exergy input and output. The exergy destruction ratio at a system component is defined as the ratio of anergy there to the exergy input by source fluid. Then summation of all anergy ratios of the system and the exergy efficiency becomes unity [21]:

$$\eta_{ex} = W_{net} / E_{in}, \qquad (7)$$

$$\eta_{ex} + D_{sout} + D_h + D_c + D_{cout} + D_r + D_w = 1 \qquad (8)$$

where $D_{sout}$, $D_h$, $D_c$, $D_{cout}$, $D_r$, $D_w$ are exergy destruction ratio of the source exhaust, heat exchanger, condenser, coolant exhaust, regenerator, and net work (turbine and pump), respectively.

In this paper, the thermodynamic properties of ammonia-water mixture in AWRCR were evaluated by using the methods of [22-23], and the thermodynamic properties of the working fluids in ORCR were evaluated by using Patel-Teja equation [24-25].

## RESULTS AND DISCUSSIONS

In this study, it is assumed that the source fluid is water with a mass flow rate of 1 kg/s The basic operation data use for the simulation of this study are as follows; source temperature, $T_S$ = 200°C, turbine inlet temperature, $T_H$ = 185°C, condensation temperature, $T_L$ = 30°C, coolant temperature, $T_C$ = 15°C, turbine inlet pressure, $P_H$ = 15 bar, pinch temperature difference, $\Delta T_{pp}$ = 8°C, isentropic efficiencies of pump and turbine, $\eta_p$ = 0.80 and $\eta_t$ = 0.85. The basic ammonia mass fractions are considered as $x_b$ = 50%, 60%, 70%, and 80% [18-19].

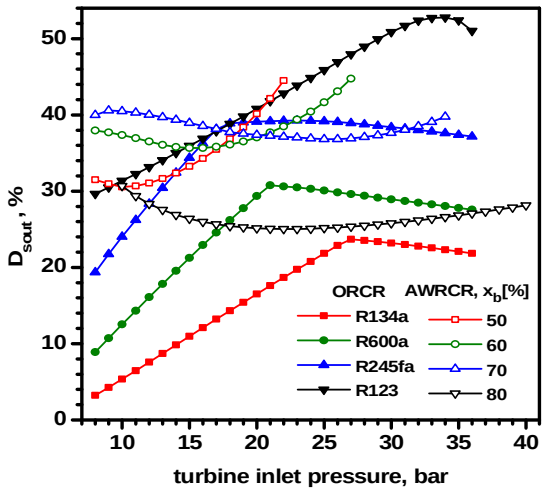



**Fig. 2. Effects of turbine inlet pressure on the exergy destruction ratio of source exhaust, $D_{sout}$.**

Fig. 2 shows the effects of turbine inlet pressure on the exergy destruction ratio of source exhaust, $D_{sout}$. As turbine inlet pressure increases in ORCR, the ratio firstly increases for low pressures, reaches the maximum value and then decreases. It can be explained as follows. The evaporation temperature of the working fluid increases with increasing pressure, which leads to higher exit temperature of the source fluid. When the inlet pressure becomes higher, however, the effect of decrease in the turbine exit temperature becomes dominant, which reduces the heat transfer with regenerator and consequently the exit temperature of the source fluid. For a given turbine inlet pressure, the ratio increases with increasing critical temperature of the working fluid, so the ratio is the highest for R123 and the lowest for R134a. In AWRCR, the ratio shows a minimum value with respect to the turbine inlet pressure, however, the variations of the ratio due to the pressure are insignificant compare with ORCR.

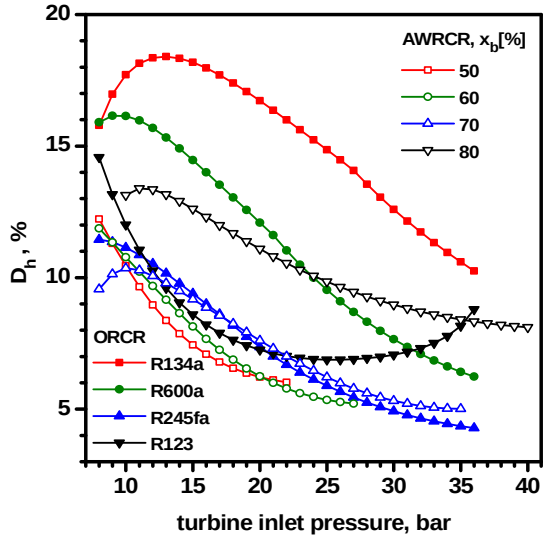



**Fig. 3. Effects of turbine inlet pressure on the exergy destruction ratio of heat exchanger, $D_h$.**

Fig. 3 illustrates the effects of turbine inlet pressure on the exergy destruction ratio of the heat exchanger, $D_h$. In ORCR, the ratio becomes lower for higher turbine inlet pressures. It is because as the turbine inlet pressure increases, the evaporation latent heat decreases, and it leads to less heat transfer in the heat exchanger. However, it can be seen from the figure that the ratio increases with increase in the turbine inlet pressure for lower pressure when the working fluid is R134a or R600a, and for higher pressures when the working fluid is R123. For a specified pressure, the ratio decreases with increasing critical temperature of the working fluid, so the ratio is the highest for R134a and the lowest for R123. In AWRCR, the ratio decreases with increase in the turbine inlet pressure, since the heat transfer in the heat exchanger decreases with increasing turbine inlet pressure. The ratio becomes higher when the ammonia mass fraction increases higher, due to higher mismatch between hot and cold streams in the heat exchanger.

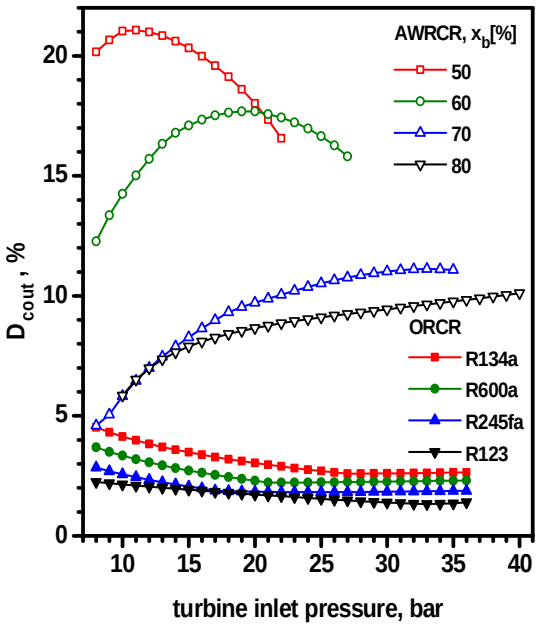



**Fig. 4. Effects of turbine inlet pressure on the exergy destruction ratio of coolant exhaust, $D_{cout}$.**

Fig. 4 shows how the exergy destruction ratio of the coolant exhaust, $D_{cout}$, is affected by the turbine inlet pressure. In ORCR, the ratio drops with increase in the pressure, since as the pressure becomes higher, the expansion ratio of the working fluid through the turbine increases, and consequently the turbine exit temperature of the working fluid drops. On the other hand, the ratio drops with increasing critical temperature of the working fluid, so the ratio is the highest for R134a and the lowest for R123. In AWRCR, the ratio drops as the pressure increases, since higher turbine inlet pressure leads to a lower temperature of working fluid at the turbine exit. It can be observed from the figure that the exergy destruction

ratios in ORCR are much lower than those in AWRCR.

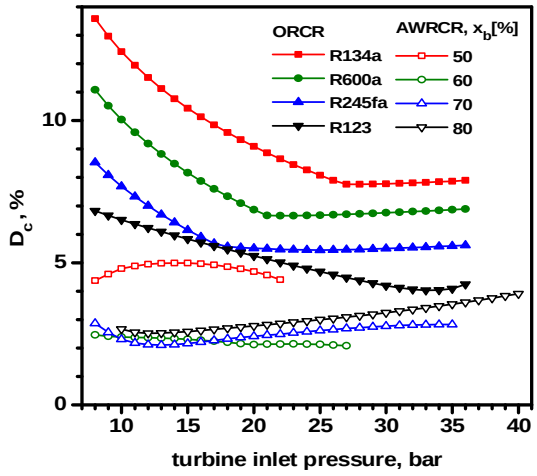



**Fig. 5. Effects of turbine inlet pressure on the exergy destruction ratio of condenser, $D_c$.**

Fig. 5 shows how the exergy destruction ratio of the condenser, $D_c$, is affected by the turbine inlet pressure. In ORCR, the ratio firstly decreases and reaches a minimum value and the increases again with increasing pressure. It can be explained as follows. When the turbine inlet pressure is low, the higher pressure causes lower temperature of the working fluid at turbine exit and consequently lower heat removal at the condenser. But when the turbine inlet pressure is high, the ratio increases with pressure due to the reduced heat transfer by regeneration. On the other hand the ratio becomes lower for higher critical temperature of the working fluid, so the ratio is the highest for R134a and the lowest for R123. It is to be noted that the exergy destruction ratio of coolant exhaust for ORCR is much smaller than AWRCR, but the ratio of condenser for ORCR is much greater than AWRCR.

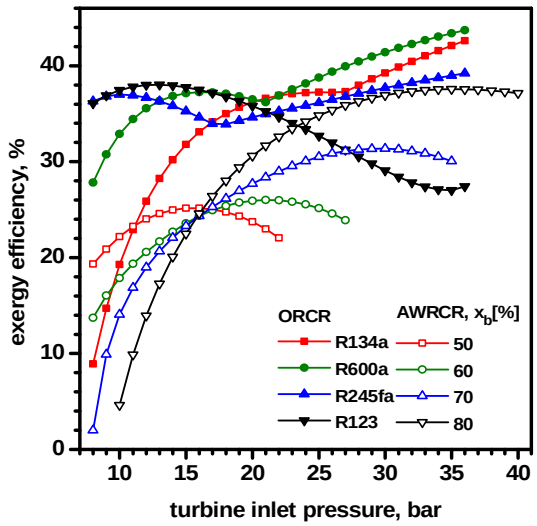



**Fig. 6. Effects of turbine inlet pressure on the exergy efficiency.**

Fig. 6 displays the effects of the turbine inlet pressure on the exergy efficiency. As the turbine inlet pressure increases in ORCR, the exergy efficiency firstly increases, reaches a local maximum value, decreases, and then increases again, so the performance is complex. The exergy efficiency is the highest when the working fluid is R123 for lower turbine inlet pressures than 20 bar, but it is the highest when the working fluid is R600a for the pressures higher than 20 bar. In AWRCR, the exergy efficiency has a peak value with respect to the turbine inlet pressure. The maximum efficiency is 25.2% at 16 bar for ammonia mass fraction of 50%, 26.0% at 21 bar for 60%, 31.4% at 30 bar for 70% and 37.6% at 35 bar for 80%. So the maximum exergy efficiency and the corresponding optimum turbine inlet pressure become higher for higher ammonia mass fraction. It is worth to note that the exergy efficiencies in ORCR are higher than those in AWRCR in most cases.

Fig. 7 illustrates the effects of the turbine inlet pressure on the exergy destruction ratios in ORCR when the working fluid is R600a. As the turbine inlet pressure increases, the exergy destruction ratio of turbine and pump increases, and those of the coolant exhaust, condenser, and the regenerator decrease. On the other hand, the exergy destruction ratio of heat exchanger has a peak with respect to the turbine inlet pressure, and the exergy efficiency has a peak and then becomes higher for higher pressures. Among the exergy destruction ratios of the system, the maximum exergy destruction occurs at regenerator for the turbine inlet pressures lower than 12 bar but at source exhaust higher than 12 bar.

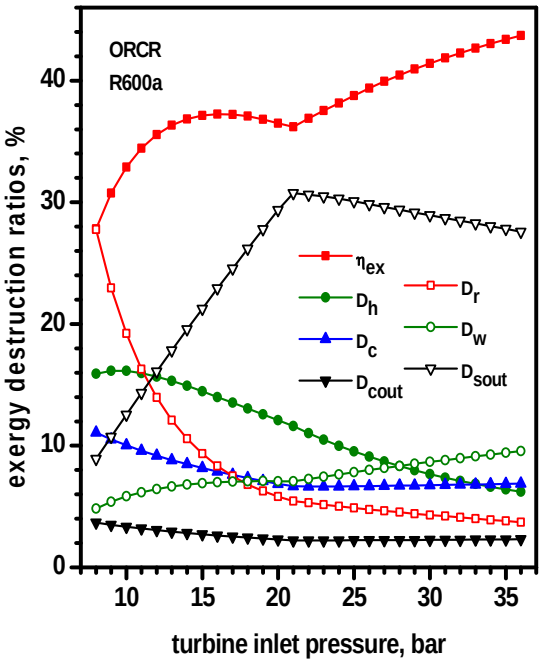



**Fig. 7. Effects of turbine inlet pressure on the exergy destruction ratios in ORC for R600a.**

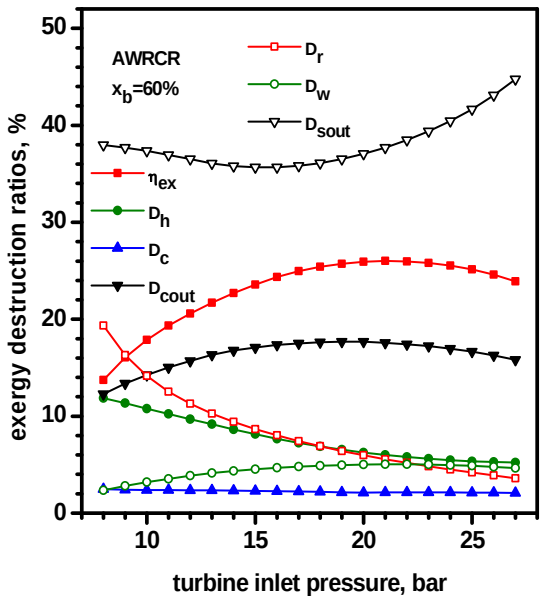



**Fig. 8. Effects of turbine inlet pressure on the exergy destruction ratios in AWRC for $x_b$ = 60%.**

Fig. 8 shows the effects of the turbine inlet pressure on the exergy destruction ratios in AWRCR when the ammonia mass fraction is 60%. The exergy destruction ratios of regenerator, heat exchanger, and condenser decrease with increasing turbine inlet pressure. However, the exergy efficiency and the exergy destruction ratios of coolant exhaust, turbine and pump have a local maximum value, while the exergy destruction ratio of the source exhaust has a local minimum value with respect to the turbine inlet pressure. Among the exergy destruction ratios of the system, the maximum exergy destruction occurs always at the source exhaust. The second greatest exergy destruction occurs at regenerator for the turbine inlet pressures lower than 10 bar, but at coolant exhaust higher than 10 bar. It is worth to note that the exergy destruction ratio of source exhaust in AWRCR is higher than that in ORCR, and the ratio of heat exchanger is the opposite.

## CONCLUSIONS

In this paper a comparative exergetical analysis is carried out for organic Rankine cycle with regeneration (ORCR) and ammonia-water Rankine cycles with regeneration (AWRCR) using low-grade heat source. Water with 1 kg/s at 200°C is assumed to be the heat source. R134a, R600a, R245fa, and R123 were considered as the working fluids in organic Rankine cycle and ammonia mass fraction from 50% to 80% were considered in ammonia-water Rankine cycle. The results show that the exergy efficiencies in ORCR are higher than those in AWRCR in most cases. The exergy destruction ratio of source exhaust in AWRCR is higher than that in ORCR, and the ratio of heat exchanger is the opposite.

## ACKNOWLEDGMENTS

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