# EXERGY ANALYSIS OF COMBINED ORGANIC AND LNG RANKINE CYCLES WITH DIFFERENT SOURCE TEMPERATURES

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**Abstract-** The performance of power generation system can be improved by using liquefied natural gas (LNG) cold energy and thus the utilization of LNG cold energy has been an interesting area of study. In this paper an exergetical analysis is carried out for a combined cycle of an organic Rankine cycle (ORC) and a LNG Rankine cycle utilizing low-grade heat source in the form of sensible energy. The effects of the system parameters such as turbine inlet pressure of the working fluid or source temperature on the exergy destruction at each component as well as the total exergy efficiency are investigated extensively. The results indicate that the greatest exergy destruction ratio of the system depends on the reduced turbine inlet pressure and source temperature. The exergy efficiency decreases for low source temperature but increases for high source temperature as the turbine inlet pressure increases.

**Keywords**- Organic Rankine Cycle (ORC), Liquefied Natural Gas (LNG), Exergy, Exergy Destruction, Exergy Efficiency.

## I. INTRODUCTION

The transportation of natural gas in the form of liquid is more appealing and reliable, because the energy density of liquefied natural gas is approximately 600 times greater than that of natural gas [1-2]. Production of one ton of LNG by liquefying NG requires approximately850 kWh of electric energy, and regasification also consumes energy[3]. Kumar et al. [4] presented an overview on the characteristics of LNG, the present state of affairs of LNG, the eco-friendliness of natural gas fuel, and the potential of natural gas production from different sources.

The power generation systems based on ammonia-water mixture are proven to be one of the feasible methods for the conversion of low-grade heat sources in the form of sensible energy into useful work. Ammonia and water have the similar molecular weights and thus, traditional design of steam turbines can be used in the ammonia-water power cycles after some minor modifications. In addition, the boiling point of ammonia is substantially lower than that of water, which makes it practically useful to utilize the low-temperature waste heat in the power generation systems [5-7].

Shi and Che [8] investigated a combined cycle of ammonia-water and LNG Rankine cycles using a separator of the ammonia-water mixture. Wang et al. [9] studied the optimal performance of an ammonia-water Rankine cycle with LNG as a heat sink. Kim et al. [10-11] performed a parametric energy and exergy analysis study for a combined cycle of ammonia-water and LNG Rankine cycles to examine the effects of key system parameters on the system performance.Choi et al. [12] suggested and investigated a cascade Rankine cycle that consisted of multiple stages of ORC and recovered LNG cold energy for power generation. Rao et al. [13] investigated a combined cycle that consisted of the ORC and the LNG Rankine cycles using solar energy as a low-temperature heat source.

The organic Rankine cycle (ORC) has been considered as one of the promising technologies for recovery of low-gradeheat source and the selection of working fluid which matches with the available heat source and temperature range is important. [14-16].Saleh et al. [17] performed a thermodynamic screening of 31 pure working fluids for the temperature range typical to geothermal power plants. Mago et al. [18] presented an analysis of regenerative ORCs using dry organic fluids. Drescher and Brueggemann [19] proposed a method to find suitable fluids for ORCs in biomass plants and found that the family of alkylbenzenes showed the highest efficiency. Heberle and Brueggemann [20] investigated the combined heat and power generation for geothermal resources with an ORC and suggested an exergy-based fluid selection method.

Soffiato et al. [21] studied ORC for recovery of the low-grade waste heat rejected by a ship power generation plant-driven LNG carrier. Xue et al. [22] performed an analysis of a two-stage ORC with the low-grade heat of the exhaust flue gas of a gas-steam combined cycle power-generating unit, as well as the cryogenic energy of LNG. Lee and Kim [23] reported energy and exergy analyses for a combined cycleconsisting of an organic Rankine cycle (ORC) and a liquefied natural gas (LNG) Rankinecycle for the recovery of low-grade heat sources and LNG cold energy.

Exergy is a measure of the departure of the state of a systemfrom that of the environment, and the exergyanalysis is well suited for furthering the goal of more energyresource use, for it enables the location, cause, and truemagnitude of waste and loss to be

determined [24-27]. In this study an exergy analysis of a combined power cycle consisting of ORC and LNG Rankine cycles is carried out, where LNG is used to produce power output, as well as to be used as a heat sink. This work focuses on the effects of key system parameters, such as the turbine inlet pressure and the source temperature, on the system performance, including exergy destruction ratio at various components of the system as well as the exergy efficiency.

## II. SYSTEM ANALYSIS

A schematic diagram of the combined cycle, consisting of the ORC and the LNG power generation cycle by direct expansion is shown in Fig 1.

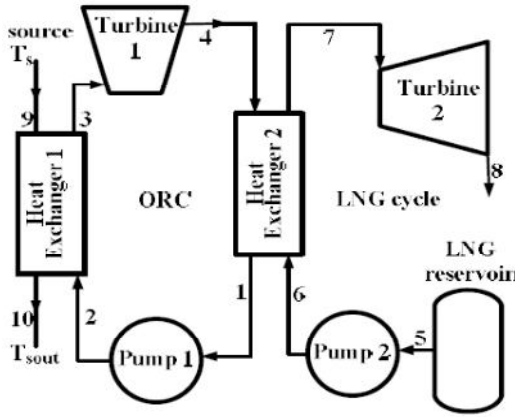



**Fig.1. Schematic diagram of the system.**

The important assumptions made for the proposed system analysis are as follows: 1) the flow is steady 2) all components are well insulated. 3) the LNG is assumed to be pure methane. 4) the fluid is in a pure vapor form at the turbine inlet. 5) the performances of the pumps or turbines are characterized by constant isentropic efficiencies. 6) the turbine inlet pressure is lower than the critical pressure of the working fluid, so the cycle is limited to a subcritical one. Additionally, 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 [23].

For a specified mass flow rate of the source fluid $m_s$, the mass flow rate of the working fluid mw in the ORC and the LNG mass flow rate $m_c$ in the LNG cycle can be determined from the energy balances at the evaporator and condenser. The specific exergy e and the rate of source exergy input $E_{in}$ to the system by source fluid and LNG can be calculated as

$$e = h - h_0 - T_0(s - s_0) \quad (1)$$

$$\dot{E}_{in} = E_s + \dot{E}_{LNG} \quad (2)$$

where T is the temperature, h is the specific enthalpy, s is the specific entropy. The subscript 0, s, and LNG refer the dead state, source and LNG supply, respectively. Then, the exergy efficiency of the system $\eta_{ex}$, which is defined as the ratio of net work to exergy input, can be written as follows.

$$\eta_{ex} = \dot{W}_{net} / \dot{E}_{in} \quad (3)$$

The exergy destruction or anergy of the adiabatic system is calculated as the difference of exergy input and output. The anergy ratio at a system component is defined as the ratio of anergy there to the exergy input by source fluid. The anergy ratios at the components can be obtained as follows.

$$DCD = E_4 + E_6 - E_1 - E_7 \quad (4)$$

$$DEV = E_2 + E_9 - E_3 - E_{10} \quad (5)$$

$$DLE = E_8 \quad (6)$$

$$DSE = E_{10} \quad (7)$$

$$DWK1 = E_1 + E_3 - E_2 - E_4 - W_{net,ORC} \quad (8)$$

$$DWK2 = E_5 + E_7 - E_6 - E_8 - W_{net,LNG} \quad (9)$$

$$DWK = DWK1 + DWK2 \quad (10)$$

Then summation of all anergy ratios of the system and the exergy efficiency becomes unity.

$$\eta_{ex} + DCD + DEV + DLE + DSE + DWK = 1 \quad (11)$$

where DCD, DEV, DLE, DSE and DWK are anergy ratios of the condenser, heat exchanger, LNG exhaust, source exhaust, and net work production, respectively.

In this paper, thermodynamic properties of working fluid and LNG are evaluated by using the Patel-Teja equation [28-29].

## III. RESULTS AND DISCUSSION

In this study, it is assumed that the inlet pressure of Turbine 1 is lower than critical. Therefore, the reduced turbine inlet pressure (RTIP), which is defined as the ratio of the turbine inlet pressure to the critical pressure of the working fluid, is limited to values lower than unity. It is also assumed that the source fluid is standard air with a mass flow rate of 1 kg/s and the working fluid is R123. The basic data used for the simulation are as follows: inlet temperature of turbine 1 $T_{H1}$ = $T_s$ - 10°C, condensation temperature $T_c$ = -20°C, dead state temperature $T_0$ = 25°C, dead state pressure = 1 atm, inlet pressure of turbine 2 = 15 bar, exit pressure of turbine 2 = 1atm, isentropic pump efficiency $\eta_p$= 0.7, isentropic turbine efficiency $\eta_p$=0.7, pinch temperature difference $\Delta T_{pp}$ = 8°C.

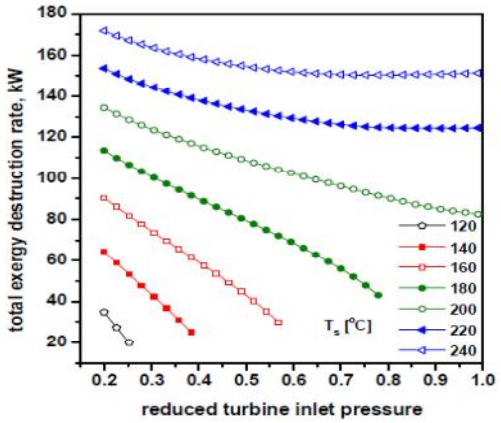



**Fig.2. Effects of RTIP on the total exergy destruction rate for various source temperatures.**

Fig. 2 displays the effects of turbine inlet pressure on the total exergy destruction of the system for various source temperatures. The exergy destruction decreases with increasing RTIP, since both the mass flow rates of source fluid and LNG increase as RTIP increases. The decreasing rate of exergy destruction with respect to RTIP becomes smaller when the source temperature increases. For a given RTIP, the exergy destruction increases with increasing source temperature, since the exergy input rate increases as the source temperature increases.

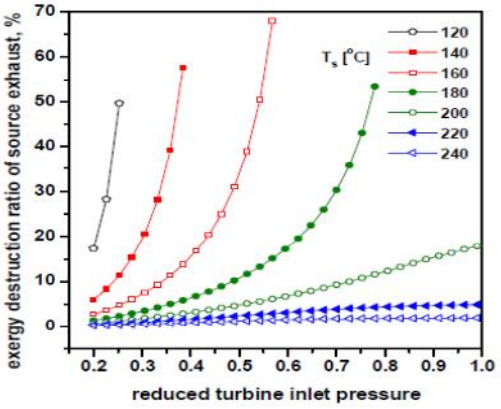



**Fig. 3. Effects of RTIP on the exergy destruction ratio of source exhaust for various source temperatures.**

Fig. 3 shows the effects of turbine inlet pressure on the exergy destruction ratio of source exhaust DSE, for various source temperatures. As RTIP increases, the exergy destruction ratio increases, since as RTIP increases, the evaporating temperature of working fluid increases, which leads to an increased source exhaust temperature. The increasing rate of the exergy destruction ratio with respect to RTIP decreases with increasing source temperature, so the exergy destruction ratio remains almost constant with varying RTIP for high source temperatures such as Ts = 220°C or 240°C. For a specified RTIP, the exergy destruction ratio decreases with increasing ratio, since as the source temperature increases, the exergy destruction of source exhaust decreases while the exergy input rate increases.

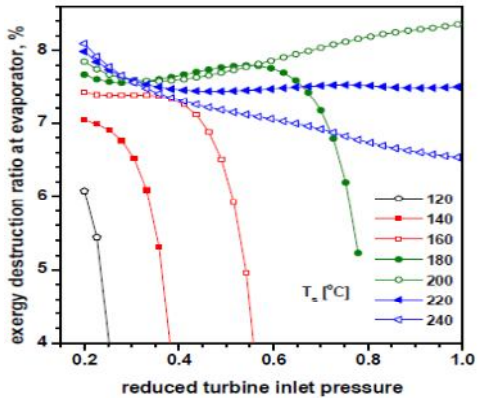



**Fig. 4. Effects of RTIP on the exergy destruction ratio of evaporator for various source temperatures.**

Fig. 4 illustrates the effects of turbine inlet pressure on the exergy destruction ratio of evaporator DEV, for various source temperatures. It can be seen from the figure that as RTIP increases, the exergy destruction ratio decreases for low source temperatures of 120°C , 140°C , 160°C, and 180°C, but increases for the source temperature of 200°C, and decreases again for source temperatures of 220°C and 240°C. These complex phenomena occur, since the heat transfer rate decreases with increasing RTIP, however, the input rate of exergy also decreases with increasing RTIP. For a given RTIP, the exergy destruction ratio increases with increasing the source temperature, reaches a peak value, and then decreases again with increasing the source temperature. So the exergy destruction ratio has a peak value with respect to the source temperature.

Fig. 5 displays the effects of turbine inlet pressure on the exergy destruction ratio of condenser DCD, for various source temperatures. The exergy destruction ratio decreases with increasing RTIP, and the decreasing rate of the exergy destruction ratio with respect to RTIP decreases with increasing source temperature. So the exergy destruction ratio remains almost constant for the high source temperatures of 220°C and 240°C. For a specified RTIP, the exergy destruction ratio at condenser increases with increasing source temperature.

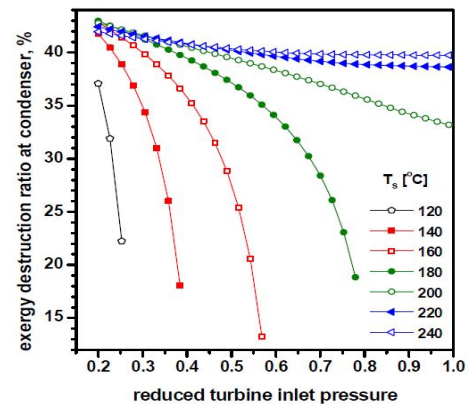



**Fig. 5. Effects of RTIP on the exergy destruction ratio of condenser for various source temperatures.**

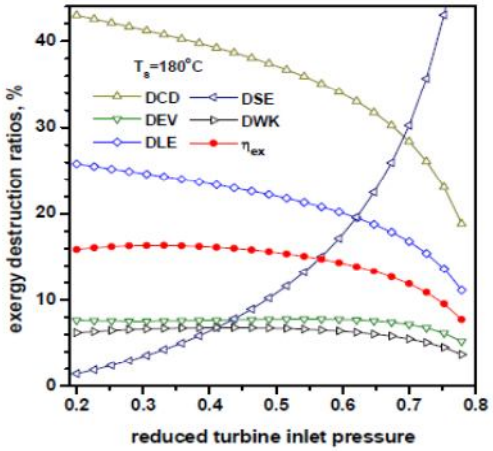



**Fig. 6. Effects of RTIP on the exergy destruction ratios for the source temperature of 180°C.**

Fig. 6 shows the effects of turbine inlet pressure on the exergy destruction ratios of various components and the exergy efficiency for the source temperature of 180°C. It can be seen from the figure that all of exergy destruction ratios and the exergy efficiency, except the exergy destruction ratio of source DSE exhaust, decreases with increasing RTIP. Especially, DSE increases significantly with increasing RTIP. So DSE is the smallest among the exergy destruction ratios for the range of low RTIP, but is the greatest for the range of high RTIP.

Fig. 7 shows the effects of turbine inlet pressure on the exergy destruction ratios of various components and the exergy efficiency for the source temperature of 240°C. It can be seen from the figure that as RTIP increases, the exergy destruction ratios of source exhaust DSE and of the net work DWK, and the exergy efficiency increase, while the exergy destruction ratios of condenser DCD, of evaporator DEV, and of the LNG exhaust DLE decrease. The exergy destruction ratio of condenser DCD is the greatest, while the exergy destruction ratio of source exhaust DSE is the smallest among the components.

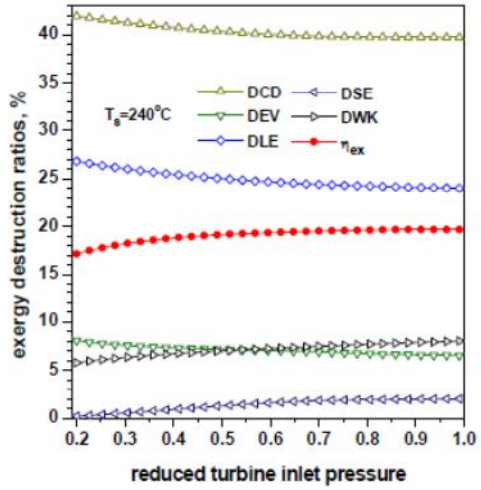



**Fig. 7. Effects of RTIP on the exergy destruction ratios for the source temperature of 240°C.**

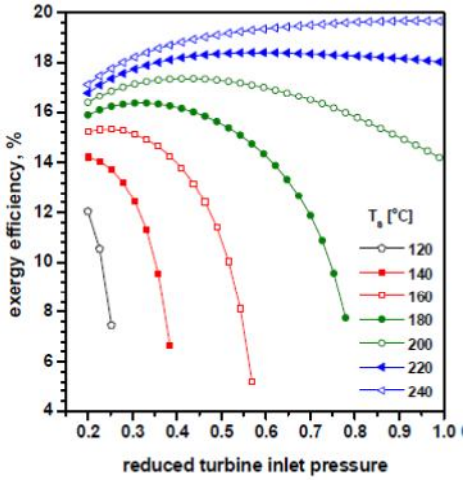



**Fig. 8. Effects of RTIP on the exergy efficiency for various source temperatures.**

Fig. 8 shows the effects of turbine inlet pressure on the exergy efficiency for various source temperatures. It can be seen from the figure that the exergy efficiency decreases with increasing RTIP for low source temperatures of 120°C and 140°C , has a peak value with respect to RTIP for the source temperatures of 160°C , 180°C , 200°C , and 220°C , and increases with increasing RTIP for high source temperature of 240°C. For a given RTIP, the exergy efficiency increases with increasing source temperature.

## CONCLUSIONS

This paper presents anexergy analysis of a combined cycle consisting of an organic Rankine cycle and an LNG Rankine cycle for the recovery of low-grade heat source and LNG cold energy. Air with 1 kg/s is assumed to be the heat source, and R123 is considered as the working fluid. The parametric study is carried out with respect to reduced turbine inlet pressure (RTIP) and source temperature.The results indicate that the greatest exergy destruction ratio of the system depends on the reduced turbine inlet pressure and source temperature. The exergy efficiency decreases for low source temperature but increases for high source temperature as the turbine inlet pressure increases.

## ACKNOWLEDGMENTS

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