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Investigation of the combined TLC-ORC and the combined ORC-ORC power systems

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***Abstract* - One of the best performances in waste heat and power generation systems is the organic Rankine cycle. The difference of the Organic Rankine Cycle from the basic Steam Rankine Cycle is the use of organic fluids as the working fluid. Power generation can be achieved from low temperature heat sources (80-90ºC) with organic fluids. In this study, studies on dual loop combined power systems and system structures were investigated. As a result of the investigations, it was concluded that higher thermal efficiency and lower exergy destruction were obtained from combined Trilateral Cycle-Organic Rankine Cycle power system.**

***Keywords* – Organic fluids, Organik Rankine cycle, Trilateral cycle, Combined power systems.**

I. INTRODUCTION

ENERGY is one of the necessities of the one in which we operate it in our daily lives. With the increase of the world population, the energy demand in both daily and industrial areas have increased. With the insufficient reserves of fossil fuels, new energy sources are searched for. The Rankine cycle is one of the most widely used methods for converting high capacity thermal energy into power and the system uses water as working fluid. Power can be generated from high-temperature heat sources with the Rankine cycle, but power generation from low-temperature sources (solar, geothermal, biomass technology, renewable etc.) with the Organic Rankine cycle.

Organic Rankine Cycle (ORC) uses a low-temperature waste heat source; Concentrating solar energy systems generate power from the exhaust gases and gas turbines of diesel engines, waste heat in industrial processes, geothermal energy and waste heat produced by biomass [1]. For this reason, ORCs are widely used around the world and their usage continues to increase.

A. Organic Rankine Cycle

When water is used as the working fluid in small and medium power cycles, there is a risk of corrosion in turbine blades, high pressure operation in the evaporator, and the use of complex turbines. The problems encountered with the use of water can be partially reduced by the use of appropriate fluid [2]. Fluids with a higher molecular weight and lower critical temperature than water are called organic fluids. Rankine cycles using these fluids are also called Organic Rankine Cycle (ORC). The working principle of ORC is the same as the Rankine cycle. ORC has pump, evaporator, turbine and condenser elements. ORC is used for heat recovery from low temperature heat source. The yield of ORCs varies between 8-20% [3].

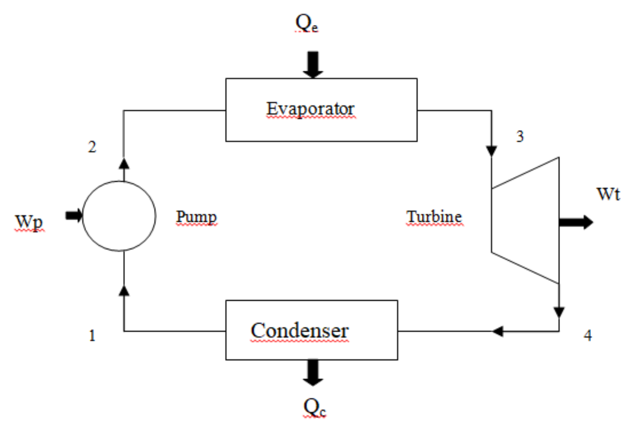

Figure 1: System structure of simple ORC.

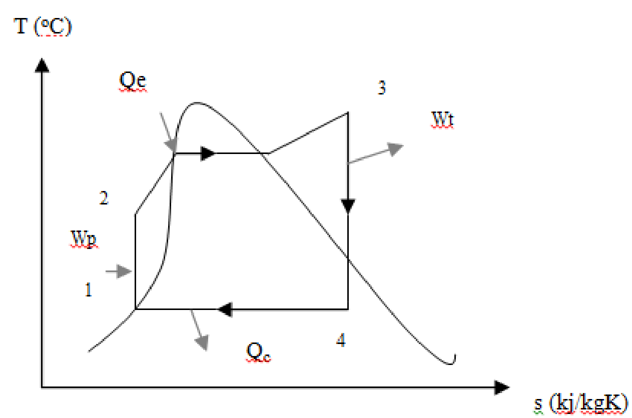

Figure 2: T-s diagram of the simple ORC.

In the cycle, respectively;
1-2: Isentropic compression in the pump
2-3: Heat input at constant pressure in the evaporator
3-4: Isentropic expansion in the turbine
4-1: Steps of throwing heat at constant pressure in the condenser take place.

B. Trilateral Cycle

Trilateral Cycle (TLC) generates power from low-temperature waste heat, such as ORC. TLC basically has the same elements as the Rankine cycle, but unlike the Rankine cycle, the working fluid is heated without evaporation and enters the expander in its saturated phase. A two-phase expander is used in the cycle. The working fluid exits the expander as liquid vapor mixture or saturated vapor. As the working fluid enters the expander without evaporation, a better temperature match is achieved with heat transfer from the heat source to the working fluid. In other words, low exergy degradation occurs according to ORC and thermal efficiency increases. System components of TLCs are pump, evaporator, two-phase expander and condenser. The thermal efficiency of the cycle is around 19-24%.

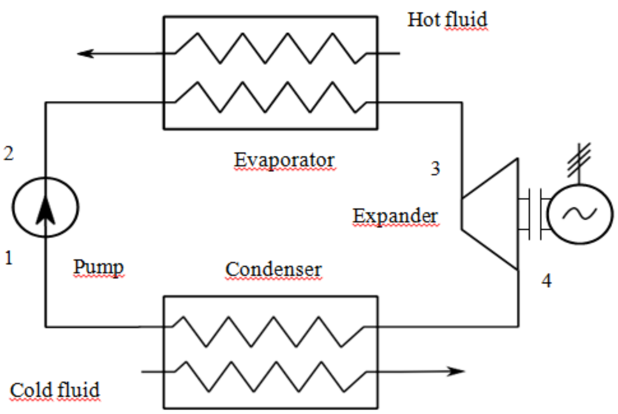

Figure 3: TLC system structure [4]

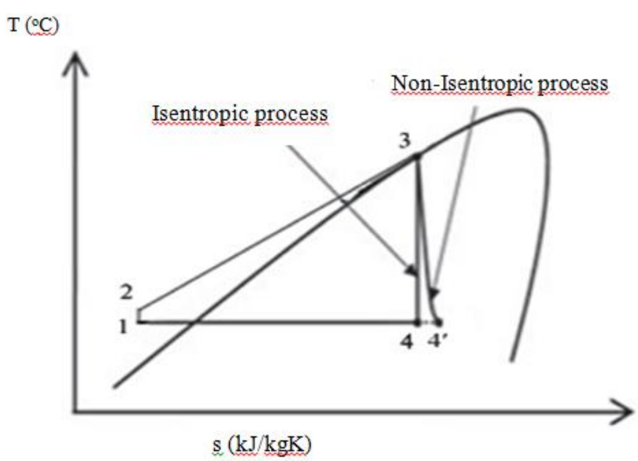

Figure 4: T-s diagram of TLC [5].

II. COMBINED POWER SYSTEMS

A. The Combined ORC-ORC Power Systems

Great efforts have been made by different organizations, including the government, research institutes, companies and colleges, to draw more attention to energy conservation today, facing environmental and energy challenges such as global warming and fossil fuel shortages. In a typical industrial country, internal combustion engines (ICE) are the primary consumers of fossil fuel. However, in an ICE, about 55-70% of the fuel heat is not used and is exhausted [6], so that to recover energy from ICE's waste heat to save energy: including the Organic Rankine cycle many thermodynamic cycles [7], Kalina cycle [8] and Brayton cycle [9] have been considered effective methods. Among these, ORC has received great attention due to its safety, high efficiency, high reliability and flexibility, low costs and easy maintenance [10].

This system includes two cycles, one high temperature cycle and one low temperature cycle, and ORC is used in both cycles. With the high temperature cycle, the engine exhaust waste heat and fuel waste heat are passed through the evaporator of the cycle and used by the working fluid and the fluid exits the evaporator and continues to cycle. In the low temperature cycle, while the working fluid is circulated in the cycle, the refrigerant passing through the condenser gives heat to the fluid and condenses into a saturated liquid. In this way, waste heat is recovered. The efficiency of ORC – ORC systems is in the order of 18 -19%.

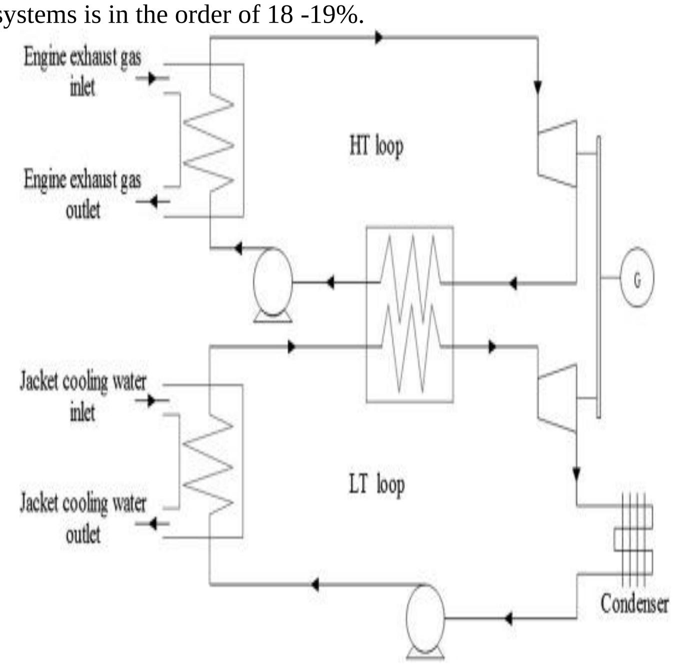

Figure 5: ORC-ORC system structure [11].

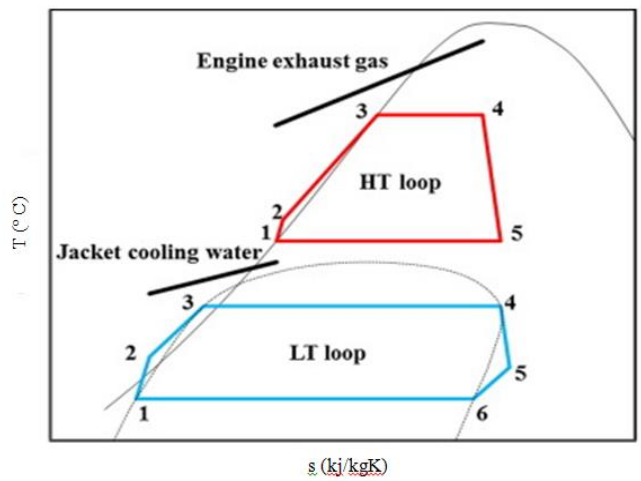

Figure 6: T-s diagram of ORC-ORC system [11].

Zhang et al. examined a system that combines a diesel engine with an ORC-ORC power cycle and recovers heat from the engine exhaust, inlet air and coolant. They found that the net power of the low temperature cycle was higher than that of the high temperature cycle and that the thermal efficiency increased by 16 - 43% [12].

Tian et al. proposed a regenerative transcritical ORC-ORC system in order to recover the exhaust waste heat and the whole waste heat of the engine coolant. Among the working fluids, it was found that if the use of toluene in high temperature cycle and R134a in low temperature cycle, the system thermal efficiency was 12.77% and exergy yield was 51.92%. The increase in temperature of the HT cycle reduces system performance by reducing net power and energy conversion efficiency. The condenser of the LT cycle and turbine of the HT cycle also has the least irreversibility [13].

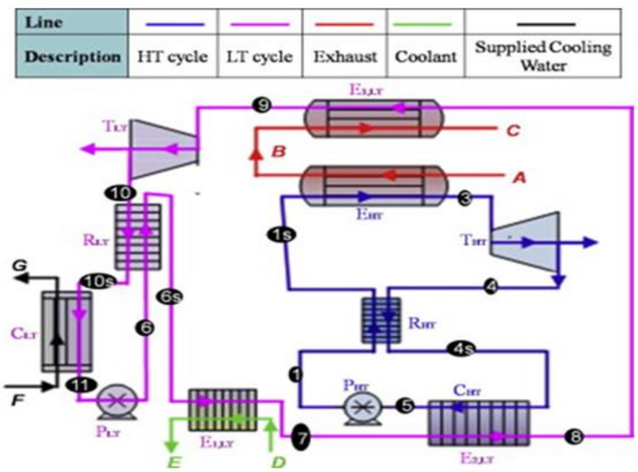

Figure 7: Regenerative ORC-ORC system structure [13].

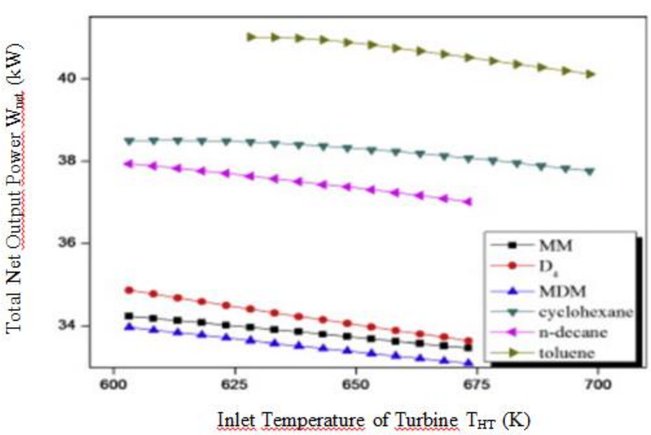

Figure 8: Variation of turbine inlet temperature and net power output [13].

Chen et al. proposed a cascade expansion ORC (CCE-ORC) system that is more suitable for the engine waste heat recovery, which has a simpler architecture, smaller volume and higher efficiency than the traditional ORC-ORC system. The thermodynamic simulation method was created by considering the non-design performances of the main components of the system and the working fluid pressure drop in the condenser. System performance simulations under full engine operating conditions have been found to be able to increase the thermal efficiency of the engine from 45.3% to 49.5% when applied to a heavy duty truck diesel engine. Compared to the traditional ORC-ORC system, the CCE-ORC system produces net power more than 8%, while the total heat exchanger volume is less than 18% [14].

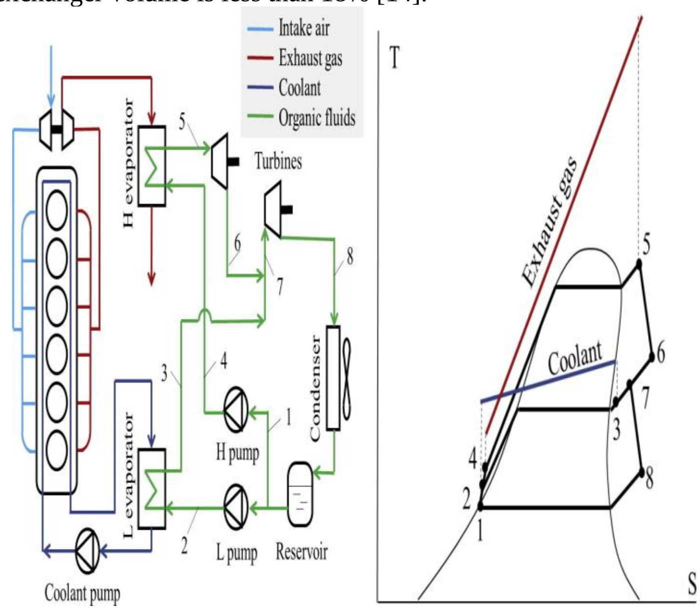

Figure 9: CCE-ORC system structure and T-s diagram [14].

Wang et al. (2018) examined the thermo-economic performance of the system by using isobutane as the working fluid for ORC-ORC and single-pressure evaporating ORC. A performance comparison was made between the two systems for the same source inlet temperature and optimized state. The results showed that the net power output of the ORC-ORC is higher at the low heat source temperature. [15].

B. Combined TLC-ORC Power Systems

Heat recovery technologies; the increase in fuel prices, meticulous emission regulations and the related increase in environmental problems related to the use of existing energy systems have received increasing attention worldwide [16, 17]. The heat transfer process in the evaporator of a conventional ORC system is a low temperature match between the heat source and the working fluid, depending on the evaporation process of the phase change. This leads to high exergy destruction and low thermodynamic performance [18, 19]. The characteristic of TLC is that the working liquid enters the expander directly after being heated in the evaporator without any evaporation process. Therefore, the temperature difference between the working fluid and the heat source in the evaporator may be smaller than that of a conventional ORC, which in general may result in a smaller exergy loss in the evaporator [20]. Johann Fischer (2011) compared the performance of a TLC and an ORC for waste heat recovery. The results showed that under the same operating conditions, the exergy efficiency of TLC could be 14-29% higher than that of a conventional ORC [21].

In the TLC - ORC system, higher thermal efficiency is aimed by using TLC instead of ORC as high temperature cycle. In TLC, the working fluid is heated without evaporation and then enters the turbine as a saturated liquid. Heat passes from the heat source to the working fluid, thereby providing a better temperature match between the heat source and the fluid than the ORC. In other words, low exergy destruction occurs according to ORC in the turbine. Therefore, thermal efficiency is increased.

Thermal efficiency of TLC-ORC systems varies between 17-25% [22].

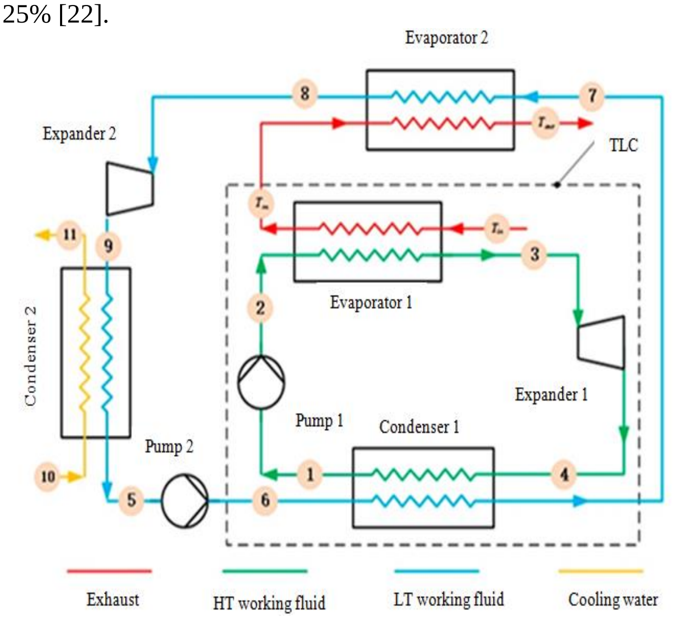

Figure 10: TLC-ORC combined power system structure [22].

Yu et al. articles, comprehensive comparisons between ORC-ORC and TLC-ORC systems have been made by using first and second law analysis. The values of the TLC-ORC system are 34.1%, 33.7% and 31.2% higher than the values of ORC-ORC, respectively [22].

Li et al. proposed a TLC-ORC combined power system for better thermal mapping between heat source and working fluid and for waste heat recovery. By selecting four different working fluids for the high temperature cycle, thermodynamic analysis of the system was performed under different evaporation temperatures for high temperature cycle and low temperature cycle. The results show that toluene has the best performance of fluids of other studies. The maximum net power output for toluene was 11.3 kW, thermal efficiency was 24.2% and exergy efficiency was 63.2% [23].

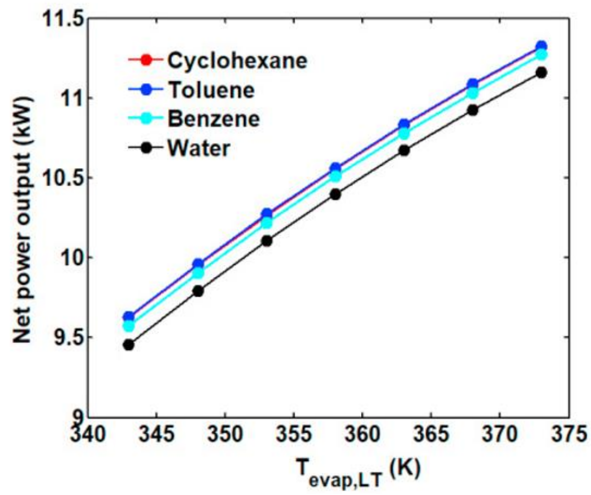

Figure11: Net power output variation of high temperature work fluid at different evaporation temperatures [23].

III. CONCLUSION

Waste heat recovery applications with ORCs are quite common today. The fact that it is one of the most effective methods for generating power from low and medium heat sources undoubtedly indicates that the use of ORC technologies will continue.

In this paper, the combined ORC - ORC and combined TLC - ORC power systems have been searched for waste heat recovery and the structures of the systems have been investigated. The only challenge of the combined TLC-ORC power system compared to the combined ORC-ORC power system is to use a dual-phase expander in the system. As a result of this research, it is seen that the combined TLC – ORC power system loops from these two different combined power systems work with higher thermal efficiency than ORC - ORC systems since two phase expander is used.

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