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A study on efficiency and electric production in a basic and a recuperative Organic Rankine Cycle

Temel ve reküperatif bir Organik Rankine Çevriminde verim ve elektrik üretimi üzerine bir çalışma

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Abstract

Reusing waste heat is one of the techniques for increasing energy efficiency, which is a highly emphasized issue today. The organic Rankine cycle, also known as ORC, is increasingly recognized as a promising technique for converting low-temperature heat into electricity. ORCs are designed to operate without human intervention and require minimal maintenance. Although basic ORC is increasingly accepted by the industry, there is still a need to improve cost effectiveness. For the purpose of this review, calculations of the ORC system were made for the purpose of generating electricity by utilizing the recovery of heat energy at low temperatures for companies that discharge waste heat into the environment. EES program was used to investigate the relationship between efficiency rates as well as fluid properties to be used in the ORC system. Among the various fluids used in this system, cyclohexane, R123 and R290 were determined to have the highest efficiency rates. Estimated efficiencies for these fluids are 26%, 18.28% and 8% respectively. Condenser and turbine powers were calculated and compared to determine which fluid had the optimum efficiency rate and waste heat capacity. It has been noted that as the temperature of the condenser increases, the power output of the turbine decreases. The most effective fluids for turbine power generation are cyclohexane and R123.

Keywords: Waste Heat Recovery, Engineering Equation Solver, Thermodynamic Analysis, Organic Rankine Cycle

Öz

Atık ısının yeniden kullanılması, günümüzde oldukça üzerinde durulan bir konu olan enerji verimliliğini artırma tekniklerinden biridir. ORC olarak da bilinen organik Rankine döngüsü, düşük sıcaklıklardaki ısıyı elektriğe dönüştürmek için umut verici bir teknik olarak giderek daha fazla tanınmaktadır. ORC'ler insan müdahalesi olmadan çalışacak ve minimum düzeyde bakım gerektirecek şekilde tasarlanmıştır. Temel ORC'nin endüstri tarafından giderek daha fazla kabul edilmesine rağmen, hala maliyet etkinliğinin arttırılmasına ihtiyaç vardır. Bu incelemenin amacı doğrultusunda atık ısıyı çevreye deşarj eden firmalar için düşük sıcaklıklarda ısı enerjisinin geri kazanılmasından yararlanılarak elektrik üretimi amacıyla ORC sisteminin hesaplamaları yapılmıştır. ORC sisteminde kullanılacak akışkan özelliklerinin yanı sıra verim oranları arasındaki ilişkiyi araştırmak için EES programı kullanıldı. Bu sistemde kullanılan çeşitli akışkanlar arasında sikloheksan, R123 ve R290'ın en yüksek verim oranlarına sahip olduğu belirlendi. Bu sıvılar için tahmini verimlilikler sırasıyla %26, %18,28 ve %8'dir. Hangi akışkanın optimum verim oranına ve atık ısı kapasitesine sahip olduğunu belirlemek için kondenser ve türbin güçlerini hesaplayıp karşılaştırılmıştır. Kondenserin sıcaklığı arttıkça türbinin güç çıkışının düştüğü kaydedilmiştir. Türbin güç üretimi için en etkili akışkanlar sikloheksan ve R123'tür.

Anahtar Kelimeler: Atık Isı Kazanımı, Mühendislik Denklem Çözücü, Termodinamik Analiz, Organik Rankine Çevrimi

1 Introduction

The exponential increase in global population and economic expansion has precipitated an energy resource catastrophe from a historical vantage point. Undoubtedly, the extensive utilization of fossil fuels has undeniable adverse impacts on human health and causes significant environmental degradation. In the present era, as the global energy demand rises, it is crucial to build energy systems that are both ecologically friendly and sustainable. [1]. Researchers are now exploring diverse methodologies to enhance the efficacy of energy systems with the aim of mitigating carbon emissions and lessening reliance on fossil fuels. Specifically, waste heat recovery is a notable field of study because it has the capacity to enhance the efficiency of energy systems and mitigate carbon emissions.

The emission of flue gas from power plants results in a significant loss of energy and financial resources, as it discharges the majority of its low temperature thermal energy into the environment. Waste heat recovery technology converts the wasted energy into a valuable form by recycling it using certain equipment. The waste heat recovery process typically utilizes a source temperature that is below 350 °C [2].

The working fluid states that several papers in the literature have investigated the effectiveness of the Organic Rankine Cycle (ORC) [3].

Yamamoto et al., performed simulation modeling for ORC to find the research conditions. They used HCFC-123, which has a low latent heat and low boiling point, as the working fluid. According to the research findings, they concluded that the

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selected fluid affects the system performance and turbine power in a good way [4].

Alkanes and others were approved by Lai et al. as working fluids for ORCs at high temperatures, and they first looked into the "isolated" ORC system at subcritical or supercritical maximum pressures at 250 °C and 300 °C. In order to enable heat transfer for the ORC working fluid from an external heat and heat carrier, they also applied compression analysis to the system. They discovered that cyclopentane was the best operating fluid for all states that were observed [5].

Zhang et al. looked at a system that uses a cross-flow heat exchanger with a mixture of water and air to move waste heat from the condenser cooling water to the air flow. They claimed that the turbine and generator set mounted on the thermal chimney could be run by accelerated air [6].

In another study on ORC, Auld et al., examined ORC by evaluating three different waste heats. These sources range from 10 kW to 10 MW. They modeled using different working fluids for each heat source. In the conclusion part, these models were compared [7].

Larsen et al., designed ORC with WHR for marine applications. The system performance was investigated for different types of fluids (wet, dry and isentropic). In addition, they investigated how process management in the system affects productivity. As a result, they found that dry type fluids perform best and non-flammable fluids work with high efficiency [8].

Lecompte et al., made general reviews on ORC systems. Existing experimental data were also included in these reviews. They also clearly stated the performance criteria and boundary conditions for the system [2].

Homamil et al., investigated cogeneration systems that generate heat and electricity for paper, petrochemical and textile production. They designed an ORC system using transbutene fluid. Taking advantage of the low pressure, they made a plan for fresh water, electricity and cooling in these facilities. As a result, they determined that 10000 kg/hour of water and 1533 kW of electricity were produced [9].

Mirzaeia et al., discussed the ORC system from a thermodynamic and economic point of view by utilizing the waste heat of the metal melting furnace. As a result of the research, they found that the fluids that provided the lowest cost and high system efficiency were m-xylene, P-xylene and Ethylbenzene, respectively [10].

Kilic et al., investigated the exhaust gas waste heat in order to increase the efficiency of the annealing furnace. They concluded that the system efficiency is 16% and the electrical energy of 1.626 GWh / year can be reached. In the cost analysis, they found a financial value of 436032.18 TL/year and a payback period of 8.12 years. They stated that the investment would be appropriate with the furnace working 8000 hours/year and above [11].

In their study, Sahin et al. modeled an ORC operating with R600a, R290, and R152a fluids, and they calculated the exergy of each. This study was conducted with a variety of values for the turbine's inlet temperature (oC) and pressure (kPa). In their research, they utilized MATLAB and the Engineering Equation Solver (EES) software[12]. Castelli et al., made ORC optimization by utilizing the waste heat of the aluminum production facility to be established in Norway. They investigated the highest energy performance by determining the most suitable working fluid among 102 fluids. As a mixture, they observed that the most efficient fluid was isobutane-isopentane [13].

Pili et al., conducted a study on three main industrial sectors (steel, cement and glass manufacturing) for the purpose of electricity generation with ORC. They emphasized that ORC application may be suitable for the steel industry in terms of economic and technical aspects. They also stated that there will be 0.9 and 2.7 Mt CO2 reduction annually with ORC systems [14].

Another study that looked into the impact of losses on system performance was conducted by Zhang et al., who built an ORC system to use the diesel engine's exhaust waste heat. Exergy loss from the evaporator was calculated to be 60 kW, with a loss rate of between 65 and 69%, based on their research. Furthermore, the screw expander's shaft and exergy efficiencies were determined to be 49.8% and 38.4%, respectively. They recommend beginning system upgrades in the evaporator before moving on to the expander [15].

The Organic Rankine Cycle (ORC) is a common method of transforming low-temperature heat into electricity that is utilized extensively throughout the world. The evaporator, turbine, condenser, and pump are the system's four main parts, and according to the ORC principle, they transform waste heat energy into mechanical energy, which is then transformed into electrical energy using a generator. The refrigerants employed in the system rank top among the elements influencing system efficiency in the Organic Rankine Cycle. In this study, we used several fluid types to compare the recuperator ORC system and the straightforward ORC system. In accordance with the quantity of waste heat and the evaporator capacity, we investigated the thermal efficiency of the ORC system at various condenser temperatures. Additionally, we contrasted the isentropic turbine efficiency's contribution to system efficiency. A common power generation technology that transforms low temperature heat energy into electrical energy is the Organic Rankine Cycle (ORC). The system, which is based on the ORC operating principle, is made up of four fundamental components and it converts waste heat energy first into mechanical energy, then into electrical energy using an electrical generator.

2 Material and Methods

2.1 System description

The term "waste heat recovery" refers to the process of collecting energy from waste heat that is produced as a consequence of numerous activities that take place in industrial infrastructure.

This system consists of evaporator, turbine, recuperator, condenser and pump. Between points 1-2, the pump pressurizes the circulation fluid and delivers it to the recuperator. The fluid that circulates through the recuperator (3) comes out of the evaporator (4) as superheated steam (5-6). The next steps is the saturated vapour enters the turbine. The fluid coming out of the turbine energizes the recuperator (7) and enters the condenser (8), completing the cycle.

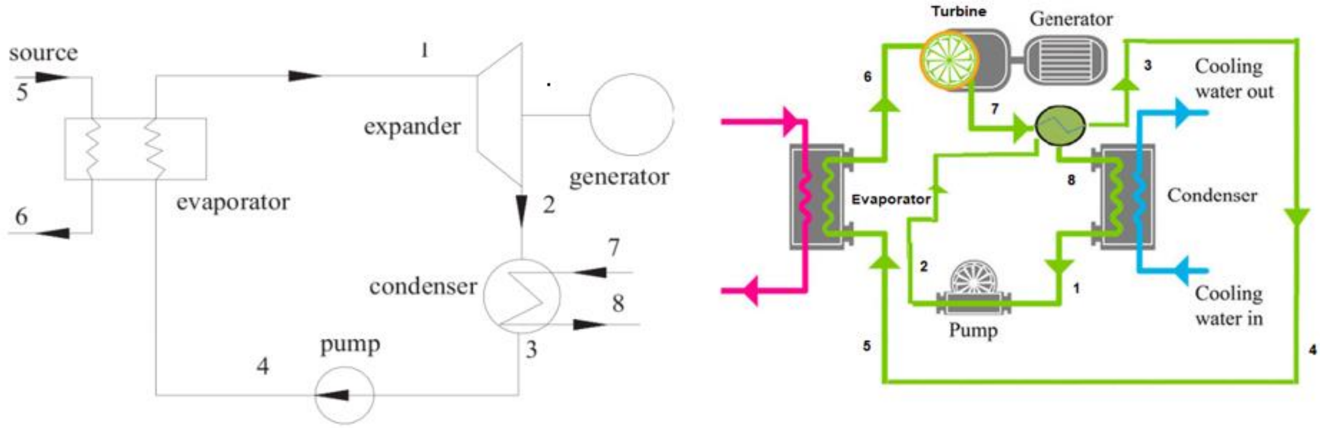


Figure 1. Simple and recuperative ORC system components.

Table. 1 Critical temperature and pressure, Global Warming Potential (GWP) and Ozone Depletion Potential (ODP) values of the fluids.

Refrigerant Fluid	$T_{critical}$ (K)	$P_{critical}$ (MPa)	Type of fluid	ODP	GWP (100 year)
Cyclohexane	553.64	4.075	Dry	0	Low
R123	467.7	3.66	Wet	0.020	4
R290	368.89	4.25	Wet	0	3

The ORC system has many advantages compared to other steam cycle systems. Since steam-operated systems operate at high temperature and pressure, the equipment used in the system is more costly to maintain. In the ORC system, the mechanical stresses on the equipment are less since it is operated at low temperatures and pressures. In addition, an operator is not needed to control the system under these conditions. In ORC systems, the turbine rotates at low speeds compared to other steam turbines, minimizing events such as water hammer and high turbine efficiency (up to 85%) can be achieved [16].

The ozone layer is badly impacted by the release of hydrogen and carbon-based chemicals, among other substances. As much ozone as 100,000 chlorine atoms can damage. Ozone depletion and widespread ozone layer degradation result from this [17]. Thermal insulation's impact on ozone depletion and climate change is discussed in 2016. Table 1 provides the critical temperature and pressure, GWP, and ODP values for the fluids.

2.2 Working fluid selection

Fluid selection is one of the important factors in ORC systems. When choosing the fluid, it is necessary to evaluate several criteria (Critical temperature and pressure, etc.). In this study, we chose internal fluid (R123, R290 and Cyclohexane).

Table 1 displays the fluids' physical characteristics. Dry and highly pressurized, cyclohexane is a fluid with extreme properties. Wet fluids R123 and R290 have a high critical temperature and pressure.

2.3 Energy system equations

For an ideal cycle to occur, there are four basic processes through which the working fluid passes through the system. In this process, according to Figure 1, the mathematical Equations (1-6) for the ORC system are as follows;

Saturated liquid is pushed from the condenser to the evaporator at a constant entropy. Even under the best-case scenario, the efficiency of energy conversion will fall short of 100%. Point 1 in Figure 1 represents the working liquid condition at the pump intake, whereas point 2 represents the working liquid condition at the pump output. The pump's specific work (1-2) is calculated using Eq.(1).

$$W_p = \dot{m}(h_2 - h_1) = \frac{\dot{m}(h_{2s} - h_1)}{\eta_p} \tag{1}$$

where W_p is the power of pump (kj/kg), h the enthalpy (J.kg^{-1}), mass flow rate (kg.s^{-1}) and is the η_p efficiency of pump respectively.

The heat rate of the recuperator (2-3) is calculated as follows:

$$\dot{Q}_{rec} = \dot{m}(h_3 - h_2) = \dot{m}(h_7 - h_8) \tag{2}$$

Where Q_{rec} is the heat rate (kW).

Point 6 represents the evaporator outlet when heat is added to the working fluid and The heat rate in the evaporator (5-6) is evaluated by the following equation:

$$\dot{Q}_{evap} = \dot{m}(h_5 - h_6) \tag{3}$$

Where Q_{evap} is the heat rate (kW).

In this process, energy is absorbed in the evaporator as the fluid expands in the turbine to obtain mechanical work. Point 7 shows the turbine output where the work takes place and turbine (6-7) work of the ORC system is evaluated according to Eq.(4):

$$W_t = \dot{m}(h_6 - h_7) = \dot{m}(h_6 - h_{7s}) \times \eta_t \tag{4}$$

Where W_t is the power of turbine (kW) and η_p efficiency of turbine.

The working fluid from the condenser is transferred to the pump in step (8-1). After passing through the condenser, the working fluid reaches its maximum saturation. 1 in Figure 1, refers to the condenser outlet and the pump inlet. The amount of heat rejected can be calculated as:

$$\dot{Q}_{cond} = \dot{m}(h_8 - h_1) \tag{5}$$

Where Q_{evap} is the heat rate (W).

System efficiency is the ratio of the network output to the heat generated in the evaporator. The thermal efficiency (efficiency ratios) of the ORC was calculated by expressing it in Eq.(6):

$$\eta = (W_t - W_p)/\dot{Q}_{evap} \tag{6}$$

The total power output of the system was calculated as follows:

$$W_{net} = (W_t - W_p) \tag{7}$$

Where η and W_{net} are thermal efficiency and total power output (kW).

The necessary thermodynamic calculations for the analysis were made using the EES program. EES is a program that analyzes thermodynamic properties for refrigerants in-house. It calculates the thermodynamic properties at every point of the system according to the input values to the equipment used.

2.4 Assumptions

The thermodynamic equation in the system relies on the following assumptions: Throughout the cycle, the system remains in a stable state, maintaining a consistent flow. The energy and heat conduction inside the system are both aligned in the correct direction. At a state of equilibrium, the turbine exhibits an isentropic efficiency of 85%, while the pump and engine show efficiencies of 70% each. The superheated temperature (Tsh) was 10 degrees Celsius below the ambient temperature range of 30-60 degrees Celsius. The program presupposes a boiler capacity of 250 kW.

3 Results and Discussion

The temperatures of the condenser were altered, and the thermal efficiency (efficiency ratios) were analyzed (Figure 2). These adjustments were made in accordance with the critical temperature and pressure values of the fluids. While the evaporator temperature is kept constant, the condenser temperature varies between 30-60 ˚C.

When the ORC efficiency was compared for simple and recuperator systems, it was found 19.92% and 26.28% (Figure 3) for Cyclohexane fluid at 30°C condenser temperature, respectively. At 60°C, these values were calculated as 16.67% and 22.62%. In the system in which R123 fluid is used, thermal efficiency of 15.84% and 18.28% were obtained for simple and recuperator ORC at 30 °C condenser temperature. For 60°C, it was found 12.39% and 14.37%. For the R290 fluid, these values were lower and were found to be 7% and 3% at 30 and 60°C, respectively, in the simple ORC system, and 8% and 3.7% at 30 and 60°C in the recuperator system. The highest thermal efficiency was found in the system where cyclohexane fluid was selected at 30°C condenser temperature.

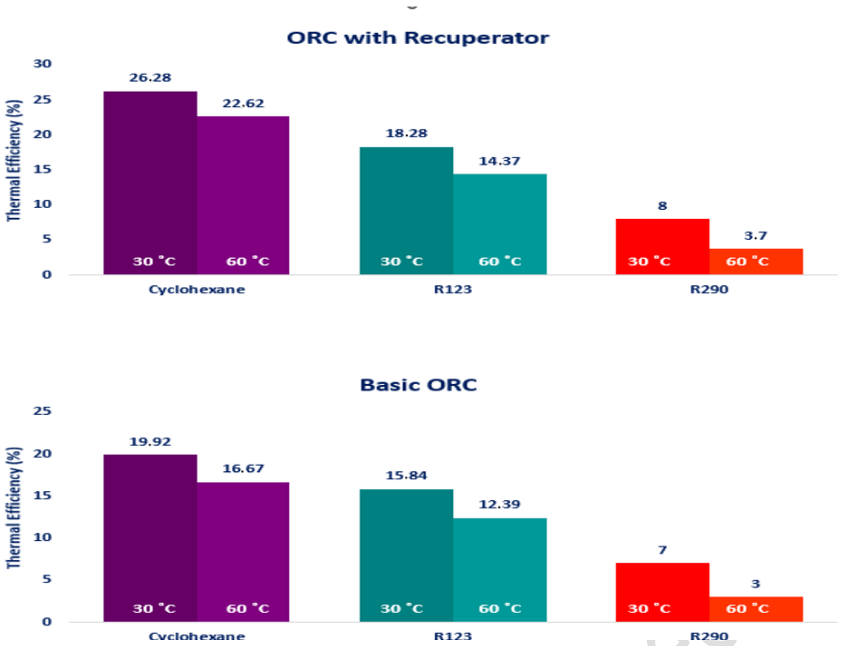
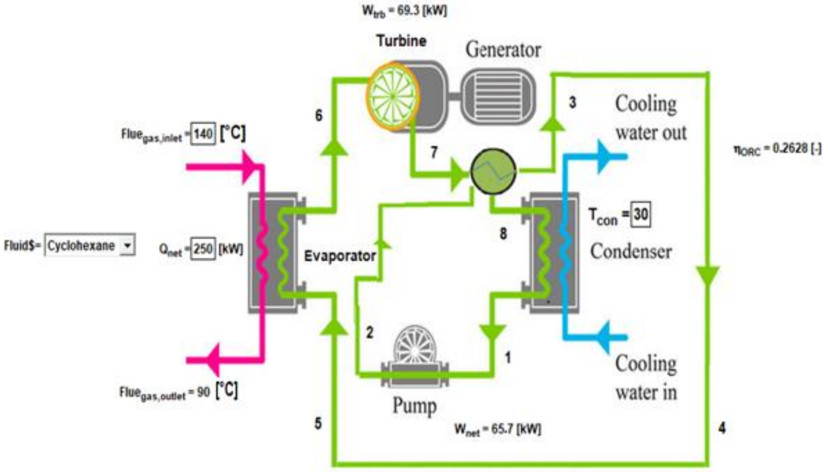


Figure 2. Thermal efficiency of recuperative ORC system for different fluids.



W_{trb} = 69.3 [kW]

$Flue_{gas,inlet}$ = 140 [°C]

Fluid$= Cyclohexane

Q_{net} = 250 [kW]

$Flue_{gas,outlet}$ = 90 [°C]

T_{con} = 30

η_{ORC} = 0.2628 [-]

W_{net} = 65.7 [kW]

Figure 3. The efficiency of the ORC system with recuperator for Cyclohexane in the EES diagram window.

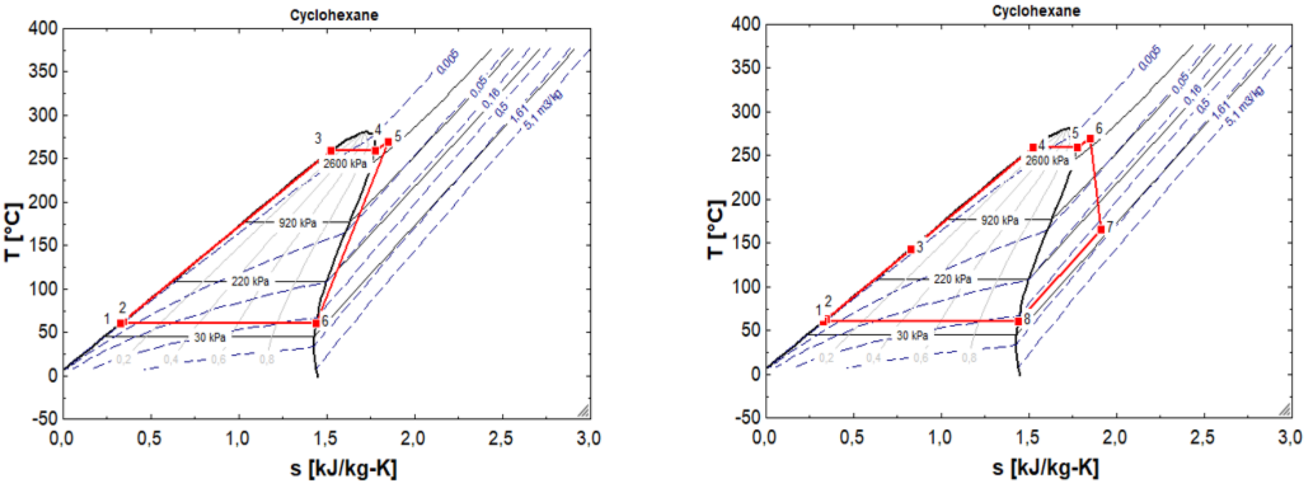


Figure 4. T-s diagrams of the cyclohexane basic ORC and ORC with recuperator

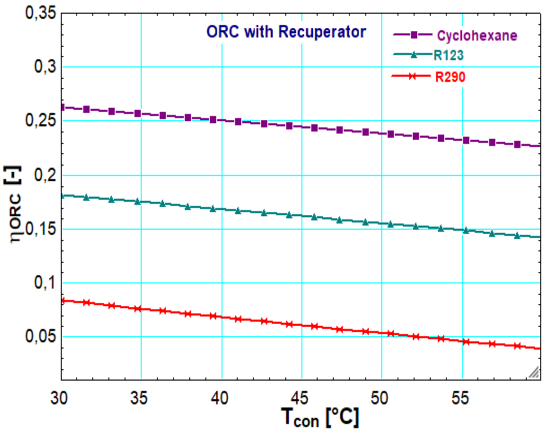


Figure 5. Efficiency ratio variation with condenser temperature for different fluids (cyclohexane, R123 and R290) basic ORC and ORC with recuperator.

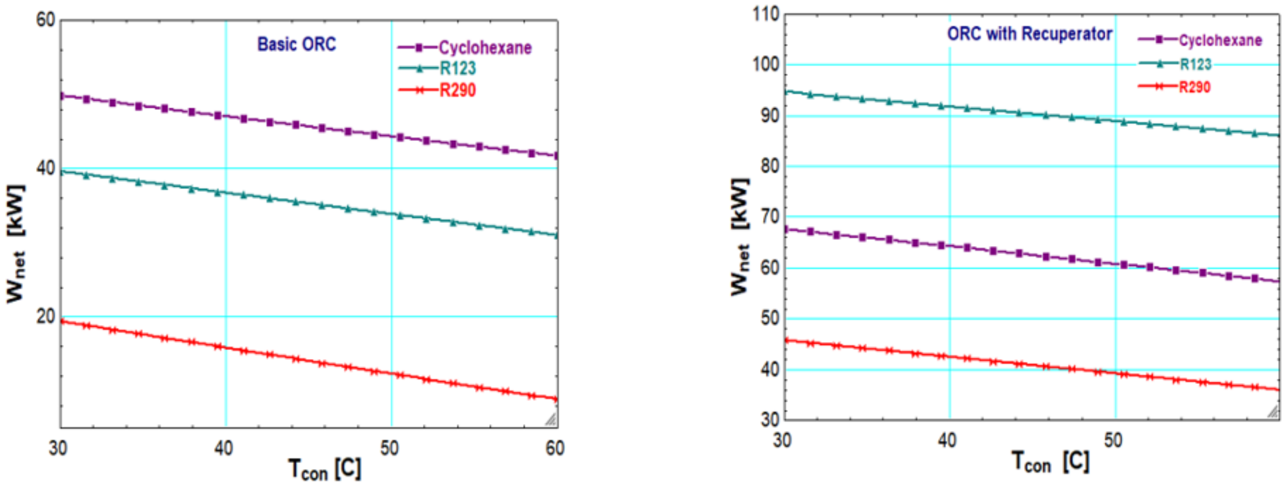


Figure 6. Condenser and turbine power variation for Cyclohexane, R123 and R290 fluids basic ORC and ORC with recuperator.

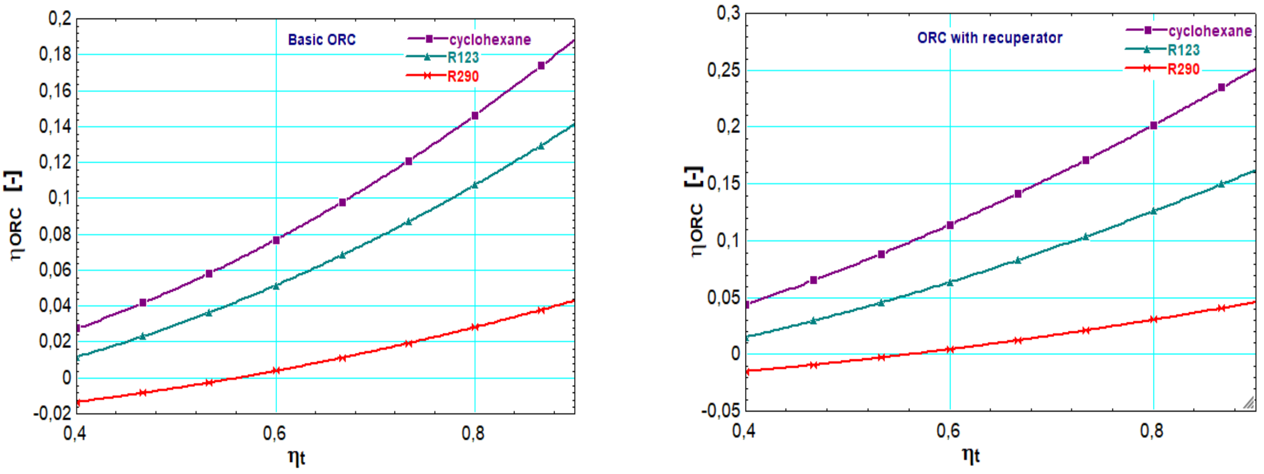


Figure 7. Efficiency ratio and turbine isentropic efficiency variation for Cyclohexane, R123 and R290 fluids basic ORC and ORC with recuperator.

The thermodynamic properties calculated by the EES program for Cyclohexane fluid in ORCs. According to these found points, T-s diagram was created for the cycle (Figure 4). The efficiency of the system was investigated by changing the evaporator temperature according to the critical temperature values for three different fluids used in the system (Figure 3). According to the calculations, increasing the evaporator temperature increased the thermal efficiency of the ORC system. Figure 5 shows, the efficiency rate was highest in the system with recuperator where cyclohexane and R123 fluids were used. These values were found to be 26% for cyclohexane and 18% for R123.

For R123, R290 and cyclohexane fluid, the increase in evaporator temperature decreased the heat removed from the system and increased the turbine power. The highest turbine power was reached in the system where cyclohexane fluid is used (Figure 6). The last parameter was efficiency ratio and isentropic efficiency of the turbine. In this study, thermal efficiency was calculated for isentropic turbine efficiencies between 0.40 and 0.90. The research results are given in Figure 7.

The amount of heat discharged from the condenser and turbine power were calculated for the three fluids (Cyclohexane, R123 and R290) selected to be used in the ORC system.

4 Conclusion

The thermal efficiency of the cycle varied depending on the fluid used in the ORC system. The efficiencies of the three distinct fluids used in the basic ORC system, namely Cyclohexane, R123, and R290, have been determined to be 19.92%, 15.84%, and 7.74% respectively. The waste heat emitted from the condenser and turbine powers were compared for these three fluids. The waste heat amounts for Cyclohexane, R123, and R290 range from 79 to 90 kW, 38 to 40 kW, and 10 to 18 kW, respectively. The turbine power ranges from 60 to 70 kW, 41 to 51 kW, and 16 to 29 kW for Cyclohexane, R123, and R290, respectively. The rise in the evaporator temperature resulted in a reduction of waste heat, while simultaneously causing an increase in turbine power. The maximum turbine power was determined to be 6.3 kW while using Cyclohexane as the fluid. Optimal turbine power was attained with the use of Cyclohexane and R123 fluids.

5 Author contribution statements

Author 2 helped carry out the research and develop the concept for this study. Authors 1, 2, and 3 conducted a literature review, arranged references for sources of materials used, evaluated the outcomes acquired, and wrote and proofread the paper.

6 Ethics committee approval and conflict of interest statement

The prepared article does not require approval from the ethics committee. No organization or individual has a vested interest in the outcome of this article.

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