DESIGN, MANUFACTURING AND EXPERIMENTAL INVESTIGATION OF ORGANIC RANKINE CYCLE APPARATUS

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Abstract: Turkey has a variety of heat sources between 90 and 125 ˚C which are not suitable for power generation. These sources are waste sources or used only for heating purposes. Whereas these sources can be used to produce electricity with Organic Rankin Cycle (ORC) so that economic recovery may be obtained. Because of technical difficulties and non-economic situation to utilize low temperature heat traditionally constitutes challenging. Traditionally, steam turbine is used in power generation. But it requires high temperature and pressure for proper operation. Preferred technology at low temperatures is the Organic Rankin Cycle (ORC). The ORC technology uses liquids which boils at lower temperatures than water, less risk of corrosion and high molecular weight instead of high pressure water and steam. In this study, low-temperature waste heat source ORC system is designed, produced and used in power generation. Experimental studies were performed using R134a and R22 refrigerant in the produced system. At the end of the experimental studies, the performance of the system were determined.

Keywords: Energy analysis, ORC, Power Production, Waste Heat

Introduction

Demand for energy increases due to technological developments and population rise every passing day. Today, energy is considered to be a criterion of development in all countries. As Turkey is just at the threshold of development, its energy need increases every passing day. However, although it has a great variety of energy sources, its current sources cannot meet its energy need for consumption. Incapability to use domestic sources in energy generation shows Turkey's external dependence. External dependence in energy increases every passing year. Hence, a big move has to be made in energy generation through domestic sources. If such move is not made, such external dependence is likely to rise to above 80s% in the forthcoming periods. Therefore, Turkey has to make use of its energy sources in the most economical and efficient way and utilize alternative energy sources (Türkyılmaz, 2014). In this regard, organic Rankine cycle (ORC) appears as a strong alternative. Although ORC technology has a long past, it is a new energy generation method for Turkey. Today, there are ongoing new studies aimed at generating stronger energy and providing more efficient working conditions in ORC systems. In general, ORC systems are designed and used based on waste heat, geothermal energy, and solar energy (Ergün, Özkaymak & Kılıçaslan, 2016; Ergün 2014). Agahi et al. (2011) conducted a study about optimal air-cooled condenser sizing in geothermal ORC (binary) systems. They proposed a new methodology for an air-cooled condenser optimization and used a registered simulation software to evaluate the performance of the geothermal power plant by changing the condenser design parameters. Based on the data obtained from the simulation, they determined the economical factors and the optimal design parameters of the air-cooled condenser. Yılmaz et al. (2015) made energy and exergy analyses by examining a solar ORC system run by R-410a organic fluid according to the solar power data of Isparta province. They determined the thermal efficiency and exergy efficiency of the system to be 10% and 70% respectively and stated that rise in turbine inlet pressure and boiler pressure increased the thermal efficiency and exergy efficiency. Özden and Paul (2011) examined Denizli, Sarayköy geothermal power plant where electricity is generated through ORC technology and provided information about selection of the working fluid, installation of the system, and advantages of the ORC system. Etemoğlu et al. (2006) analyzed the usability of geothermal energy in Bursa province and its surrounding and used and explored ORC technology in a geothermal source with the inlet conditions of 161 kPa and 102.2 ˚C. In the system in which isopentane was used as a working fluid, the biggest irreversibility was found to be in the vaporizer (43%). Eyidoğan et al. (2016) made the technical and economic analyses of ORC systems in Turkey and indicated the areas of application in detail. In their study in which they gave information about the incentive programs of the government, they made the feasibility analyses of a biomass-supported 1MW ORC power plant as an example and found the payback period to be approximately 2.7 years. Kavasoğlu and Cihan (2015) made the energy and exergy analyses of a conventional refrigeration cycle run by an ORC system using waste hot water as heat source. They used R123, R600, R245fa, R141b, and R600a fluids in the system and investigated the exergy efficiency, performance coefficient, and exergy destruction values of the system and found R141b to be the most appropriate fluid. Zheng et al. (2015) used one-kilowatt rotating type piston expander and the R245fa working fluid to explore the dynamic testing of the expander. They established an experimental system and used a hot water boiler as a source at low temperature. They explored and analyzed experimental results such as the mass flow of the fluid, expander inlet-outlet temperature and pressure, the obtained power, and rotational speed. At the end of the experimental study, they found out that the expander worked in the range of 350-800 rpm and had a maximum output power of 0.35 kW at 90°C source temperature.

Based on such information, they calculated the maximum expander isentropic efficiency to be 43.3% and ORC efficiency to be 5%. Eyidoğan et al. (2015) made the energy and exergy analyses of a biomass-based ORC system obtained from forestry products. They used real system data and employed biomass-based hot oil boiler as the source temperature of the ORC unit. They made energy and exergy analyses on the evaporator, condenser, and turbine, which are the main equipment of the ORC system, under two different working conditions. They also investigated the effects of the condenser pressure on energy and exergy efficiency. Under the first working condition, they found energy efficiency to be 12.57% and exergy efficiency to be 33.26%. Under the second working condition, they found energy efficiency to be 13.2% and exergy efficiency to be 35.5%. The distribution of exergy destruction in the system equipment in a descending order was found to be as follows: evaporator, condenser, turbine, regenerator, and pump. Dai et al. (2009) examined a waste-heat recovery ORC system by using different working fluids. They analyzed the effects of thermodynamic parameters on ORC performance and optimized thee parameters for each fluid. Quoilin et al. (2011) carried out the thermodynamic and thermoeconomic optimization of small-size water-heat recovery ORC system. They examined the cycle performances determined through R245fa, R113, n-butane, n-pentane, and R1234yf organic fluids and different equipment sizes. For n-butane fluid, they determined a specific cost of 2136 €/kW, a net output power of 4.2 kW, and a system efficiency value of 4.47% for thermoeconomic optimization. Thermodynamically, they determined the system efficiency to be 5.22% for the same fluid. Al-Sulaiman et al. (2013a,b) conducted a two-part study. In the first one, they provided equations and calculations related to the thermodynamic optimization of a fuel cell, biomass, and solar power trigeneration system integrated with three new ORCs. In the second part, they made the calculations of three new systems whose equations they showed. In the end, they found the highest trigeneration exergy efficiency to be 38% in the fuel cell ORC system. It was followed by the biomass system (28%) and the solar power system (18%).

In the present study, power was generated by designing and manufacturing an ORC system based on low temperature waste heat working according to the organic Rankine cycle principle. In addition, experiments were carried out in this ORC system by using the R-134a and R-22 working fluids, thereby making the performance and efficiency analyses of the system.

Materials and Methods

ORC systems are the systems which have quite a similar working to the known Rankine cycle, but use the organic fluids passing to the vapor phase at lower temperatures instead of working fluid. The layout of a simple ORC system is seen in the Figure 1 below.

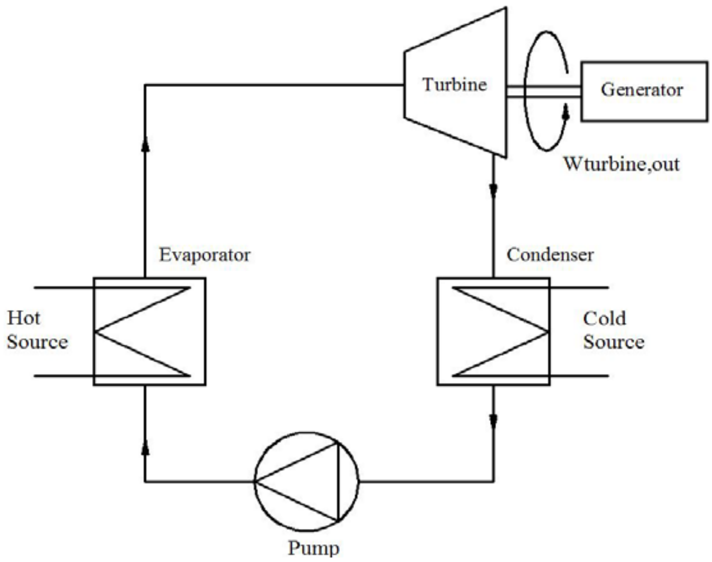

Figure 1. Organic Rankine cycle (ORC) layout

As is known, a fossil-origin fuel is burnt, thereby turning the fluid into superheated vapor in Rankine cycle. In the ORC system, on the other hand, superheated vapor is obtained at lower temperatures without burning any fuel with an external heat source. The fluid pressurized with the pump is converted into mechanical work in the turbine. It turns into the liquid phase in the condenser. The cycle of the system goes on in this way.

In this study, a system working according to the organic Rankine cycle principle was defined and manufactured. The designed and manufactured system is showed in the Figure 2 below in detail.

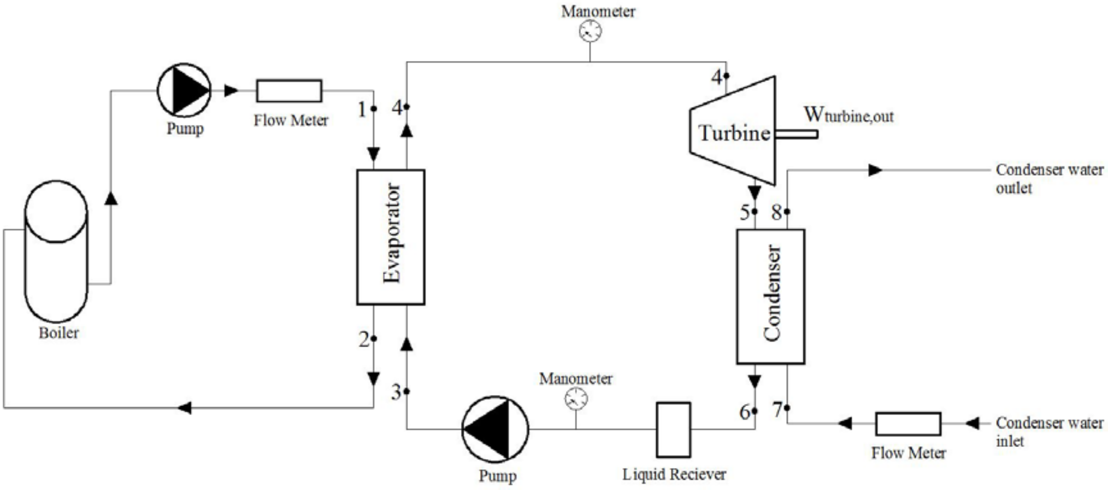

Figure 2. The Designed and Manufactured System

In the system, two plate heat exchangers (to be used as evaporator and condenser), Sanden scroll compressor (as turbine), and a magnetic pump (for the circulation of the organic fluid) were used. In addition, a 15-liter capacity boiler was designed as the heat source (evaporator) of the system. It was manufactured in a way allowing control via thermostat. A 50 W pump was used for the circulation of the boiler water. City water was connected to the heat exchanger for the cold source of the system (condenser). Evaporator and condenser water flows were determined via float type flow meters. In the system, pressure values were checked via manometers while temperature values were checked via Picolog data logger.

Thermodynamic Analysis of the System

The organic fluent flow in the system can be determined by writing energy equation for the heat exchanger used as an evaporator.

$$Q_{su} = Q_{oa} \quad (1)$$

$$m_{water} \times c_{p_{water}} \times \Delta T_{water} = m_{oa} \times c_{p_{oa}} \times \Delta T_{oa} \quad (2)$$

The energy entering the system is equal to the difference between the enthalpy in the entrance of the hot water obtained in the boiler and the enthalpy in its exit multiplied by mass flow. It is expressed with the Equation 3.

$$Q_{entering} = m_{hot,water} \times (h_1 - h_2) \quad (3)$$

The mechanical work obtained from the system is equal to turbine work. It is showed in the Equation 4 below.

$$W_{turbine} = m_{oa} \times (h_4 - h_5) \quad (4)$$

The network obtained from the system (Wnet) is calculated by subtracting the pump powers from the power obtained in the turbine. The powers of the pumps used in the system were taken as 300 and 50 Watt from the catalog. This values shows the net power to be used while calculating the energy efficiencies. It is calculated with the Equation 5.

$$W_{net} = W_{turbine} - W_{pump} \quad (5)$$

The thermal efficiency of the system is calculated through the Equation 6.

$$\eta_{Termal} = \frac{W_{net}}{Q_{entering}} \quad (6)$$

Results and Discussion

In the present study, data were obtained by carrying out five experiments for each one of the R134a and R22 fluids at the intervals of 10 minutes. The data obtained through the equations given above are presented in graphs.

The mass flows calculated by using the Equation (2) based on the values measured during the 50-minute experiment are graphically showed for both fluids in the Figure 3.

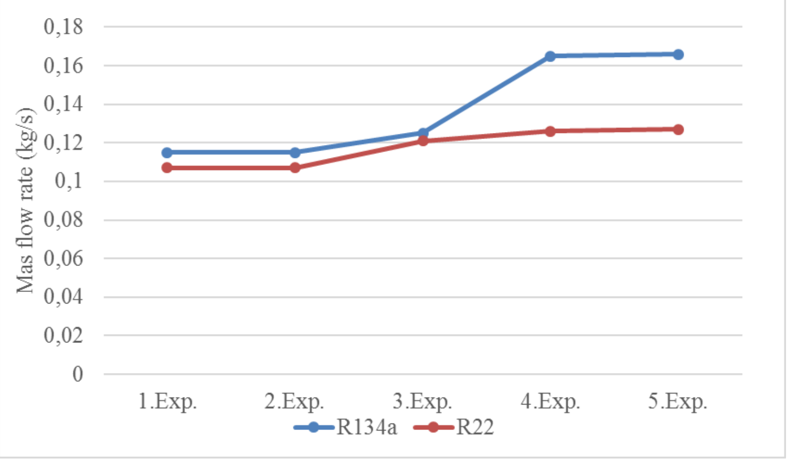

Figure 3. The flow values of the R134a and R22 fluids

Figure 4 and Figure 5 show the change in net work changing depending on the source temperature and turbine inlet temperature in the system for the R134a gas. As is seen in the figure also, as source temperature and turbine inlet temperature rise, the net work produced increases as well.

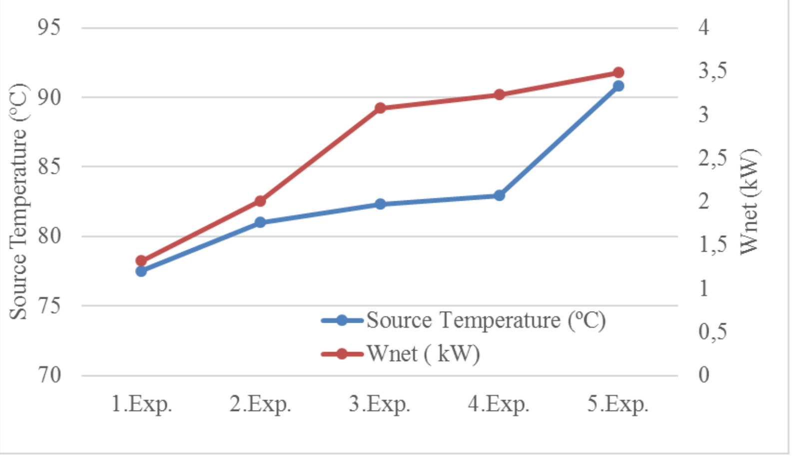

Figure 4. The net work produced based on the source temperature

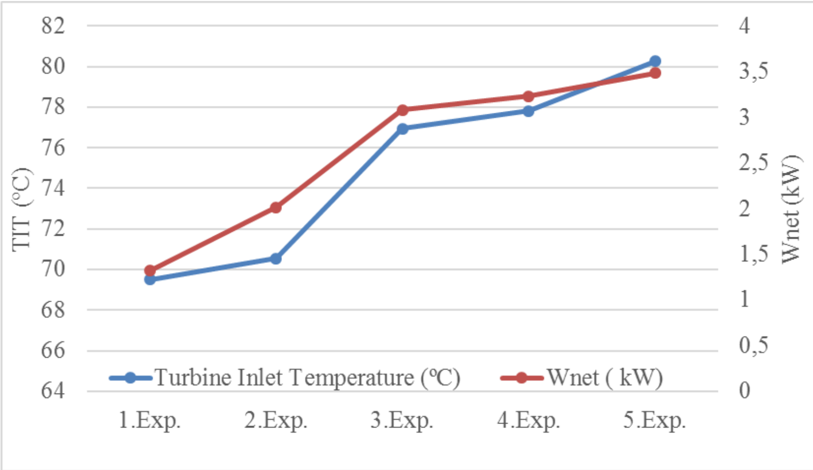

Figure 5. The net energy values produced by the R134a fluid based on the turbine inlet temperature

Figs. 6 and 7 show the change in net work based on the source temperature and turbine inlet temperature for the R22 gas. In a similar way to the R134a fluid, net work increased as the source temperature and turbine inlet temperature rise.

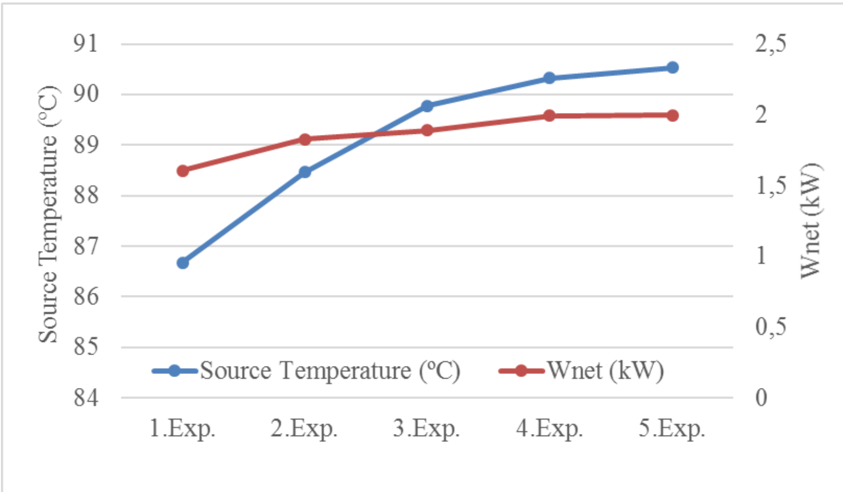

Figure 6. The energy values produced by the R22 fluid based on the source temperature

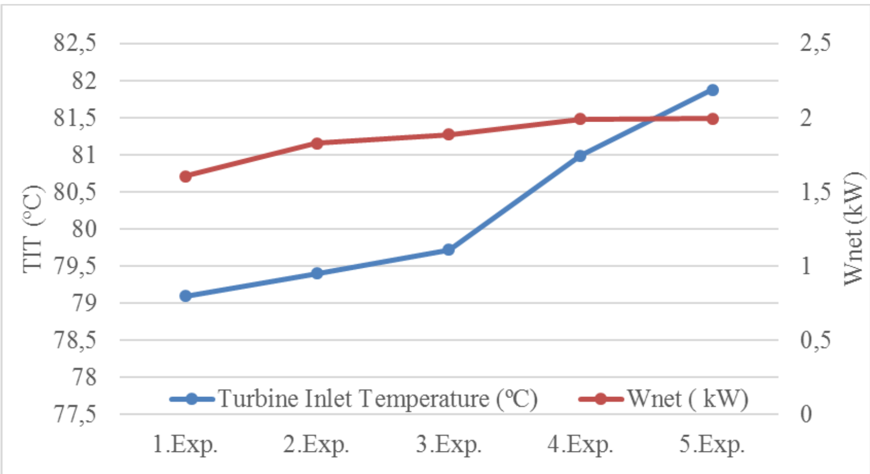

Figure 7. The energy values produced by the R22 fluid based on the turbine inlet temperature

Figs 8 and 9 provide efficiency and net work comparisons for the two fluids. The net work and efficiencies are higher for R134a fluid.

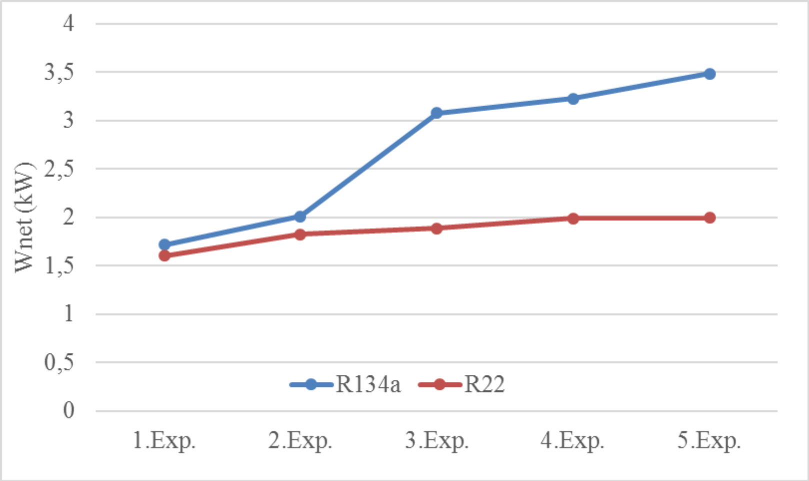

Figure 8. Comparison of the network generated by the R134a and R22 fluids through the turbine

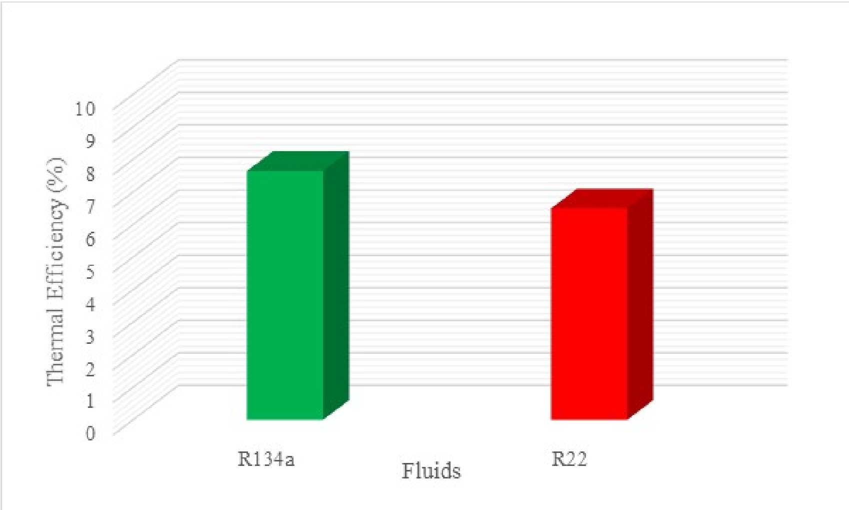

Figure 9. Comparison of the efficiencies

Conclusion

In the present study, the following findings were obtained based on the experimental data:

- Especially waste-heat recovery and geothermal systems working according to the organic Rankine cycle principle are suitable for continuous electricity production. The use of these sources stands as an alternative solution that can reduce Turkey's external dependence in energy.
- Source temperature is very important in ORC systems. The higher the source temperature is, the higher net work and efficiency are.
- Besides the source temperature, the turbine inlet temperature of the organic fluid is one of the most critical parameters. Transferring the source temperature to the organic fluid with minimum loss possible will enhance the efficiency of the system. Hence, the design of the heat exchanger used as evaporator is of great importance.
- The R134 gas used in the system provided more efficient working conditions. The main criterion in these kinds of power generation plants is the net power generated. It is reported in the literature that calculating exergy efficiency rather than thermal efficiency yields more accurate results in the comparison of ORC systems. Therefore, it is recommended to make exergy analysis of these systems besides their thermal analysis.

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