THERMODYNAMIC ANALYSIS OF REFRIGERANTS USED IN ORC-VCC COMBINED POWER SYSTEMS FOR LOW TEMPERATURE HEAT SOURCES

by

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Fossil resources are largely used for energy supply. This situation causes environmental pollution. In recent years, studies in the field of more environmentally friendly and sustainable energy conversion technologies have increased. In this context, organic Rankine cycle (ORC) technology is combined with RES. In this study, combined ORC and vapor compression cycle (VCC) were investigated. The electricity produced in the combined ORC-VCC system was used both in the compressor of the VCC system and in the plant. The main factor affecting the efficiency of the combined ORC-VCC system is the refrigerant. Therefore, it is necessary to examine the selection of the most suitable refrigerant for an ORC-VCC based system. Fifteen different refrigerants were optimized with the enginering equation solver program, and energy and exergy analyzes of the systems were made separately. According to the results, the best energy efficiency and COP values among the refrigerants was found to be R40 (η_{ORC} = 0.1206) for the ORC system and R113 (COP = 4.405) for the VCC system. For all system components in the VCC, the most exergy destruction occurs in the evaporator, followed by the compressor, condenser, and throttle, respectively. In ORC, the most exergy destruction is in the evaporator, followed by the condenser, tube and pump, respectively. The total efficiency was found to be (β = 0.53) for the combined ORC-VCC system. The total exergetic efficiency was found to be (ψ_{glob} = 0.26) for the combined ORC-VCC system.

Key words: *ORC, VCC, refrigerants, exergy, energy*

Introduction

The increase in energy costs and energy consumption, which is prominent with economic developments, and the global negativities brought by the pandemic have revealed the problem of not meeting the energy demands fully. The efficient use of energy has emerged as an inevitable situation in order to rapidly meet the global needs in energy and make it sustainable [1].

In general, one of the two main threatening problems facing humanity today is global warming and the other is a pandemic. Studies are focused on ending the pandemic and minimizing global warming. In order to reduce global warming, it will be necessary to move away from fossil sources and use more RES instead. When using RES, the most important element to be considered is the use of energy at the maximum level. In addition RES, it is necessary to use

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waste energy sources effectively. The use of ORC systems, especially for the use of waste heat, provides more effective and efficient results. Resources used for ORC systems. Renewable sources such as geothermal heat sources, biomass heat and solar energy heat, and energy sources such as all kinds of waste heat. All of these resources are preferred for ORC systems. In this context, systems that combine ORC and vapor compression refrigeration cycles in combined power cycles are the most widely used systems (ORC-VCC combined system).

The ORC-VCC combined system allows simultaneous output of heating, cooling, electricity and hot water. The ORC-VCC combined system studies in the literature are given. Saha and Chakraborty [2] conducted research for the reuse of low grade waste energy using the ORC technology. Khatoon *et al.* [3], performed a performance analysis of a combined power and cooling system consisting of ORC and VCC in their study. In the VCC system, using refrigerants R123, R134a, and R245fa, they found COP values of 2.85, 2.58, and 2.7089, respectively. They used propane and R245fa for ORC. Toujani *et al.* [4], analyzed the performance of the Rankine-vapor compression cycle for electricity and refrigeration cogeneration. The parameters were evaluated using ammonia for ORC and R600a fluids for VCC.

Hernandez-Fernandez *et.al*. [5], five organic liquids were used in their analysis. (R1234yf, R1234ze, R143a, R152a, and propylene). They found that the liquid that best met the criteria under operating conditions was R1234yf. Dibazar *et al*. [6], in their study, simulated three different types of ORC, basic ORC (BORC), single regenerated ORC (SRORC), and double regenerated ORC (DRORC), using the same heat source in three different ORC. They stated that improvement priority in system components should be given to turbines, evaporators, condensers and feed water heaters, respectively. Lecompte *et al*., [7], performed their thermodynamic analysis by using zeotropic (R245fa-pentane, R245fa-R365mfc, isopentane-isohexane, isopentane-cyclohexane, isopentane-ishexane, isobutane-isopentane, and pentane–hexane) fluids as refrigerants. As a result of the study, it was found that the evaporator was responsible for the highest exergy loss. Saleh [8], evaluated the energy analysis for R1234yf and R1234ze working fluids in the ORC-VCR system. They stated that the maximum COPS values were obtained using R245fa and R600. They stated that R600 fluid is the best refrigerant for the ORC-VCR system in terms of environmental problems and system performance. In their study, Liang *et al*. [9], designed a refrigeration system that integrates the ORC power plant with a VCC refrigerator. With the ORC subsystem, it is aimed to recover energy from the exhaust gases of internal combustion engines to generate mechanical power. The results showed that the proposed concept is promising for the development of heat-operated cooling systems to recover the waste heat from the exhaust gas of internal combustion engines. Jeong and Kang [10], evaluated different refrigerants (R123, R134a, and R245ca) in the cycle they designed in their study. They stated that the R123 refrigerant gave the highest cycle efficiency. They stated that the efficiency of the basic cycle will be low due to the high temperature at the turbine outlet. In order to recover the heat at the turbine outlet, they stated that the R245ca fluid increased the total COP by 47% in the cycle condition. Pektezeland and Acar [11], used R134a, R1234ze (E), R227ea, and R600a fluids as working fluids in combined systems in their study. They showed the Second law efficiency, exergy destruction rate, and exergy destruction rates for each component in the systems. They stated that R600a is the most efficient working fluid for the applied systems. In order to achieve high efficiency of ORC combined systems, new working fluids have been studied in different ways in recent years.

After determining the refrigerants, thermodynamic analyzes of fifteen different refrigerants for both the ORC system and the VCC refrigeration cycle are presented for the designed combined power system.

System description

In this study, the ORC system was designed as in fig. 1 by utilizing renewable heat energy sources (industrial waste heat, solar energy, geothermal energy, biomass, and biogas heat energies) used for ORC systems. In the designed system, the power produced in the ORC turbine meets the compressor power of the VCC. After providing the electrical power required for the combined system, it is aimed to use the remaining eclectic power and the low waste heat obtained from the heaters in the operation.

In the ORC, compression is carried out in the pump. Then, the temperature of the fluid increases with the heat it receives from the heat source under constant pressure in the evaporator. Then expansion occurs in the turbine and the turbine power obtained is transmitted to both the compressor and the operation. The operation of the VCC system is that after the liquid is compressed in the compressor, the heat is discharged under constant pressure in the condenser. Then the liquid passes through the expansion valve under constant enthalpy, resulting in pressure drop. Finally, while the fluid passes through the evaporator under constant pressure, it absorbs the heat of the environment to be cooled and the VCC cycle completes the process. For both cycles (ORC-VCC), 15 different refrigerants (R600A, Re245fa, R134a, R600, R227ea, R22, R717, R290, R236fa, R40, R113, R152a, R1234yf, R123, and R142b) were studied.

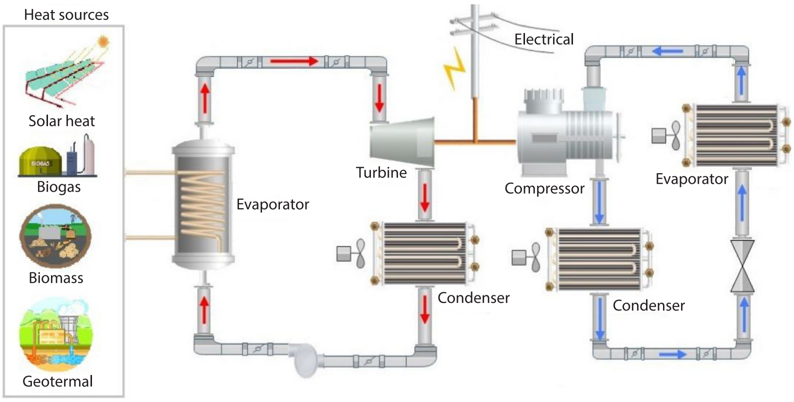

Figure 1. Schematic of combined ORC-VCC

As seen in fig. 1, the heat energy provided from the heat source was first used in the ORC system, and the electricity produced was used for both VCC compressor power and electricity need. In fig. 2, the *T-s* diagram of the constant temperature parameters of different fluids is presented.

In the temperature/enthalpy diagram in fig. 2, the operating directions and processes for fifteen different refrigerants have been realized: 1-2 – the ORC expansion (steam turbine), 2-4 – the ORC isobaric heat output (condenser), 4-5 – the ORC compression (pump), 5-1 – the ORC isobaric heat input (evaporator), 7-8 – the VCC compression (compressor), 8-4– the VCC isobaric heat inlet (evaporator), 10-11– the VCC isenthalpic expansion (throttle valve), and 11-7 – the VCC isobaric heat output (condenser).

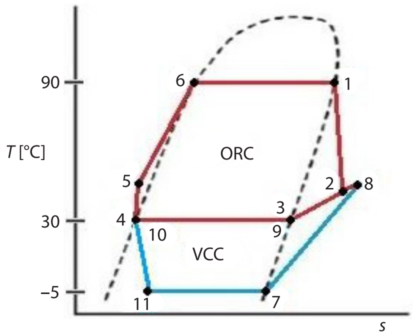

Figure 2. The *T-s* (temperature/enthalpy) diagram

Assumptions and fixed parameters:

- All of the heat of all heat exchangers (condenser, evaporator) has been transferred without loss from heat sources.
- Pressure losses that may occur on the pressure line in all components in the system are neglected.
- The variations in kinetic and potential energy are not considerable.
- For each fluid, evaporator 90 °C, condenser 30 °C, turbine efficiency 85%, and pump efficiency 75% constant are calculated in ORC.
- For each fluid, the condenser at VCC is 30 °C, the evaporator is –50 °C, and the compressor efficiency is 65%.
- The VCC compressor consumes 80 kW of electrical power, the ORC turbine produces 100 kW of electrical power.
- Dead state 20 °C is taken.

Thermodynamic analysis

The basis of a thermodynamic analysis is mass balance. In the steady-state condition, the mass balance equation can be given [12]:

$$\sum \dot{m}_{\text{in}} = \sum \dot{m}_{\text{ex}} \tag{1}$$

where $\dot{m}$ is the mass-flow rate, the subscripts in and ex are the inlet and exit conditions, respectively. The energy balance is given:

$$\dot{Q}_{\text{in}} + \dot{W}_{\text{in}} + \sum_{\text{in}} \dot{m}\left(h + \frac{v^2}{2} + \text{g}z\right) = \dot{Q}_{\text{ex}} + \dot{W}_{\text{ex}} + \sum_{\text{ex}} \dot{m}\left(h + \frac{v^2}{2} + \text{g}z\right) \tag{2}$$

where $\dot{Q}$ is the heat transfer rate, $\dot{W}$ – the power, h – the specific enthalpy, v – the velocity, z – the elevation, and g – the gravitational acceleration. The entropy balance equation for steady-state conditions is written as:

$$\sum_{\text{in}} \dot{m}_{\text{in}} s_{\text{in}} + \sum_{k} \frac{\dot{Q}}{T_k} + \dot{S}_{\text{gen}} = \sum_{\text{ex}} \dot{m}_{\text{ex}} s_{\text{ex}} \tag{3}$$

where s is the specific entropy and $\dot{S}$ – the entropy generation rate. The exergy balance equation can be written [13]:

$$\sum \dot{m}_{\text{in}} ex_{\text{in}} + \sum \dot{E}x_{Q,\text{in}} + \sum \dot{E}x_{W,\text{in}} = \sum \dot{m}_{\text{ex}} ex_{\text{ex}} + \sum \Sigma \dot{E}x_{Q,\text{ex}} + \sum \dot{E}x_{W,\text{ex}} + \dot{E}x_D \tag{4}$$

where $\dot{E}x_D$ is the exergy destruction rate, and can be defined:

$$\dot{E}x_D = T_0 \dot{S}_{\text{gen}} \tag{5}$$

where $\dot{E}x_W$ is the exergy rates releated with work, and is given:

$$\dot{E}x_W = \dot{W} \tag{6}$$

where $\dot{E}x_Q$ is the the exergy rates releated with heat transfer, and is given:

$$\dot{E}x_Q = \left(1 - \frac{T_o}{T}\right)\dot{Q} \tag{7}$$

The specific flow exergy can be written:

$$ex = x_{\text{ph}} + ex_{\text{ch}} + ex_{\text{pt}} + ex_{\text{kn}} \tag{8}$$

The kinetic and potential parts of exergy appear in the previous equation are assumed to be negligible. Also, chemical exergy is assumed to be negligible. The physical or flow exergy, ex_{ph}, is defined:

$$ex_{\mathrm{ph}} = \left(h - h_{\mathrm{o}}\right) - T_{\mathrm{o}}\left(s - s_{\mathrm{o}}\right) \tag{9}$$

where h and s are the specific enthalpy and entropy at the real case, respectively, also, h_{o} and s_{o} are the enthalpy and entropy at the reference environment states, respectively.

Energy and exergy efficiency analyses

Authors are obliged to use System International (SI) for Units (including non-SI units accepted for use with the SI system) for all physical parameters and their units.

Energy efficiency, COP of a system can be described [14]:

$$COP = \frac{\sum \text{useful output energy}}{\sum \text{input energy}} \tag{10}$$

The combined ORC-VVC systems based integrated system efficiency can be calculated:

$$\text{For VCC system } COP_{\mathrm{VCC}} = \frac{\dot{Q}_{\mathrm{evap}}}{\dot{W}_{\mathrm{comp}}}$$

$$\text{For ORC system } \eta_{\mathrm{ORC}} = \frac{\dot{W}_{\mathrm{net}}}{\dot{Q}_{\mathrm{in}}} = 1 - \frac{\dot{Q}_{\mathrm{out}}}{\dot{Q}_{\mathrm{in}}} = \frac{\dot{W}_{\mathrm{turb}} - \dot{W}_{\mathrm{pump}}}{\dot{Q}_{\mathrm{evap}}} \tag{11}$$

The exergy efficiency, ψ, can be defined [11]:

$$\psi = \frac{\sum \text{useful output exergy}}{\sum \text{input exergy}} = 1 - \frac{\sum \text{exergy loss}}{\sum \text{input exergy}} \tag{12}$$

The ORC-VCC system exergy efficiency can be calculated:

$$\text{The VCC system efficiency } \psi_{\mathrm{VCC}} = \frac{\dot{E}x_{\mathrm{cooling}}}{\dot{W}_{\mathrm{comp}}}$$

$$\text{The ORC system efficiency } \psi_{\mathrm{ORC}} = \frac{\dot{W}_{\mathrm{turb}} - \dot{W}_{\mathrm{pump}}}{Ex_{QL}^{\mathrm{ORC}}} \tag{13}$$

The total efficiency, β, of the combined ORC-VCC system was calculated [15]:

$$\beta = \eta_{\mathrm{ORC}} \times COP_{\mathrm{VCC}} \tag{14}$$

The total exergetic efficiency of the combined ORC-VCC system:

$$\psi_{\mathrm{glob}} = \psi_{\mathrm{ORC}} \times \psi_{\mathrm{VCC}} \tag{15}$$

Results and discussion

In this study, thermodynamic analyzes were made using fifteen different refrigerants in both ORC and VCC systems. Thermodynamic analysis results were calculated in the enginering equation solver program and the results are presented in graphics.

Among the fluids used in the VCC system in fig. 3, R113 is the refrigerant that gives the most optimum result in terms of both exergy efficiency percentage and COP value.

As seen in fig. 4, the most exergy destruction in all systems is in the evaporator, followed by the compressor, condenser and throttling valve.

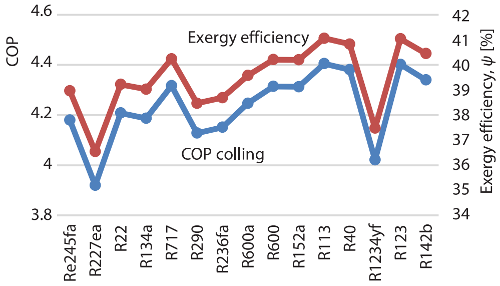

Figure 3. The COP and exergy percentage in VCC system

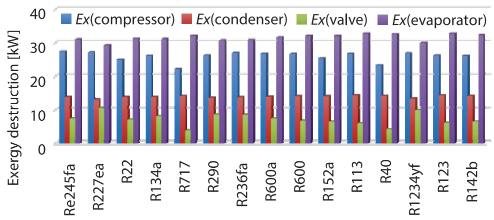

Figure 4. Exergy destruction of components in VCC system [kw]

Looking at the fluids used in the VCC system in fig. 5, it is seen that the system operating with the R717 refrigerant gas, which has the highest heat load, has the least mass-flow rate. In addition, the system working with R227ea refrigerant, which provides the lowest heat loads, has the highest mass-flow rate.

Among the fluids used in the ORC system in fig. 6, the refrigerant that gives the most optimum result in terms of energy and exergy efficiency is R40.

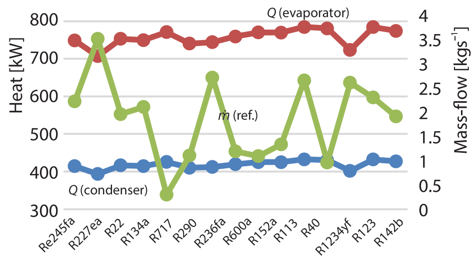

Figure 5. Evaporator, condenser, and mass values of the components in the VCC system

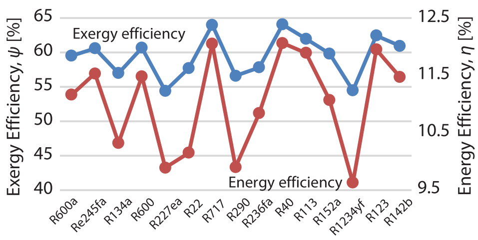

Figure 6. Energy and exergy efficiencies in the ORC system

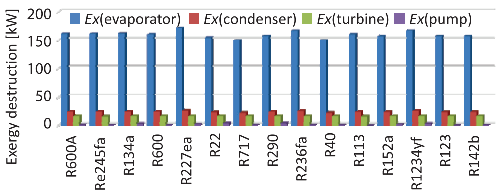

Figure 7. Exergy destruction of components in ORC system [kw]

In fig. 7, it is seen that R227ae refrigerant has the most exegeal destruction in ORC system refrigerants. In addition, the component with the highest exergy destruction in all systems is the evaporator, followed by the condenser, tube and pump.

Figure 8 shows the heat loads of the heat exchangers in the ORC systems and the mass-flow rates of the fluids in the systems operating with these heat loads. It is seen that the mass-flow rate in the ORC system is directly proportional to the heat loads. The maximum heat load in the heat exchangers is seen in R227ea. In addition, R227ea is also seen at the highest mass-flow rate.

In this study, fifteen different fluids were evaluated thermodynamically. The R40 refrigerants gave the most optimum results in VCC system and R113 refrigerants in ORC system. Below, the changes in both evaporator and condenser temperatures of these fluids, as well as COP, exergy efficiency and exergy destruction of the components are presented graphically.

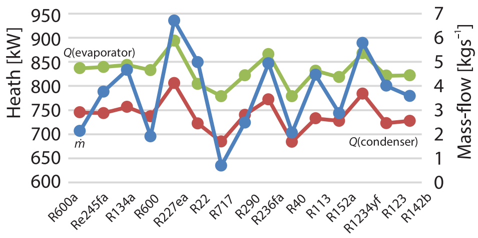

Figure 8. Evaporator, condenser and mass values of the components in the ORC system

In fig. 9, there was not much change in the compressor and throttling valve with the increase in the condenser temperature in the VCC system. However, increasing the condenser temperature decreased the exergy destruction in the evaporator and increased the exergy destruction in the condenser. In addition, this situation negatively affected the exergy efficiency and COP values in the VCC system.

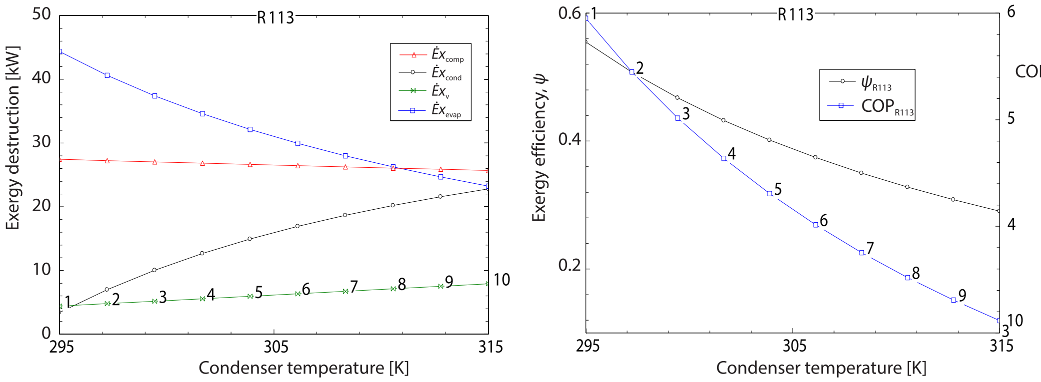

Figure 9. Exergy destruction [kW], exergy efficiencies [ψ] and COP change in VCC system depending on condenser temperature

In fig. 10, with the increase in evaporator temperature in the VCC system, the exergy destruction in the evaporator decreased and the exergy destruction in the condenser increased. In addition, this situation caused an increase in the exergy efficiency of the VCC system and a decrease in the COP values.

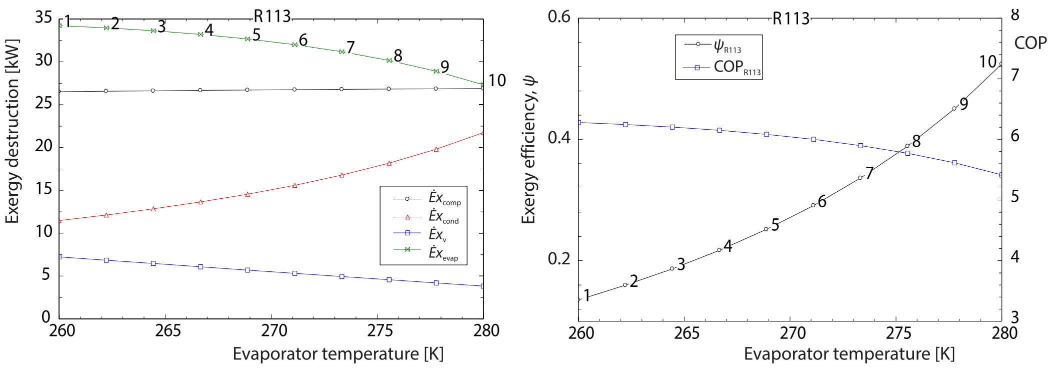

Figure 10. Exergy destruction [kW], exergy efficiencies, ψ, and COP change in VCC system depending on evaporator temperature

In fig. 11, the exergy destruction of the evaporator and condenser increased with the increase in condenser temperature in the ORC system. In addition, energy and exergy efficiencies decreased depending on the condenser temperature.

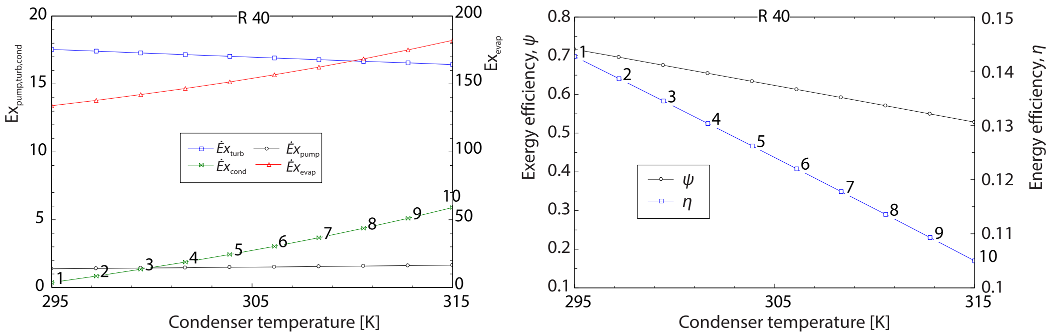

Figure 11. Change of exergy destruction [kW], exergy efficiencies, ψ, and energy efficiency, η, in ORC system depending on condenser temperature

In fig. 12, the evaporator and condenser exergy destructions decreased with the increase in the evaporator temperature in the ORC system. In addition, while the energy and exergy efficiencies increased slightly, the energy efficiency increased depending on the condenser temperature.

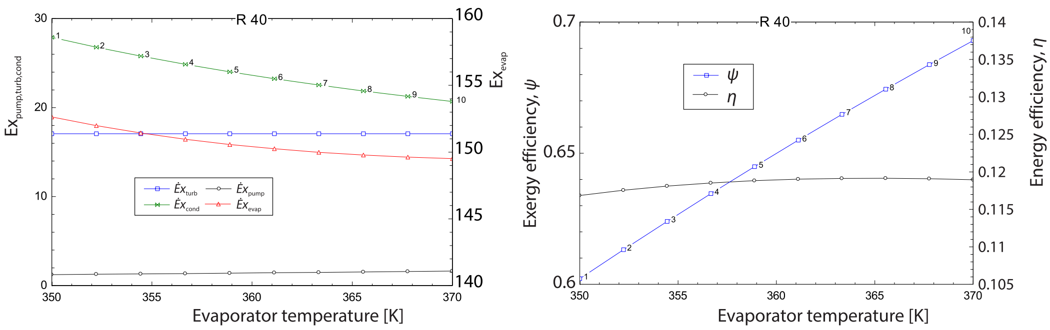

Figure 12. Change of exergy destruction [kW], exergy efficiencies, ψ, and energy efficiency, η, in ORC system depending on evaporator temperature

Conclusions

There are ORC and VCC systems working with different fluids in the literature. The most important parameter in these systems is the type of refrigerant. Studies have focused on the fluid selection that gives the best efficiency. In this study, the energy and exergy efficiencies of fifteen different fluids in both ORC and VCC systems were investigated. The results were obtained by making analyzes using the enginering equation solver program.

Among the fluids used in the VCC system, the refrigerant that gives the most optimum result is R113 are as follows.

- For all system components in VCC, the most exergy destruction occurs in the evaporator, followed by the compressor, condenser and throttle valve.
- Looking at the fluids used in the VCC system, it is seen that the system operating with the R717 refrigerant, which has the highest heat load in the heat exchangers, has the least

mass-flow rate. In addition, the system working with R227ea refrigerant, which provides the lowest heat loads, has the highest mass-flow rate.

- Among the fluids used in the ORC system, the refrigerant that gives the most optimum result in terms of energy and exergy efficiency is R40.
- It is seen that the system fluid with the most exergy destruction in ORC system refrigerants is R227ae. In addition, in all systems, the most exergy destruction occurs in the evaporator, followed by the condenser, turbine and pump.
- It is seen that there is a direct proportionality between the mass-flow rate in the ORC system and the heat loads in the heat exchangers. The maximum heat load in the heat exchangers is seen in R227ea. In addition, R227ea is also seen at the highest mass-flow rate.
- Among the ORC systems, the pump of the system using R22 fluid consumes the most power. In addition, the pump using R113 refrigerant provides the least power consumption.

The ORC and VCC systems have come to the fore in recent years in terms of environmentalism and sustainability. For this purpose, system design and optimization of refrigerants gain importance.

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