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EES Analysis of Low-Grade Thermal Energy Organic-Rankine-Vapor Compression-Refrigeration System

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Abstract. Utilizing the integrated organic rankine cycle (ORC) and vapour compression refrigeration (VCRs) cycle powered by low-grade thermal energy, the performance of different hydrocarbons, hydrofluorocarbons (HFCs), and novel hydrofluoroole fins was investigated. In this work Engineering Equation Solver (EES) program was utilised for simulation and the results were validated with available experimental results in literature. For low-grade thermal energy, VCRS normally operates in range of 5 and 40 °C, whereas ORC typically operates between 80 and 40 °C. Two essential criteria used to evaluate the system's performance were the coefficient of performance (COPs) and total mass flow rate for each kilo watt total cooling capacity. For the condenser, evaporator, and boiler, the influence of temperature on effectiveness was investigated. The effect of temperature on system performance was studied for the condenser, evaporator, and boiler. Among all the working fluids tested in this combined system, R600a was proven to be the best. Its flammability, though, should draw enough attention. The assumptions and constraints of the modeling were also examined, and model improvement are proposed.

Keywords: Organic Rankine Cycle (ORC)1, VCR2, HFC3, ESS4, HC5.

INTRODUCTION

Refrigeration and air-conditioning equipment consume the highest energy in the world. A vapour–compression refrigeration cycle has been the most extensively utilized refrigeration system. A mechanical compressor is needed to raise the refrigerant pressure within that process, and it is the part which utilizes the most energy, which is primarily in the form of electrical energy. Nowadays, multiple initiatives are being made to use renewable energy sources in this regard clean energy is also an option for power generation and cooling operations which include geothermal energy, heat, wind energy, and solar energy. Because waste heat is a free source of energy with there is no direct emissions, it is also known as renewable and clean energy [1]. Depending on the industrial processes, waste heat might be excluded at a broad variety of temperatures [2]. The subsystem comprises of a Pump, an ORC Evaporator a turbine and Condenser. The ORC–VCR system is depicted schematically in Figure 1 [3]. The ORC and VCR cycles make up this system. This system has the following characteristics (1) It utilizes the similar hydraulic fluid in both cycles. (2) Both the expander shaft and the compressor shaft are directly connected. (3) Uses same common condenser for both cycles. (4) The expander's capacity is adequate to run the pump and compressor. In the current study, renewable

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energy-activated organic Rankine cycle (ORC) power or cooling power generation is combined with a steam compression refrigeration cycle (VCR). ORC is a great way to alter low-grade thermal energy into valuable work that can run a VCR cycle [4]. The expander shaft and compressor shaft, both are coupled to curtail energy transformation loss [5]. The combined cycle offers many benefits, including the capacity to generate electricity without the need for cooling, causing the system to utilise thermal energy throughout the year. [6]. In the summer, all of the thermal energy can be used for cooling, however in the spring and fall, only a portion of the thermal energy can be used for cooling. In winter, there is no heat conversion for cooling. All of the thermal energy can be converted to electricity and transmitted to the grid when cooling isn't required.

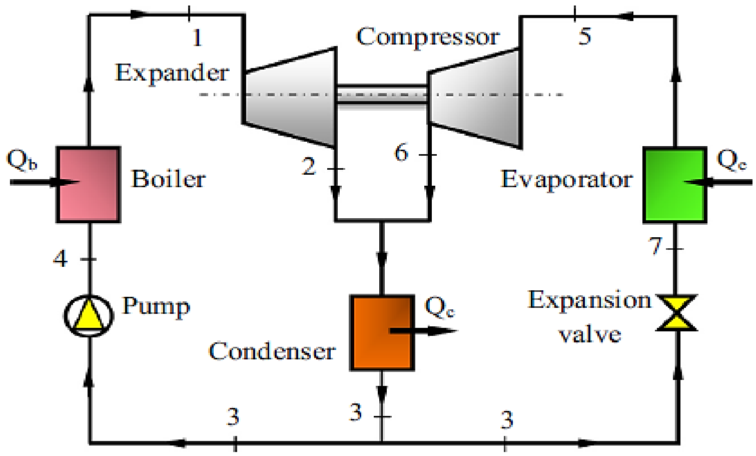

FIGURE 1. Diagram of the Organic Rankine Cycle -Vapour Compression Refrigeration system

The ORC-VCR system's processes can be defined as follows. Process (1-2s) represents the isentropic expansion of the entire expander, process (1-2a) represents the actual expansion of the entire expander, process (2a-3) represents the heat dissipation process in the condenser, process (3-4s) represents the isentropic pumping process, process (3-4a) represents the actual pumping process, and process (4a-1) represents the heat addition in the ORC boiler in Figure 2(a). Expansion Process (3-7) by an expansion valve, heat addition process (7-5) by an evaporator, isentropic compression process (5-6s) by a compressor, and process (5-6a) by actual compression by a compressor are shown in Figure 2(b). Process (6-a3) is a heat release process in the VCR cycle's condenser [1]. The various working fluid is kept as saturated vapor when it exits the evaporator and boiler. In ORC-VCR systems, the choice of working fluid is critical [7,8]. A proper working fluid achieves excellent system performance while posing minimal environmental concerns. In this research R600a (Nasir et al. 2019) [9], R1270 (propylene), R290(propane), R236ea (hexafluoropropane)(Bounefour and Ouadha 2014)[10].

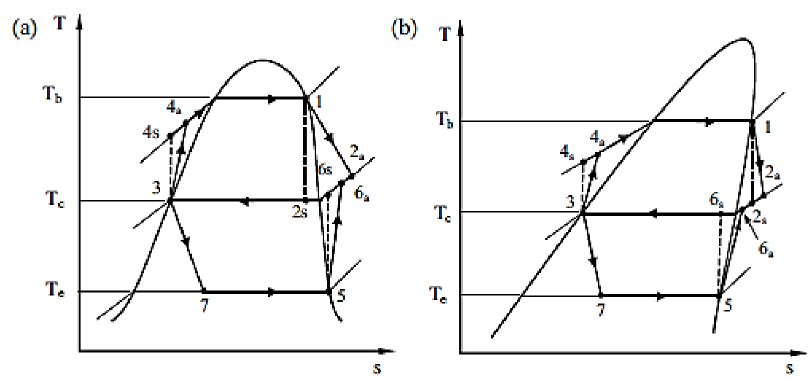

FIGURE 2. Diagrams of the basic ORC-VCR system (a) bell-shaped Temperature vs. specific entropy diagram (b) overhanging Temperature vs. specific entropy diagram

NUMERICAL ANALYSIS AND ANALYTICAL TECHNIQUE

For the ORC-VCR system's thermodynamic mathematical model can be represented by (with respect to Figure 2):

The work done by expander $W_{\exp} = morc(h_1 - h_{2a}) = morc(h_1 - h_{2s})\eta_{\exp}$ ……………………..…..(1)

where, h_1, h_{2a}, and h_{2s} (kJ/kg) represents the intake, exit and isentropic specific enthalpy at expander respectively, and $\eta_{\exp}$ represents the isentropic efficiency.

The work input in pump $W_p = morc(h_{4a} - h_3) = morc(h_{4s} - h_3)\eta_p$ ……………………..…...……..(2)

where, h_{4a}, h_3, and h_{4s} (kJ/kg) is the pump's actual, inlet and isentropic specific enthalpy respectively, and η_p is the pump's isentropic efficiency.

The Organic Rankine cycle efficiency $\eta_{ORC} = \frac{W_{net}}{Q_b}$……………………………………….……………..…..(3)

where, W_{net} is the net work done, and Q_b is the working fluid heat transfer.

The evaporator's heat transfer rate $Q_e = \dot{m}_{vcr}(h_5 - h_7)$…………………………………………………….…(4)

where, Q_e (kW) denotes the heat transfer rate at process (7-5), $\dot{m}_{vcr}$ (kg/s) denotes the mass flow rate at the vapour compression refrigeration, h_5 and h_7 (kJ/kg) denotes the inlet and outlet specific enthalpy respectively.

The vapour compression refrigeration cycle's performance coefficient is as follows [12]:

$$COP = Q_e/W_e \quad (5)$$

where, W_e is the work done in evaporator.

The compression ratio (CMR) of the compressor can be represented by:

$$CMR = P_{6a}/P_5 \quad (6)$$

The expansion ratio (EPR) of the expander can be calculated by:

$$EPR = v_{2a}/v_1 \quad (7)$$

where, P_{6a} - Discharge Pressure Absolute, P_5 - Suction Pressure Absolute

With reference to the optimization carried out by (Touaibi et al. 2019) [11], the basic values and ranges of the system's operational parameters are collected, modified and depicted in Table 1.

TABLE 1. Comparison of thermal properties with previous literature

Parameter	Past Research	Present work
Mass flow rate in kg/s	1	-
Compressor Isentropic efficiency	85%	-
Expander Isentropic efficiency	80%	-
Temperature of Condenser in Celsius	40	30-55
Boiler Temperature in Celsius	80	60-105
Temperature of Evaporator in Celsius	80	-15 to 15
Feed pump Isentropic efficiency	85%	-

RESULTS AND DISCUSSION

EES Code Validation and Outcomes

The suggested model was validated by comparing the simulation outcomes with the existing numerical information from the literature using R600a as the working fluid [3]. The combined system performances for the identical operating conditions employed are presented in Table 2, the agreement between the two simulation results appears to be good based on comparison.

TABLE 2. Comparison of analytical data with previous research work

Parameter	Past Research	Present Work
η_{ORC}	0.0757	0.09895
COP_{VCR}	5.01	7.354
η_s	0.49	0.6622
COPs	0.38	0.7277

TABLE 3. Performance of ORC-VCR's system for different fluids

Parameter	R600a	R1270	R290	R236ea
η_s	0.6654	0.5450	0.6790	0.6469
COP_s	0.73	0.6170	0.7470	0.7102
CMR	2.192	1.530	2.81	2.407
EPR	3.538	6.870	4.291	4.454

Table 3 shows that the highest and identical COP values are found for R600a and R290 by the highest critical temperatures, whereas R236ea and R1270 by the lowermost critical temperatures have the smaller COP values.

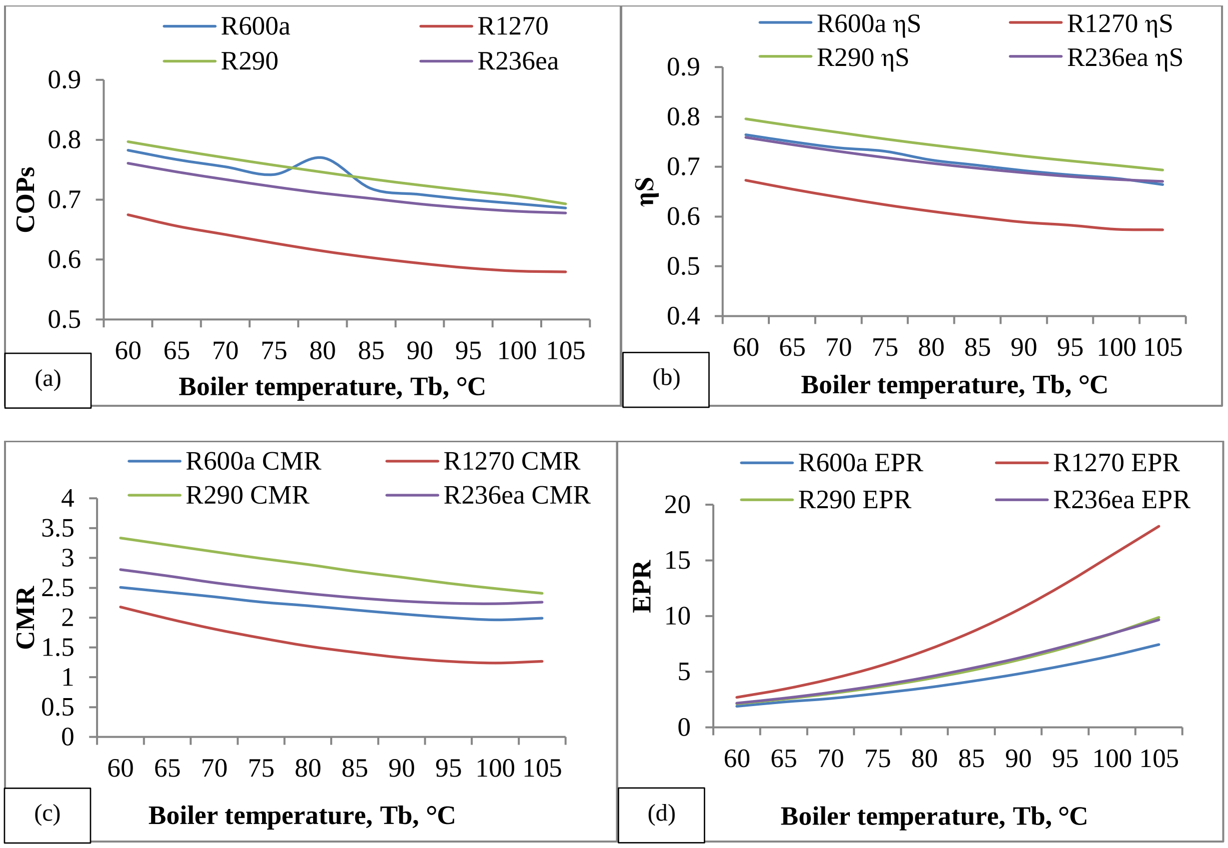

FIGURE 3. Boiler temperature effect on (a) COPs (b) system efficiency (c) CMR (d) EPR

The effect of boiler temperature on COP for various candidates in the elementary ORC-VCR system is shown in Figure 3(a). As the boiler temperature rises, the COP of the system decreases for all systems. R290 has the highest COP among all the working fluids tested for all boiler temperatures, whereas R1270, R600a, and R236ea have the lowest COP. Figure 3(b) depicts the dissimilarity of system as a function of T_b for most of the working fluids in a standard system. As it can be seen, increasing T_b causes a reduction in system efficiency, sys. R290 has the maximum system efficiency for all boiler temperatures. Whereas, RC1270 has the lowest system efficiency as shown in Figure 3(c), the modification in CMR data occur as a function of temperature of the boiler for various working fluids in the basic ORC-VCR system. As the boiler temperature rises, the CMR drops for all systems, as shown in this Figure 3(d). The reason for this is due to temperature rises along with the saturation pressure. For all systems, CMR values at 90°C is about twice as high as those at 60°C. R290 achieves the highest CMR value. The minimum CMR is attained by R1270, R600 and R236ea.

Effect of evaporator temperature

The COPs, efficiency, and CMR of the system variations due to evaporator temperature are represented in figure 4. The impact of evaporator temperature on coefficient of performance for various working fluids in regular ORC-VCR system is depicted in the figure 4(a). As the boiler temperature rises, the COP of the system increases for all systems. R290 has the highest COP among all the working fluids tested for all evaporator temperatures, whereas R1270 have the lowest COP. Figure 4(b) depicts the change of system as a function of Te for all working fluids in a regular system. As it can be seen, increasing Te causes an increase in system efficiency, R290 has the maximum system efficiency for all evaporator temperatures. Whereas, RC1270 has the lowest system efficiency. The CMR drops for all systems as the evaporator temperature rises, as shown in this Figure 4(c).

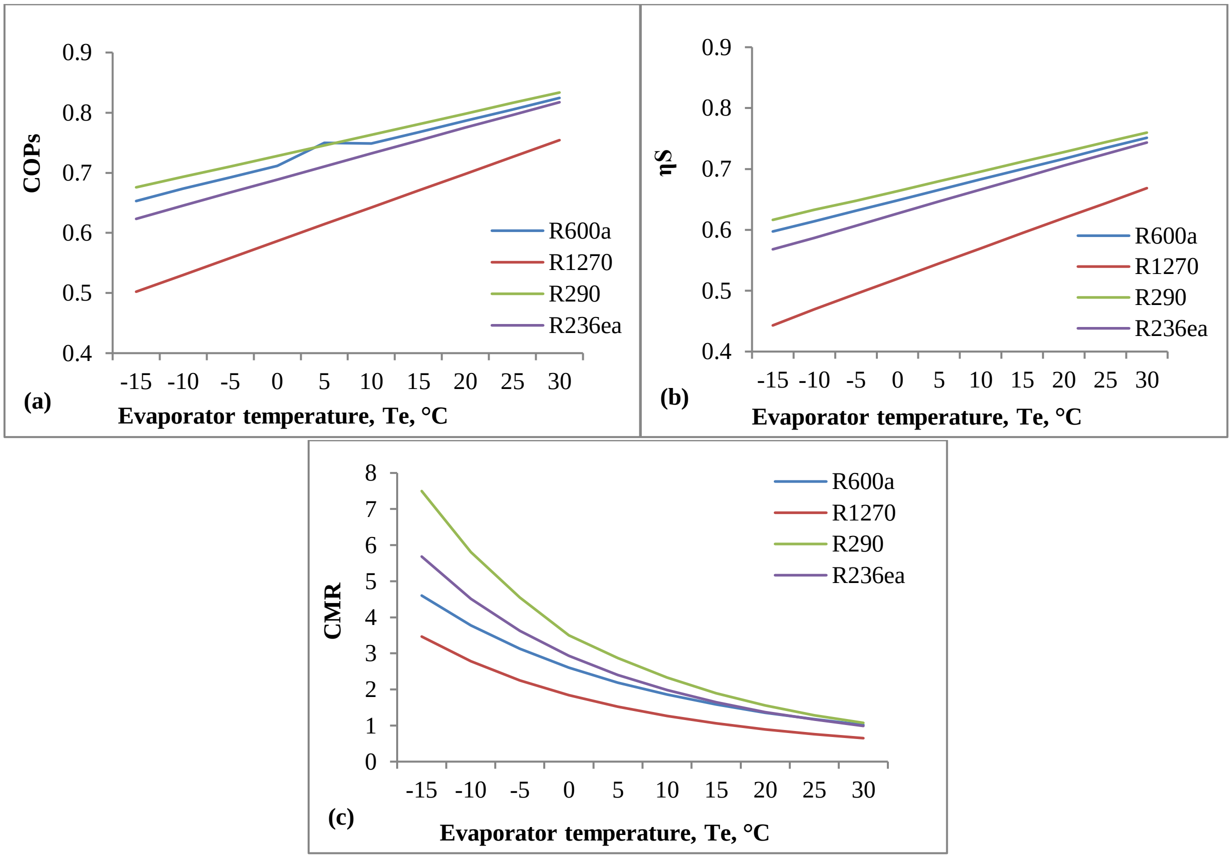

FIGURE 4. Evaporator's temperature effect of on (a) COPs for various working fluids (b) the system efficiency for different working fluids (c) CMR for various working fluids

Distribution of exergy on ORC-VCR system

Exergy destruction distribution in the system for the four working fluids; R1270, R290, R236ea and R600a are reported in Table 4.

TABLE 4. Distribution of exergy on ORC-VCR system working fluids

Components	R600a	R1270	R290	R236ea
Expander	7.94	3.504	4.495	3.594
Pump	2.093	0.173	0.122	0.16
Boiler	275.6	94.98	163.7	125.3
Evaporator	252.4	72.42	152.6	110.7
Compressor	34.63	27.96	16.36	19.35
Expansion valve	5.67	2.447	2.784	2.694
Total energy destruction	578.4	201.6	340.4	261.7

Exergy destruction rate is a useful tool for assessing the energy destruction of various system components as whole and identifying weaknesses in the system. 578.3 Kw (R600a), 201.5 kW (R1270), 340.3 (R290) and 261.8 kW (R290) (R236ea). By equating the exergy destruction rates of each component of the system, it is clear that the boiler is destroying the most exergies.

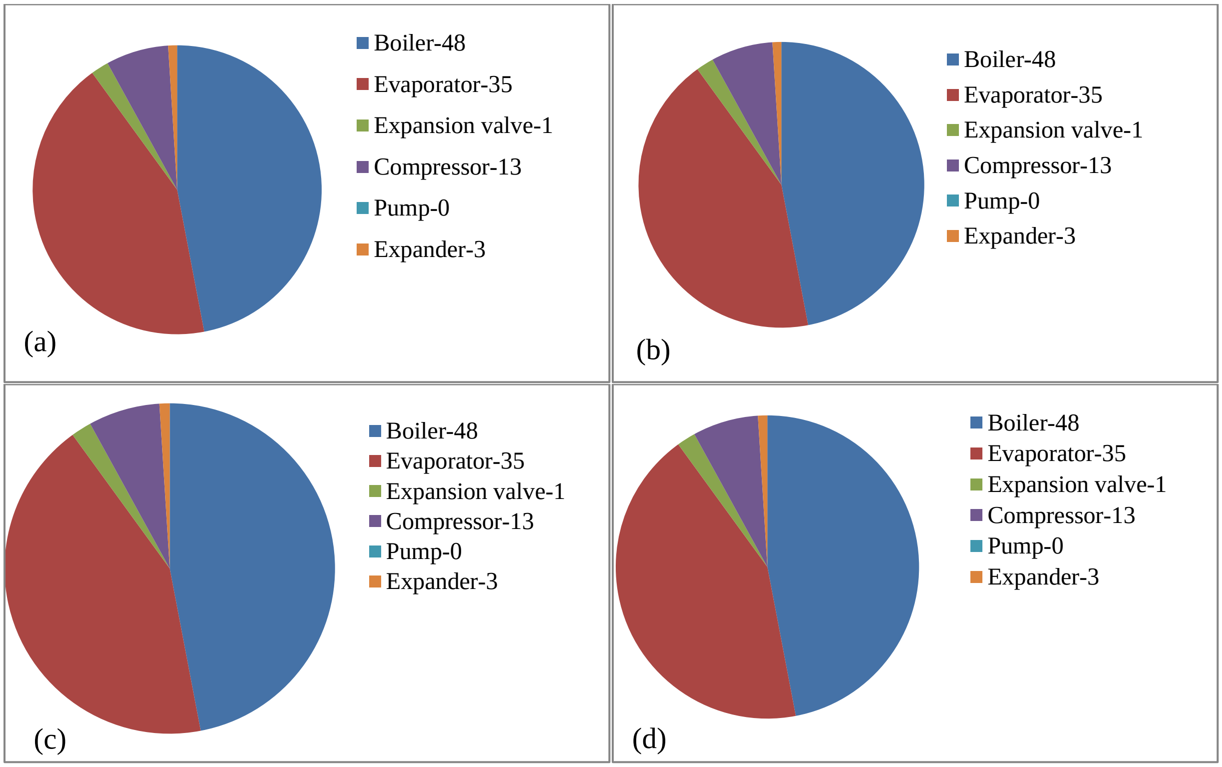

FIGURE 5. Exergy degradation is distributed differently in different working fluids (a) R600a (b) R1270 (c) R290(d) R236ea

CONCLUSIONS

The efficiency of an organic-Rankine vapour compression refrigeration system powered by low-grade thermal energy was explored in this work. The working fluids examined throughout this cycle were R1270, R600, R290, and R236ea. The performance parameters of the systems were discussed in relation to temperature fluctuations in the boiler, condenser, and evaporator.

- Based on the findings, it can be concluded that all of the investigated parameters have an impact on the system's performance for various operating fluids.
- The COP of the system decreased as the temperature of the boiler, condenser, and evaporator increased.
- In addition, with the increase of the evaporator and boiler temperatures, increment in CMR and EPR value was observed, whereas the opposite trend was observed when the condenser temperature increased.
- Based on the findings, it was determined that R600a has the highest COP values.
- For all working fluids, energy destruction distributions were demonstrated from which it was inferred that the boiler destroyed the most energy, and trailed by the ORC evaporator and condenser.
- R600a was found to be the optimal operating fluid for this system from an environmental standpoint.

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