Screening of Organic Working Fluids for a Combined Rankine-Refrigeration Cycle Driven By Renewable Energy

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Abstract

Several hydrocarbons, hydrofluorocarbons, and hydrofluoroolefins as working fluids for a combined organic Rankine cycle and vapor compression refrigeration (ORC-VCR) system driven by low-temperature renewable energy are investigated. The basic VCR cycle works between 40 and 5 °C while the basic ORC works between 40 and 80 °C. The total mass flow rate of the working fluid per kW cooling capacity (ṁtotal) and the overall system coefficient of performance (COPs) are used to characterize the combined system performance. The influences of different operating parameters as the boiler, condenser, and evaporator temperatures on the system performance are studied. The results show that the highest COPs values are accomplished with the highest critical temperature with overhanging coexistence curve working fluids, namely R245fa and R600, while R600 achieves the lowest ṁtotal under all studied operating conditions. Among all proposed working fluids, R600 is the most suitable one for the ORC-VCR system from prospects perspectives of system performance and environmental issues. However, extra precautions should be taken against its flammability. The highest COPs value is 0.72 using R600 as a working fluid at condenser temperature of 30 ºC and the basic values for the remaining operating parameters.

Keywords: Working fluids; Combined cycle; Compression refrigeration cycle; Organic Rankine cycle.

INTRODUCTION

Recently, there are many attempts to use renewable energies as solar energy, geothermal heat, and wind energy as clean energy sources to produce electricity or refrigeration. Also, waste heat can be considered as clean and renewable energy, because there is no direct carbon emission and it is free. Waste heat is released at a broad range of temperatures relying on the industrial processes [1, 2].

An ejector refrigeration cycle and an absorption refrigeration cycle can be activated by thermal energy sources with a temperature between 100 to 200 ºC. They have many advantages such as simple structure, low investment cost, slight maintenance, long lifetime, and low running cost [3, 4]. However, they are not suitable for working neither in high-temperature surroundings nor with sources have temperatures lower than 90 ºC. Moreover, the lowest temperature could be attained by both cycles is 5 ºC [5-7].

In the present study, another heat-driven refrigeration system is suggested to produce electricity or refrigeration. The system consists of an organic Rankine cycle (ORC), driven by renewable energy, and a vapor compression refrigeration (VCR) cycle. The ORC is a favorable cycle for converting low-grade thermal energy to mechanical work, which can be used to driver the VCR cycle compressor. Both compressor and expander shafts are directly connected to decrease energy conversion losses. The combined cycle has several advantages such as the flexibility to produce electricity when refrigeration is not required. This leads the system to use the thermal energy all the year. In winter where cooling is undesirable, the whole thermal energy turns into electricity. In summer, the whole thermal energy turns into refrigeration.

The working fluid has a significant effect on the combined organic Rankine cycle-vapor compression refrigeration (ORC-VCR) system performance [8-9]. Many researches have been done on the selection of working fluids for the ORC-VCR system to specify the best one, which achieves the maximum system coefficient of performance (COPs) [10-13]. The refrigerants R134a, R245ca, and R123 were examined to identify the most appropriate one for the ORC-VCR system by Aphornratana and Sriveerakul [14]. They concluded that R123 accomplishes the greatest system performance. Kim and Perez-Blanco [7] analyzed an ORC-VCR system activated by a low-temperature source uses R134a. The lowest temperature could be attained was -10 °C. Wang et al. [8] studied an ORC-VCR system using two different working fluids for the power and refrigeration cycles, namely R245fa and R134a, respectively. The COPs reached nearly 0.5. Yue et al. [15] studied an ORC combined with a vehicle air conditioning system utilizing R134a, R245fa, cyclopentane, and pentane as working fluids. They concluded that R134a gives the highest thermal and economic performance. Bu et al. [16] examined six candidates, i.e. R134a, R123, R290, R600, R245fa, and R600a to determine the most suitable one for ORC-VCR system. The results indicated that that R600a is the most
appropriate candidate. Molés et al. [17] studied an ORC-VCR system activated by low-grade thermal energy utilizing two different candidates for the refrigeration and power cycles. The results indicated the best working fluid for the refrigeration and power cycles are R1234ze(E) and R1336mzz(Z), respectively.

From the abovementioned review, it is clear that there is still a need to search for suitable alternative working fluids for the ORC-VCR system. The present study concentrates on the production of electricity or refrigeration from low-temperature renewable energies with a temperature around 100 °C. The possibility to use the pure substances R152a, R290, R1270, RC318, R134a, R161, R227ea, R236fa, R236ea, R600a, R600, R245fa, R1234yf, R1234ze(E), and R1234ze(E) as working fluids in the ORC-VCR system is assessed. The total mass flow rate of the working fluid per kW cooling capacity ($\dot{m}_{\text{total}}$) and the COPs are used to describe the system performance. The working fluid accomplishes the highest COPs and the lowest $\dot{m}_{\text{total}}$ is recommended. The effects of different operating conditions such as the boiler, condenser, and evaporator temperatures in addition to the isentropic efficiencies of the expander and the compressor on the ORC-VCR system performance are also studied.

DESCRiPTION OF THE ORC-VCR SYSTEM AND WORKING FLUIDS SELECTION

Figure 1 shows a schematic diagram of the ORC-VCR system. The system consists of a VCR cycle and an ORC. The system has the following features: (1) both the compressor and the expander shafts are directly connected; (2) both cycles use the same working fluid; (3) the expander power is just enough to drive the pump and the compressor; and (4) the two cycles use one common condenser.

The various processes of the system can be described as follows. In the ORC: (1-2) is an isentropic expansion process across the expander, (1-2) is the actual expansion process, (2-3) is a heat rejection process across the condenser, (3-4, 3) is an isentropic pumping process, (3-4) is the actual pumping, (4-1) is a heat addition process in the boiler. In the VCR cycle: process (3-7) is an expansion across the expansion valve, process (7-5) is a heat addition in the evaporator, process (5-6) is an isentropic compression across the compressor, (5-6) is the actual compression process, process (6-3) is a heat rejection.

An important characteristic for classification the working fluids is the shape of the temperature against entropy (T-s) diagram. The saturated vapor line may either lead to a bell-shaped or overhanging T-s diagram as displayed in Figs. 2 a and b, respectively. The letters b and o are used for working fluids with bell-shaped and overhanging T-s diagram, respectively.

The selection of the working fluid is critical in the ORC-VCR systems. An appropriate working fluid attains both minimal environmental issues and maximum system performance. The following issues should be considered during the working fluids selection: (1) environmental aspects: ozone depletion potential (ODP), atmospheric lifetime (ALT), and global warming potential (GWP); (2) safety features: flammability, auto ignition, and toxicity; and (3) availability and economics.

Hydrofluorocarbons (HFCs) have been chosen as alternative working fluids instead of hydrochlorofluorocarbons (HCFCs) and chlorofluorocarbons (CFCs) in VCR cycle, ORC, and combined cycles because they have zero ODP. The HFCs are now being regulated due to their high GWP. Therefore, there is still a continual screening for alternative candidates, which may have a superior cycle performance and lower environmental issues. One possibility is utilizing hydrocarbons (HCs), which have very low GWP and very good thermophysical properties [18]. The HCs are non-toxic, chemically stable, environmentally friendly, and highly soluble in mineral oils. The only controversy against HCs is its flammability. Currently, many HCs are considered as working fluids such as R1270, R290, R600a, and R600 [19, 20]. Moreover, numerous hydrofluoroolefins (HFOs) with low GWP are suggested as working fluids [17, 21].

![Figure 1: A schematic diagram of the suggested ORC-VCR system.](image-url)
In the present study, fourteen HCs, HFCs, and HFOs, namely RC318, R1270, R290, R134a, R152a, R227ea, R161, R236ea, R236fa, R600a, R600, R245fa, R1234yf, and R1234ze(E) are proposed as working fluids for the ORC-VCR system. The basic thermodynamic properties, and safety and environmental characteristics of the proposed working fluids are listed in Table 1 [22, 23].

Table 1: Properties of the proposed working fluids for ORC-VCR system.

<table>
<thead>
<tr>
<th>Substance</th>
<th>Chemical formula</th>
<th>Physical data</th>
<th>Environmental data</th>
<th>Safety data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>M</td>
<td>NBP</td>
<td>T_crit</td>
</tr>
<tr>
<td>-----------</td>
<td>-----------------</td>
<td>---------------</td>
<td>--------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>R1270</td>
<td>CH3-CH=CH2</td>
<td>42.08</td>
<td>-47.7</td>
<td>92.4</td>
</tr>
<tr>
<td>R1234yf</td>
<td>CF3CF==CH2</td>
<td>114.04</td>
<td>-29.5</td>
<td>94.7</td>
</tr>
<tr>
<td>R290</td>
<td>C3H8</td>
<td>44.10</td>
<td>-42.1</td>
<td>96.7</td>
</tr>
<tr>
<td>R134a</td>
<td>CH2F-CF3</td>
<td>102.03</td>
<td>-26.1</td>
<td>101.1</td>
</tr>
<tr>
<td>R227ea</td>
<td>CF3-CHF-CF3</td>
<td>170.03</td>
<td>-16.3</td>
<td>101.8</td>
</tr>
<tr>
<td>R161</td>
<td>CH3-CH2-F</td>
<td>48.06</td>
<td>-37.6</td>
<td>102.1</td>
</tr>
<tr>
<td>R1234ze(E)</td>
<td>CHF=CHCF3</td>
<td>114.04</td>
<td>-19.0</td>
<td>109.4</td>
</tr>
<tr>
<td>R152a</td>
<td>CH3-CF2</td>
<td>66.05</td>
<td>-24.0</td>
<td>113.3</td>
</tr>
<tr>
<td>RC318</td>
<td>cyclo-C3F6</td>
<td>200.03</td>
<td>-6.0</td>
<td>115.2</td>
</tr>
<tr>
<td>R236fa</td>
<td>CF3-CH2-CF3</td>
<td>152.04</td>
<td>-1.4</td>
<td>124.9</td>
</tr>
<tr>
<td>R600a</td>
<td>iso-C3H10</td>
<td>58.12</td>
<td>-11.7</td>
<td>134.7</td>
</tr>
<tr>
<td>R236ea</td>
<td>CF3-CHF-CF2</td>
<td>152.04</td>
<td>6.2</td>
<td>139.3</td>
</tr>
<tr>
<td>R600</td>
<td>C4H10</td>
<td>58.12</td>
<td>-0.55</td>
<td>152.0</td>
</tr>
<tr>
<td>R245fa</td>
<td>CF3-CH2-CF2</td>
<td>134.05</td>
<td>15.1</td>
<td>154.1</td>
</tr>
</tbody>
</table>
THERMODYNAMIC ANALYSIS OF THE ORC-VCR SYSTEM

The thermodynamic mathematical model for the ORC-VCR system displayed in Fig. 1 is defined as follows:

For the ORC:

The output power from the expander, $W_{\text{exp}}$, can be written as:

$$W_{\text{exp}} = \dot{m}_{\text{ORC}} (h_1 - h_{2a}) = \dot{m}_{\text{ORC}} (h_1 - h_{2a}) \eta_{\text{exp}}$$

(1)

where $\dot{m}_{\text{ORC}}$ is the working fluid mass flow rate in the ORC in kg/s, $h_1$ is the enthalpy at the expander inlet in kJ/kg, and $h_{2a}$ are the actual and isentropic specific enthalpies at the expander exit, and $\eta_{\text{exp}}$ is the isentropic efficiency of the expander.

The inlet power to the pump, $W_p$, can be calculated as follows:

$$W_p = \dot{m}_{\text{ORC}} (h_{4a} - h_3) = \frac{\dot{m}_{\text{ORC}} (h_{4a} - h_3)}{\eta_p}$$

(2)

where $h_3$ is the specific enthalpy at the pump inlet, $h_{4a}$ and $h_3$ are the actual and isentropic specific enthalpies at the pump exit, respectively in kJ/kg, and $\eta_p$ is the isentropic efficiency of the pump.

The net output power from the ORC, $W_{\text{net}}$, can be calculated as follows:

$$W_{\text{net}} = W_{\text{exp}} - W_p$$

(3)

The rate of heat transfer to the working fluid in the boiler, $Q_b$, which is just enough to produce saturated vapor at the boiler exit, can be expressed as:

$$Q_b = \dot{m}_{\text{ORC}} (h_1 - h_{4a})$$

(4)

where $h_1$ is the specific enthalpy at the boiler outlet in kJ/kg, and $h_{4a}$ is the specific enthalpy at the boiler inlet in kJ/kg.

The ORC efficiency, $\eta_{\text{ORC}}$, can be expressed as:

$$\eta_{\text{ORC}} = \frac{W_{\text{net}}}{Q_b}$$

(5)

For the VCR cycle:

The heat transfer rate to the working fluid in the evaporator, $Q_e$, can be defined as:

$$Q_e = \dot{m}_{\text{VCR}} (h_5 - h_{2a})$$

(6)

where $\dot{m}_{\text{VCR}}$ is the working fluid mass flow rate in the VCR in kg/s, $h_5$ is the specific enthalpy at the evaporator outlet in kJ/kg, and $h_{2a}$ is the specific enthalpy at the evaporator inlet in kJ/kg.

The inlet power to the compressor, $W_{\text{comp}}$, is calculated by the following equation:

$$W_{\text{comp}} = \dot{m}_{\text{VCR}} (h_5 - h_{6a}) = \frac{\dot{m}_{\text{VCR}} (h_5 - h_{6a})}{\eta_{\text{comp}}}$$

(7)

where $h_5$ is the specific enthalpy at the compressor inlet in kJ/kg, $h_{6a}$ and $h_{6s}$ are the actual and isentropic specific enthalpies at the compressor exit, and $\eta_{\text{comp}}$ is the isentropic efficiency of the compressor.

$$W_{\text{comp}} = W_{\text{net}}$$

(8)

The COP of the VCR cycle can be defined as:

$$\text{COP}_{\text{VCR}} = \frac{Q_e}{W_{\text{comp}}}$$

(9)

The COP_S can be calculated from the following equation:

$$\text{COP}_S = \eta_{\text{ORC}} \ast \text{COP}_{\text{VCR}}$$

(10)

The $\dot{m}_{\text{total}}$ is defined as:

$$\dot{m}_{\text{total}} = \frac{\dot{m}_{\text{ORC}} + \dot{m}_{\text{VCR}}}{Q_e}$$

(11)

The compression ratio through the compressor (CMR) and the expansion ratio through the expander (EPR) are measures for the necessary compressor and expander sizes, respectively, and defined as:

$$\text{CMR} = \frac{p_{6a}}{p_5}$$

(12)

$$\text{EPR} = \frac{v_{2a}}{v_1}$$

(13)

The COP_S and $\dot{m}_{\text{total}}$ are used to characterize the system performance. The COP_S and $\dot{m}_{\text{total}}$ are computed using equations 10 and 11, respectively. The CMR and EPR are calculated by equations 12 and 13, respectively. The thermodynamic properties of the suggested working fluids are taken from the NIST database REFPROP 9.1 [24].

The basic values of the ORC-VCR system operating parameters and their ranges are presented in Table 2. The highest boiler temperature was set at 90 °C, which permitted to use of renewable energy with a temperature of about 100 °C as a heat source. A computer Excel program was established to evaluate the ORC-VCR system performance in addition to the EPR and CMR with different candidates under different operating conditions.

RESULTS AND DISCUSSION

In the present study, the ORC-VCR system performance using fourteen HCs, HFCs and HFOs, as working fluids are investigated. The proposed candidates are R290, R134a, R1270, RC318, R152a, R161, R227ea, R236fa, R236ea, R600, R600a, R245fa, R1234yf, and R1234ze(E). Their basic thermodynamic, environmental and safety properties are listed in Table 1. The critical temperatures ranged from 92.42 °C to 9578
154.1 °C for R1270 and R245fa, respectively. This range was selected wishing to find the best candidate for ORC-VCR system for recovering low-grad thermal energy.

Table 3 displays a comparison between the performances of the basic ORC-VCR system using the proposed candidates. Also, Table 3 shows the candidate T-s diagram type and the saturated pressure at 90 °C for the whole candidates as well as the actual quality at the compressor exit (x6s). The results in Table 3 are obtained for the basic values of the operating parameters listed in Table 2. Fig. 3 displays the COPs and \( \dot{m}_{\text{total}} \) values of the basic ORC-VCR system for all candidates relative to the R600. From Fig. 3 and the results listed in Table 3 it can be concluded that among all the suggested working fluids, the highest critical temperatures with overhanging T-s diagram candidates, i.e. R245fa and R600 achieve the highest and nearly the same COPs values. The candidates with low critical temperatures, i.e. R227ea, RC318, R1270, and R1234yf achieve the lowest COPs values. On the other hand, R600 attains the lowermost \( \dot{m}_{\text{total}} \), whereas RC318 and R227ea accomplish the uppermost \( \dot{m}_{\text{total}} \). Therefore from the thermodynamic viewpoint, R600 can be considered a promising candidate for ORC-VCR system for recuperating low-temperature renewable energies.

The following subsections discuss the effects of various operating parameters such as the evaporator, boiler, and condenser temperatures, in addition to the compressor and expander isentropic efficiencies on the ORC-VCR system performance. In each case, only change the parameter whose effect is examined in the range specified in Table 2 and the rest parameters are set to the basic values given in Table 2. The analyses are displayed graphically in Figs. 4-7.

### Table 2 The basic values of the operating parameters used in the ORC-VCR system and their ranges.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Basic value</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>ORC working fluid mass flow rate</td>
<td>1.0 kg/s</td>
<td>-</td>
</tr>
<tr>
<td>Feed pump isentropic efficiency</td>
<td>75%</td>
<td>-</td>
</tr>
<tr>
<td>Boiler temperature</td>
<td>80 °C</td>
<td>60 - 90 °C</td>
</tr>
<tr>
<td>Evaporator temperature</td>
<td>5 °C</td>
<td>-15 to 15 °C</td>
</tr>
<tr>
<td>Condenser temperature</td>
<td>40 °C</td>
<td>30 - 55 °C</td>
</tr>
<tr>
<td>Compressor isentropic efficiency</td>
<td>75%</td>
<td>60 - 90%</td>
</tr>
</tbody>
</table>

### Table 3 Basic ORC-VCR system performance utilizing the proposed candidates.

<table>
<thead>
<tr>
<th>Substance</th>
<th>T-s diagram type</th>
<th>( P_{\text{sat}}, \text{MPa} )</th>
<th>( \eta_{\text{ORC}}, % )</th>
<th>COP(_{\text{VCR}} )</th>
<th>COP(_{\text{s}} )</th>
<th>( \dot{m}_{\text{total}} \times 100 )</th>
<th>EPR</th>
<th>CMR</th>
<th>( x_{6s} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1270</td>
<td>b</td>
<td>4.467</td>
<td>6.71</td>
<td>4.80</td>
<td>0.322</td>
<td>1.41</td>
<td>2.65</td>
<td>2.44</td>
<td>--</td>
</tr>
<tr>
<td>R1234yf</td>
<td>o</td>
<td>3.800</td>
<td>6.78</td>
<td>4.68</td>
<td>0.317</td>
<td>3.12</td>
<td>3.13</td>
<td>2.73</td>
<td>--</td>
</tr>
<tr>
<td>R290</td>
<td>b</td>
<td>3.764</td>
<td>6.90</td>
<td>4.81</td>
<td>0.332</td>
<td>1.32</td>
<td>2.70</td>
<td>2.48</td>
<td>--</td>
</tr>
<tr>
<td>R134a</td>
<td>b</td>
<td>3.244</td>
<td>7.13</td>
<td>4.91</td>
<td>0.350</td>
<td>2.36</td>
<td>3.01</td>
<td>2.91</td>
<td>--</td>
</tr>
<tr>
<td>R227ea</td>
<td>o</td>
<td>2.298</td>
<td>6.84</td>
<td>4.58</td>
<td>0.313</td>
<td>3.89</td>
<td>3.32</td>
<td>2.99</td>
<td>0.96</td>
</tr>
<tr>
<td>R161</td>
<td>b</td>
<td>3.985</td>
<td>7.27</td>
<td>5.00</td>
<td>0.363</td>
<td>1.24</td>
<td>2.65</td>
<td>2.66</td>
<td>--</td>
</tr>
<tr>
<td>R1234ze(E)</td>
<td>o</td>
<td>2.4755</td>
<td>7.28</td>
<td>4.89</td>
<td>0.356</td>
<td>2.40</td>
<td>3.02</td>
<td>2.96</td>
<td>--</td>
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<tr>
<td>R152a</td>
<td>b</td>
<td>2.878</td>
<td>7.54</td>
<td>5.09</td>
<td>0.384</td>
<td>1.38</td>
<td>2.77</td>
<td>2.89</td>
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<tr>
<td>RC318</td>
<td>o</td>
<td>1.668</td>
<td>6.94</td>
<td>4.58</td>
<td>0.318</td>
<td>3.98</td>
<td>3.24</td>
<td>3.15</td>
<td>0.93</td>
</tr>
<tr>
<td>R236fa</td>
<td>o</td>
<td>1.565</td>
<td>7.37</td>
<td>4.88</td>
<td>0.360</td>
<td>2.63</td>
<td>3.23</td>
<td>3.33</td>
<td>0.99</td>
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<tr>
<td>R600a</td>
<td>o</td>
<td>1.641</td>
<td>7.57</td>
<td>5.01</td>
<td>0.380</td>
<td>1.11</td>
<td>2.75</td>
<td>2.85</td>
<td>--</td>
</tr>
<tr>
<td>R236ea</td>
<td>o</td>
<td>1.263</td>
<td>7.55</td>
<td>4.96</td>
<td>0.375</td>
<td>2.36</td>
<td>3.21</td>
<td>3.50</td>
<td>0.99</td>
</tr>
<tr>
<td>R600</td>
<td>o</td>
<td>1.250</td>
<td>7.76</td>
<td>5.12</td>
<td>0.398</td>
<td>0.97</td>
<td>2.81</td>
<td>3.04</td>
<td>--</td>
</tr>
<tr>
<td>R245fa</td>
<td>o</td>
<td>1.004</td>
<td>7.77</td>
<td>5.12</td>
<td>0.398</td>
<td>1.84</td>
<td>3.26</td>
<td>3.76</td>
<td>--</td>
</tr>
</tbody>
</table>
The heat rejected is 

\[ \text{heat rejected} = \frac{\text{power output}}{\text{COP}} \]

\[ \text{COP} = \frac{\text{power output}}{\text{power input}} \]

The GWP of R245fa is 1050 and is categorized in safety group B1; inversely the GWP of R600 is 20 and is classified in safety group A3 as presented in Table 1. Accordingly, R600 is the most appropriate working fluid for the ORC-VCR system to recuperate low-grad renewable energy.

The effect of boiler temperature (\(T_b\)) on the ORC-VCR system performance is shown in Fig. 4. Figure 4a illustrates the variation in COPs as a function of \(T_b\) for different working fluids. As can be observed from Fig. 4a, with the increment of \(T_b\) the COPs improves for all working fluids. Among the whole candidates, R245fa and R600 attain the highest COPs for all studied \(T_b\) range, while R227ea, RC318, R1270, and R1234yf achieve the lowest COPs. The COPs values for both R600 and R245fa are nearly the same. They have the highest critical temperatures (\(T_{cr}\)). As \(T_b\) rises from 60 to 90 °C, the COPs using R600 or R245fa improves by approximately 106.9%. Their COPs is 0.47 with \(T_b\) equal to 90 °C, which is larger than those of R1270, R1234yf, R227ea and RC318 by about 35.3%, 33.8%, 31.5%, and 28.0%, respectively. The highest system pressures with R245fa and R600 are the lowest among all suggested working fluids, reaching 1.004 and 1.250 MPa, respectively, at \(T_b\) equal to 90°C as displayed in Table 3. This leads to lower the system investment.

The effect of \(T_b\) on \(\dot{m}_{\text{total}}\) for all candidates in the basic ORC-VCR system is exhibited in Fig. 4b. It can be observed from this figure that with the increment of \(T_b\) the \(\dot{m}_{\text{total}}\) decreases for all candidates. Within the examined \(T_b\) range, R600 achieves the lowest \(\dot{m}_{\text{total}}\), while RC318 and R227ea achieve the highest \(\dot{m}_{\text{total}}\). This can be interpreted because of they have the uppermost molecular mass among all candidates as presented in Table 1 (M, RC318 = 200.03 g/mol, M, R227ea = 170.03 g/mol).

The GWP of R245fa is 1050 and is categorized in safety group B1; inversely the GWP of R600 is 20 and is classified in safety group A3 as presented in Table 1. Accordingly, R600 is the most appropriate working fluid for the ORC-VCR system to recuperate low-grad renewable energy.

The variation of EPR values as a function of \(T_c\) for all candidates in the basic ORC-VCR system is displayed Fig. 4c. With the increment of \(T_c\) the EPR growths for all candidates, because the saturation pressure rises with the temperature. The EPR values at \(T_c\) of 60 ºC are approximately half those at 90 ºC for all candidates. The highest EPR values are accomplished by R245fa, however when \(T_b\) between 75 and 90 ºC the highest is achieved by R227ea. The lowest EPR is achieved by R1270, but when \(T_b\) changes from 80 to 90 ºC the lowest is achieved by R161. The working fluids can be divided into three groups as displayed in the Fig. 4c. The first group includes HFCs working fluids, namely R227ea, R245fa, R236fa, RC318, and R236ea. This group has the uppermost and approximately the same EPR values. The second group includes HCs working fluids, namely R290, R1270, R600, and R600a in addition to R152a and R161 HFCs working fluids. The EPR values of the working fluid in this group are the lowest and the differences between the EPR values are minor. The third group includes HFOs working fluids, namely R1234ze(E) and R1234yf in addition to HFC candidate R134a. The EPR values of this group are in between those of the first and the second groups. Furthermore, to accomplish turbine efficiency greater than 80% the EPR should be lower than 50 [25]. The EPR values for all the proposed working fluids are lower than 4.5 as shown in Fig. 4c. Accordingly, expander efficiency larger than 80% can be attained.
Figure 4: The effect of boiler temperature on the COP$_S$ (a), m$_{\text{total}}$ (b) and EPR (c) of the basic ORC-VCR system with different candidates.

Figure 5b illustrates the variation of m$_{\text{total}}$ with T$_c$ for the basic ORC-VCR system with different candidates. In general, the decrease in T$_c$ leads to the decline of m$_{\text{total}}$ for all candidates. The highest m$_{\text{total}}$ values were attained by RC318 and R227ea, while R600 achieved the lowest m$_{\text{total}}$ values for all condenser temperatures. The refrigerant R600 can be considered a superior candidate in comparison with all proposed working fluids. The COP$_S$ and m$_{\text{total}}$ using R600 as a working fluid are 0.718 and 0.006 kg/(s kW), respectively at T$_c$ of 30 ºC and the basic values for the rest operating parameters.

Figures 5c and d illustrate the effect of T$_c$ on the EPR and the CMR in ORC-VCR system for various candidates, respectively. It is noticed from Figs. 5c and d that with the decreasing of T$_c$, the EPR increases while the CMR decreases. This is reasonably when considering the thermophysical properties influence of these working fluids. The differences between the EPR values for all candidates are greater at low than that at high condenser temperatures. The contrary occurs with the variation of the CMR with T$_c$. The candidates in Fig. 5c can be characterized into three groups; the first group with the uppermost EPR values contains the HFCs working fluids (R227ea, R245fa, RC318, R236ea, and R236fa). The differences between the EPR values of this group are small. The second group with the lowest values of EPR includes the HC$_S$ working fluids (R1270, R600a, R600, and R290) in addition to R152a and R161 HFCs candidates. At T$_c$ above 50 ºC, the variations between the values of EPR of this group are small. The third group includes HFOs working fluids, i.e. R1234yf and R1234ze(E) in addition to HFC candidate R134a. The EPR values of this group are in between those of the first and the second groups.
The influence of evaporator temperature on the ORC-VCR system performance

The variations of COP\textsubscript{s}, CMR and m\textsubscript{total} as a function of evaporator temperature (T\textsubscript{e}) of the ORC-VCR system for various working fluids are illustrated in Figs. 6a, b, and c, respectively. From Fig. 6a it can be observed that the COP\textsubscript{s} improves with the increase of T\textsubscript{e}. This can be understood by the fact that as T\textsubscript{e} increases its saturation pressure rises. This causes the decline of the CMR, as exhibited in Fig. 56. This leads the required compressor work to decline at the specified operating conditions. Also, the increment of T\textsubscript{e} leads to improve the cooling capacity because of the increment in refrigeration effect. Both influences enhance the COP\textsubscript{s} of the ORC-VCR system. Besides the increase of COP\textsubscript{s} as T\textsubscript{e} increments for all proposed working fluids, the decline in m\textsubscript{total} is approximately linear as detected from Fig. 6c. Among all the suggested working fluids, R245fa and R600 accomplish the uppermost and nearly identical COP\textsubscript{s} values, while R600 attains the lowermost m\textsubscript{total} values for all studied evaporator temperatures. In the case of R00 as T\textsubscript{e} varied from -15 to 15 °C, the COP\textsubscript{s} increments nearly 180.0%, while m\textsubscript{total} deteriorations by approximately 52.0%.
The influence of compressor and expander efficiencies on the ORC-VCR system performance

The effects of both expander and compressor efficiencies on the COPs and \( \dot{m}_{\text{total}} \) of the ORC-VCR system for various working fluids are displayed in Fig. 7a and b. As noticed from these figures, \( \eta_{\text{exp}} \) and \( \eta_{\text{comp}} \) have a significant influence on the COPs. The COPs increments approximately linearly with the improvement of \( \eta_{\text{exp}} \) and \( \eta_{\text{comp}} \) for all proposed working fluids. The COPs increases by approximately 53% as the \( \eta_{\text{exp}} \) improves from 60 to 90% for all candidates. While as \( \eta_{\text{comp}} \) improves from 60 to 90%, the COPs increments by almost 50% for all proposed working fluids. The \( \eta_{\text{exp}} \) and \( \eta_{\text{comp}} \) have a small influence on \( \dot{m}_{\text{total}} \) except with RC318 and R227ea as can be observed from Figs. 7c and d. The decline in \( \dot{m}_{\text{total}} \) is nearly linearly with the improvement of \( \eta_{\text{exp}} \) and \( \eta_{\text{comp}} \).
To summarize the previous discussion, there is still no working fluid that totally achieves all requests from the standpoint of energy efficiency, and safety and environmental issues. Since this study emphasizes on the ORC-VCR system performance from the perspective of thermodynamic, COPs and \( \dot{m}_{\text{total}} \) are used to identify the system performance. In comparison with all candidates, R600 attains the highest COPs and the lowest \( \dot{m}_{\text{total}} \) under all examined operating conditions. Moreover, it should be noticed that this study focuses on the evaluation of the ORC-VCR system performance using many HFCs, HFOs, and HCs as working fluids, therefore, the examined system is simple. It should be noted that adding supplementary internal heat exchangers enhance the system performance. This demonstrates that the ORC-VCR system is a favorable system to convert low-temperature renewable energy to electricity or refrigeration.

Till now, the thermodynamic concerns of the suggested candidates for ORC-VCR system are studied. On the other hand, the environmental and safety issues of the suggested candidates for the ORC-VCR system should be considered during the choice of working fluids. Among the suggested working fluids, the HFCs candidates group (except R161), namely R134a, R152a, R227ea, R236ea, R245fa, and RC318 have the highest GWP but they are non-flammable. Consequently, extra considerations regarding environmental issues are required. Conversely, the HCs working fluids group, namely R290, R1270, R600, and R600a are flammable but have very low GWP. Therefore, extra attention should be taken against the safety concerns. The HFOs working fluids group, namely R1234ze(E) and R1234yf are slightly flammable with ASHRAE safety categorization of 2L and have a GWP lower than 1. Thus, from safety and environmental issue viewpoint, there is no perfect candidate for the ORC-VCR system; each one has its own disadvantages and advantages. Accordingly, there is no candidate exist currently that totally meets the energy efficiency, and safety and environmental concerns. The flammability is the sole actual argument against using R600 as working fluid for...
ORC-VCR system. However, the flammability will not constitute the essential challenge in utilizing R600 with adequate safety precautions.

CONCLUSIONS

The performance of ORC-VCR system activated by low-temperature renewable energy is investigated. Many hydrocarbons, hydrofluorocarbons, and hydrofluoroolefins, namely R290, R1270, R600, R600a, R134a, R152a, R161, R227ea, R236ea, R236fa, R245fa, RC318, R1234ze(E), and R1234yf, are proposed as working fluids. The influences of the boiler, evaporator and condenser temperatures, besides the isentropic efficiencies of the compressor and the expander on the ORC-VCR system performance are also examined and discussed.

The obtained results indicate that all examined operating parameters have similar effects on the performance of the ORC-VCR system for all candidates. In detail, with the rise of the evaporator and boiler temperatures in addition to the compressor and expander isentropic efficiencies, the COPs increases while the \( \dot{n}_{\text{total}} \) declines for all the proposed working fluids. The opposite is valid with condenser temperature. Also, with the increase of evaporator and boiler temperatures, the compression ratio decreases and the expansion ratio increments, respectively, whereas the opposite occurs with the condenser temperature.

Among all candidates, R245fa and R600 accomplish the highest and approximately the same COPs values, while R600 achieves the lowest \( \dot{n}_{\text{total}} \) under all examined operating parameters. Because of environmental concerns of R245fa, R600 is recommended as a promising candidate for the ORC-VCR system to recover renewable energies in a temperature range from 60°C to 90°C from the system performance and environmental issues viewpoints. The highest COPs and the corresponding \( \dot{n}_{\text{total}} \) using R600 are 0.72 and 0.006 kg/(s kW), respectively at a condenser temperature of 30 ºC and the basic values for the remaining operating parameters.

ACKNOWLEDGEMENTS

This study is supported by Taif University under a contract NO. 1-437-4888. The University is highly acknowledged for the financial support.

REFERENCES


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