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Parametric and working fluid analysis of a combined organic Rankine-vapor compression refrigeration system activated by low-grade thermal energy

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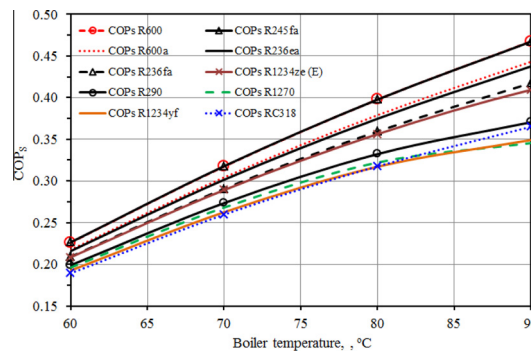
The effect of boiler temperature on the COP_S for different candidates in the basic ORC-VCR system.

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Nomenclature

Latin letters

ALT	atmospheric lifetime, years
CFCs	chlorofluorocarbons
COP	coefficient of performance
CMR	compressor compression ratio
EPR	expander expansion ratio
GWP	global warming potential
h	enthalpy, kJ/kg
HCFCs	hydrochlorofluorocarbons
HCs	hydrocarbons
HFCs	Hydrofluorocarbons
HFOs	hydrofluoroolefins
LFL	lower flammability limit, % by volume in air
M	molecular mass, kg/kmol
$\dot{m}$	mass flow rate, kg/s
NBP	normal boiling point, °C
ODP	ozone depletion potential
ORC	organic Rankine cycle
P	pressure, kPa
T	temperature, °C
v	specific volume, (m^3/kg)
VCR	vapor compression refrigeration
$\dot{Q}$	rate of heat transfer, kW
$\dot{W}$	power, kW

Greek letter

η	efficiency

Subscripts

b	boiler
c	compressor
e	evaporator
exp	expander
net	net
s	system
sat	saturated pressure
total	total
P	pump
x	quality
1, 2, 3 …	respective state points in the system

A R T I C L E   I N F O

A B S T R A C T

The potential use of many common hydrofluorocarbons and hydrocarbons as well as new hydrofluoroolefins, i.e. R1234yf and R1234ze(E) working fluids for a combined organic Rankine cycle and vapor compression refrigeration (ORC-VCR) system activated by low-grade thermal energy is evaluated. The basic ORC operates between 80 and 40 °C typical for low-grade thermal energy power plants while the basic VCR cycle operates between 5 and 40 °C. The system performance is characterized by the overall system coefficient of performance (COP$_S$) and the total mass flow rate of the working fluid for each kW cooling capacity ($\dot{m}_{total}$). The effects of different working parameters such as the evaporator, condenser, and boiler temperatures on the system performance are examined. The results illustrate that the maximum COP$_S$ values are attained using the highest boiling candidates with overhanging T-s diagram, i.e. R245fa and R600, while R600 has the lowest $\dot{m}_{total}$ under the considered operating conditions. Among the proposed candidates, R600 is the best candidate for the ORC-VCR system from the perspectives of environmental issues and system performance. Nevertheless, its flammability should attract enough attention. The maximum COP$_S$ using R600 is found to reach up to 0.718 at a condenser temperature of 30 °C and the basic values for the remaining parameters.

Introduction

Nowadays, there are numerous attempts in the utilization of renewable energies such as geothermal heat, wind energy, and solar energy as clean energy sources for electricity production or cooling processes. Also, waste heat can be considered as renewable and clean energy, since it is free energy and there is no direct carbon emission. Waste heat can be rejected at a wide range of temperatures depending on the industrial processes [1].

An ejector refrigeration system and an absorption refrigeration system can be activated by thermal energy source with a temperature range from 100 to 200 °C. They have several advantages such as simple structure, reliability, low investment cost, slight maintenance, long lifetime, and low running cost [2,3]. Nevertheless, they are not appropriate for thermal

sources less than 90 °C and are also not appropriate for working in high-temperature surroundings. Furthermore, the minimum cooling temperature could be achieved by both systems is 5 °C [4].

In the present study, an alternative refrigeration cycle using an organic Rankine cycle (ORC), activated by renewable energy, combined with a vapor compression refrigeration (VCR) cycle is suggested for electricity or cooling production. The ORC is a favorable cycle to convert low-grade thermal energy to useful work, which can be used to drive the VCR cycle. Both expander and compressor shafts are directly connected together to minimize energy conversion losses. The combined cycle has numerous advantages such as the flexibility to produce power when cooling is unwanted, which makes the system can continuously use the thermal energy throughout the year. In summer, all the thermal energy can be converted to cooling, while only part of the thermal energy is converted to cooling in spring and fall. No heat is converted to cooling in winter. When cooling is not needed, all the thermal energy can be converted to electricity and sent to the grid [5–7].

The working fluid selection has a large influence on the performance of combined organic Rankine cycle-vapor compression refrigeration (ORC-VCR) system. Several studies have been done on the working fluid selection, i.e. R12, R22, R113, and R114 for the ORC-VCR system and identified the most suitable one, which may yield highest coefficient of performance (COP) [8–13]. The refrigerants R123, R134a, and R245ca were evaluated to find the best one for the ORC-VCR system by Aphornratana and Sriveerakul [14]. The results indicated that R123 achieves the best system performance. An ORC-VCR system activated by a low-temperature source utilizes R134a was analyzed by Kim and Perez-Blanco [4]. The minimum cooling temperature could be achieved by the system was −10 °C. An ORC-VCR system utilizing two different candidates for the power and refrigeration cycles, i.e. R245fa and R134a, respectively was investigated by Wang et al. [1]. The system coefficient of performance (COP$_S$) attained approximately 0.5. Six candidates, namely R134a, R123, R245fa, R290, R600a, and R600, were investigated to determine appropriate working fluid for ORC-VCR system by Bu et al. [15]. They concluded that R600a is the most suitable candidate. A combined ORC with a vehicle air conditioning system using R245fa, R134a, pentane, and cyclopentane as working fluids was studied by Yue et al. [16]. Their results indicated that R134a gives the maximum economic and thermal performance. An ORC-VCR system powered by low-grade thermal energy using two different substances for the power and refrigeration cycles was studied by Molés et al. [17]. They concluded that the best candidates for the power and refrigeration cycles are R1336mzz(Z) and R1234ze(E), respectively.

From the aforementioned introduction, it is clear that there is still a need for screening of alternative candidates for ORC-VCR system. The present study concentrates on the production of electricity or cooling from low-temperature renewable energies such as waste heat or geothermal heat having a temperature around 100 °C. The potential use of R290, R1270, RC318, R236fa, R600a, R236ea, R600, R245fa, R1234yf, and R1234ze(E) as working fluids in the ORC-VCR system is assessed. The performance of the system is characterized by the COP$_S$ and the total mass flow rate of the working fluid for each kW cooling capacity ($\dot{m}_{total}$). The working fluid
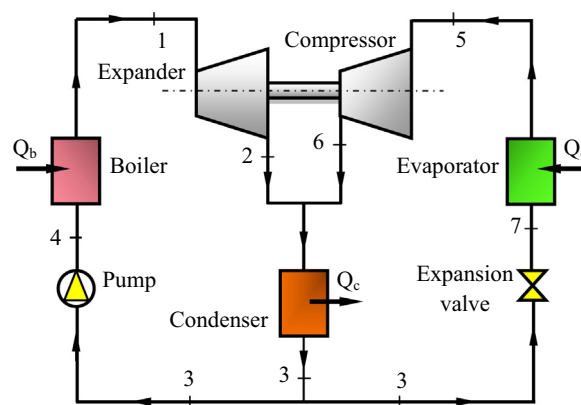

Fig. 1 ORC-VCR system schematic diagram.

accomplishes the highest COP$_S$ and the lowest $\dot{m}_{total}$ is recommended. The effects of various working conditions such as the boiler, condenser, and evaporator temperatures in addition to the compressor and expander isentropic efficiencies on the ORC-VCR system performance are also investigated.

Configurations of the ORC-VCR system and working fluid selection

Fig. 1 shows a schematic diagram of the ORC–VCR system. The system composed of the ORC and the VCR cycle. The features of this system are as follows: (1) the two cycles utilize the same working fluid; (2) both expander and compressor shafts are straightway coupled; (3) both cycles use one mutual condenser and (4) the expander power is merely sufficient to power the compressor and pump.

A substantial characteristic for sorting the ORC-VCR systems is the shape of the temperature against entropy (T-s) diagram. It may be either a bell-shaped as illustrated in Fig. 2a or it may be overhanging as displayed in Fig. 2b. Another characteristic for sorting the ORC-VCR systems is the pressure at which the working fluid receives heat in ORC from the source of heat. At subcritical pressures, the fluid is subject to a liquid–vapor phase change process during the heat addition whereas at supercritical pressures such a phase change does not take place.

The different system processes can be described as follows. For the ORC: Process (1-2$_s$) is an isentropic expansion across the expander, Process (1-2$_a$) is an actual expansion across the expander, Process (2$_a$-3) is a heat rejection process in the condenser, Process (3-4$_s$) is an isentropic pumping process, Process (3-4$_a$) is an actual pumping process, and Process (4$_a$-1) is a heat addition in the boiler. For 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$_s$) is an isentropic compression across the compressor, Process (5-6a) is an actual compression across the compressor, and Process (6a-3) is a heat rejection process in the condenser. The working fluid leaving the evaporator and boiler is maintained as saturated vapor.

The working fluid selection is essential in the ORC-VCR systems. A suitable working fluid accomplishes both high system performance and minimal environmental issues. The following concerns should be taken into account during the working fluids selection: (1) environmental issues: global
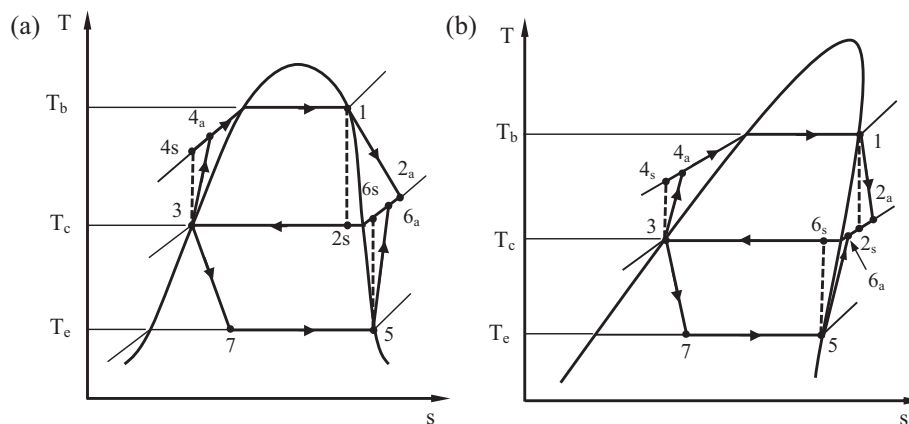
Fig. 2 (a) Bell-shaped *T-s* and (b) overhanging *T-s* diagram of the basic ORC-VCR system.

warming potential (GWP), atmospheric lifetime (ALT), and ozone depletion potential (ODP); (2) safety aspects: flammability, toxicity, and auto ignition and (3) economics and availability.

Hydrofluorocarbons (HFCs) have been selected as working fluids replacing chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) in ORC, VCR cycle, and combined cycles due to their zero ODP. Because of the HFCs have a high GWP, they are now being controlled. Accordingly there is still a continuous search for alternative working fluids, which might have a better cycle performance, lower atmospheric lifetimes, and lower manufacturing costs, or are preferable due to toxicity or flammability reasons. One possibility is using hydrocarbons (HCs), which have a very low GWP and excellent thermophysical properties [18]. The HCs are chemically stable, non-toxic, highly soluble in mineral oils and environmentally friendly, but they are flammable. Presently, the main HCs considered as working fluids are R1270, R290, R600a, and R600 [19,20]. Also, many hydrofluoroolefins (HFOs) with low GWP are suggested as working fluids [17,21].

In this study, 10 HFCs, HCs, and HFOs, i.e. R1270, R290, RC318, R236fa, R600a, R236ea, R600, R245fa, R1234yf, and R1234ze(E) are proposed as candidates for the ORC-VCR system. The basic thermodynamic properties, and safety and envi-

ronmental aspects of the candidates are listed in Table 1 [22,23].

Mathematical model and computational procedure

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

With respect to the ORC:

$$\dot{W}_{exp} = \dot{m}_{ORC}(h_1 - h_{2a}) = \dot{m}_{ORC}(h_1 - h_{2s})\eta_{exp} \tag{1}$$

where $\dot{W}_{exp}$ is the output power from the expander during process (1-2_a) in kW, $\dot{m}_{ORC}$ is the mass flow rate of the working fluid in the ORC in kg/s, h_1 is the expander inlet specific enthalpy in kJ/kg, h_{2a} is the expander exit actual specific enthalpy in kJ/kg, h_{2s} is the expander exit isentropic specific enthalpy in kJ/kg, and η_{exp} is the expander isentropic efficiency.

$$\dot{W}_P = \dot{m}_{ORC}(h_{4a} - h_3) = \frac{\dot{m}_{ORC}(h_{4s} - h_3)}{\eta_P} \tag{2}$$

where $\dot{W}_P$ is the inlet power to the pump during process (3-4_a) in kW, h_{4a} is the pump exit actual specific enthalpy in kJ/kg, h_3 is the pump inlet specific enthalpy in kJ/kg, h_{4s} is the isentropic

Table 1 Properties of the proposed candidates for ORC-VCR system.

Substance	Chemical formula	Physical data					Environmental data			Safety data	
		M	NBP	T_c	P_c	$v_c \times 10^3$	ALT	ODP	GWP 100 yr	LFL	Safety group
		g/mol	°C	°C	MPa	m³/kg	year			%	
R1270	$CH_3-CH=CH_2$	42.08	−47.7	92.4	4.67	4.477	0.001	0.0	< 20	2.7	A3
R290	C_3H_8	44.10	−42.1	96.7	4.25	4.577	0.041	0.0	~20	2.1	A3
RC318	Cyclo-C_4F_8	200.03	−6.0	115.2	2.78	1.613	320 0	0.0	10,300	None	A1
R236fa	$CF_3-CH_2-CF_3$	152.04	−1.4	124.9	3.20	1.814	242	0.0	9820	None	A1
R600a	Iso-C_4H_{10}	58.12	−11. 7	134.7	3.63	4.457	0.016	0.0	~20	1.6	A3
R236ea	$CF_3-CHF-CHF_2$	152.04	6.2	139.3	3.50	1.776	11.0	0.0	1410	None	–
R600	C_4H_{10}	58.12	−0.55	152.0	3.80	4.389	0.018	0.0	~20	2.0	A3
R245fa	$CF_3-CH_2-CHF_2$	134.05	15.1	154.1	3.65	1.934	7.7	0.0	1050	None	B1
R1234yf	$CF_3CF=CH_2$	114.04	−29.5	94.7	3.38	0.0021	0.029	0.0	< 1	6.2	A2L
R1234ze(E)	$CHF=CHCF_3$	114.04	−19.0	109.4	3.64	0.0020	0.045	0.0	< 1	7.6	A2L

specific enthalpy at the pump outlet in kJ/kg, and η_P is the pump isentropic efficiency.

$$\dot{W}_{net} = \dot{W}_{exp} - \dot{W}_P \tag{3}$$

where $\dot{W}_{net}$ is the net output power from the ORC in kW.

$$\dot{Q}_b = \dot{m}_{ORC}(h_1 - h_{4a}) \tag{4}$$

where $\dot{Q}_b$ is the heat transfer rate to the working fluid in the boiler during the process (4$_a$-1) in kW, h_1 is the boiler outlet specific enthalpy in kJ/kg, and h_{4a} is the boiler inlet actual specific enthalpy in kJ/kg.

$$\eta_{ORC} = \frac{\dot{W}_{net}}{\dot{Q}_b} \tag{5}$$

where η_{ORC} is the organic Rankine cycle efficiency.

With respect to the VCR cycle:

$$\dot{Q}_e = \dot{m}_{VCR}(h_5 - h_7) \tag{6}$$

where $\dot{Q}_e$ is the rate of heat transfer to the working fluid in the evaporator during process (7-5) in kW, $\dot{m}_{VCR}$ is the mass flow rate of the working fluid in the VCR in kg/s, h_5 is the evaporator outlet specific enthalpy in kJ/kg, and h_7 is the evaporator inlet specific enthalpy in kJ/kg.

$$\dot{W}_c = \dot{m}_{VCR}(h_5 - h_{6a}) = \frac{\dot{m}_{VCR}(h_5 - h_{6s})}{\eta_c} \tag{7}$$

where $\dot{W}_c$ is the inlet power to the compressor during process (5-6$_a$) in kW, h_5 is the compressor inlet specific enthalpy in kJ/kg, h_{6a} is the compressor outlet actual specific enthalpy in kJ/kg, h_{6s} is the compressor outlet isentropic specific enthalpy in kJ/kg, and η_c is the compressor isentropic efficiency.

$$\dot{W}_c = \dot{W}_{net} \tag{8}$$

The VCR cycle COP is defined as follows:

$$COP_{VCR} = \frac{\dot{Q}_e}{\dot{W}_c} \tag{9}$$

The COP_S can be calculated as follows:

$$COP_S = \eta_{ORC} COP_{VCR} \tag{10}$$

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

$$\dot{m}_{total} = \frac{\dot{m}_{ORC} + \dot{m}_{VCR}}{\dot{Q}_e} \tag{11}$$

The compressor compression ratio (CMR) during the process (5-6$_a$) and the expander expansion ratio (EPR) during the process (1-2$_a$) are measures for the required compressor and expander sizes, respectively, and described as follows:

$$CMR = \frac{p_{6a}}{p_5} \tag{12}$$

$$EPR = \frac{v_{2a}}{v_1} \tag{13}$$

The performance of the system is characterized by the COP_S and $\dot{m}_{total}$. The COP_S and $\dot{m}_{total}$ are calculated by Eqs. (10) and (11), respectively. The CMR and EPR are computed using Eqs. (12) and (13), respectively. The thermodynamic properties of the proposed candidates are obtained 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 adjusted at 90 °C, which allowed the usage of waste heat or geothermal energy with a temperature of approximately 100 °C or a little lower as a heat source. A computer Excel program was established to assess the ORC-VCR system performance as well as the CMR and EPR with various candidates under different working conditions.

Results and discussion

In this study, the performance of ORC-VCR system using 10 HFCs, HCs and HFOs, i.e. R1270, R290, RC318, R236fa, R600a, R236ea, R600, R245fa, R1234yf, and R1234ze(E) as working fluids was calculated and analyzed. Their basic thermodynamic properties, and environmental and safety aspects are listed in Table 1. The critical temperatures range from 92.42 °C for R1270 to 154.1 °C for R245fa. This range was specified hoping to find the best working fluid for ORC-VCR system to recapture low-grade thermal energy.

A comparison between performances of the basic ORC-VCR system using the proposed candidates is listed in Table 3. Also, the T-s diagram type and the saturated pressure at 90 °C of the working fluids as well as the actual quality after compressor (x_{6a}) are illustrated in Table 3. The letters o and b are used for fluids with overhanging and bell-shaped T-s diagram, respectively. In the present study only subcritical systems are studied. The calculations in Table 3 were done using the basic values of the operating parameters as specified in Table 2. It can be observed from Table 3 that the general trend is that with increasing critical temperature, the COPs increases. The results in Table 3 show that among all

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

Parameter	Basic value	Range
Mass flow rate of the working fluid in ORC	1.0 kg/s	–
Isentropic efficiency of the feed pump	75%	–
Boiler temperature	80 °C	60–90 °C
Isentropic efficiency of the expander	80%	60–90%
Condenser temperature	40 °C	30–55 °C
Evaporator temperature	5 °C	−15 °C to 15 °C
Isentropic efficiency of the compressor	75%	60–90%

Table 3 Performance of the basic ORC-VCR system utilizing the proposed working fluids.

| Substance	Cycle type	P_{sat}, MPa	η_{ORC}, %	COP_{VCR}	COP_S	$\dot{m}_{total} \times 100$	EPR	CMR	x_{6a}
R1270	b	4.467	6.71	4.80	0.322	1.41	2.65	2.44	–
R290	b	3.764	6.90	4.81	0.332	1.32	2.70	2.48	–
RC318	o	1.668	6.94	4.58	0.318	3.98	3.24	3.15	0.93
R236fa	o	1.565	7.37	4.88	0.360	2.63	3.23	3.33	0.99
R600a	o	1.641	7.57	5.01	0.380	1.11	2.75	2.85	–
R236ea	o	1.263	7.55	4.96	0.375	2.36	3.21	3.50	0.99
R600	o	1.250	7.76	5.12	0.398	0.97	2.81	3.04	–
R245fa	o	1.004	7.77	5.12	0.398	1.84	3.26	3.76	–
R1234yf	o	3.080	6.78	4.68	0.317	3.12	3.13	2.73	–
R1234ze(E)	o	2.4755	7.28	4.89	0.356	2.40	3.02	2.96	–

candidates, R600 and R245fa with the highest critical temperatures have the maximum and the same COP_S values, whereas RC318, R1234yf, and R1270 with the lowest critical temperatures have the minimum COP_S values. On the other hand, R600 accomplishes the lowest $\dot{m}_{total}$, while RC318 attains the highest $\dot{m}_{total}$. So from the viewpoint of thermodynamics, R600 can be considered a superior candidate for ORC-VCR system for recovering low-grade thermal energy.

The effects of different operating conditions such as the evaporator, condenser, and boiler temperatures, in addition to the compressor and expander isentropic efficiencies on the ORC-VCR system performance, are discussed in the following sections. In each case, only varies the parameter whose effect is studied within the given range in Table 2 while the remaining parameters are fixed and equal to the basic values given in Table 2. The analyses are exhibited graphically in Figs. 3–6.

The influence of boiler temperature on the system performance

Fig. 3 exhibits the influence of boiler temperature on the basic ORC-VCR system performance. Fig. 3a displays the alteration in COP_S as a function of the boiler temperature for different candidates in the basic ORC-VCR system. This figure shows that the COP_S of the system improves as the boiler temperature increases for all candidates. Among the proposed working fluids, R600 and R245fa achieve the highest COP_S for all boiler temperatures, while RC318, R1234yf, and R1270 attain the lowest COP_S. The COP_S values of R245fa are approximately the same as those of R600. They have the highest critical temperatures (T_c, R245fa = 154.05 °C, T_c, R600 = 151.98 °C). When the boiler temperature increases from 60 to 90 °C, the COP_S using R245fa or R600 improves by about 107.0%. When the boiler temperature is 90 °C, the COP_S using both working fluids is 0.47, which is greater than those of RC318, R1234yf, and R1270 by approximately 28.0%, 33.8%, and 35.3%, respectively. The maximum system pressures using R600 and R245fa are the lowest among all candidates, reaching 1.250 and 1.004 MPa, respectively, at a boiler temperature of 90 °C as exhibited in Table 3, resulting in lower system investment.

R245fa has a high GWP of 1050 and is characterized in safety group B1; contrariwise, R600 has a very low GWP of 20 and is characterized in safety group A3 as shown in Table 1. Consequently, R600 can be considered as a promising candidate for the ORC-VCR system to recover low-grade thermal energy with a temperature range from 60 °C to 90 °C.
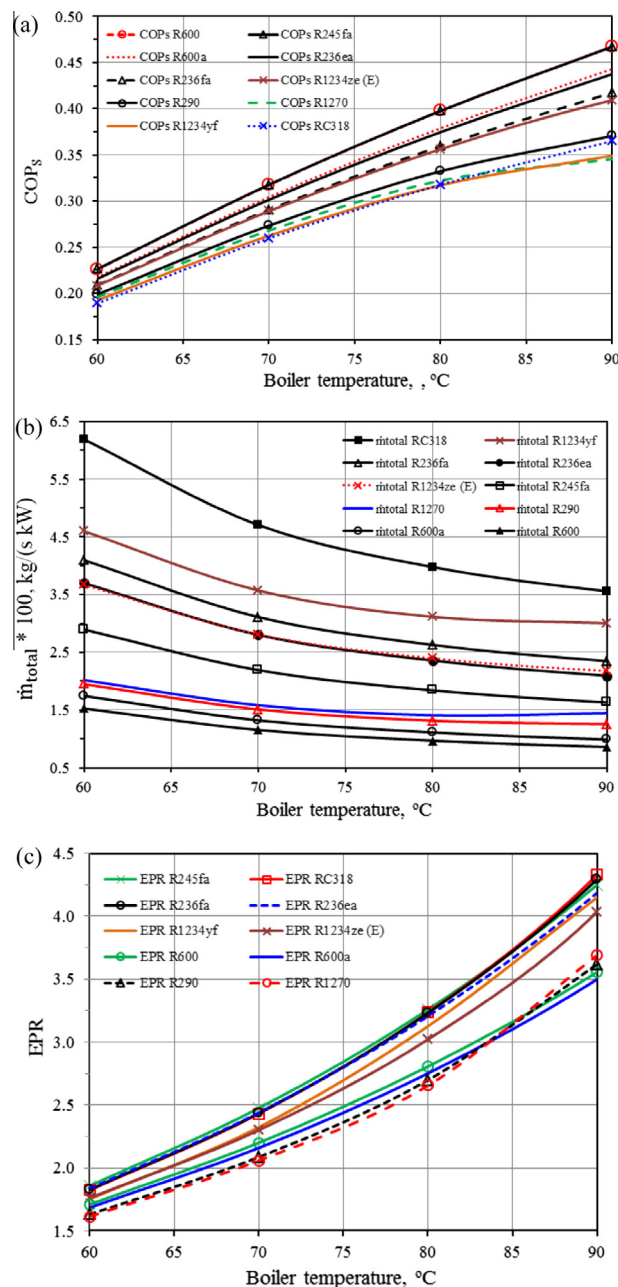
Fig. 3 The effect of boiler temperature on the COP_S (a), $\dot{m}_{total}$ (b) and EPR (c) for various candidates in the basic ORC-VCR system.

Fig. 3b shows the influence of boiler temperature on the $\dot{m}_{total}$ for different candidates in the basic ORC-VCR system. This figure exhibits that the $\dot{m}_{total}$ reduces as the boiler temperature increases for all proposed working fluids. Within the studied boiler temperature range, R600 attains the lowest $\dot{m}_{total}$, while RC318 achieves the highest $\dot{m}_{total}$ which has the highest molecular mass (200.03 kg/kmol).

Fig. 3c exhibits the change in EPR values as a function of the boiler temperature for different candidates in the basic ORC-VCR system. This figure shows that the EPR rises as the boiler temperature increases for all candidates. This is due to the rise of saturation pressure with the temperature. The EPR values at a boiler temperature of 90 °C are nearly twice those at 60 °C for all candidates. The maximum EPR is achieved by R245fa, but when the boiler temperature was between 80 and 90 °C the maximum is attained by RC318. The minimum EPR is attained by R1270, but when the boiler temperature ranges from 84 to 90 °C the lowest is accomplished by R600a. As shown in the figure the candidates can be divided into three groups, the first one contains HFCs candidates, i.e. RC318, R236fa, R236ea, and R245fa where they have the highest and nearly the same values of EPR. The sec-ond group contains HCs candidates, i.e. R1270, R290, R600a, and R600 where they have the lowest EPR values and the variations in the EPR values are slight. The maximum difference is about 7.0% between R1270 and R600. The third group contains HFOs candidates, i.e. R1234yf and R1234ze(E) where their EPR values are in between those of HFCs and HCs groups. Moreover, the EPR should be lower than 50 to accomplish a turbine efficiency higher than 80% [25]. As exhibited in Fig. 3c, the EPR for all candidates is less than 4.5; consequently, expander efficiency greater than 80% can be accomplished.

The influence of condenser temperature on the system performance

The variation of COP_S with the condenser temperature for all candidates in the basic ORC-VCR system is illustrated in Fig. 4a. It is observed from the figure that, the condenser temperature has a large effect on the COP_S. This is because the condenser temperature has an effect on both VCR cycle and ORC individually. The rejected heat is governed by condenser
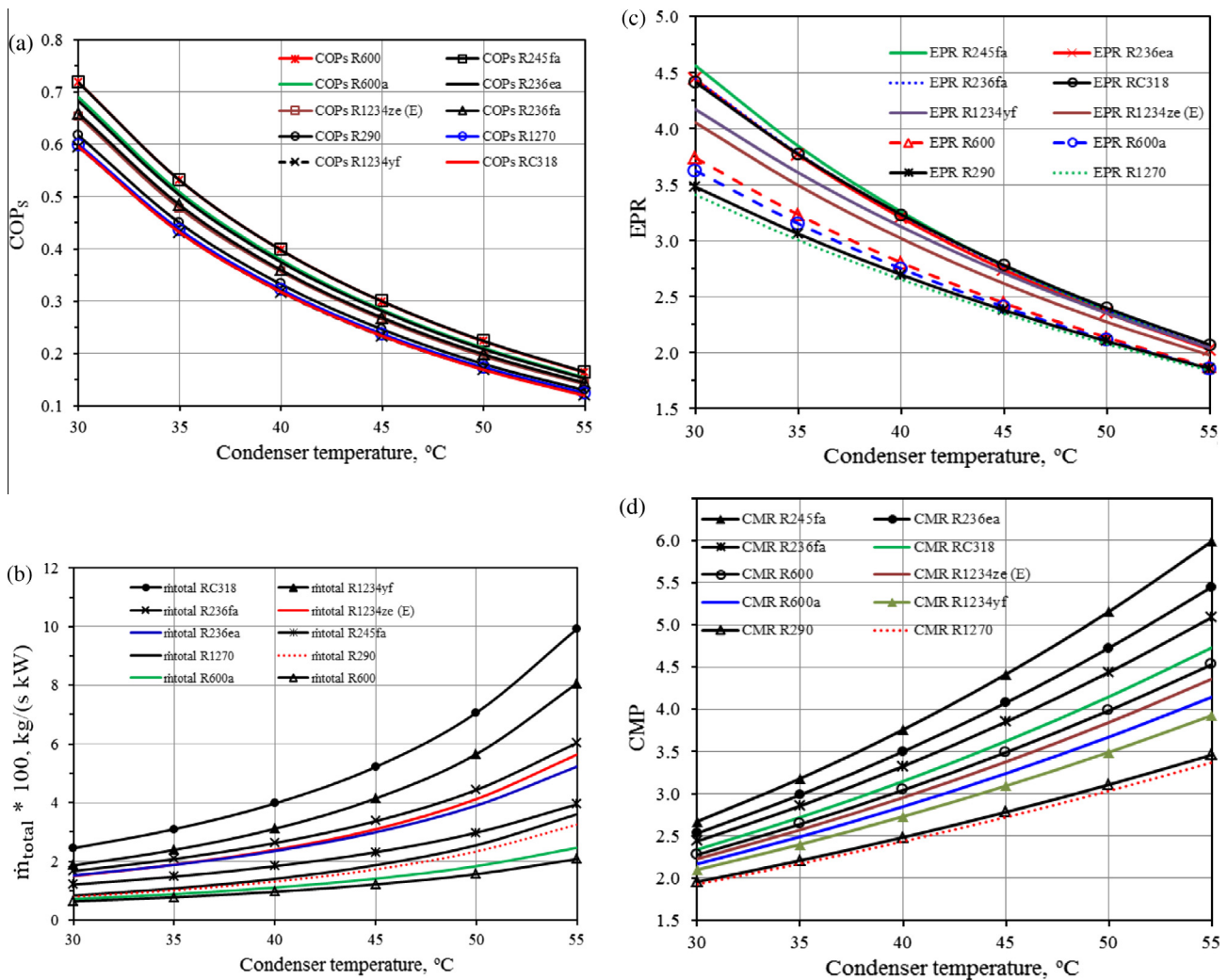

Fig. 4 The effect of condenser temperature on the COP_S (a), $\dot{m}_{total}$ (b), EPR (c) and CMR (d) for various candidates in the basic ORC-VCR system.

temperature, which is an additional parameter to boost the cycle efficiency in addition to the boiler temperature. Small values of rejected heat are preferable to achieve high efficiencies in both cycles. It can be noticed from Fig. 4a that the COP$_S$ reduces with the increase in condenser temperature for all candidates. This is justified by the truth that as the temperature and pressure kept constant at the inlet of the compressor, the increase in condenser temperature causes the rise of pressure and enthalpy at the compressor exit. This leads to the decrease in COP$_S$ and the increase in CMR according to Eqs. (6–9) and (13). When the condenser temperature rises

from 30 to 55 °C, the COP$_S$ reduces by about 21% for all candidates. Among the proposed working fluids, R600 and R245fa achieve the highest and approximately the same COPs values for all condenser temperatures, while RC318 attains the lowest COP$_S$.

The variation of $\dot{m}_{total}$ with the condenser temperature for various candidates in the basic ORC-VCR system is displayed in Fig. 4b. Generally, the increase in condenser temperature leads to increase of $\dot{m}_{total}$ for all candidates. R600 attained the lowest $\dot{m}_{total}$, while the highest was achieved by RC318 for all condenser temperatures. Compared with other candidates, R600 can be considered the best one. At condenser temperature of 30 °C and the basic values for the remaining parameters, the COP$_S$ and $\dot{m}_{total}$ using R600 are 0.718 and 0.006 kg/(s kW), respectively.

The influences of condenser temperature on the EPR and the CMR for different working fluids in ORC-VCR system are illustrated in Fig. 4c and d, respectively. It is detected from these figures that with the increase in condenser temperature, the EPR decreases while the CMR increases. This is logically when taking into account the thermophysical properties effect of these candidates. The variations between the EPR values for the proposed working fluids are smaller at high than that at low condenser temperatures. The reverse is valid for the change of the CMR with the condenser temperature. The working fluids in Fig. 4c can be divided into three groups: the first one includes the HFCs candidates (R245fa, R236ea, R236fa, and RC318) which include the largest values of EPR. The EPR values of this group are approximately the same. The second group contains the HCs candidates (R600, R600a, R290, and R1270) which include the smallest values of EPR. The differences between the EPR values for this group are teeny at condenser temperature greater than 50 °C. The third group contains HFOs candidates (R1234ze(E) and R1234yf) in which the EPR values are in between those of HFCs and HCs groups.

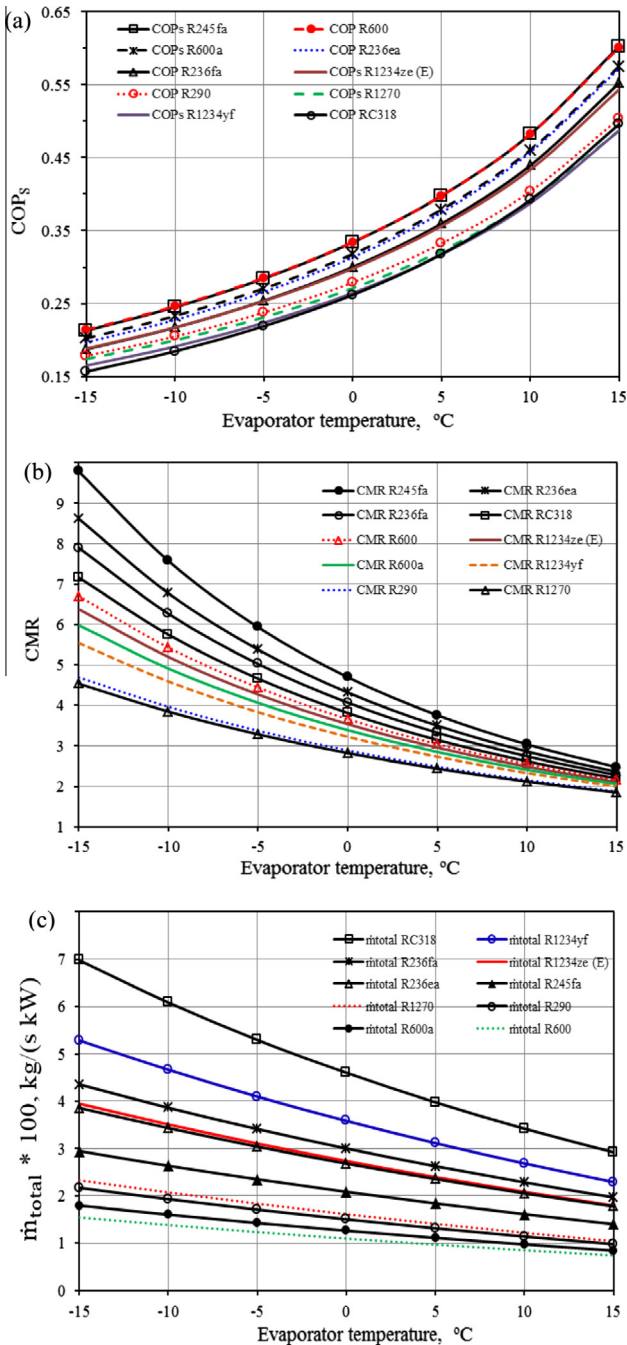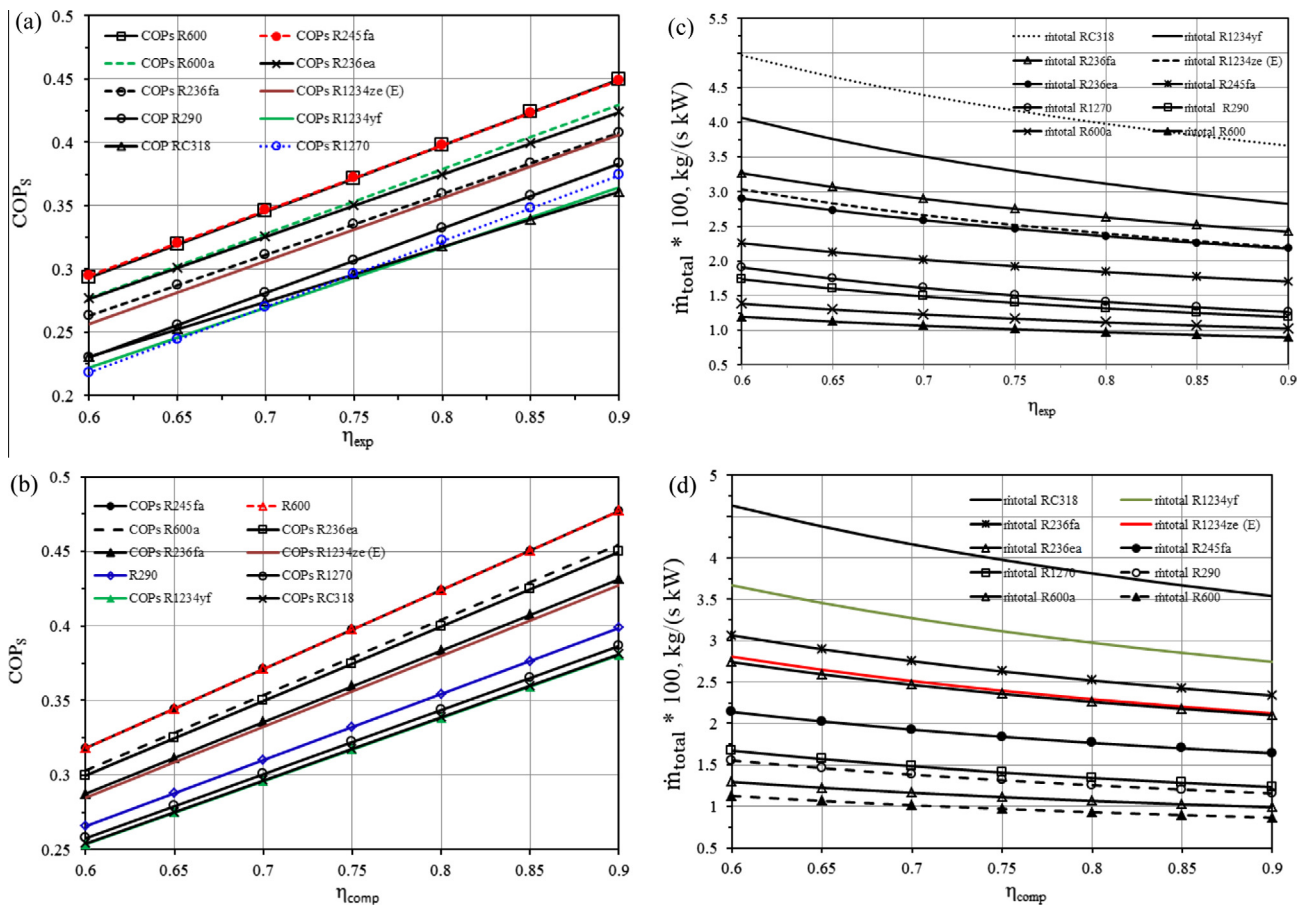### The influence of evaporator temperature on the system performance

Fig. 5 displays the influence of evaporator temperature on the COP$_S$, CMR and $\dot{m}_{total}$, respectively for different candidates in the basic ORC-VCR system. It can be noticed from Fig. 5a that, the increment in evaporator temperature leads to improvement of the COP$_S$. This can be interpreted by the truth that with the increase in evaporator temperature its saturation pressure increases, which results in decreasing the CMR, as displayed in Fig. 5b. This causes the required work for the compressor to decrease at the particular working conditions. Also as the evaporator temperature rises, the cooling capacity improves due to the increment in refrigeration effect. Both effects boost the ORC-VCR system COP$_S$. In addition to the improvement of COP$_S$ with the rise of evaporator temperature for all candidates, the reduction in $\dot{m}_{total}$ is nearly linear as observed from Fig. 5c. Among the proposed candidates, R600 and R245fa attain the highest and approximately the same COP$_S$ values, while R600 has the lowest $\dot{m}_{total}$ values for all evaporator temperatures. With the increase in evaporator temperature from −15 to 15 °C using R600, the COP$_S$ improves by approximately 180.0%, while $\dot{m}_{total}$ declines by about 52.0%.

Fig. 5 The effect of evaporator temperature on the COP$_S$ (a), CMR (b) and $\dot{m}_{total}$ (c) for various candidates in the basic ORC-VCR system.

Fig. 6 The effect of expander and compressor isentropic efficiencies on the COP_S (a), (b) and $\dot{m}_{total}$ (c), (d) for various candidates in the basic ORC-VCR system.

The influence of compressor and expander efficiencies on the system performance

Fig. 6 shows the variations of COP_S and $\dot{m}_{total}$ as a function of the compressor and expander isentropic efficiencies for different candidates in the basic ORC-VCR system. It can be observed from Fig. 6a and b that the expander and compressor efficiencies have a considerable effect on the COP_S. As the compressor and expander isentropic efficiencies increase, the COP_S improves nearly linearly for all candidates. As the expander efficiency varies from 60% to 90%, the COP_S increments by about 53% for all working fluids. While as the compressor efficiency increases from 60% to 90%, the COP_S improves by about 50% for all candidates. It can be seen from Fig. 6c and d that, the expander and compressor efficiencies have a weak effect on $\dot{m}_{total}$ except in the case of RC318. With the enhancement of the compressor and expander isentropic efficiencies, the decrement in $\dot{m}_{total}$ is almost linear.

To sum up the above discussion, there is still no substance that totally meets the whole requirements from the viewpoint of COP_S, $\dot{m}_{total}$, EPR, CMR, and environmental and safety aspects. Since the present study focuses on the performance of the ORC-VCR system from the viewpoint of thermodynamics, the system performance is characterized by COP_S and $\dot{m}_{total}$. Compared with all candidates, R600 achieves the highest COP_S and the lowest $\dot{m}_{total}$ under all considered operating conditions. Furthermore, it should be mention that the emphasis of this study is to assess the performance of HFCs, HCs, and HFOs in the ORC-VCR system; therefore, the studied system is simple. To improve the system performance, internal heat exchangers should be added. This shows that the ORC-VCR system is a superior system for conversion of low-grade thermal energy to cooling or electricity.

Up to now, the thermodynamic aspects of the proposed candidates for ORC-VCR system are considered. On the other side, the safety and environmental issues of the proposed candidates for the ORC-VCR system should be taken into account during selection of the working fluids. Among the proposed candidates, the HFCs group, i.e. R236fa, R236ea, R245fa, and RC318 are non-flammable but they have the maximum GWP. Therefore, they need special attention concerning environmental aspects. On the other hand, the HCs candidate group, i.e. R1270, R290, R600a, and R600 have the advantage of being very low GWP; however, they are flammable. Accordingly, the safety issues should receive extra attention. The new HFOs candidates group, i.e. R1234yf and R1234ze(E) have a GWP less than 1 and are mildly flammable working fluids with ASHRAE safety classification of 2L. Therefore, from the viewpoint of environmental and safety aspects, there is no an ideal working fluid for the ORC-VCR system, and every candidate has advantages and disadvantages. Consequently, there is no working fluid exist now that totally meet the energy efficiency, safety and environmentally friendly. The only actual

controversy against using of R600 is the flammability. However, with satisfactory safety precautions, the flammability will not constitute a problem in using R600.

Conclusions

In the present research, the performance of ORC-VCR system activated by low-grade thermal energy is investigated. Some common hydrofluorocarbons and hydrocarbons, as well as new hydrofluoroolefins, i.e. R1270, R290, RC318, R236fa, R600a, R236ea, R600, R245fa, R1234ze(E), and R1234yf, are proposed as working fluids. The effects of evaporator, condenser, and boiler temperatures, in addition to the compressor and expander isentropic efficiencies on the ORC-VCR system performance are also examined and discussed.

The results indicate that all studied parameters have comparable influences on the ORC-VCR system performance for all candidates. In detail, as the evaporator and boiler temperatures as well as the compressor and expander isentropic efficiencies increase, the COP_S improves while the $\dot{m}_{total}$ decreases for all candidates. The reverse is valid for the condenser temperature. Also, as the evaporator and boiler temperatures increase, the compression ratio reduces and the expansion ratio increases, respectively, while the reverse occurs with the condenser temperature.

From the acquired results it can be concluded that, among all candidates, R600 and R245fa achieve the highest and approximately the same COP_S values, while R600 achieves the lowest $\dot{m}_{total}$ under all considered operating conditions. Due to environmental issues of R245fa, R600 is recommended as a superior candidate for the ORC-VCR system for retrieving low-grade thermal energy in a temperature range from 60 °C to 90 °C from perspectives of environmental concerns and system performance. With condenser temperature of 30 °C and the basic values for the remaining parameters, the maximum COP_S and the corresponding $\dot{m}_{total}$ using R600 are 0.718 and 0.006 kg/(s kW), respectively.

Conflict of Interest

The authors have declared no conflict of interest.

Compliance with Ethics Requirements

This article does not contain any studies with human or animal subjects.

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