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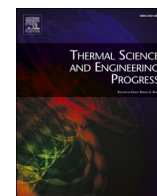
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Theoretical and experimental study on the selection of pure and mixed refrigerants for a power-cooling system driven by ultra-low-grade heat

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ABSTRACT

This study theoretically and experimentally evaluates the performance of a system that combines an organic Rankine cycle (ORC) and a vapor compression cycle (VCC) driven by ultra-low-grade heat (ULGH). A systematic method is developed for the selection of pure refrigerants for the efficient performance of ORC over a temperature range between 50 °C and 100 °C. Binary and ternary mixtures are developed followed by sensitivity analyses and composition optimization to determine the optimal performance of these mixtures. Several experimental tests are conducted to ensure the operability of the system with the developed refrigerants. The results show that the use of ternary and binary mixtures enhances the performance of the system with lower GWP and ODP compared to pure refrigerants. Several mixtures are developed with energy efficiencies higher than 9 % at a heat source temperature of 75 °C. A mixture of R142b/R152a/R600 improves the energy efficiency of the system by 22.80 %, reduces the back work ratio by 19.40 % with an increase in the evaporation capacity by 13.25 %. The methodology and results presented herein will be useful in the development, design, and optimization of power and cooling systems driven by ULGH with pure and mixed refrigerants.

Introduction

Reducing and reusing the waste heat from industrial processes plays a key role in the improvement of their energy efficiency and economic benefits [1]. In addition, waste heat recovery is a fundamental step to mitigate the global warming problem [2]. However, more than 52% of the global waste heat is considered a low-grade heat source with temperatures less than 220 °C [3]. In particular, about 25 % of the total unrecovered waste heat exists at ultra-low temperatures (less than 120 °C). Thus, developing suitable systems to reuse this heat efficiently is challenging. At the same time, refrigeration systems consume about 17 % of the global electrical energy [4]. Moreover, they cause negative environmental issues including global warming and ozone depletion due to the nature of their refrigerants [5], especially hydrofluorocarbon (HFC) refrigerants [6]. Thus, it is vitally important to consider the efficient recovery of ultra-low-grade heat for cooling applications using eco-friendly refrigerants, which is the main aim of this study.

Different engineering systems can reuse waste heat in cooling and refrigeration systems including sorption systems [7], ejector-based systems [8], and organic Rankine cycle (ORC) based systems [9]. However, sorption systems have bulky sizes and limited evaporation temperatures,

while ejector-based systems have poor and unstable performance due to the inflexible design of the ejector. In contrast, ORC is a mature technology and requires the least initial investment to be paid back compared to other systems used to reuse waste heat as reported in [3]. However, a key challenge for the ORC is extending its use over the range of ultra-low-grade heat due to the technical limitations of the current screw and rotary expanders. To reuse ultra-low-grade heat via ORC to drive the vapor compression cycle (VCC) efficiently, an expander-compressor unit (ECU) is introduced by Sleiti et al. [10]. This unit directly coupled the ORC with the VCC to convert the thermal energy to mechanical energy to drive the cooling cycle. The ECU-based ORC-VCC system is analyzed theoretically [10] and experimentally [11] using R134a as a working fluid. Furthermore, the performance of the system with various pure refrigerants applied for the power loop (ORC) was analyzed by Sleiti [12]. However, it is noticed that the investigated refrigerants have energy efficiencies mostly less than 3 % at heat source temperatures less than 80 °C and a pressure difference of 20 bar between the high-pressure and low-pressure sides of the ORC. Thus, developing new mixed refrigerants to enhance the performance of the ECU-based ORC-VCC is needed, which is one of the main objectives of this study.

The right selection of pure and mixed refrigerants for ORC significantly enhances the efficiency of the cycle, improves the design of the

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Nomenclature*Symbol*

P_1, P_2, \dots	Pressures at state points of Fig. 1, bar
$\dot{m}_1, \dot{m}_2, \dots$	Mass flow rate at state points of Fig. 1, kg/s
Q_h	Heat transfer rate to the heater from the ultra-low-grade heat source, kW
Q_{ev}	Evaporation capacity of the evaporator, kW
x_1, x_2, \dots	Vapor quality at state points of Fig. 1
T_1, T_2, \dots	Temperatures at state points of Fig. 1, °C
$\dot{W}_{Exp.}, \dot{W}_p, \dot{W}_{Comp.}$	Work rate produced/consumed by the expander, pump, and compressor, respectively, kW
η_{pl}	Energy efficiency of the power loop (ORC), %

Abbreviations

BWR	Back work ratio
BM	Binary mixture
ECU	Expander-compressor-unit
GWP	Global warming potential
HFC	Hydrofluorocarbons
HCFO	Hydrofluoroolefins
LGH	Low-grade-heat
ODP	Ozone depletion potential
ORC	Organic Rankine cycle
PR	Pure refrigerant
TM	Ternary mixture
ULGH	Ultra-low-grade heat
VCC	Vapor compression cycle

cycle components, and increases its economic benefits. The exergetic performance of R32 with 8 low GWP refrigerants was evaluated by Braimakis et al. [13]. They reported that when the heat source temperature is high, the relative exergetic efficiency improvement of zeotropic mixtures over pure fluids decreases, from a maximum of 36.39 % (at 100 °C) to less than 5 % at temperatures above 200 °C. The energy and exergy efficiencies of the ORC exceed 14 % and 36 %, respectively, using refrigerant mixtures at temperatures higher than 300 °C as investigated in [14–16]. A few studies have evaluated the performance of the ORC with mixed refrigerants driven by low-grade heat (LGH, 120 °C – 223 °C) and ultra-low-grade heat (ULGH, less than 120 °C) sources. Several pure refrigerants as working fluids for ORC with a heat source temperature of 150 °C were investigated by Le et al. [17]. They reported that maximum energy efficiency of 13.1 % is obtained by R152a in a supercritical regenerative ORC scheme with heater pressure higher than 47 bar. Wang et al. [18] introduced a method of zeotropic mixture selection for ORC driven by the LGH of a marine engine with a temperature higher than 220 °C. A mong of 40 pure refrigerants, they recommended (R601a and R245ca) and (toluene and m-xylene) for low (220 °C) and high (380 °C) exhaust engine temperatures, respectively. Also, they reported that the net power is improved by 6.9 % using a zeotropic mixture of benzene/m-xylene compared to the pure fluid of benzene and m-xylene.

A similar analysis is performed for subcritical ORC at a temperature of 220 °C is presented by Rowshanaie et al. [19]. They compared the performance of the pure, binary, and ternary zeotropic mixture of R134a, R1234yf, and R1234ze(E). They reported that R1234yf/R134a mixture achieves the highest exergy efficiency of 69.29 % without analyzing the energy efficiencies of these mixtures. Andreasen et al. [20] evaluated the performance of ORC with pure and mixed refrigerants at two heat source temperatures of 90 °C and 120 °C. They mentioned that a net power increase of 12.9 % is achieved at a temperature of 120 °C and 11.1 % at 90 °C using an optimized ethane/propane mixture. However, their study only analyses the performance at two values of temperatures without a systematic methodology for the selection and evaluation of the investigated refrigerants. Other studies were performed on ORC driven by ULGH experimentally. Over the heat source temperature range of 80 °C to 100 °C, a pumpless ORC with R1233zd(E) is examined experimentally by Lu et al. [21]. They reported an energy efficiency of 3.5 % at a water temperature (heat source) of 95 °C. Another experimental work on ORC over heat source temperature of 40 °C to 80 °C using HCFO-1233zd (E) is conducted by Araya et al. [22]. They reported a maximum energy efficiency of 5 % at a temperature of 85.7 °C.

In general, the theoretical studies on ORC with mixed refrigerants are either limited to temperatures higher than 200 °C or randomly conducted at selective temperatures higher than 90 °C. Furthermore, the experimental studies on ORC at temperatures less than 90 °C are limited

to single pure fluids. Moreover, no study evaluated the performance of the integrated ORC-VCC using pure and mixed refrigerants at ULGH. Thus, the objectives and main contributions of the present study are:

- Developing a systematic method for the selection of pure and mixed refrigerants suitable for efficient operation of ORC and VCC.
- Analyzing and optimizing the performance of the ORC-VCC over the range of the ULGH (45 °C to 100 °C).
- Evaluating the performance of an ECU-based ORC-VCC with mixed refrigerants experimentally.

The rest of this study is organized as follows: Section 2 describes the configuration of the ORC-VCC with the conservative assumptions and limitations that were imposed to assess the performance of the system. Section 3 explains the selection criteria of the pure refrigerants, the performance indicators of the system, and the procedures for developing and evaluating the binary and ternary mixture for the ORC-VCC system. Section 4 presents the results of ORC-VCC performance with pure and mixed refrigerants, the optimization results of the developed mixtures, and the experimental results of the ECU-based ORC-VCC system. Also, Section 4 compares the results of the present study with existing literature. Finally, the main findings of this study are presented in Section 5.

System configuration

To examine the effects of the working fluid on the performance of the ORC-VCC system over the range of ULGH, an ORC-VCC model is created in Aspen HYSYS software with the constraints shown in Fig. 1. The use of Aspen HYSYS allows to model the integrated ORC-VCC system and simulate its loops with mixed refrigerants using several accurate equation of states such as Peng-Robinson equation, which is implemented in this study. The ORC forms the power loop and comprises a heater, expander, cooler, and pump. The VCC forms the cooling loop and is composed of a compressor, condenser, expansion valve (EV), and evaporator.

First, for the feasible design and operation of the cooler and condenser, the outlet temperature of the refrigerant was set as 25 °C with a vapor quality of zero. Then, the temperature at the inlet of the expander (T_3) was set as 70 °C, assuming a temperature difference of 5 °C with the heat source. The available power provided to the heater was set as 60 kW, which is equivalent to hot water passing through the heater with a flow rate of 2.86 kg/s and a temperature difference of 5 °C. The mass flow rate of the ORC refrigerant is calculated based on these constraints. Also, through the basic evaluation of the refrigerants, the pressure gradient through the ORC (ΔP_{12}) was set at 8 bars. Moreover, the evaporator inlet temperature (T_8) was set at –10 °C as a reference for the desired cooling quality in this study. Furthermore, the vapor quality at the inlet of the compressor (x_5) was set as 1, to ensure its efficient

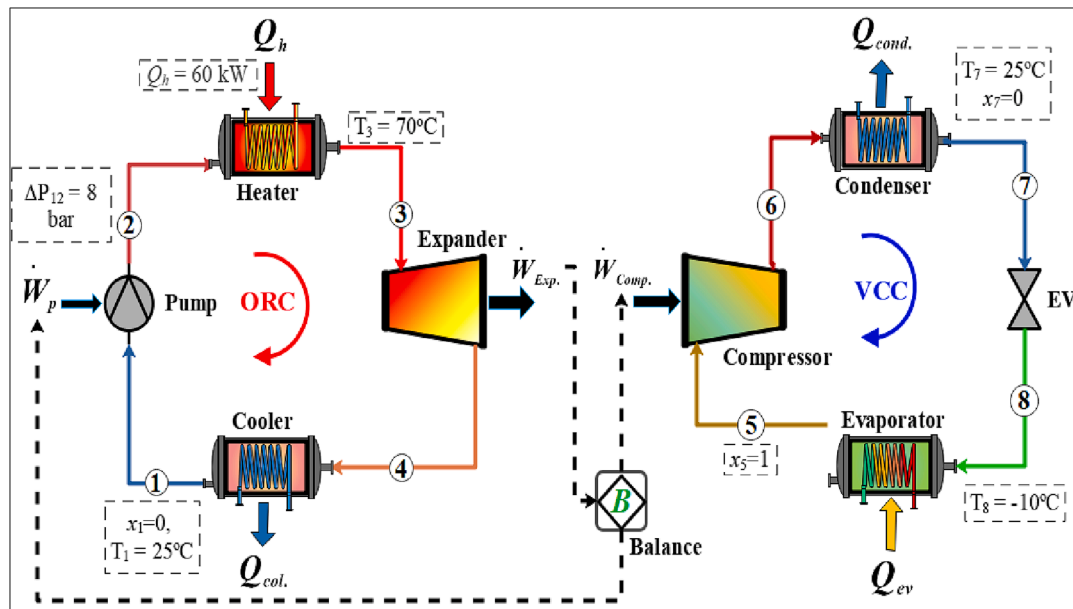


Fig. 1. Schematic diagram of the ORC-VCC system.

operation.

A balance operator was inserted to calculate the net output power provided by the ORC after subtracting the consumed power by the pump (\dot{W}_p) from the produced power by the expander ($\dot{W}_{Exp.}$). Thus, the flow rate through the VCC depends on the available power delivered to the compressor ($\dot{W}_{Comp.}$). After the systematic selection of the best pure refrigerants and mixtures as working fluids for both power and cooling loops, sensitivity analyses for the key operating parameters were conducted over wide practical ranges. For instance, T_3 is investigated over a range of 45 °C to 95 °C, to cover the range of the ULGH, which was not investigated before. Table 1 shows the input parameters used in the assessment of the pure and mixed refrigerants for the ORC-VCC system in this study.

Methodology

Before the experimental evaluation of the mixed refrigerants in the ECU-based ORC-VCC system, a systematic process was applied for the selection of the pure refrigerants, which is explained in this section. Then, the performance of the pure selected refrigerants was evaluated to create binary and ternary mixtures for the system with improved performance, lower GWP, zero ODP, and acceptable safety characteristics as discussed in Section 4.

Table 1

Input parameters used in the assessment and sensitivity analyses.

Parameter	Value / (Range)
Reference refrigerant	R134a
Heater load (Q_h), kW	60
Expander inlet temperature (T_3), °C	70 / (45 to 95)
Polytropic efficiency of the pump	0.80
Pump inlet pressure (P_1), bar	2 / (2 to 8)
Pump outlet pressure (P_2), bar	6 / (6 to 20)
Isentropic efficiency of the pump	0.80
Evaporator inlet temperature (T_8), °C	-10 / (-20—5)
Compressor outlet pressure (P_6), bar	4 / (4 – 10)
Vapor quality at pump inlet (x_1)	0
Vapor quality at compressor inlet (x_5)	1
Vapor quality at EV inlet (x_7)	0

Selected criteria

The preselection of pure refrigerants for the ORC-VCC driven by ULGH is organized based on the following criteria (the selected refrigerant has to meet at least one of the following criteria):

- The critical temperature is less than 160 °C, and the critical pressure is higher than 20 bar to operate the ORC under subcritical/superheated mode.
- GWP is less than that of the reference refrigerant (R134a, GWP = 1300).
- ODP of zero or less than 1.
- Safety group of A1 (not toxic, not flammable).

Performing these criteria to pure refrigerants available in Aspen HYSYS shows that only R744 and R227ea met the full criteria, see Table 2. Other listed refrigerants in Table 2 met the condition of the critical temperature and pressure except for R1233zd which has a critical temperature of 165.60 °C. However, R1233zd and the other four refrigerants have a safety class of A1 (including R744, R13B1, R500, R227ea). Three of the listed refrigerants have higher GWP than R134a including R13B1, R143a, and R500. In addition, four refrigerants have high flammability including R1270, R290, R600, and R600a. Also, some refrigerants have moderate flammability with safety class of A2 including R32, R143a, R152a, R141b, and R1132a. While the flammability of these refrigerants may limit their engineering applications, their GWP is very low, less than 20, which is significantly lower than that of R134a (GWP = 1300). Thus, these refrigerants were investigated and recommended for low-grade heat applications (such as R600 in [23,24], R600a in [25], R142b in [26], and R152a in [26–28]). The flammability issue of these components can be addressed by mixing them with flame retardants (as demonstrated by Yang et al. [5]) alongside the stringent application of safety standards. In addition, optimum blends could be made to meet the requirements for low flammability, low toxicity, and good thermodynamic performance as explained by Bolaji in [28]. Furthermore, the refrigeration industry has established various standards, procedures, and applications to manage the flammability of refrigerants, including rules and regulations, reduced charge in systems, optimized system designs, and the use of improved compact heat exchangers [28]. For the ODP, all of the preselected refrigerants have ODP less than 1 except for R13B1. Thus, a trade-off design strategy must be

Table 2

Preselected refrigerants for ORC-VCC based on their environmental, safety, and thermophysical properties [28–30].

Refrigerant	Boiling point [C]	Freezing point [C]	Critical temp. [C]	Critical pressure [bar]	GWP	ODP	Safety group
R1132a	−82.81	−144.00	29.66	44.6	1	0	A2
R744	−87.88	−56.56	30.98	73.77	1	0	A1
R170	−88.64	−182.8	32.17	48.72	3	0	–
R13B1	−57.79	−168	67	39.71	7140	16	A1
R143a	−47.31	−111.8	72.7	37.61	4470	0	A2
R32	−52.00	−136.80	78.10	57.80	675	0	A2
R1270	−47.78	−185.2	92.42	46.65	3	0	A3
R1234yf	−29.00	−53.15	94.70	33.80	4	0	A2L
R290	−42.16	−187.7	96.68	42.47	20	0	A3
R134a	−26.16	−104.3	101	40.59	1300	0	A1
R227ea	−16.00	−126.80	101.80	29.30	257	0	A1
R500	−33.57	−77.7	105.5	44.55	4080	0.66	A1
R152a	−24.12	−118.6	113.3	45.20	138	0	A2
R717	−33.38	−77.65	132.3	113.33	0	0	B2L
R600a	−11.75	−159.6	134.7	36.40	20	0	A3
R142b	−9.175	−130.4	137.1	40.55	2310	0.06	A2
R600	−0.6052	−138.3	152	37.96	4	0	A3
R245fa	15.00	−102.10	154.00	36.50	925	0	B1
R1233zd	18.31	−78.00	165.60	35.73	5	0	A1

applied for the selection of refrigerants to create binary and ternary mixtures. This strategy is started by examining the energetic performance of the pure refrigerants. Then, the most efficient refrigerants will be used to form binary and ternary mixtures. The selected components for ternary mixtures should have efficient performance as pure refrigerant, low or zero GWP and ODP, and acceptable safety group. In this study, the priority is given for the energetic performance followed by the environmental impacts and safety group as the efficient performance is crucial for the economic feasibility of the proposed system with ultra-low-grade heat conditions.

Performance indicators

As the preselected refrigerants did not meet all the factors of the selection criteria, their performance must be evaluated to determine their potential for the ORC-VCC from an energetic point of view. The energetic performance of the refrigerants (pure or mixtures) can be indicated using the energy efficiency (η_{pl}), back work ratio (BWR) of the ORC, and the COP, evaporation capacity (Q_{ev}), and evaporation temperature of the VCC (T_g).

The energy efficiency (η_{pl}), is defined to express the ratio of the net output power of the ORC relative to the rate of absorbed energy from the ULGH source (Q_h) as [31]:

$$\eta_{pl} = 100 \times \left[\frac{\dot{W}_{Exp.} - \dot{W}_p}{Q_h} \right] = 100 \times \left[\frac{[h_3 - h_4] - [h_2 - h_1]}{[h_3 - h_2]} \right] \quad (1)$$

While the BWR is defined as the ratio of the produced power by the expander to that consumed by the pump to characterize the turbomachinery features of the ORC as [32]:

$$BWR = 100 \times \left[\frac{\dot{W}_p}{\dot{W}_{Exp.}} \right] = 100 \times \left[\frac{[h_2 - h_1]}{[h_3 - h_4]} \right] \quad (2)$$

The mass flow rate of the refrigerants through the ORC is calculated from the energy balance through the heater such that:

$$\dot{m}_1 = Q_h / [h_3 - h_2] \quad (3)$$

For the VCC, assuming the net output power of the ORC is used to drive the compressor of the VCC, then the flow rate of the refrigerant through the VCC is:

$$\dot{m}_8 = \frac{\dot{m}_1 \times [(h_3 - h_4) - (h_2 - h_1)]}{[h_6 - h_5]} \quad (4)$$

and the COP is defined as:

$$COP = \frac{Q_{ev}}{W_{Comp.}} = \frac{\dot{m}_8 \times [h_5 - h_8]}{\dot{m}_1 \times [(h_3 - h_4) - (h_2 - h_1)]} \quad (5)$$

Assessment procedures

Referring to Fig. 2, the performance of the selected refrigerants is evaluated by applying the following procedures:

(1) An Aspen HYSYS model for the ORC-VCC is created with the conservative conditions discussed in Section 2. R134a is taken as a reference refrigerant for both loops (ORC and VCC).

(2) Each refrigerant in Table 2 is tested as a pure refrigerant (PR) in the power loop with R134a in the cooling loop. This scenario is referred to as PR-R134a. Then, the PR is tested in the cooling loop with R134a in the power loop. This scenario is referred to as R134a-PR.

(3) Then, the performance indicators of the pure refrigerants in step 2 are compared alongside the environmental and safety aspects of the refrigerants to select the best candidate refrigerants to create alternative binary mixtures (BMs) for the pure refrigerants.

(4) Repeat steps 2 with BM instead of PR in the power loop (BM-R134a), and cooling loop (R134a-BM). The mass fractions of the components in the BM are determined by starting with a 0.50 fraction for each component. Then, increase the fraction of one element and decrease the other and oppose the process with continuous calculations for their performance indicators.

(5) From the results of step 4, the best BMs are determined based on their energetic, environmental, and safety aspects. These BMs are used to organize ternary mixtures (TMs) to enhance the performance of the system.

(6) Repeat step 2 with TM instead of PR in both power (TM-R134a) and cooling (R134a-TM) loops. The mass fraction of the TM is defined by starting with 0.50 for one element and equal fractions for the other elements (0.25). Then, these fractions are changed iteratively with the use of the BMs results as guidelines to reach the optimum composition.

(7) Using the best TM, sensitivity analyses are conducted to examine the performance of the system with the variation of key operating conditions. Then, at the optimal conditions obtained from the sensitivity analysis, the composition of the BMs and TMs is further optimized.

(8) After the theoretical assessment of the PR, BM, and TM on the performance of the ORC-VCC, an experimental analysis is conducted to

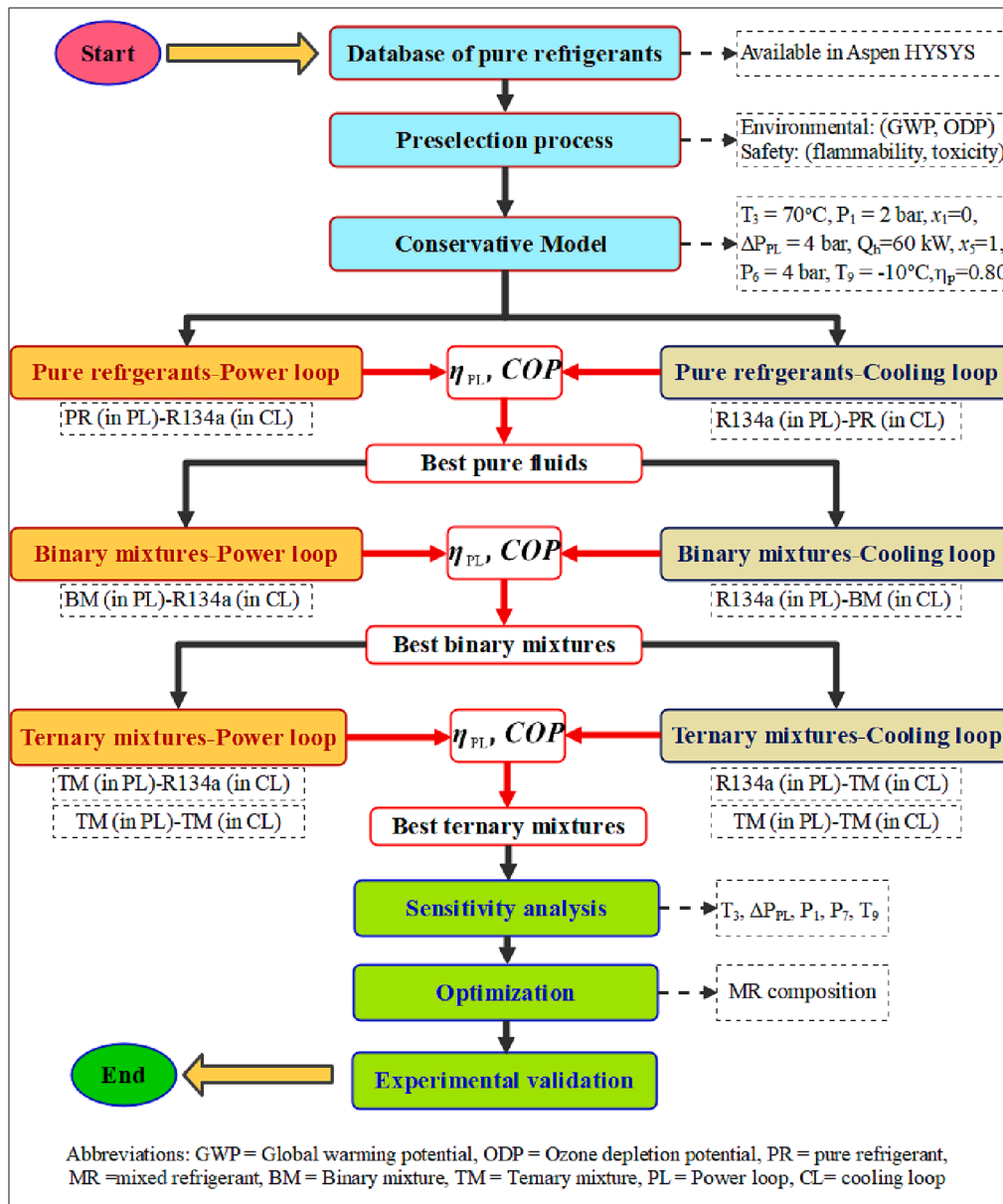


Fig. 2. Assessment procedures for the selection and optimization of the pure and mixed refrigerants for the ORC-VCC system driven by ultra-low grade heat.

examine these results.

Results and discussion

In this section, the results of the pure and mixed refrigerants' performance are presented and discussed in Section 4.1 and Section 4.2. The sensitivity analyses and performance optimization are presented in Section 4.3 and Section 4.4, respectively. Then, the details and results of the experimental tests are explained in Section 4.5. Finally, a comparison between the results of the present study with previous studies in the literature is introduced in Section 4.6.

Performance of pure refrigerants

Table 3 shows the performance indicators of the pure refrigerants (PR) in the power loop (PR-R134a) and cooling loop (R134a-PR). The refrigerants are sorted in the first column in ascending order based on their critical temperatures (R134a was set as a reference refrigerant in the first row).

For the power loop scenario (PR-R134a), R142b is the best-performing fluid in terms of the energy efficiency of the power loop ($\eta_{pl} = 7.38\%$) while R744 has the lowest η_{pl} of 1.53 %. In terms of the BWR, R1132a has the highest BWR of 61.87 % and R717 has the smallest BWR of 2.48 %. R1270 and R32 show an average performance relative to other refrigerants with η_{pl} of 5.16 %, and 5.81 %, respectively. R500 and R1233zd, which have safety class of A1, show competitive efficiency (6.20 %, and 6.27 %, respectively) over that of R134a (6.36 %). Environmentally, all refrigerants shown in Table 3 have ODP less than 1. But R142b and R500 have higher GWP than R134a. In addition, R142b and R152a are flammable fluids (A2). On the other hand, R717, R1270, and R170 have lower GWP with higher hazard levels than R134a. As these refrigerants show a trade-off between the energy performance, environmental, and safety aspects, they are selected as base fluids for the development of the binary mixtures (BMs) for the power loop. The mixing process will target the increase the energy efficiency, mitigating the GWP and hazard level of the mixed fluids.

For the cooling loop scenario (R134a-PR), R600a, R142b, and R600 show higher COP than R134a, but their evaporation temperature is

Table 3

Performance indicators of the pure refrigerants in the power loop (PR-R134a) and cooling loop (R134a-PR) at a heat source temperature of 75 °C.

Refrigerants	PR-R134a (Power loop)			R134a-PR (Cooling loop)		
	η_{pl}	BWR	Q_{ev}	COP	Q_{ev}	T_8
	[%]	[%]	[kW]	[-]	[kW]	[°C]
R134a (reference)	6.36	5.82	9.13	2.31	10.34	-10.00
R1132a	2.28	61.87	5.94	2.64	5.88	-72.07
R744	1.53	34.67	2.19	0.24	1.04	-76.37
R170	2.13	36.58	3.06	0.22	0.96	-75.07
R13B1	4.07	14.07	5.84	0.78	3.36	-42.28
R143a	4.64	8.73	6.65	1.05	4.55	-31.68
R32	5.81	9.74	4.12	1.86	5.45	-37.43
R1270	5.16	8.84	7.40	1.14	4.93	-31.70
R1234yf	4.12	5.93	6.27	1.43	2.46	-10.30
R290	5.72	8.17	8.20	1.34	5.78	-25.66
R227ea	4.11	5.71	5.88	1.71	2.82	-9.60
R500	6.20	8.19	8.89	1.79	7.72	-16.81
R152a	7.12	4.70	10.22	2.49	10.76	-7.79
R717	5.06	2.48	7.27	1.70	7.36	-18.64
R600a	5.18	23.12	7.43	4.97	21.52	6.84
R142b	7.38	3.97	10.58	6.20	26.82	9.84
R600	5.16	22.61	7.40	6.25	70.29	18.90
R245fa	4.83	5.13	5.37	1.09	2.44	-0.004
R1233zd	6.27	8.77	4.66	1.88	4.21	-11.52

higher than 5 °C. Thus, their use is suited only for air conditioning applications. Therefore, these refrigerants are not considered for the development of the BMs for the cooling loop. Some refrigerants show low COP but their evaporation temperatures are very low such as R32 (-37.43 °C), R1270 (-31.70 °C), R1132a (-72.07 °C), and R170 (-75.07 °C). Therefore, these refrigerants are suited for refrigeration applications rather than air conditioning systems. Compared to the COP of R134a (2.39), R152a and R1132a show higher COP (2.49, and 2.64 respectively) with evaporation temperature suited for refrigeration applications. R290 has an average performance relative to other refrigerants with COP of 1.34, and an evaporation temperature of -25.66 °C. Therefore, R1132a, R152a and R290 are selected as base fluids for the BMs of the cooling loop with R134a. Their mixing process target enhancing the COP with a low evaporation temperature (less than 0 °C) suited for refrigeration applications. The next section presents the results of the BMs for the power and cooling loops.

Performance of mixed refrigerants

The BMs of the ORC-VCC system are organized using the selected pure refrigerants as base fluids for the BMs of the power loop (R142b, R152a, R500, R717, R1270, R170, R32, and R1233zd), and of the cooling loop (R134a, R152a, R290, and R1132a). The performance indicators of 16 BMs for the power loop and 6 BMs for the cooling loop are presented in Table 4. The BM is created based on the equal mass fraction to facilitate the analysis before the development of the ternary mixtures (TMs).

For the BMs of the power loop, it is found that the BM of R142b/R152a has the highest efficiency ($\eta_{pl} = 6.89\%$), see Table 4. Although this efficiency is lower than that of the pure fluid case, the resulting mixture has a lower GWP as R152a has GWP = 0. But, both R142b and R152a are flammable refrigerants (A2). Thus, the BM of R717/R500 and R717/R1233zd are a better alternative for R142b/R152a from a safety point of view with lower η_{pl} of 4.89 %, and 5.55 %, respectively. Also, it is noted that the presence of R170 in a BM slightly improves its performance relative to its pure case. However, BMs with R170 have lower efficiencies than other mixtures. Thus, R170 is not considered in the development of TMs. In contrast, the presence of R717 in a mixture with R142b reduces the BWR compared to the pure case of R142b with higher efficiency than the pure case of R717. A similar effect is noted for the presence of R1270, and R1233zd with R142b. As R1233zd has no

Table 4

Performance indicators of the binary mixtures in the power loop (BM-R134a) and cooling loop (R134a-BM) at a heat source temperature of 75 °C. The mass fraction is 0.50 for each component in each mixture.

Refrigerants	BM-R134a (Power loop)		
	η_{pl}	BWR	Q_{ev}
	[%]	[%]	[kW]
R134a (reference)	6.36	5.82	9.13
R142b/R500	6.23	6.31	8.94
R142b/R1270	5.23	7.65	7.51
R142b/R152a	6.89	4.72	9.88
R142b/R717	5.69	3.00	7.45
R142b/R170	2.12	23.34	3.04
R142b/R32	6.29	9.25	8.26
R142b/R1233zd	5.96	5.45	8.58
R152a/R717	5.09	3.42	7.30
R152a/R170	2.53	19.88	3.64
R152a/R32	5.46	8.40	7.86
R152a/R1233zd	5.21	5.90	9.72
R717/R500	4.89	3.70	7.01
R717/R1270	4.64	4.61	6.66
R717/R170	2.65	9.53	3.81
R717/R32	5.03	4.95	2.06
R717/R1233zd	5.55	4.98	3.41

Refrigerants	R134a-BM (Cooling loop)		
	COP	Q_{ev}	T_8
	[-]	[kW]	[°C]
R134a (reference)	2.31	10.34	-10.00
R134a/R290	1.55	6.70	-20.98
R134a/R152a	2.40	10.38	-8.74
R134a/R1132a	1.24	3.45	-53.81
R290/R152a	1.68	7.25	-18.96
R290/R1132a	1.95	5.48	-50.24
R152a/R1132a	1.74	4.89	-50.53

flammability, it can be recommended to be mixed with R142b to obtain relatively efficient performance with mitigated flammability compared to pure R142b. Tacking that the BMs based on R142b, R152a, R500, R717, and R1233zd show a competitive performance for R134a in terms of energy efficiency, environment, or safety aspects, these refrigerants are considered base fluids for the TMs of the power loop. The BMs in the cooling loop show better performance than pure fluids in terms of evaporation capacity and cooling quality. For instance, mixing R134a with R290 reduces the evaporation temperature (T_8) from -10 °C (for pure R134a) to -20.98 °C, which improves the cooling quality compared to pure R134a. Even though the resulting T_8 is higher than that of the pure R290 (-25.66 °C), the evaporation capacity is increased by 16 % compared to that of the R290 pure case. Moreover, the addition of R1132a to R143a, R290, or R152a provides evaporation temperatures less than -50 °C, which is higher than of pure R1132a (-72.07 °C). Also, the COP of pure R1132a is higher than mixing it with the other refrigerants. This implies that mixing R290 or R1132a with R134a improves the cooling quality for R134a and the cooling capacity of R290. A similar effect is noted for mixing R290 with R152a or R1132a. But mixing R152a with R134a negatively affects the evaporation temperature with a negligible increase in the evaporation capacity. Thus, R134a, R290, and R152a are selected as the TMs of the cooling loop with the target to reach optimal cooling quality and evaporation capacity compared to the pure case of R134a. Furthermore, it is recommended to mix R1132a with R132a in order to achieve a very low evaporation temperature (between -10 °C to -70.07 °C), while maintaining favorable safety characteristics. Both refrigerants possess a safety classification of A1, making this combination a safe option for refrigeration purposes.

Table 5 shows the results of TMs for the power and cooling loops. Iterative processes are performed for each ternary mixture until the

Table 5

Performance indicators of the ternary mixtures in the power loop (TM-R134a) and cooling loop (R134a-TM) at a heat source temperature of 75 °C.

Refrigerants	Mass fractions	TM-R134a (Power loop)		
		η_{pl} [%]	BWR [%]	Q_{ev} [kW]
R134a	1.00	6.36	5.82	9.13
R142b/R152a/R717	0.50/0.25/0.25	5.26	3.92	7.54
	0.60/0.25/0.15	5.46	4.30	7.84
	0.7/0.25/0.05	6.03	4.64	8.65
	0.4/0.35/0.25	5.26	4.01	7.55
	0.4/0.45/0.15	5.49	4.46	7.88
R142b/R152a/R134a	0.30/0.65/0.05	6.14	4.84	8.81
	0.20/0.85/0.05	6.22	4.86	8.93
	0.50/0.25/0.25	6.65	4.98	9.53
	0.50/0.15/0.35	6.54	5.10	9.38
	0.50/0.35/0.15	6.75	4.87	9.68
	0.50/0.45/0.05	6.84	4.77	9.82
	0.40/0.55/0.05	6.89	4.78	9.88
	0.25/0.70/0.05	6.96	4.78	9.99
	0.05/0.90/0.05	7.07	4.74	10.14
	0.05/0.90/0.05	6.95	4.93	9.97
R142b/R152a/R500	0.05/0.90/0.05	7.06	4.81	10.13
R142b/R152a/R717	0.05/0.90/0.05	6.24	4.86	8.96
R142b/R152a/R600a	0.05/0.90/0.05	7.18	4.74	10.31
R142b/R152a/R600	0.05/0.90/0.05	7.81	4.69	10.34
R142b/R152a/R1233zd	0.05/0.90/0.05	6.64	6.28	6.54
Refrigerants	Mass fractions	R134a-TM (Cooling loop)		
		COP	Q_{ev} [kW]	T_g [°C]
R134a	1.00	2.31	10.34	−10.00
R134a/R152a/R290	0.50/0.25/0.25	1.84	7.97	−15.85
	0.50/0.35/0.15	2.02	8.72	−13.31
	0.50/0.45/0.05	2.24	9.69	−10.38
	0.45/0.55/0.05	2.27	9.80	−10.13
	0.20/0.75/0.05	2.32	10.01	−9.67

optimal performance is obtained. The detailed fractions for two ternary mixtures are provided in Table 5 as examples of that iterative process. The proportion of the ternary mixtures are organized based on two scenarios. First scenario is to give higher proportion for the higher energetic performance refrigerant despite its environmental impact (as shown for the first three iterations for R142b/R152a/R717 mixture, see Table 5). Second scenario is to give higher portion for the lower ODP, lower GWP, and lower flammable refrigerants despite its energetic performance, then optimize the composition with the help of the first scenario results (as shown for the last four iterations for R142b/R152a/R717 mixture, see Table 5). Mixing of the selected refrigerants based on the results in Table 4 provides energy efficiencies between 5.26 % and 7.07 %, which enhances the output power by 11.16 % compared to the pure R134a. Other iterations for the insertion of R600 and R600a in the TMs process are performed and presented in Table 5. This is done as R600 and R600a have low GWP and zero ODP with a higher potential to boost the evaporation capacity. Among the TMs of the power loop, the mixture of R142b/R152a/R600 (0.05/0.90/0.05) shows superior performance compared to R134a in terms of efficiency and GWP. It improves the energy efficiency by 22.80 % and reduces the BWR by 19.40 % with an increase in the evaporation capacity by 13.25 %. But, the flammability of the mixture is higher than R134a. To mitigate the flammability of this mixture, R600 can be replaced with R1233zd. However, the power loop efficiency will decrease from 7.81 % (for R142b/R152a/R600) to 6.64 % (for R142b/R152a/R1233zd). For the cooling loop, a TM of R134a, R152a, and R290 is organized with different compositions as shown in Table 5. To obtain COP higher than 2 with evaporation temperature (T_g) lower than that of the pure R134a, the composition of (0.50/0.35/0.15) is selected for the cooling loop with COP of 2.04 and T_g of −13.13 °C.

The pure fluorinated hydrocarbon R152a has a structure remarkably similar to that of R134a. It is compatible with all materials, refrigeration equipment, thermostatic valves, compressors, and lubricating lubricants since it has a vapor pressure curve that is equivalent to R134a and has variances of only 2 °C. R152a is also categorized as a class A2, a medium-safe refrigerant that is non-toxic but low flammable. The use of medium-safe refrigerants is restricted in direct expansion commercial refrigeration applications under the refrigeration plant safety rule, although it is permitted in indirect systems and direct expansion industrial applications without a charge limit [33].

Although the optimized ternary mixture of R142b/R152a/R600 shows efficient performance compared to R134a, it composed of flammable components with ODP = 0.06 for R142b. As shown in Table 2 (Section 3.1), it is difficult to organize a mixed refrigerant that provides efficient performance with ultra-low-grade heat with components that have zero ODP, zero GWP, and safety group of A1. For example, if the mixed refrigerants comprise R744 (GWP = 1, ODP = 0, safety group is A1), and R134a (GWP = 1300, ODP = 0, safety group is A1) with mass fraction of (0.50, 0.50), the power loop efficiency will be 1.88 % compared to 7.81 % for R142b/R152a/R600 mixture under the same operating conditions. Therefore, to optimize the trade-off between the thermal performance, environmental effects, and safety standards, this study proposes the use of R142b/R152a/R600 as it enjoys (1) efficient performance, (2) non-toxicity, (3) zero GWP, and (4) mitigated ODP as the mass fraction of R142b is only 5 % of the mixture. To obtain zero ODP, a binary mixture of R152a/R600 (0.95, 0.05) can be used with power loop efficiency of 7.76 % compared to 7.81 % of the ternary R142b/R152a/R600 mixture. However, the major drawback of R142b/R152a/R600 or R152a/R600 mixtures are their flammability, which can be controlled following using flame retardants with application of established standards associated with these refrigerants [28]. Alternatively, mixtures of R744, R1233zd, and R134a can be used which is safe, and have zero ODP with low GWP with the penalty of losing the efficient performance of the recovery of the waste heat at ultra-low temperatures.

Sensitivity analysis

For the sensitivity analysis of the ORC-VCC system over the ultra-low temperature range of the heat source, the TMs of R142b/R152a/R600 (0.05/0.90/0.05) and R134a/R152a/R290 (0.50/0.35/0.15) are used as working fluids of the power and cooling loops, respectively.

For the feasible design (size and cost) of the ECU-based ORC-VCC system, the pressure difference through the ORC ($\Delta P_{12} = P_2 - P_1$) is simulated over a range between 4 bar and 14 bar as shown in Fig. 3. It is found that the increase of ΔP_{12} improves the performance of power loop up to an optimal value of 12 bar. The η_{pl} increased from 4.61 % at ΔP_{12} of 4 bar to 8.52 % at ΔP_{12} of 12 bar even with the increase of the BWR from 3.60 % to 7.35 % over the same range of ΔP_{12} . At ΔP_{12} higher than 12 bar, the expander power decreases due to the isentropic nature of the R152a (which is the dominant component of the mixture) with a sharp increase in the consumed power by the pump, see Fig. 3. At the optimal value of ΔP_{12} (12 bar), the evaporation capacity reach 11.70 kW, which is 85 % higher than at ΔP_{12} of 4 bar (6.33 kW).

The previous results of the pure and mixed refrigerants were calculated at a heat source temperature (T_h) of 75 °C. For the sensitivity analysis of T_h , ΔP_{12} was set at the optimal value of 12 bar, then the expander inlet temperature (T_3) is changed over a range of 45 °C to 95 °C (which is assumed to be 5 °C less than the heat source temperature). However, it is noted that the power loop has very poor performance at T_3 less than 58 °C as the fluid did not reach a superheated or saturated vapor phase under these conditions. This implies that the heat source temperature must be higher than 63 °C for the feasible operation of the present system. Thus, the results of the T_3 simulation are presented over the range of 60 °C to 95 °C. As shown in Fig. 4, as T_3 increased from 60 °C to 70 °C, the η_{pl} increased from 3.81 % to 8.52 %, which is 2.34 times higher than at 60 °C. Then, the η_{pl} increased from 8.52 % to 9.14 %

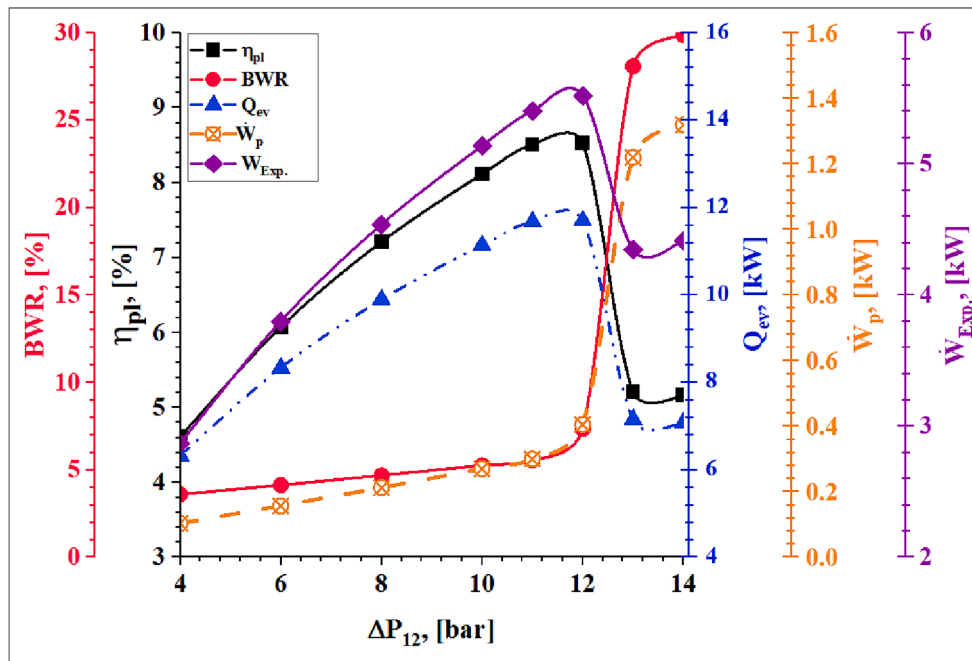


Fig. 3. Performance indicators of the ORC-VCC with the variation of the pressure gradient through the pump (ΔP_{12}) at a heat source temperature of 75 °C.

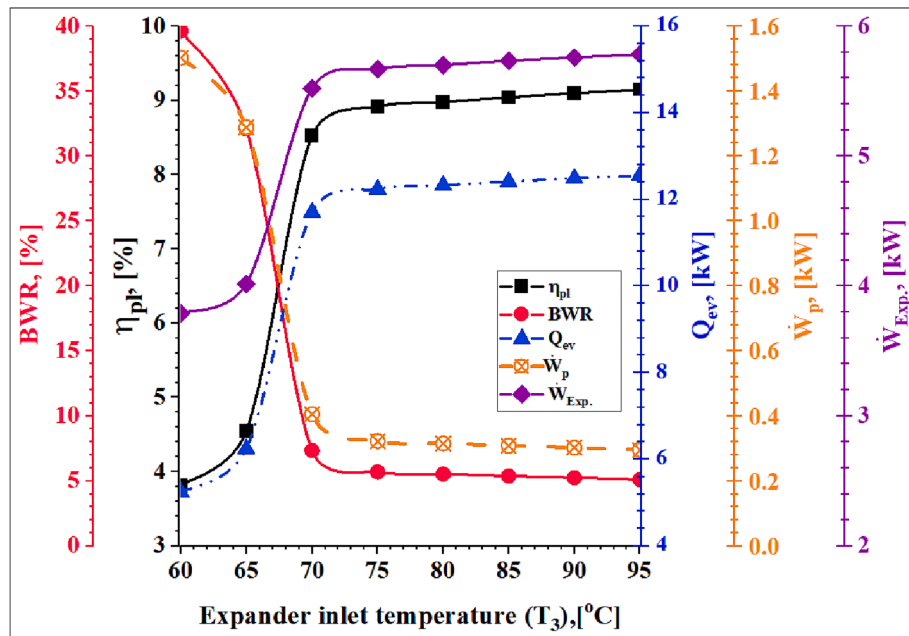


Fig. 4. Performance indicators of the ORC-VCC with the variation of the expander inlet temperature (T_3).

as T_3 increased to 95 °C (increased by 7.28 %). This implies that the effect of the heat source temperature plays a key role in the performance of the system at T_3 lower than 70 °C. Also, the BWR is higher than 30 % below this temperature. This is explained that with lower values for T_3 with fixed heater load (60 kW), higher flow rates are imposed on the power loop. This increases the pumping power more than the increase of the expander power at T_3 less than 70 °C.

The adjustment of the evaporator pressure is the key factor for the evaporation capacity and cooling quality of the cooling loop. As shown in Fig. 5, the increase of the evaporator pressure (P_8) from 0.50 bar to 4.0 bar increases the evaporation capacity from 4.45 kW to 25.29 kW (5.68 times) which enhances the COP from 0.87 to 4.95. However, the evaporation temperature (which indicates the cooling quality) is

increased from -41.13 °C to 10.06 °C. Therefore, for refrigeration applications with evaporation temperatures less than 0 °C, the COP varies between 0.87 and 2.57 at T_3 of 70 °C and ΔP_{12} of 12 bar. For air conditioning applications, the COP varies from 3.17 to 4.95 at evaporation temperature between 1.5 °C and 10 °C. Competitive performance for the R134a case is obtained by the used TMs at evaporator pressure of 2 bar with COP of 2.07.

Composition optimization

After the sensitivity analysis, the optimal conditions of $\Delta P_{12} = 12$ bar, $T_3 = 75$ °C, and P_8 of 2 bar are set as the base conditions to optimize the composition of the BMs and TMs of the present study.

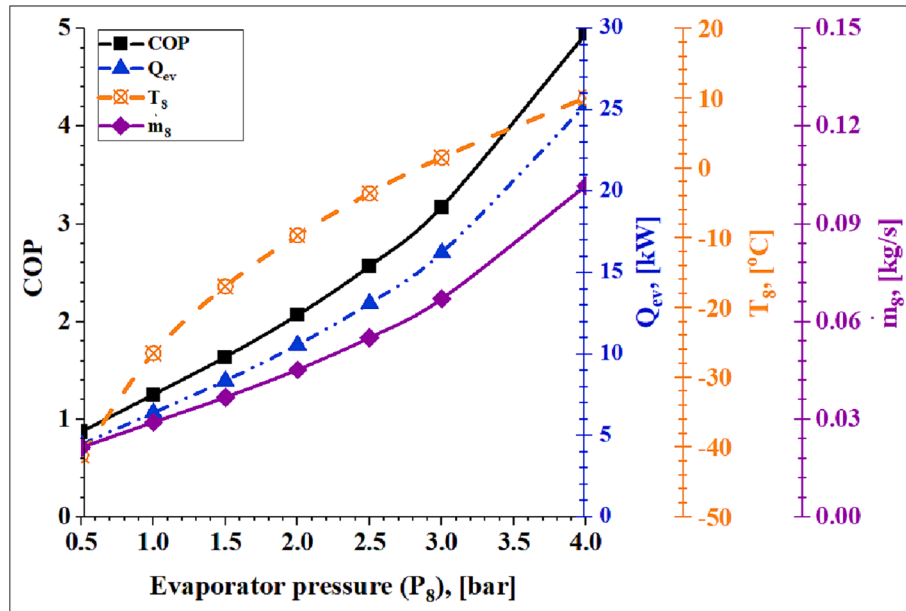


Fig. 5. Performance indicators of the ORC-VCC with the variation of the evaporator pressure (P_8).

As mentioned above, the TM of R142b/R152a/R600 is used as a working fluid for the power loop with mass fractions of (0.05/0.90/0.05). Tuning this composition is performed by adjusting the mass fractions of the pure components as shown in Fig. 6. If R142b is eliminated from the mixture (iteration 1), the η_{pl} is 9.14 %, which is 2.50 % higher than at the base TM under the same optimal conditions. However, the thermophysical properties of R142b (critical pressure, critical temperature, and boiling point) are located between those for R152a and R600, see Table 2. Thus, several iterations were performed by a gradual increase for its fraction as shown in the table of Fig. 6. It is noticed that a maximum η_{pl} of 9.54 % is obtained (iteration 7) with mass fractions of (0.01/0.95/0.04), which is 7.10 % higher than that at the previous fractions under the same optimal conditions. Also, this optimized composition yields higher efficiency than using R152a as pure fluid (iteration 4) by about 1.5 %. A similar iterative process was performed to

optimize the composition of the TM in the cooling loop (R134a/R152a/R290) as shown in Fig. 7. Compared to the base compositions presented in Table 5, the composition of (0.15/0.75/0.10) is recommended as it achieves relatively high COP (2.56) with lower evaporation temperature of -11.01°C and evaporation capacity of 14.62 kW. This composition is competitive with the pure R134a under the same optimal conditions, which has a COP of 2.81 and evaporation capacity of 16.31 kW but with a higher evaporation temperature of -7.97°C .

Experimental test of the ECU-based ORC-VCC system

To ensure the operability of the ECU-based ORC-VCC over the desired range of the ULGH using mixed refrigerants, experimental tests are performed using a pure refrigerant (PR, R134a), binary mixture (BM, R142b/R152a), and ternary mixture (TM, R142b/R152a/R600) as

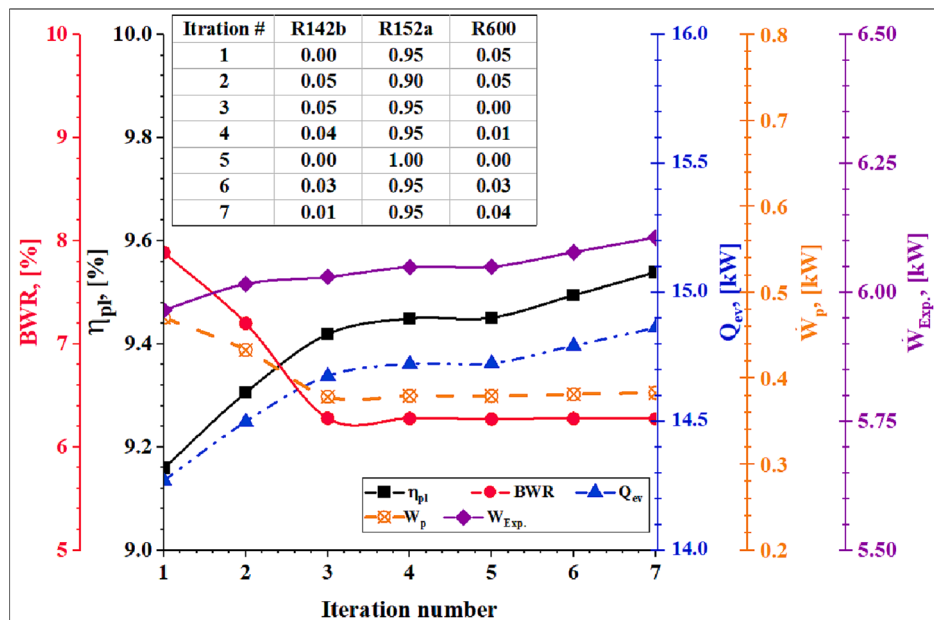


Fig. 6. Performance evaluation with the optimization of the ternary mixture (R142b/R152a/R600) in the power loop.

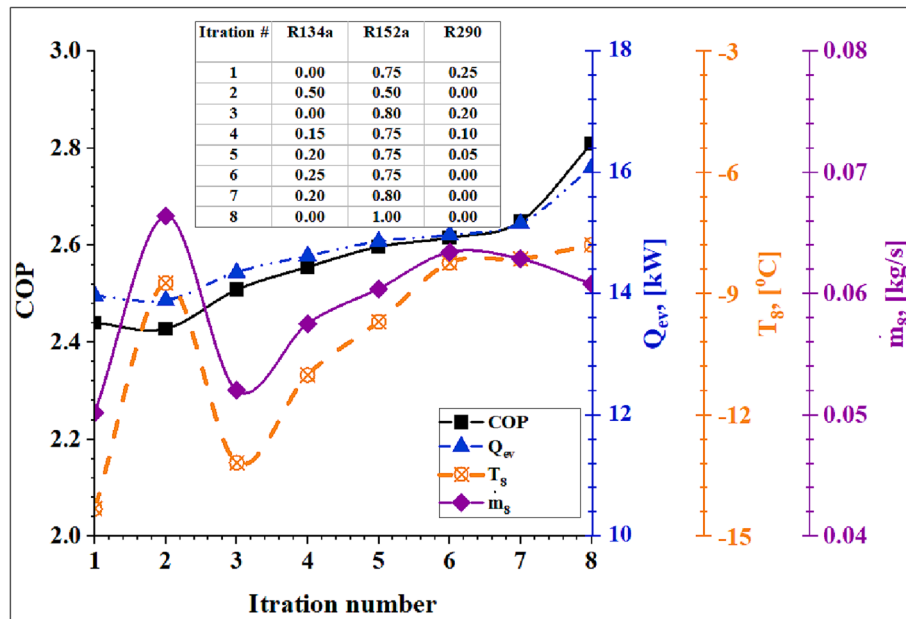


Fig. 7. Performance evaluation with the optimization of the ternary mixture (R134a/R152a/R290) in the cooling loop.

working fluids in the power loop with R134a as working fluid in the cooling loop. A top view of the experimental setup is presented in Fig. 8. A detailed description of the experimental setup is the [supplementary material](#) of this study. The detailed model of the setup components and its uncertainty analyses were presented in the published experimental evaluation of the system with R134a as working fluids in both loops [11]. The setup was originally designed for a cooling capacity of 1 kW at a heat source temperature of 85 °C.

To simulate the ULGH source, hot water is used to provide the heat load of the heater with an inlet temperature (T_h) between 50 °C and 85 °C. Also, the ECU is operated at a frequency of 0.33 Hz. The water itself is heated using an electric heater that is equipped with a temperature controller and control valve to heat a specified water flow to the desired temperature. At the full capacity of the pneumatic pump used to drive the power loop, the hot water temperature gradually decreases from 85 °C to 50 °C. However, the system did not work at T_h less than

63 °C for R134a and T_h less than 52 °C for R142b/R152a and R142b/R152a/R600 mixtures. Therefore, the performance indicators of the setup are presented herein for the range of T_h between 65 °C and 85 °C as shown in Fig. 9. Then, T_h was fixed at 75 °C and the capacity of the pneumatic pump is changed by reducing its stroke length from the full length (100 %) to quarter length (25 %) with 25 % step. The performance indicators with the variation of the pneumatic stroke length are presented in Fig. 10.

As shown in Fig. 9, the η_{pl} is improved by an average of 27 % over the range of T_h for the used PR, BM, and TM. However, based on average values, a higher η_{pl} of 6.02 % is obtained by the TM which is 4.87 % higher than the BM (5.74 %) and 15.90 % than of PR (5.19 %). Furthermore, the BWR of the TM and BM are close to each other as R152a is the dominant component for both mixtures. But, the average BWR of R134a (2.98 %) is higher than that for BM (2.51 %), and TM (2.44 %) by 18.72 % and 22.13 %, respectively. This emphasizes that the

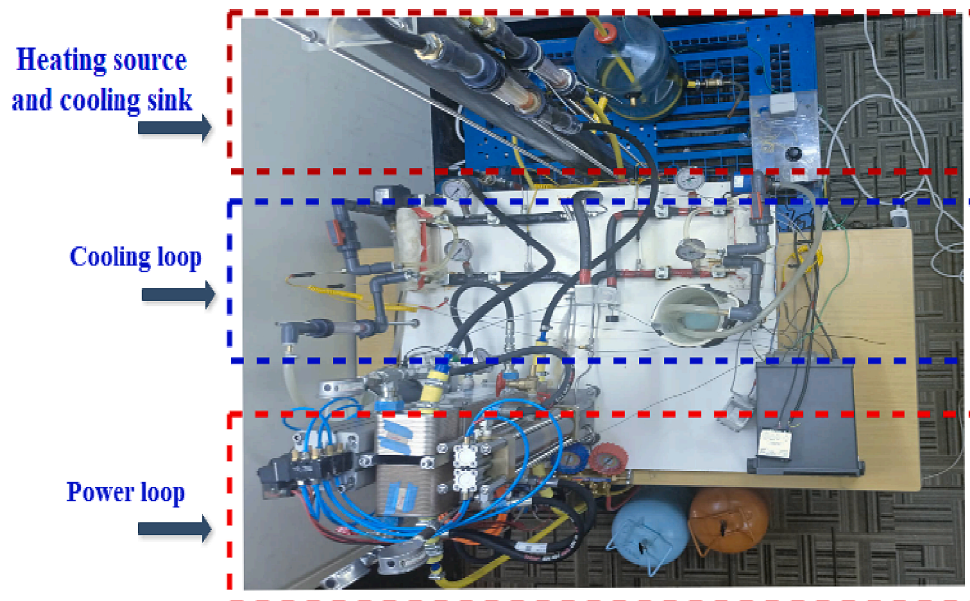


Fig. 8. A top view of the ECU-based ORC-VCC experimental setup.

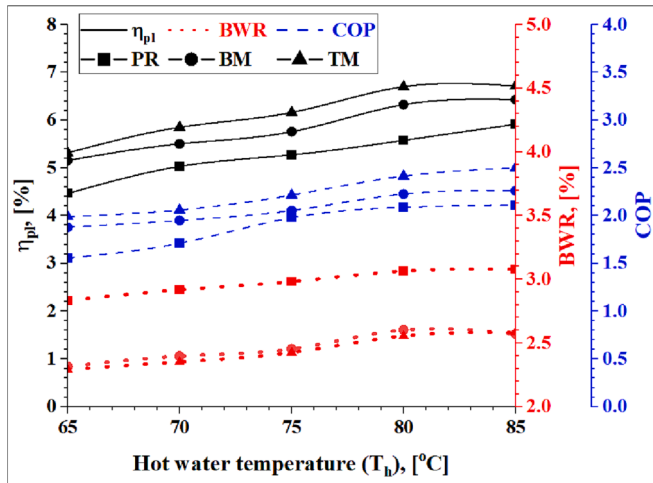


Fig. 9. Performance indicators based on the experimental test for the ECU-based ORC-VCC system with hot water temperature between 65 °C and 85 °C. Note: PR = pure refrigerant (R134a), BM = binary mixture (R142b/R152a with mass fractions of 0.50/0.50), and TM = ternary mixture (R142b/R152a/R600 with mass fractions of 0.05/0.90/0.05).

operation of the ECU with the developed TM can efficiently replace R134a with improved performance and compatibility with the system component. However, as R152a is low flammable, stringent safety procedures must be applied.

As the sensitivity analyses show that the pressure difference (ΔP_{12}) notably affects the performance of the ORC-VCC, its effect is examined experimentally by adjusting the stroke length of the pneumatic pump. The full stroke length of the pump is 160 mm (referred to as 100 %). The stroke length gradually decreases to 120 mm (75 %), 80 mm (50 %), and 40 mm (25 %). The ΔP_{12} is reduced with the reduction of the stroke length which negatively affects the performance of the system as shown in Fig. 10.

It is found that as the stroke length reduced to a percentage of 25 %, the η_{pr} is reduced by 57.35 % for R134a, 50.88 % for R142b/R152a, and 42.03 % for R142b/R152a/R600. This implies that R142b/R152a/R600

is less sensitive to the variation of ΔP_{12} than R134a or R142b/R152a. In addition, at 25 % of the stroke length, the COP of the system declined to less than 1 for R134a and close to 1 for the mixtures (58.10 % reduction). However, at 50 % of the stroke length, the COP is around 2 for the pure and mixed refrigerants. This confirms the efficient operability of the ECU-based system even at the half capacity of the pneumatic pump.

Comparison

Table 6 introduces a comparison between the best results reported in some studies that investigate the ORC with pure and/or mixed refrigerants at low-grade heat with the present study. It is found that only two studies [22,25] cover the temperature range of less than 80 °C with specified refrigerants. In contrast, this study covers the range of the ULGH with a systematic investigation of pure refrigerants and develops new binary and ternary mixtures that enhance the performance of the ORC. Other studies focused on the performance of ORC at temperatures higher than 80 °C with a maximum efficiency of 8.8 % at a temperature of 120 °C. In this study, the developed ternary mixture of R142b/R152a/R600 achieves an energy efficiency of 9.54 % at a temperature of 75 °C. This confirms that the working fluid composition plays a key role in the efficient operation of the ORC.

Conclusions

In this work, theoretical and experimental evaluations are conducted for the performance of an integrated organic Rankine cycle (ORC) with vapor compression cycle (VCC). The evaluation study is performed over the range of ultra-low-grade heat (ULGH) (45 °C to 100 °C) using pure and mixed refrigerants. Systematic procedures are performed to theoretically assess the effect of several pure and mixed refrigerants on the performance of the ORC-VCC system, which is coupled with an expander-compressor unit (ECU). The investigated refrigerants are selected based on specific criteria that consider the energy efficiency of the refrigerants alongside their environmental and safety aspects. Based on the results of the theoretical evaluation, experimental tests are conducted to ensure the operability of the ECU-based ORC-VCC system with R134a (pure refrigerant (PR)), R142b/R152a (binary mixture (BM)), and R142b/R152a/R600 (ternary mixture (TM)) as working fluids in the

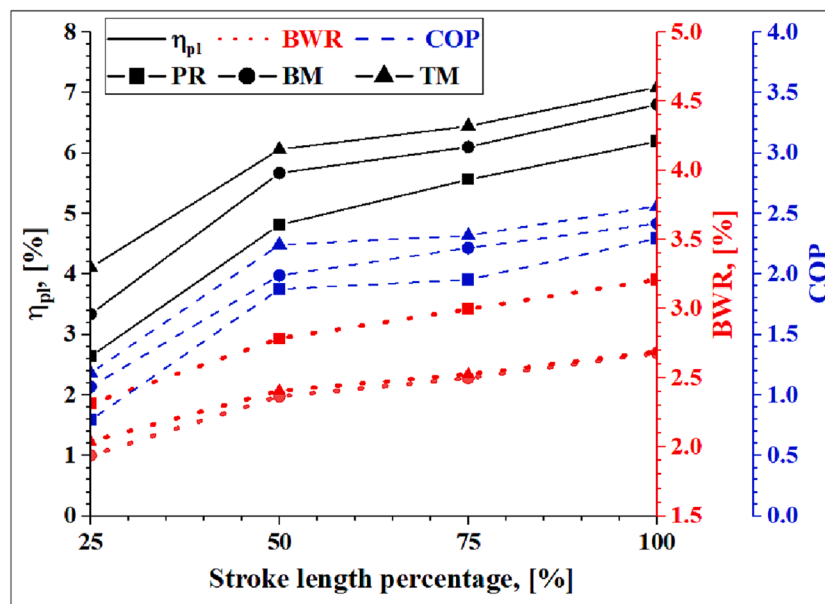


Fig. 10. Performance indicators based on the experimental test for the ECU-based ORC-VCC system at various stroke length percentages for the pneumatic pump. Note: PR = pure refrigerant (R134a), BM = binary mixture (R142b/R152a with mass fractions of (0.50/0.50)), and TM = ternary mixture (R142b/R152a/R600 with mass fractions of (0.05/0.90/0.05)).

Table 6

Comparison between available studies that investigate the performance of ORC over the range of ultra-low-grade heat using pure and/or mixed refrigerants. Data presented for the best performance case of each study.

Refs.	Temp. range, [°C]	Best performed Fluid(s)	η_{pt} , [%]	Remarks
[20]	90, 120	R218, R170/R290	6.1–8.8	Theoretical study. At T_h of 120 °C, R218 achieves the highest net output power and R170/R290 mixture increases the net output power by 12.9% compared to pure R170.
[22]	40–85	R245fa, R1233zd	1.9–5.0	Experimental study. The highest efficiency is obtained by R1234zd(E) at T_h .
[25]	30–80	R600a/R141b	2.45–3.05	ORC is driven by waste heat from the condenser of a VCC with a cooling capacity of 34 kW.
[34]	80–130	R1233zd(E)	Not available	A theoretical and experimental study. The results show that R1233zd (E) has the best performance followed by R1234ze(Z), R1366mzz(E), and R245fa.
[21]	80–100	R1233zd(E)	2.75–3.50	Experimental study. The study was conducted on pumpless small-scale ORC.
Present study	50–100	R142b/R152a/R600	9.16–9.54	A theoretical and experimental study. The energy efficiency of the system is improved by 22.80%, and the BWR reduces by 19.40% with an increase in the evaporation capacity by 13.25%, compared to pure R134a.

power loop and R134a as working fluid in the cooling loop. The main findings of this study can be summarized as:

- R152a and R142b show higher energy efficiencies than R134a or other pure refrigerants over the range of the ULGH. However, they are low flammable and need stringent safety procedures.
- R1233zd can be mixed with R142b to obtain relatively efficient performance with mitigated flammability compared to pure R142b as R1233zd has a safety class of A1.
- The use of ternary and binary mixtures enhances the performance of the system with lower GWP and ODP compared to pure refrigerants.
- Mixing R1132a with R134a in the cooling loop is recommended for a safe combination for refrigeration applications with evaporation temperatures between (–10 °C to –70.07 °C).
- Among the TMs of the power loop, the mixture of R142b/R152a/R600 (0.05/0.90/0.05) improves the energy efficiency of the system by 22.80 %, reduces the BWR by 19.40 % with an increase in the evaporation capacity by 13.25 %.
- There is an optimal value of the pressure difference through the ORC over the range of the ULGH temperature. At the optimal value of ΔP_{12} (12 bar), the evaporation capacity reaches 11.70 kW, which is 85 % higher than at ΔP_{12} of 4 bar (6.33 kW) and 65 % than at ΔP_{12} of 14 bar (7.09 kW).
- At the optimized composition of the TM (R142b/R152a/R600, 0.01/0.95/0.0), an energy efficiency of 9.54 % is obtained, which is 7.10 % higher than that of R134a under the same operating conditions.

- The experimental tests show that the ORC is running with ultra-low temperature up to 52 °C with the BM (R142b/R152a, 0.50/0.50) and TM (R142b/R152a/R600, 0.05/0.90/0.05). However, with R1435, it needs heat source temperatures higher than 63 °C.

Finally, the experimental tests emphasize that R134a can be replaced with more efficient refrigerant mixtures with very low GWP and ODP. Also, the results ensure the reliability and operability of the ECU-based ORC-VCC over the range of ULGH with higher pressures of less than 20 bar.

CRediT authorship contribution statement

Ahmad K. Sleiti: Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Resources, Formal analysis, Project administration, Funding acquisition, Supervision. **Wahib A. Al-Ammari:** Conceptualization, Writing – original draft, Investigation, Software, Data curation, Validation, Formal analysis. **Farayi Musharavati:** Conceptualization, Project administration, Funding acquisition, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.tsep.2023.101962>.

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