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Exergy analysis of a novel low-heat recovery organic Rankine cycle (ORC) for combined cooling and power generation

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ABSTRACT

A thermodynamic modification of an ORC integrated with turbine bleeding and regeneration (ORCTBR) is presented. The objective is to modify the ORCTBR for both cooling and power generation (ORCNOV). First, a thermodynamic break down of the components based on exergy was performed followed by a sensitivity analysis. The results indicate that at based conditions the maximum efficiency obtained with ORCNOV was about 52% using R245fa at a heat input of 252 kW. The improvement in efficiency was estimated at 7.2% when compared with ORCTBR. The highest cooling rate was achieved using R1234yf, R245fa, and R1234ze by 11.14, 10.60, and 10.11 kW, respectively. Additionally, the ORCNOV showed improved performance in turbine output power of approximately 2%. However, the sensitivity studies show that the exergy destruction gap was not greater than 45% between the ORCTBR and ORCNOV, and high cooling rates are feasible at increased condenser (1) pressure.

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Energy; ORC; cooling; heat input; turbine bleeding

Introduction

In spite of the utilization of low-temperature waste heat in today's industries, the rate of heat recovering is still inefficient as a substantial portion of the waste heat is released into the atmosphere or environment. Some existing waste heat reprocessed thermodynamic cycles comprise the Rankine cycle (steam power generation) and the flash or partial evaporation power production. The latter is not very economical except if the waste heat exists between medium and high temperature (Wenqiang, Xiaoyu, and Yanhui 2017). However, in recent times the organic Rankine cycle (ORC) has demonstrated a high efficiency for the application of low-grade temperature energy sources, especially for small-scale power generation (Li et al. 2011; Quoilin, Lemort, and Lebrum 2010). The ORC has the capacity to be adopted for the utilization of low heat from micro-grid turbines, waste heat from metal industries and other heat sources such as biomass and agricultural residues. There exist several reasons why the ORC has been a topical issue as the best technology for low heat recovery. This include, the simplistic mechanism, low maintenance cost, small pressure requirement, and good recovering efficiency (Li et al. 2011; Wenqiang, Xiaoyu, and Yanhui 2017).

Additionally, to improve the performance of ORCs, the cycle has undergone modifications from the generic cycle to ORC with an internal heat exchanger, ORC with turbine bleeding and ORC with turbine bleeding and regeneration (Dai, Wand and Gao 2009; Roy, Mishra, and Misra 2010). In all

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this technical improvement, the ORC has continued to have some marginal improvement from the generic cycle. To further improve the performance of the ORCs many researchers have carried out designs, modeling and optimization of ORC, either at hybrid form or non-hybrid form. For example, Wenqiang, Xiaoyu, and Yanhui (2017) evaluated the efficiency of a combined cycle ORC with an absorption refrigeration system (ARC). The results obtained show that the ARC cannot couple well with ORC section at waste heat temperature greater than 220°C or lower than 140°C. However, the combined ORC and ARC maintained a higher exergy efficiency than the generic system.

Further works by Marin et al. (2013) proposed first a solar ORC-ARC absorption refrigeration system with capacity to generate power and produce cooling while Nord, Lear, and Sherif (2001) also proposed a solar combined power cycle that includes a thermal management subsystem and a power generating subsystem all integrated in a single unit. Furthermore, organic Rankine cycles with turbine bleeding system connected to a thermal heat exchanger (direct contact) are typically regarded as regenerative recuperation (Kim and Park 2015). Researchers have considered studies for ORC with turbine bleeding. This includes the works of Mago et al. (2008) who presented a thermodynamic evaluation of a regenerative ORC and compared results with the generic ORC. Their study reveals that the regenerative ORC showed high thermal performance and efficiency as well as low system irreversibilities. Similarly, Desai and Bandyopadhyay (2009) investigated a modified ORC with turbine bleeding and regeneration using different working fluids. The study obtained an improvement of 16.5% in the thermal efficiency. Meinel *et al.* (2014) presented a comprehensive simulation study for a double-stage ORC with internal system recovery. The performance of the ORC was observed using different working fluids. The results show that performance with ethanol as working fluid produce the highest overall efficiencies for all thermodynamic considerations. Other studies based on environmental and thermo-sustainability indicators for different ORCs using different working fluids were considered in (Abam et al. 2018b, 2018a, 2018c). The results concluded that ORC-turbine bleeding and regeneration had the highest value of exergetic sustainability index (ESI) and showed good ecological stability with R245fa refrigerant. Additionally, from the reviewed ORCs studies above it was evident that each level of ORCs modification improves the system operational performance thus system modification and optimization is important to evolve more efficient cycles. Furthermore, studies on exergoenvironmental and life cycle analysis combined for ORC was proposed by (Ayres, Ayres, and Martinis 1998) and this method has two merits: the exergy-based efficiency can be evaluated through the exergy breakdown of the system and the exergy analysis cannot be replaced by the energy and material analysis. . On this basis, Yang et al. (2018) carried out an environmental analysis of ORC including the refrigerant leakage and the components manufacture. In their study, a component-wise modeling was performed and the impact of the refrigerant was allocated same to each of the system components. The environmental and the lifecycle analysis was evaluated based on the corresponding exergy destruction in the components. The result indicated that the environmental impact caused by refrigerant escape or leakage was between 35.71% and 75.62%. Similarly, the exergoenvironmental analysis has been applied to different thermal systems. Kecebas (2016) applied this concept to a geothermal power plant used for district heating while Fergani, Touil, and Morosuk (2016) and Petrakopoulou et al. (2011) has applied the concept for heat recovery in a cement industry and in a combined cycle thermal plant with chemical looping, respectively.

The increasing worries about the efficient utilization of energy resources and performance of energy conversion systems have compelled researchers to advance techniques for addressing the actual losses that occur in thermodynamic processes. One of these techniques is the application of exergy analysis. Exergy analysis gives a true representation of actual losses that occur in an energy conversion system by identifying where this occurs and the magnitude of the losses (Abam et al. 2017, 2018c; Kecebas 2016; Petrakopoulou et al. 2011). The latter provides a measure for effective plant design and modification for improved efficiency. In this study, a theoretical thermodynamic modification is performed on an ORC-turbine bleeding and regeneration to produce both power and cooling simultaneously from one energy source. The application of ORC for such dual purpose especially for non-hybrid ORCs are barely found in the open literature. The novelty of the studies is

circumscribed in the replacement of the feedwater heater in the generic cycle with a condenser and a second evaporator for cooling. The authors considered this modification noteworthy as it may result in proper energy utilization and reduction in overall system irreversibilities. Further study specifics will include the effects of the turbine bleeding, condenser pressure, turbine inlet temperature for different working fluids on cooling, rate, power production, exergy efficiencies, and system irreversibilities.

Systems description

ORC-turbine bleeding/regeneration and ORC-novel

Figure 1(a) depicts the ORC with turbine bleeding and regeneration (ORCNOV). The system comprises the evaporator, the turbine, the feedwater heater, heat exchanger, condenser, and pump. The superheated vapor from the turbine is extracted at point 7 while the remaining vapor expands in the turbine producing shaft work. The expanded steam condenses at the condenser (point 9). The condensate is pumped through the heat exchanger (point 1) to the feedwater heater (point 3) where the enthalpy is further increased, and the fluid is returned to the evaporator (1) to start the process. Fig 1(b) is the modified ORC cycle of Fig 1(a). In this cycle, the feedwater heater is replaced by a condenser. Part of the vapor is extracted at point 2, and the remaining is allowed to expand in the turbine at point 3 producing shaft work. The extracted vapor at point 2 is throttled through the valve (1) at constant enthalpy and then condenses in the condenser at point 4 where the external water source is used to facilitate cooling. The saturated fluid (condensate) is allowed to evaporate in the second evaporator at point 6 thus producing cooling. The vapor condenses in the second condenser at point 9 which is pumped at point 11 through the heat exchanger to the evaporator (1) for a repeat of the process.

Thermodynamic approach

Assumptions

The following assumptions are considered (1) the flow condition is at equilibrium state, (2) pressure, heat, and friction losses in components are neglected. (3) The evaporator inlet temperature is taken at 298 K whereas condenser pressure is maintained between 2.5 and 3.5 MPa based on the working fluids. (4) The turbine and pump isentropic efficiencies were set at 85% and 90%, respectively. (5) The evaporator heat input (Q_{in}) is a stream of hot gas taken at 252 kW, at 120°C (393 K) from an open cycle micro gas-turbine plant (Wei et al. 2007). (7) The exergy stream from the evaporator and that of water inflowing and from the condenser are insignificant. (8) The fluid condition to the turbine is superheated. (8) The turbine and pump isentropic efficiencies are kept at 85% and 75% respectively (Li, Wang, and Du 2012). (10) The difference in pitch point temperature for the evaporator and condenser are kept at 5 and 10°C, respectively (Di Maria and Micale 2015).

Thermodynamic modeling of the ORCs

Steady-state flow processes involving energy and exergy streams are presented in Eqs. (1) and (2) (Fathia et al. 2015; Tchanche et al. 2010).

$$\sum \dot{Q}_k + \sum \dot{m}_i \left(h_1 + \frac{C_i^2}{2} + gz_1 \right) \cdot = \cdot \sum \dot{m}_i \left(h_0 + \frac{C_0^2}{2} + gz_0 \right) \cdot + \cdot \sum W \quad (1)$$

$$\sum \left(1 + \frac{T_0}{T} \right) \dot{Q}_k + \sum (\dot{m}_i \dot{\phi}_i) = \sum \dot{\phi}_w + \sum (\dot{m}_0 \dot{\phi}_0) + E_D \quad (2)$$

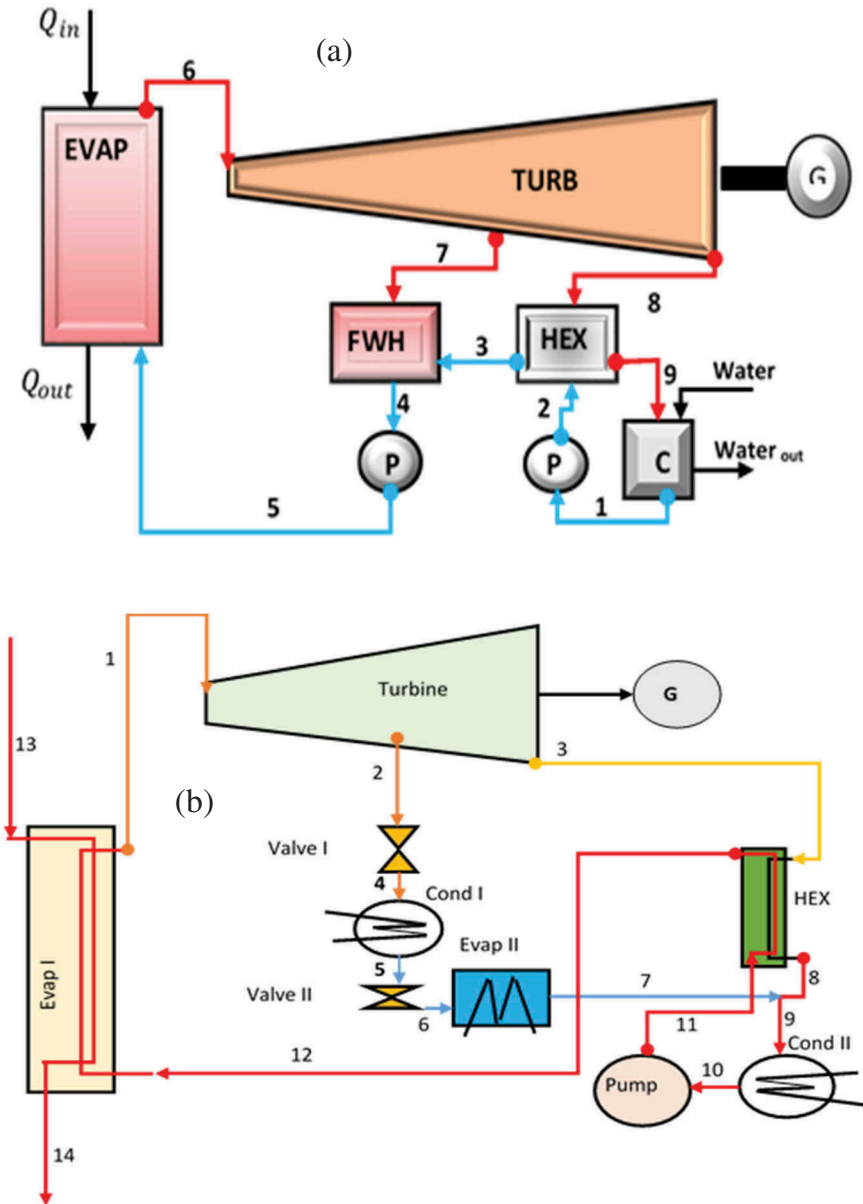


Figure 1. (a) Organic Rankine cycle with turbine bleeding and regeneration (ORCTBR). (b) Organic Rankine cycle novel (ORC-Novel)

The energy, exergy, and mass balances are equally defined for equilibrium state neglecting all forms of energies specifically, potential and kinetic energy:

$$\sum \dot{m}_i = \sum \dot{m}_0 \tag{3}$$

$$Q - W = \sum \dot{m}_0 h_0 - \sum \dot{m}_i h_i \tag{4}$$

$$W + \sum (\dot{m}_i \varphi_i) = Q + \sum (\dot{m}_0 \varphi_0) \quad (5)$$

The exergy transfer rate by heat φ_Q at the temperature T is obtained in Equation (6)

$$\varphi_Q = Q \left(1 - \frac{T_0}{T} \right) \quad (6)$$

Specific exergy flow is given by

$$\varphi = \{(h - h_0) - T_0(s - s_0)\} \quad (7)$$

Hence, the total exergy flow in a system can be expressed as:

$$E_x = \dot{m} \varphi = \dot{m} \{(h - h_0) - T_0(s - s_0)\} \quad (8)$$

Where h_0 and s_0 are specific enthalpy and entropy terms at dead state temperature and pressure (P_0, T_0) respectively.

The expression for the rate of entropy generation is shown in Equation (9) (Cengel and Boles 2007).

$$\sum \frac{Q_k}{T_k} - \sum \dot{m}_e s_e + \sum \dot{m}_i s_i + \dot{s}_{gen} = \frac{ds_{cv}}{dt} \quad (9)$$

$\frac{ds_{cv}}{dt} = 0$, for steady state situation thus Equation (9) reduces as:

$$\sum \dot{m}_e s_e - \sum \dot{m}_i s_i - \sum \frac{\dot{Q}_k}{T_k} = \dot{s}_{gen} \quad (10)$$

Where:

\dot{m} , T_k and \dot{Q}_k denotes mass flow, waste heat temperature, and rate of heat transfer, respectively.

The above exergy equation has been applied to the component by component for the ORC novel (ORCNOV) as presented in Table 1.

Working fluids selection

Working fluids used in thermodynamic cycles are critical to system performance. This implies that they must possess the required properties required for a preferred application. The fluid choice affects the overall system performance, operating conditions, efficiency, economic feasibility, and environmental impact. However, to attain an adequate thermal match, it is imperative for the working fluid critical temperature to be near the waste heat temperature or source temperature (Vikas et al. 2017). In this study, thus, three types of the HFC refrigerants (R245fa, R1234yf, and

Table 1. Components exergy balance and efficiency for the ORCNOV (Figure 1b).

Component	Exergy balance	Exergy efficiency
Evaporator	$\dot{E}_{12} + \dot{E}_{13} = \dot{E}_1 + \dot{E}_{14} + \dot{E}_{EVAP}$	$\psi_{VG} = \frac{\dot{E}_1 - \dot{E}_{12}}{\dot{E}_{13} - \dot{E}_{14}}$
Turbine	$\dot{E}_1 = \dot{E}_2 + \dot{E}_3 + \dot{E}_{WT} + \dot{E}_{D, TURB}$	$\psi_{TURB} = \frac{\dot{E}_{WT}}{\dot{E}_1 - \dot{E}_2 - \dot{E}_3}$
Valve 1 (2,4)	$\dot{E}_2 = \dot{E}_4 + \dot{E}_{D,VI}$	$\psi_{val,1} = \frac{\dot{E}_4}{\dot{E}_2}$
Condenser	$\dot{E}_4 = \dot{E}_5 + \dot{E}_{D, COND}$	$\psi_{COND} = \frac{Q_{COND} \left(1 - T_0/T_C \right)}{\dot{E}_4 - \dot{E}_5}$
Valve II (5, 6):	$\dot{E}_5 = \dot{E}_6 + \dot{E}_{D,II}$	$\psi_{val,1} = \frac{\dot{E}_6}{\dot{E}_5}$
Evaporator (6, 7):	$Q_{evap} \left(1 - \frac{T_0}{T_\infty} \right) + \dot{E}_6 = \dot{E}_7 + \dot{E}_{D, EVAP}$	$\psi_{EVAP} = \frac{\dot{E}_7 - \dot{E}_6}{Q_{evap} \left(1 - \frac{T_0}{T_\infty} \right)}$
Heat exchanger (3, 8, 11, 12)	$\dot{E}_3 + \dot{E}_{11} = \dot{E}_8 + \dot{E}_{12} + \dot{E}_{D, HEX}$	$\psi_{HEX} = \frac{\dot{E}_{12} - \dot{E}_{11}}{\dot{E}_3 - \dot{E}_8}$
Condenser (9, 10)	$\dot{E}_9 = \dot{E}_{10} + \dot{E}_{D, COND}$	$\psi_{COND} = \frac{Q_{COND} \left(1 - T_0/T_C \right)}{\dot{E}_9 - \dot{E}_{10}}$
Pump (10, 11)	$\dot{E}_{10} + \dot{E}_{WP} = \dot{E}_{11} + \dot{E}_{D, PUMP}$	$\psi_{PUMP} = \frac{\dot{E}_{11} - \dot{E}_{10}}{\dot{E}_{WP}}$
Net exergy efficiency		$\psi_{total} = \frac{W_1 + E_{ref, total}}{\dot{E}_{13} - \dot{E}_{14}}$

Table 2. Physical and environmental properties of the working fluids (Meinel, Wieland and Spliethoff, 2014; Saleh 2016).

Substance	Chemical formula	Molecular weight	NDP °C	T _c °C	P _c MPa	ODP 100 yr	GDP	LFL	ALT (year)
R245fa	CF ₃ -CH ₂ -CHF ₂	134.05	15.1	154.1	3.65	0.0	1050	None	7.7
R1234yf	CF ₃ CF=CH ₂	114.04	-29.5	94.7	3.38	0.0	<1	6.2	0.029
R1234ze	CHF=CHCF ₃	114.04	-19.0	109.4	3.64	0.0	<1	7.6	0.045

NBP = normal boiling point, ODP = ozone depleting potential, ALT = atmospheric lifetime years, LFL = low flammability limit.

Table 3. Thermodynamic flow parameters for the ORCs with R245fa, R1234yf, and 1234ze refrigerants for ORCTBR.

Points	R245fa				R1234yf				R1234ze			
	T (°C)	P (MPa)	e (kJ/kg)	E(kW)	T (°C)	P (MPa)	e (kJ/kg)	E (kW)	T (°C)	P (MPa)	e (kJ/kg)	E(kW)
1	25.00	0.149	0.000	0.000	25.00	0.687	0.0000	0.0000	25.00	0.500	0.000	0.000
2	25.12	0.492	0.256	0.236	25.16	1.717	0.0095	0.0087	25.52	1.350	0.319	0.295
3	40.00	2.500	0.756	0.698	40.00	3.146	0.9026	0.8273	40.00	3.500	0.818	0.757
4	62.00	2.500	3.406	3.213	62.00	3.146	4.3920	4.6560	62.00	3.500	3.501	3.711
5	63.00	2.500	4.880	5.131	62.88	3.146	4.5970	4.8730	63.98	3.500	5.424	5.750
6	153.80	0.492	61.290	64.96	177.60	1.717	57.350	60.790	174.30	1.350	59.55	63.120
7	98.85	2.500	27.940	3.818	155.50	3.146	40.960	5.8740	136.20	3.500	34.45	4.641
8	68.29	0.149	3.010	2.779	126.80	0.686	15.720	14.410	103.10	0.500	8.291	7.671
9	47.63	0.149	1.022	0.944	107.20	0.686	10.560	9.6830	83.75	0.500	4.677	4.328

R1234ze) are chosen with critical temperatures close to the heat source temperature. The thermodynamic properties of the three working fluids are got from REFPROP 8.0 as presented in Table 2. The thermodynamic flow parameters calculated for the ORCTBR and ORCNOV for different refrigerants at different state points are presented in Tables 3 and 4.

Results and discussion

Thermodynamic performance

The thermodynamic analysis of ORCNOV and ORCTBR is presented. A program was written using Engineering Equation Solver (EES) based on the assumptions in this study to simulate the ORCs performance. The performance of the ORCNOV was compared with ORCTBR at standard conditions for the different refrigerants. Tables 2 and 3 present the thermodynamic flow parameters at different state points for the two cycles. The exergy flow rates were identified to be highest with ORCNOV than the ORCTBR for R245fa refrigerants. Maximum exergy efficiency was obtained with ORCNOV by about 52% using R245fa with an efficiency improvement estimated at 7.2% when compared with ORCTBR. The maximum cooling rate for ORCNOV was attained using R1234yf

Table 4. Thermodynamic flow parameters for the ORCs with R245fa, R1234yf, and 1234ze refrigerants for ORCNOV.

Points	R245fa				R1234yf				R1234ze			
	T (°C)	P (MPa)	e (kJ/kg)	E(kW)	T (°C)	P (MPa)	e (kJ/kg)	E (kW)	T (°C)	P (MPa)	e (kJ/kg)	E(kW)
1	138.20	2.500	54.113	57.360	156.5	3.146	48.490	51.4	154.3	3.500	51.09	54.16
2	78.79	0.492	24.150	12.800	133.9	1.717	33.490	17.75	114.5	1.350	28.35	15.03
3	47.89	0.149	1.0401	0.5513	105.1	0.686	10.050	5.327	80.87	0.500	4.218	2.236
4	71.82	0.492	3.4622	1.8350	126.1	1.717	15.518	8.225	105.0	1.350	8.703	4.613
5	25.30	0.492	0.0003	0.00021	25.21	1.717	0.0002	0.000136	25.00	1.350	0.412	0.218
6	25.30	0.149	0.0003	0.00021	25.21	0.686	0.0002	0.000136	25.00	0.500	0.412	0.218
7	10.00	0.149	0.4981	0.264	10.00	0.686	0.5190	0.2751	10.00	0.500	0.309	0.163
8	25.30	0.149	0.0627	0.03512	25.21	0.686	0.0682	0.03821	25.00	0.500	0.356	0.199
9	25.30	0.149	0.0211	0.02239	25.21	0.686	0.0234	0.02481	25.00	0.500	0.400	0.424
10	25.00	0.149	0.0000	0.0000	25.00	0.686	0.000	0.000	25.00	0.500	0.000	0.000
11	25.80	2.500	1.7520	1.8580	26.57	3.146	0.0313	0.03325	26.67	3.500	2.159	2.289
12	45.00	2.500	2.6264	2.784	45.00	3.146	3.3839	3.5870	45.00	3.500	3.021	3.203
13	227.00	2.500	-	101.80	227.00	3.146	-	101.80	227.00	3.500	-	101.8
14	39.00	2.500	-	11.310	39.00	3.146	-	11.310	39.00	3.500	-	11.31

followed by R245fa and R1234ze by 11.14, 10.60, and 10.11 kW, respectively. Equally, the maximum turbine output (TOP) of 43.27 kW was obtained with ORCNOV using R245fa.

Sensitivity evaluation of key indicators

Effect of heat input on exergetic efficiency. The effect of heat input (HIP) on exergetic efficiency (EE) is presented in Figure 2 for the ORCTBR and ORCNOV using R1234yf, R1234ze, and R245fa. The HIP was ranged between 150 and 252 kW. Within this limit, the EE for the cycles were estimated between, $26.66 \leq EE \leq 37.46\%$ for ORCTBR, and $47.68 \leq EE \leq 52.14\%$ for ORCNOV. Maximum EE values for ORCTBR and ORCNOV were obtained using R245fa by 37.46% and 52.14% at heat inputs of 221.8 and 227.4 kW, respectively. Further increase in the HIP for ORCNOV shows a decreasing trend in EE with R1234yf and R1234ze. This disparity may be ascribed to fluid thermodynamic properties.

Effect of heat input on exergy destruction. The effect of HIP on the overall cycle exergy destruction (ED) is presented in Figure 3 for the different working fluids. The ED rate increases for increasing HIP. The ED is highest using R1234ze for ORCTBR and least using R245fa for ORCNOV. The difference in the ED at the extreme value of 255 kW shows that between ORCTBR and ORCNOV, the ED gap was about 45% using R245fa approximately 32.22%, and 32.43% using R1234yf and R1234ze, respectively. The discrepancy in the ED rate is ascribed to fluid properties and the temperature difference between the evaporator and the working fluid. Also, the addition of cooling as a product in the ORCNOV has led to the reduction in the cycle ED.

The effect of turbine bleeding pressure (TBP) on exergetic efficiency and turbine output (TOP). The effect of turbine bleeding pressure (TBP) and turbine output (TOP) for different refrigerants are depicted in Figure 4(a–c). The two cycles show an increasing trend in EE with R1234yf and R1234ze except with R245fa in (Figure 4(a)) which shows a decreasing trend for all values of TBP. Similarly, the TOP increases for increasing TBP except for R1234yf (Figure 4(b)) where the TOP decreases for increasing TBP. For ORCTBR high EE values were got with R245fa at low TBP while low EE values at High TBP were got with R1234ze and R1234yf refrigerants. However, EE values of 60.93% (Figure 4(a)) was got with the ORCNOV using R245fa whereas low EE values of 30.88% (Figure 4(b)) and 24.89% (Figure 4(c)) were obtained using R1234ze and R1234yf, respectively. In the same vein, the

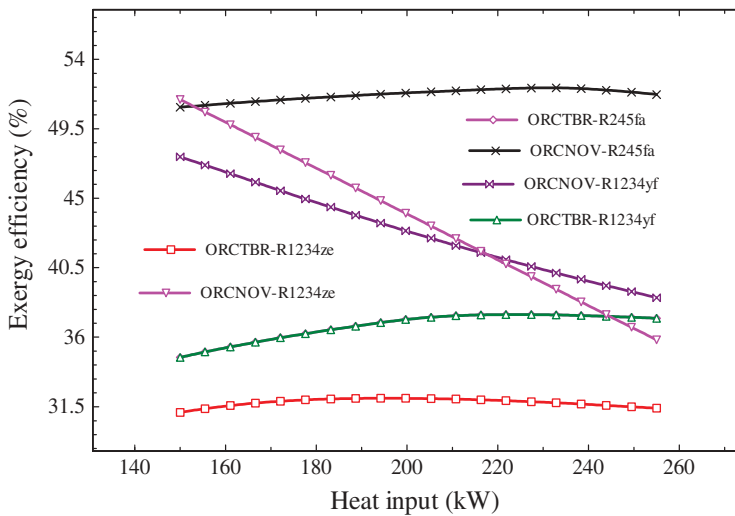


Figure 2. Effect of heat input on exergetic efficiency for ORCTBR and ORCNOV.

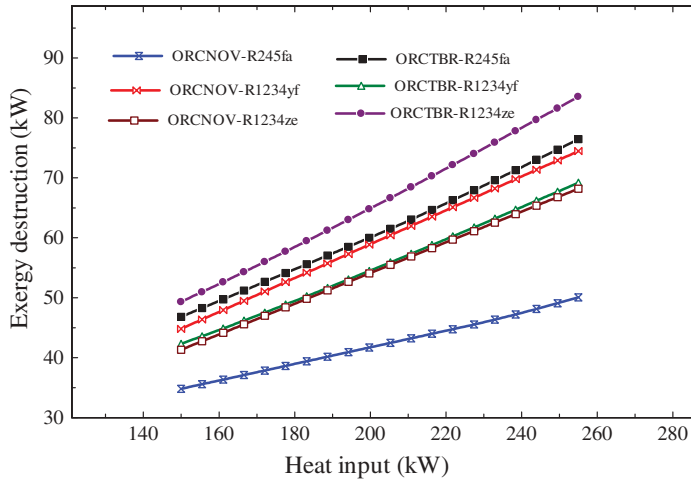


Figure 3. Effect of heat input on exergy destruction for ORCTBR and ORCNOV.

maximum TOP of 59.95 kW and 55.25 kW were obtained with ORCNOV and ORCTBR which gave a net power increase of about 7.38%. However, the study shows that the performance of the ORCNOV was further enhanced using R245fa as working fluid.

The effect of condenser (1) pressure on cooling capacity. The effect of condenser 1 pressure on cooling rate is shown in Figure 5(a–c) for the three working fluids. The results show that the cooling rate increases for increase in condenser (1) pressure (CNP). All the working fluids show a similar trend for increased CNP but different cooling rates. For example, at CNP between $0.478 \leq \text{CNP} \leq 1 \text{ MPa}$, the cooling rates increased from 11.91 to 32.01 kW. Furthermore, in (Figure 5(b)), at CNP values of 0.478 and 1 MPa for R1234yf, the cooling rate increased from 2.043 to 22 kW while for R1234ze (Figure 5(c)) at CNP range between $0.33 \leq \text{CNP} \leq 1 \text{ MPa}$, the cooling rate increases from 1.118 to 28.19 kW. The results indicate that increasing the CNP lead to an increase in cooling rate and reduction in TOP for both ORCTBR and ORCNOV. The reason is due to the reduction in vapor extraction that is the reduction in the mass flow rate of vapor should have caused expansion in the turbine. Nonetheless, the ORCNOV using R245fa showed high cooling rate for all CNP.

Effect of evaporator temperature. Figure 6 presents the effect of evaporator temperature on cooling rate using R245fa, R1234yf, and R1234ze. The result showed a high cooling capacity is attainable with R1234yf, though the cooling capacity decreases with all the refrigerants for increasing evaporator temperature. Further calculations show that a degree rise in evaporator temperature resulted in about 7.05% reduction in cooling rate. It is a thermodynamic fact that evaporator temperatures should be well controlled and certain to achieve maximum cooling capacity. The latter can be adequately achieved by optimization of the thermodynamic variables and note the conditions of applications for the different refrigerants used.

Error analysis

This study adopted the mean absolute percentage error (MAPE) method to determine the variation in operating data and the overall results. Real data with similar experimental studies were got from Kuo et al. (2011), Aboaltaboq et al. (2016), Kim, Kim, and Lee (2017). The operating data point in the present study was used as a reference to estimate the variation with real data from the reference

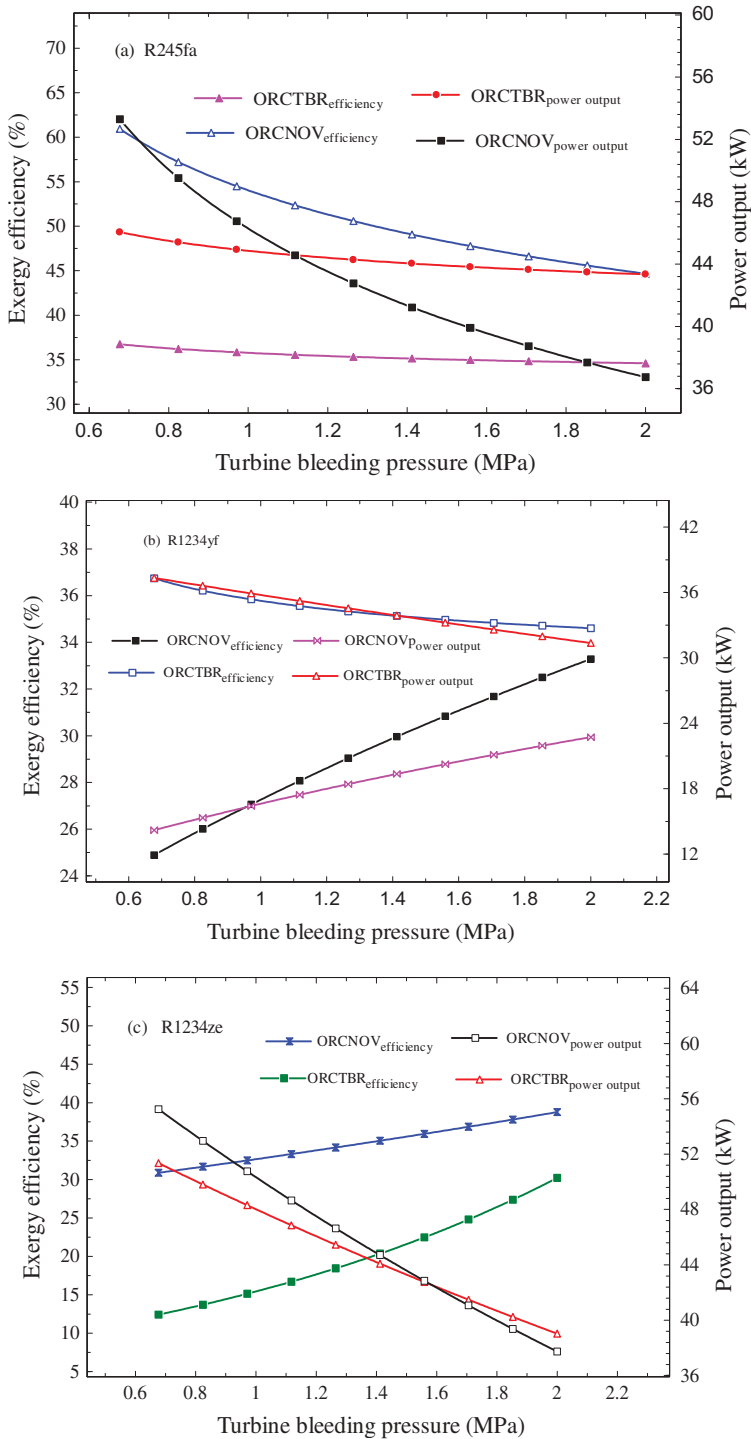


Figure 4. Effect of TBP on exergy efficiency and TOP for (a) R245fa, (b) R1234yf and (c) R1234ze.

literature as well as final data obtained from the results. The heat source temperature (T_s), heat input from (Q_s) in absolute term, turbine inlet temperature (TIT), and condensation temperature (T_c) were selected as reference operating variables. Similarly, for the results, the cycle net exergy efficiency (ψ),

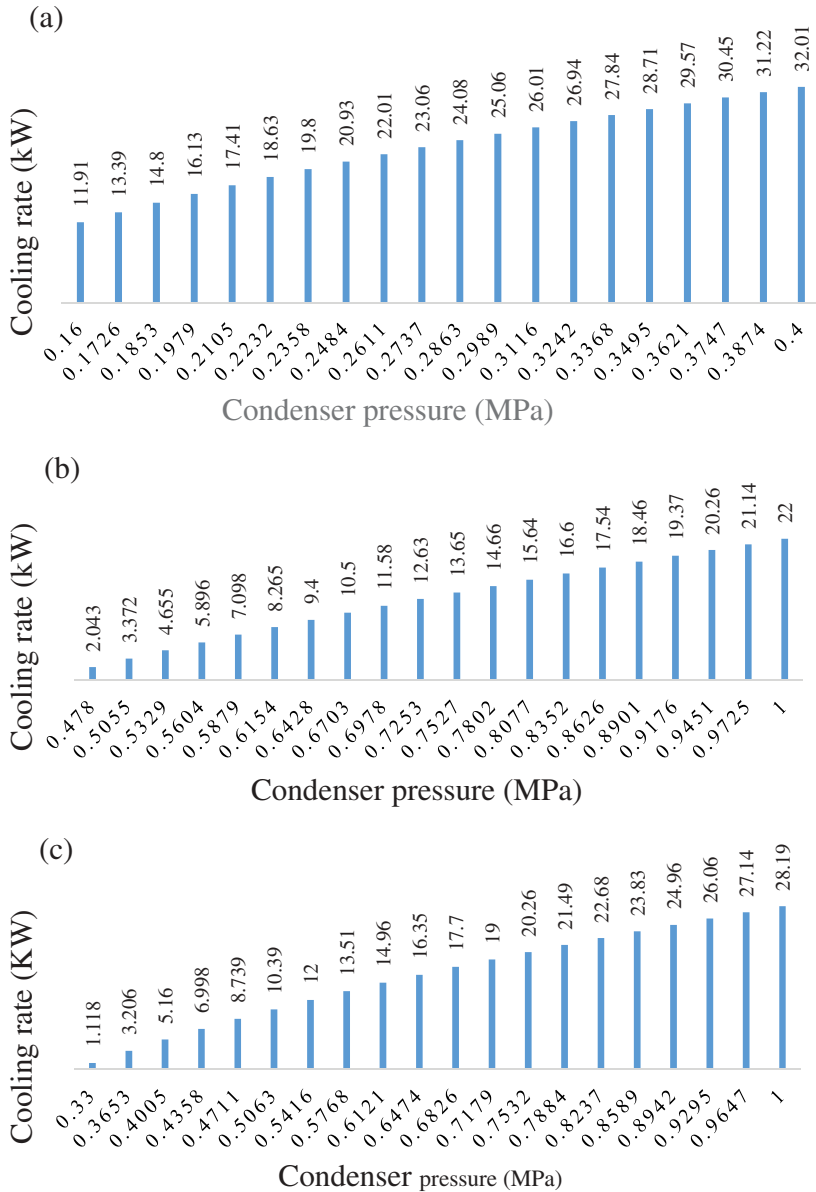


Figure 5. Effect condenser 1 pressure on cooling rate for ORCNOV using (a) R245fa, (b) R1234yf and (c) R1234ze.

total exergy destruction (E_D), and the net turbine power output (TOP) were used for the MAPE analysis. The error calculations are presented in Tables 5 and 6 for the operating data and the simulated results, respectively. The estimated MAPE values are presented as maximum and average percentage errors. Additionally, the variations in data with similar experimental studies in literature were calculated for both the average error (AE) and maximum error (MAE). The solutions indicate that for AE, 1.6%, 3.1%, 1.45%, and 3.8% was calculated for the T_s , Q_s , TIT, and T_C whereas 1.8%, 4.7%, 1.9%, and 5.9%, was calculated for MAE in that order. In the same vein, AE and MAE were evaluated for the performance indices, ψ , E_D , and TOP as 1.6%, 3.4%, and 1.8% and 1.9%, 4.8%, and 2.7%, respectively.

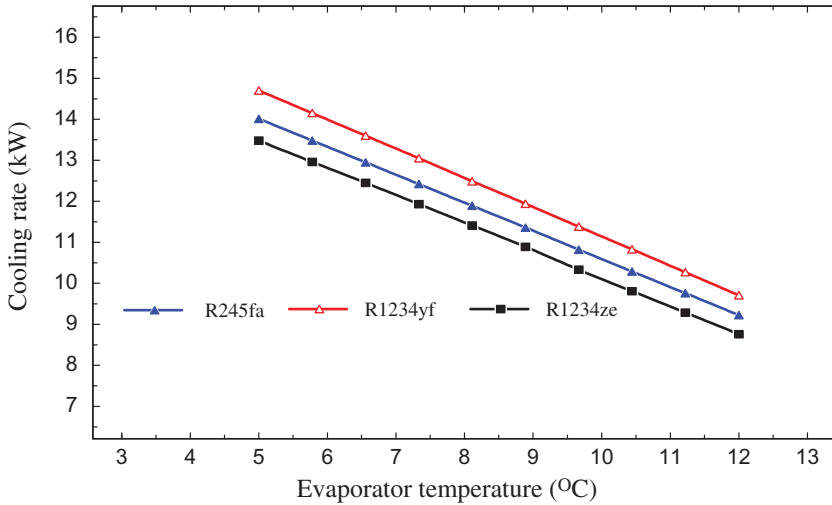


Figure 6. Effect of evaporator (1) temperature on cooling rate for ORCNOV using (a) R245fa, (b) R1234yf and (c) R1234ze.

Model validation

In validating the models developed for the simulation of the ORCTBR and ORC-novel for cooling and power generation, data in the open domain were used (Di Maria and Micale 2015, Li, Wang, and Du 2012, Wei et al. 2007). Furthermore, the obtained simulation results were compared with that reported in the open literature as depicted in Table 7. From Table 7, an explicit agreement between the parametric results obtained in this study with the data published in the preceding literature. The thermal and exergy efficiency were chosen as an index of performance for the compared systems.

Conclusion

The thermodynamic analysis of a novel ORC (ORCNOV) for a dual thermal application using different refrigerants is presented. The findings are summarized as follows:

- The calculated exergy efficiency for heat inputs between 150 and 252 kW ranged between $26.66 \leq EE \leq 37.46\%$ for ORCTBR, and $47.68 \leq EE \leq 52.14\%$ for ORCNOV.

Table 5. System operating data error analysis based on MAPE.

Objective	T_s	Q_s	TIT	T_c	T_s	Q_s	TIT	T_c	T_s	Q_s	TIT	T_c
	(Kim, Kim, and Lee 2017)				(Kuo et al. 2011)				(Aboalatabooq et al. 2016)			
Max. % error	1.8	4.7	1.9	5.9	2.6	3.1	2.7	2.9	2.8	3.2	2.2	2.6
Avg. % error	1.6	3.1	1.45	3.8	1.44	1.9	1.5	1.67	1.9	1.8	1.7	1.8

T_s = Heat source temperature, Q_s = Heat input, TIT = Turbine inlet temperature, T_c = Condenser temperature.

Table 6. System error analysis based on MAPE for some thermodynamic performance indicators.

Objective	ψ	E_D	TOP	ψ	E_D	TOP	ψ	E_D	TOP
	(Kim, Kim, and Lee 2017)			Kuo et al. 2011)			(Aboalatabooq et al. 2016)		
Max. % error	1.9	4.8	2.7	2.7	5.8	3.3	2.6	5.4	4.2
Avg. % error	1.6	2.4	1.8	1.6	3.2	1.7	1.9	2.5	2.1

ψ = Exergy efficiency, E_D = Exergy destruction, TOP = Net turbine output.

Table 7. Comparison of performance of the novel ORC with related studies.

References	ORC configuration	Working fluid	Thermodynamic Results
Ghaebi et al. (2018)	Basic ORC, modified ORC with turbine bleeding, regenerative ORC, and ORC incorporating both turbine bleeding and regeneration	R113, R141b, n-pentane, R123, R245fa, R600, isobutane, R236fa)	The range of thermal efficiency for basic ORC, ORC with turbine bleeding, regenerative ORC, and ORC with both turbine bleeding and regeneration were (15.28–22.96), (15.66–23.21), (17.51–26.05), and (17.98–26.54)%, respectively.
Meinel et al., (2014)	Two-stage ORC	R601, R236ea, R245fa	The operating pressure and thermal efficiencies were obtained for R601, R236ea, and R245fa as 20% at 30 bar, 15.1% at 30 bar, and 18.3% at 30 bar, respectively.
Sun, Yue, and Wang (2017)	ORC combined with Absorption Refrigeration Cycle (ORC-ARC) and ORC combined with Ejector Refrigeration Cycle (ORC-ERC)	R113	Thermal and exergy efficiencies of 13.65% and 32.86% respectively.
Safarian and Aramoun (2015)	Regenerative ORC	R113	Thermal and exergy efficiencies (22.8% and 35.5%), respectively.
The present study	Novel low-heat ORC for Cooling and power generation	R1234yf, R1234ze and R245fa	Exergy efficiency range 26.66 to 37.46% for R1234yf, 47.68 to 52.14 for R1234ze and 37.46 to 52.15% for R245fa

- The maximum EE for ORCTBR and ORCNOV were achieved using R245fa by 37.46% and 52.14% at the HIP of 221.8 kW and 227.4 kW, respectively. Similarly, the exergy destruction rates were high for ORCTBR.
- Reducing the turbine bleeding pressure (TBP) lead to an increase in EE and TOP, except for R1234yf where the TOP decreases for increasing TBP for both ORCs. The cooling rates increase for increase in condenser (1) pressures. Also, the ORCNOV using R245fa showed high cooling rate for all variations in condenser pressure.
- The cooling rate decreases for all increasing evaporator temperature. A degree rise in evaporator temperature resulted in about 7.05% reduction in cooling rate.
- The study shows that the ORCNOV could be promising for sustainable energy supply. Also, the system configuration in addition to operating parameters governs the performance of the ORCs. The ORCNOV can be useful as a refrigeration system for turbine inlet air in a region where the temperature of ambient is high. It can also be applied to utilities where high refrigerating effect may be required.

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