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Parametric Exergy Analysis of a Biomass-assisted Organic Rankine Cycle Tri-generation Energy System

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ABSTRACT

The study applied conventional exergy analysis to a biomass-assisted multi-generation energy system for power generation, heating and cooling. The parametric assessment was done using environmentally friendly refrigerants - R245fa, R1234yf, and R1234ze. To understand optimum operating parameters for the proposed system, both first and second law thermodynamic models were used to simulate the cycle with Engineering Equation Solver (EES). The results demonstrate that the exergy efficiency of the system is greatly enhanced under the new organic Rankine cycle (ORC) configuration to include cooling and heating as products. This led to an increase in exergy efficiencies of 28.34 %, 22.32 %, and 29.61 % with refrigerants R245fa, R1234yf, and R1234ze, respectively, compared to an earlier study with a similar configuration. The net power output ranged between 14.08 and 32.55 kW at a very moderate refrigerant mass rate of 2.05 kg/s and 0.3071 kg/s of the biomass syngas. This provision allows the operation of the system at relatively low external heat content but at flue gas temperatures up to 600°C. Therefore, the system can be fired with a Brayton topping cycle at controlled mass flow rates of flue gas (0.3071 kg/s). Furthermore, turbine inlet temperatures were spread as 120°C, 95°C and 90°C, respectively for R245fa, R1234yf, and R1234ze. This low range can facilitate the system's operation from very low-temperature waste heat from many sources.

1. Introduction

The organic Rankine cycle (ORC) is a bottoming cycle requiring energy from a topping cycle that can have various configurations and energy grades. In addition, waste heat from industrial processes and solar irradiance are often used, with the latter known as the solar organic Rankine cycle (SORC). While ORCs have many advantages such as an energy cycle, they are relatively limited to low energy efficiency systems. One way to enhance its efficiency is by modifying its basic cycle with other components. Numerous studies have investigated several novel ORC configurations. This includes a novel proton exchange membrane fuel cell combined ORC for power generation (Liu *et al*., 2020). A confluent cascade expansion ORC (CCE-ORC) system for engine waste heat recovery (Chen *et al*.,2017). A liquid separation condenser-based composition-adjustable zeotropic ORC, where thermodynamic performance is enhanced by improving the heat matching between the mixture and heat source/sink through composition adjusting (Lu *et al*., 2021). Amongst many other novel ORC combined configurations are the works of (Ariyanfar *et al*., 2016; Zhang *et al*., 2019; Wang *et al*., 2022; Zhang *et al*., 2013).

Furthermore, to reduce the environmental impact of the flue gas used for driving ORCs, an alternative method has been the adoption of SORCs and the use of biomass to power these systems other than industrial waste. Biomass is an attractive option since it is carbon neutral because the carbon released during its combustion is offset by the carbon absorbed by the plant during its growth. It is cost-effective as it is available at a low cost compared to fossil fuel.

Additionally, using biomass as fuel can help in the proper disposal of agricultural by-products and waste materials. Therefore, its use in powering many energy generation systems, including ORCs has been well reported. Liu *et al*., (2011) performed a biomass-fired CHP system with ORC using HFE7000, HFE7100 and n-pentane as working refrigerants. They indicated that the highest predicted ORC efficiency was 16.6%. Qiu *et al*. (2012) presented results from an experimental investigation on a biomass-fired ORC-based micro-CHP system. The biomass-fired CHP system had a lower power output efficiency than predicted by the thermodynamic modelling at 3.9 %. Similarly, Ismail *et al*., (2020) presented the performance of several biomass-fired ORC systems to select the best working fluid and system configurations. They discovered that toluene was the best option in a simple ORC system configuration. Ahmadi *et al*. (2013) developed a novel multi-generation system based on a biomass combustor, an organic Rankine cycle (ORC), an absorption chiller and a proton exchange membrane electrolyzer to produce hydrogen, and a domestic water heater for hot water production. The energy condition of the heat source which powers the vapour absorption system is a comparatively weak refrigerant stream after expansion in the turbine and condensation in the condenser.

Additionally, as contained in Kanu, (2017), the details for powering a novel ORC configuration were only limited to specified energy states and quanta which can come from a multiplicity of energy sources. The proposed energy system is shown in Figure 1, and the working principle is as follows. Biomass is partly combusted with a limited supply of air in a gasifier. Hot gas is allowed to pass through a cyclone, where any traces of ash are settled down. The resulting hot gas stream is passed to an evaporator which acts as a heat exchanger for powering the novel ORC. The ORC, which is novel due to its simple configuration for power generation and cooling, receives heat from the evaporator at gasifier temperature and pump pressure expands in a turbine to produce electricity. A part of the refrigerant is bled after expansion, while the remaining part expands completely to the condenser pressure. The bled refrigerant vapour exists at a high temperature and pressure which is suitable for condensation and evaporation.

However, following the high pressure after part expansion in the turbine, an expansion valve is provided to reduce the pressure before condensation. Another expansion valve is provided to further reduce the pressure before evaporation which brings cooling. The refrigerant stream which leaves the evaporator adds up to the fully expanded vapour after interacting with a heat exchanger.

This stream is condensed and pumped through a heat exchanger which increases its energy level before it enters the evaporator to start the cycle again. Here, a specified and properly modelled energy source which powers such novel arrangement is proposed in biomass. This will not only enhance efficiency but will result in environmental sustainability consequent upon the utilization of biomass for its operation. This enhanced configuration is not in open literature and hence justifies this research work. Consequently, the amount of cooling is severely reduced, resulting in minimal exergy efficiency of the plant at 22 %.

The listed literature on novel ORC configurations is reported to have very low energy efficiency due to the limitation of the system to low electricity generation as the main product. ORC efficiency can be enhanced with modifications to produce additional products using the same energy input. To remedy this shortcoming and augment the overall system performance, the proposed cycle incorporates turbine bleeding at a high energy level for cooling, in addition to whole power generation in the turbine as well as heating.

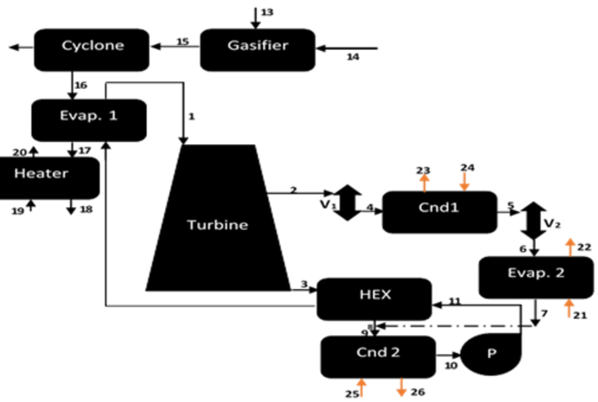

Figure. 1: Schematic diagram of the multigeneration plant

2. Materials and Method

2.1 Materials

The system is modelled using the energy flow equation at steady state conditions for a control volume. Thus, for the kth component, the energy balance is generally obtained as follows:

$$\dot{Q}_k + \sum_k |H_i + KE_i + PE_i| = \dot{W}_k + \sum_k |H_j + KE_j + PE_j| \quad (1)$$

The terms in equation 1 are represented as: $\dot{Q}_k$ = heat rate to the kth component, $\dot{W}_k$ = rate of work output from the kth component, while H_i, KE_i, and PE_i, represent the enthalpy, kinetic energy, and potential energy, respectively at the component inlet. Similar expressions are used for controlling volume at the outlet. However, since the potential and kinetic energy effects are negligible, equation 1 is reduced to equation 2 as:

$$\dot{Q}_k + \sum_k |H_i| = \dot{W}_k + \sum_k |H_j| \quad (2)$$

Equation 2 is applied to all components of the system. Similarly, the mass balance is obtained at the component level with the term:

$$\sum \dot{m}_i = \sum \dot{m}_j \quad (3)$$

2.2 Methods

2.2.1 Exergy modelling of the plant

Similarly, the exergy modelling of the system is performed at steady state conditions using the second law of thermodynamics. Exergy based modelling has the potential to identify components in the system with large irreversibility and quantify them. The analysis considers each component as a control volume while applying the general exergy balance expression in equation 4 (Bejan & Tsatsaronis, 1995) as:

$$\dot{E}_{Q_k} + \sum_k \dot{E}_i = \dot{E}_{W_k} + \sum_k \dot{E}_j + \dot{E}_{D_k} \quad (4)$$

Where $\dot{E}_{D_k}$ is the exergy destruction rate, $\dot{E}_{Q_k}$ is the exergy flow rate associated with heat transfer, $\dot{E}_{W_k}$ is the rate of work done within the control volume, $\sum_k \dot{E}_i$ and $\sum_k \dot{E}_j$ is the sum of exergy flow rate in and out of the control volume, respectively. The subscript 'k' represents the kth component. The exergy associated with heat and work are each represented as:

$$\dot{E}_{W_k} = \dot{m}_i |h_j - h_i| \quad (5)$$

$$\dot{E}_{Q_k} = Q_k \left|1 - \frac{T_0}{T_k}\right| \quad (6)$$

The exergy terms in equation 4 can be obtained with the general relationship in equation 7 when it is easier to compute their specific heats at the stated conditions:

$$\dot{E}_i = \dot{m}_i \left\| c_p[T_i - T_0] - T_0 \left\{ c_p ln\left[\frac{T_i}{T_0}\right] - R * ln\left[\frac{P_i}{P_0}\right] \right\} \right\| \quad (7)$$

The terms with subscript '0' represent ambient thermodynamic properties. Also, equation 7 can be written and obtained in the form:

$$\dot{E}_i = \dot{m}_i \| |h_i - h_0| - T_0 |s_i - s_0| \| \quad (8)$$

The syntax for equation 8 is obtained with the expression:

$$\dot{E}_i = [H(t_i, P_i) - H(t_0, P_0)] - t_0 * [S(t_i, P_i) - S(t_0, P_0)] \quad (9)$$

Exergy destruction can also be expressed in terms of product and fuel exergy as:

$$\dot{E}_{D,k} = \dot{E}_{F,k} - \dot{E}_{Pk} \quad (10)$$

A summary of the component exergy balance terms is shown in Table1.

3. Results and Discussion

3.1 Performance Index in Design Conditions

The performance index of the system is shown in Table 2. It comprises the exergy efficiency of the plant. Other indices are the gross turbine output, the quantity of refrigeration, the exergy value associated with refrigeration, the exergetic sustainability index, the turbine inlet temperature (TIT), and the quantity of heating from the domestic water heater. These indices are presented with respect to the three refrigerants considered in the study.

Table 1. Summary of component exergy balance

Component	Exergy balance	Exergy of Fuel	Exergy of Product
Condenser 1	$\dot{E}_4 + \dot{E}_{23} = \dot{E}_5 + \dot{E}_{24} + \dot{E}_{D,CND}$	$\dot{E}_4 - \dot{E}_5$	$\dot{E}_{24} - \dot{E}_{23}$
Condenser 2	$\dot{E}_9 + \dot{E}_{25} = \dot{E}_{10} + \dot{E}_{26} + \dot{E}_{D,CND}$	$\dot{E}_9 - \dot{E}_{10}$	$\dot{E}_{26} - \dot{E}_{25}$
Evaporator 1	$\dot{E}_{12} + \dot{E}_{16} = \dot{E}_1 + \dot{E}_{17} + \dot{E}_{EVAP}$	$\dot{E}_{16} - \dot{E}_{17}$	$\dot{E}_1 - \dot{E}_{12}$
Evaporator 2	$Q_{evap}\left(1 - \frac{T_E}{T}\right) + \dot{E}_6 = \dot{E}_7 + \dot{E}_{D,EVAP}$	$\dot{E}_6 - \dot{E}_7$	$\dot{E}_{22} - \dot{E}_{21}$
Heater		$\dot{E}_{17} - \dot{E}_{18}$	$\dot{E}_{20} - \dot{E}_{19}$
Heat Exchanger	$\dot{E}_3 + \dot{E}_{11} = \dot{E}_8 + \dot{E}_{12} + \dot{E}_{D,HEX}$	$\dot{E}_3 - \dot{E}_8$	$\dot{E}_{12} - \dot{E}_{11}$
Pump	$\dot{E}_{10} + \dot{E}_{WP} = \dot{E}_{11} + \dot{E}_{D,PUMP}$	$\dot{W}_P$	$\dot{E}_{11} - \dot{E}_{10}$
Turbine	$\dot{E}_1 = \dot{E}_2 + \dot{E}_3 + \dot{E}_{WT} + \dot{E}_{D,TURB}$	$\dot{E}_1 - \dot{E}_2 - \dot{E}_3$	$\dot{W}_T$
Valve 1	$\dot{E}_2 = \dot{E}_4 + \dot{E}_{D,VI}$	$\dot{E}_2$	$\dot{E}_4$
Valve 2	$\dot{E}_5 = \dot{E}_6 + \dot{E}_{D,VII}$	$\dot{E}_5$	$\dot{E}_6$

Table 2: Performance of the system at standard conditions

Refrigerant	Exergy efficiency (%)	Net Power (kW)	Cooling (kW)	Exergy of cooling (kW)	TIT (°C)	Heating (kW)
R245fa	28.34	26.8	165.3	13.82	120	8.915
R1234yf	22.32	32.55	87.35	7.305	95	11.81
R1234ze	29.61	14.08	143	11.96	90	5.419

Table 3: Total exergy destruction

Refrigerant	Destruction	Total output
R245fa	219.3	201
R1234yf	358.2	131.7
R1234ze	169.3	162.5

Table 2 shows comparatively all listed performance with respect to simulations subject to R245fa, R1234yf, and R1234ze refrigerants. The exergy efficiency of the system is greatly enhanced by virtue of the ORC arrangement to include cooling as a product. The conventional ORC with a heat exchanger (Sahar and Fereshteh, 2015) reports exergy efficiencies of 15.33 %, 14.06 %, and 13.25 %, respectively for R245fa, R1234yf, and R1234ze refrigerants. However, incorporating the cooling arrangement led to an EE increase in exergy efficiencies in the order of 28.34 %, 22.32 %, and 29.61 % with refrigerants R245fa, R1234yf, and R1234ze in that order. The net power output ranged between 14.08 and 32.55 kW at a very moderate refrigerant mass rate of 2.05 kg/s and 0.3071 kg/s of the biomass syngas. This provision allows the operation of the system at a relatively low external heat content, but at temperatures up to 600°C. Accordingly, the system is suitable for direct coupling with a Brayton topping cycle at controlled mass flow rates of flue gas. Furthermore, turbine inlet temperatures were spread as 120°C, 95°C and 90°C, respectively, for R245fa, R1234yf, and R1234ze. This low range has been selected to facilitate the system's use for very low thermal applications.

The exergy destruction of the system with respect to the refrigerants is presented in Table 3 and reflects the geometry of the system and the working fluid. The choice of the operating parameters was made to be as close as possible to similar practical systems. Granted, with these operating parameters, the system's susceptibility to internal thermodynamic irreversibility is somewhat higher than the total products. This mode of exergetic destruction thus limited the sustainability of the system to about 0.9165, 0.3677, and 0.9602 respectively, for R245fa, R1234yf, and R1234ze. Thus, it is more practical to run the system with R245fa and R1234z.

3.2 Results From Sensitivity Analysis of The System

The results presented in section 3.1 were subject to the initial design conditions in terms of the chosen operating variables. In this section, however, several changes were made to the initial data, and their effects were investigated on certain performance indices of the system. In that order, the pinch point temperature, turbine inlet temperature, and pump inlet temperature are investigated on some selected performance indices of the system.

3.2.1 *Effect of pinch point temperature on exergy efficiency*

The pinch point temperature for the system has been selected to correspond with conditions at the lower side of the vapour generator since the temperatures at the inlet to the turbine and that into the evaporator have been fixed. In Figures 2, 3, and 4, the lower pinch point temperature difference is investigated on the exergetic efficiency of the system for the three refrigerants considered. Variation in pinch point temperature directly affects the quantity of heating since the temperature of the working fluid at inlet to the vapouriser is constrained by the effectiveness of the system's heat exchanger. Therefore, with unchanging turbine output and refrigerating cooling, but slight increase in the quantity of heating, the exergetic efficiency for the cycle with tri-products (cooling, heating and power) increases linearly for the refrigerants while the basic cycle with one product (power) is observed to be constant in Figures 2 through 4.

The tri-product cycle efficiency increased from 20.83 % to 29.68 %, 14.80 % to 23.65 %, and 22.1 % to 30.95 % respectively for R245fa, R1234yf, and R1234ze. On the other hand, the exergy efficiency for the system with turbine output as its product gave constant values of 15.33 %, 14.06 %, and 13.25 %, respectively for R245fa, R1234yf, and R1234ze.

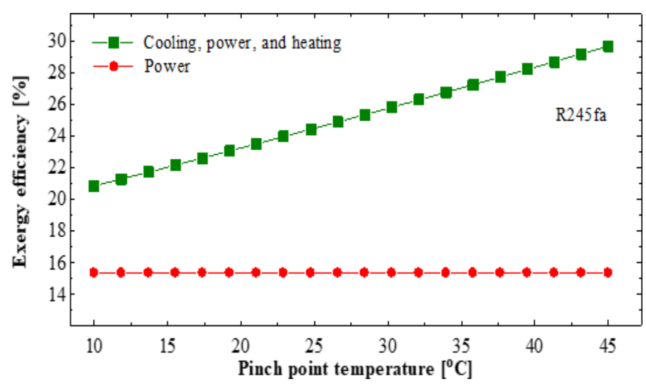

Figure 2: Effect of pinch point temperature on exergy efficiency [R245fa]

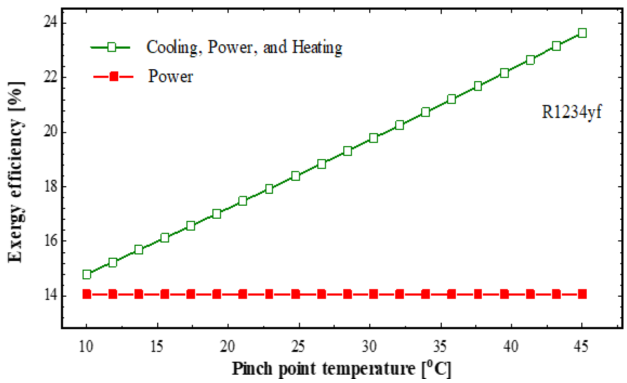

Figure 3: Effect of pinch point temperature on exergy efficiency [R1234yf]

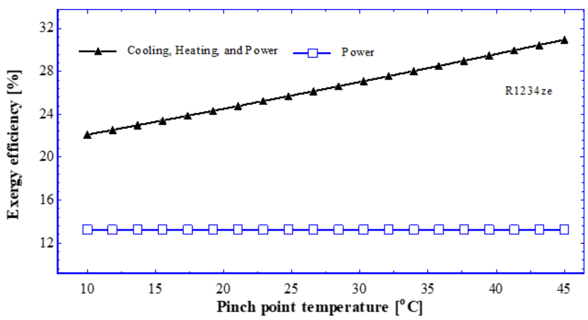

Figure. 4: Effect of pinch point temperature on exergy efficiency [R1234ze]

3.2.2 *Effect of pinch point temperature on heating and cooling*

Pinch point temperature variation at the lower side in the system significantly affects subcomponents down that line. And since the water heater is located there, its effect is investigated for the refrigerants and shown for the refrigerants in Figures. 5, 6, and 7. The magnitude of the variation in pinch point temperature grossly affects the temperature of the flue gas leaving the evaporator to the water heater since conditions at inlet to the ORC condenser have been defined and thermodynamic properties of the refrigerants en route to the evaporator are constrained by operating conditions like pump isentropic efficiencies and pressures.

Consequently, pinch point temperature increase resulted in an increasing magnitude of domestic water heating for the three considered working fluids though at different quantities while cooling capacities remain unaffected. For example, the magnitude of constant cooling and variable heating capacities are 165.3 kW; 4.356 kW to 13.605 kW for R245fa, 143 kW; 2.658 kW to 8.29 kW for R1234ze, 87.35 kW; and 5.793 kW to 21.29 kW for R1234y.

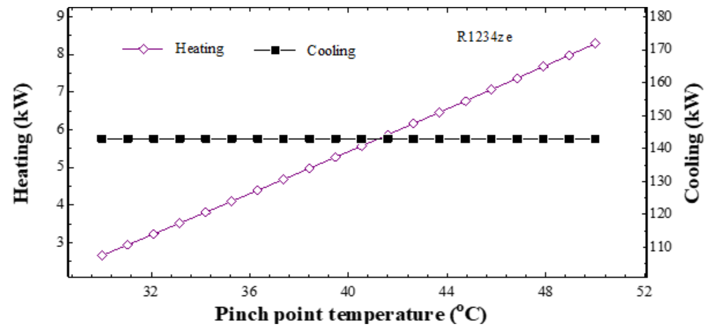

Figure. 5: Effect of varying pinch point temperature on heating and cooling loads of the system [R1234ze]

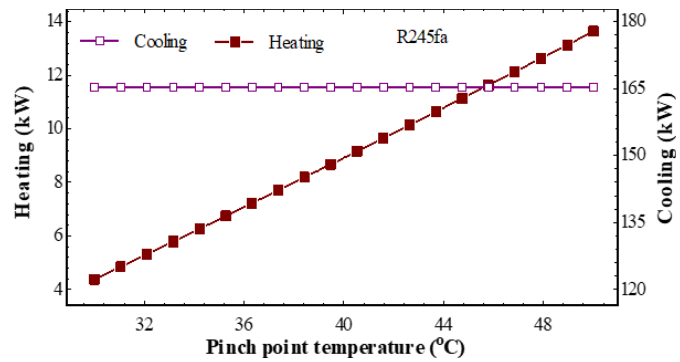

Figure 6: Effect of varying pinch point temperature on heating and cooling loads of the system [R1234yf]

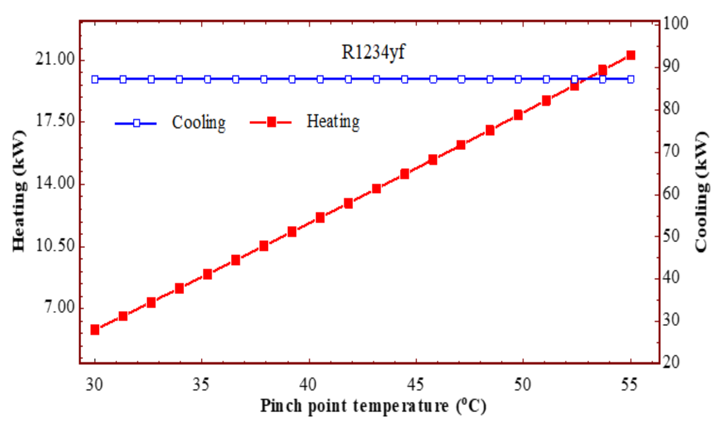

Figure 7: Effect of varying pinch point temperature on heating and cooling loads of the system [R245fa]

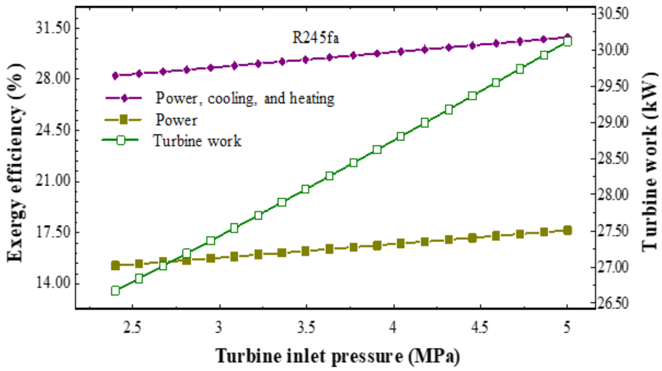

Figure 8: Effect of varying turbine inlet pressure on exergy efficiency and turbine work [R245fa]

3.3 Effect of turbine inlet pressure on exergy efficiency and turbine output

In Figure 8, the effect of turbine inlet pressure on turbine output and exergy efficiency is investigated at base conditions and an adjusted condition that yields three products. An increase in turbine inlet pressure at constant turbine back pressure creates a higher-pressure gradient, resulting in increased fluid expansion. This, in turn, results in higher turbine output for the three refrigerants, respectively. Additionally, with constant heat interaction in the evaporator of the system, a larger pressure gradient will result in increasing exergetic efficiencies. The variation in exergy efficiency increase is linearly related to the configuration of the system in the generation of products. This trend is shown for R245fa, where turbine work and exergetic efficiencies increased in tandem with turbine inlet pressures.

4. Conclusion

The research focused on the application of conventional exergy analysis to a biomass-assisted multi-generation energy system for power generation, heating and cooling using environmentally friendly refrigerants (R245fa, R1234yf, and R1234ze). The aim is to increase the overall system efficiency by incorporating turbine bleeding at a high energy level for cooling, in addition to whole power generation in the turbine as well as heating. The following conclusions were drawn:
The incorporation of the bleeding in the cycle led to an increase in exergy efficiencies of 28.34 %, 22.32 %, and 29.61 % with refrigerants R245fa, R1234yf, and R1234ze, respectively, compared to an earlier study with a similar configuration. The net power output ranged between 14.08 and 32.55 kW at a very moderate refrigerant mass rate of 2.05 kg/s and 0.3071 kg/s of the biomass syngas. This provision allows the operation of the system at relatively low external heat content, but at flue gas temperatures up to 600°C. Therefore, the system can be fired with a Brayton topping cycle at controlled mass flow rates of flue gas (0.3071 kg/s). Furthermore, turbine inlet temperatures were spread as 120°C, 95°C and 90°C, respectively for R245fa, R1234yf, and R1234ze. This low range can facilitate the system's operation from very low temperature waste heat from many sources. These findings could provide a valuable addition to subsequent studies on the creation and improvement of turbine power plants.

5. Recommendations

The study recommends that additional research should focus on trigeneration systems, which are more appealing for reducing heat loss and promising better turbine performance.
Incorporation of other mechanical devices like turbochargers and economisers is further recommended to assist the waste heat recovery mechanism to lower emissions into the environment and generate more power

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Competing Interest
The authors declare no conflict of interest.

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