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RESEARCH ARTICLE

OPTIMAL DESIGN OF ORGANIC RANKINE CYCLE POWER PLANTS FOR EFFICIENT UTILIZATION of BIOMASS ENERGY IN NIGERIA

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ABSTRACT

This study investigated the optimal design choice among four organic Rankine cycle (ORC) configurations for efficient utilization of solid biomass energy in Nigeria. Although vast opportunities exist for large-scale biomass power plants in the country, there has been little or no practical implementation yet, due to the limitation of technical know-how regarding thermodynamic conversion technologies. To bridge this gap, a thermodynamic optimization technique was applied in this study to the ORC. Specifically, the subcritical ORC (SUBORC), the regenerative subcritical ORC (SUBORC-REGEN), the supercritical ORC (SUPERORC), and the regenerative supercritical ORC (SUPERORC-REGEN) configurations were compared using established zero-dimensional optimization models implemented in MATLAB. Results showed that the SUPERORC-REGEN would be the most preferred choice amongst the options compared. Specifically, a palm kernel expeller (PKE) biomass fuel considered could yield about 1.98 MW of power at a thermal efficiency of about 28%. Additionally, it was obtained that the supercritical ORC would always outperform the subcritical types technically, with or without a regenerator. For the regenerative configurations, results showed that the supercritical ORC would generate 113 kW and 429 kW more net power than the subcritical ORC, respectively for n-pentane and n-butane working fluids. Similarly, the study reiterated that adopting a regenerative configuration would improve ORC performance. For instance, the SUPERORC-REGEN yielded 63% and 73% more power than the SUPERORC, respectively for n-pentane and n-butane working fluids. The practical economic implications of the different ORC configurations should be examined in future studies, alongside the investigation of exergy-based optimization potentials on component basis.

Keywords: *Organic Rankine Cycle, Biomass Energy, Renewable Power Plant, Sustainable Energy System, ORC Thermodynamic Optimization*

1. INTRODUCTION

The global energy scene has been saturated in recent times with debates on the need to transition from fossil-reliant infrastructure to systems that would use clean, renewable, and affordable energy sources. The reasons for these are not far-fetched; combustion of fossil fuels for energy generation is always associated with the emission of obnoxious gases into the atmosphere, which not only damages the ecosystem but also poses grave challenges to human health. Additionally, the non-renewable nature of most fossil fuels means that the reserves around the world would be depleted someday, even if it takes centuries. Thus, lots of scientific, socio-economic, political, and technical efforts are required worldwide to facilitate the practical deployment of renewable energy systems and to ameliorate the aforementioned consequences of conventional energy systems [1]. Additionally, although lots of research and practical activities have been carried out hitherto on modern energy systems powered by renewable resources [2], [3], [4], [5], [6], [7], [8], only a few of such systems are at commercial scale today.

Biomass is one renewable energy resource that has attracted unprecedented attention in the 21st century as a sustainable alternative to fossil fuels [9], [10]. It is formed from metabolic processes undergone by inanimate and animate living species [11]. Several resources are often referred to as biomass, but the main classes include forest biomass (woods and residues), agricultural biomass (energy crops, rotation crops, etc), and renewable wastes (industrial wastes and municipal wastes) [12], [13]. Depending on the sources of generation, biomass fuels can be solid, liquid, or gaseous in states. However, it is widely acknowledged that biomass fuels exist most abundantly as solids, which makes solid biomass the most commonly applied [14]. Several countries have formulated policies to identify and quantify biomass fuel reserves available locally and to promote their use for energy generation [15], [16], [17]. Additionally, similar efforts are currently being made at regional and global levels to campaign for the progressive use of biomass energy especially in energy-intensive sectors, such as the steel and cement industries, where low-temperature renewable sources might find limited or no relevance [18]. An example of such an international campaign effort is being made through the European Biomass Conference and Exhibition (EUBCE), an annual event that is currently in its 30th edition in the year 2022.

The research and practical efforts aimed at promoting energy generation from biomass fuels are not limited to developed countries. Several developing economies such as Nigeria have also acknowledged the potential roles of biomass in achieving the United Nation's Sustainable Development Goal (SDG) number 7 on clean and affordable energy. To justify this, a few of the many research on the assessment of biomass availability and potential usage for energy in Nigeria are summarized in this section. Olanrewaju et al. [19] assessed the potential of biomass energy in Nigeria and reported that more than 200 billion kg of biomass resources are available each year for energy generation in Nigeria, 80% of which are woody fuels and charcoals. Ben-Iwo et al. [20] corroborated the assertion that biomass resources are abundant in Nigeria, reporting specifically that it could contribute about 80% of the total energy consumed in the country. In a similar study, Ezealigo et al. [21] estimated that crop residues available in Nigeria could be processed into 8 Mtoe of cellulosic ethanol and 13 Mtoe of biogas each year, further reiterating the vast potential of biomass fuels for energy generation in the country. The same assertion was confirmed in the study by Jekayinfa et al.

[22] where bioenergy producible from several biomass resources in Nigeria was estimated at 2.3 EJ. However, the authors stated explicitly that despite the huge potential, little or nothing has been done towards the practical realization of large-scale bioenergy plants in the country. In the Southwestern part of the country alone, Elehinafe et al. [23] identified over 100 different types of woody/forest biomass which, if properly managed, could provide an inexhaustible biomass fuel reserve for powering thermal power plants in this region of the country. That is notwithstanding other aforementioned agricultural residues, municipal wastes, and industrial wastes which have been reported substantial in quantity in Nigeria [24]. Apart from the studies aimed at assessing biomass energy potential in Nigeria, other authors have focused on experimental characterization of different biomass fuels to facilitate their practical applications in biomass power plants [25], [26], [27]. The legal perspectives on the challenges and prospects of converting organic wastes to electrical energy in Nigeria were the focus of [28], where the authors remarked that a coherent and explicit legal framework is required to promote biomass energy in the country. Moreover, the life cycle assessment of selected Nbiomass fuels available abundantly in Nigeria has also been x-rayed in the literature [29], [30].

It is inferable from the foregoing literature review that huge potential exists for the generation of electricity from biomass in Nigeria. However, there is hardly one large-scale biomass thermal power plant existing in the country at the moment. Although all the studies reviewed above are congruent that biomass energy is sustainable in Nigeria, there is a lack of detailed technical information on the potential performance of power plants for the exploitation of Nigerian biomass fuels. To bridge this research gap, it is aimed in this study to assess different configurations of organic Rankine cycle (ORC) plants for optimal power generation from a typical biomass fuel in Nigeria. The choice of ORC technology is due to its global acceptance as a sustainable power conversion technology that is particularly suited for renewable energy resources [31], [32], [33], [34], [35], [36], including industrial waste heats [37], [38]. More so, several biomass-fired ORC plants have been installed in several countries already, most of which are currently running profitably [39], [40]. The specific objectives of this study are:

- To obtain optimal design configurations of ORC plant for efficient conversion of biomass to energy based on the features of a typical agricultural residue in Nigeria;

- To study the effects of the temperature at which the biomass fuel interacts with the ORC plant on system performance; and

- To analyze the sensitivity of system performance to the minimum cycle temperature.

The description of methods applied in the study, the main results obtained and their interpretation, and the summary of the entire study in the form of a conclusion, are presented in sections 2, 3, and 4 of this document, respectively.

2. METHODOLOGY

2.1. System Configurations

For the biomass section of the plant, a small-scale design is considered with a distinct zone for the combustion of biomass fuels, separated from the heater where hot flue combustion gases heat a heat transfer fluid (HTF) moving in cross flow to the gases. To achieve crossflow, a shell and tube heat exchanger configuration was employed with Therminol 66 considered as the HT flowing on the liquid side, interacting with the gases majorly by the convection heat transfer process. The combustion air is pre-heated at the entrance to the combustion chamber by the unused exhaust heat leaving the boiler with the high-temperature gases. It is possible to easily control the thermal capacity of this type of boiler, which makes it fit for this study. More details about the referenced biomass boiler can be found in the literature [41].

For the ORC section, four different configurations were compared for optimal exploitation of the biomass thermal energy produced by the furnace. The first configuration assumes a subcritical ORC type without regeneration, tagged here as SUBORC. It is subcritical because the maximum cycle pressure is below the critical pressure of the working fluid, and it is without regeneration because the working fluid leaving the turbine is condensed directly without recovering its heat within the cycle. In the second configuration, a subcritical ORC type is also assumed, but with the addition of a regenerator, tagged here as SUBORC-REGEN. In the regenerator, the heat content of the working fluid at the turbine exit is exploited within the cycle to pre-heat the liquid working fluid leaving the pump, before the external heat source is applied in the evaporator/pre-heater. The third configuration is considered a supercritical ORC type without a regenerator, tagged here as SUPERORC. In supercritical/transcritical ORC, the minimum cycle pressure is below the working fluid critical pressure but the maximum cycle pressure is greater than the working fluid critical pressure. Finally, the fourth configuration assumes a supercritical ORC type with a regenerator, tagged here as SUPERORC-REGEN. For each of the four ORC configurations, toluene, n-pentane, and n-butane were compared as working fluids. The choice of these working fluids is centered on their wide applications in real biomass ORC plants operating in different parts of the world [42], [43]. Air is considered as the heat sink for all the ORC configurations, so as not to mount additional pressure on water in the potential plant site, which is already inadequately supplied. Moreover, the biomass section interacts with the ORC plant mainly through the HTF for all configurations. At nominal conditions, the inlet temperature of the HTF leaving the boiler coincides with the ORC heat source temperature, while the temperature of the HTF exiting the ORC is the same as that entering the biomass boiler. Figure 1 illustrates the interactions of the biomass heat source with the ORC plant, based on a recuperative configuration.

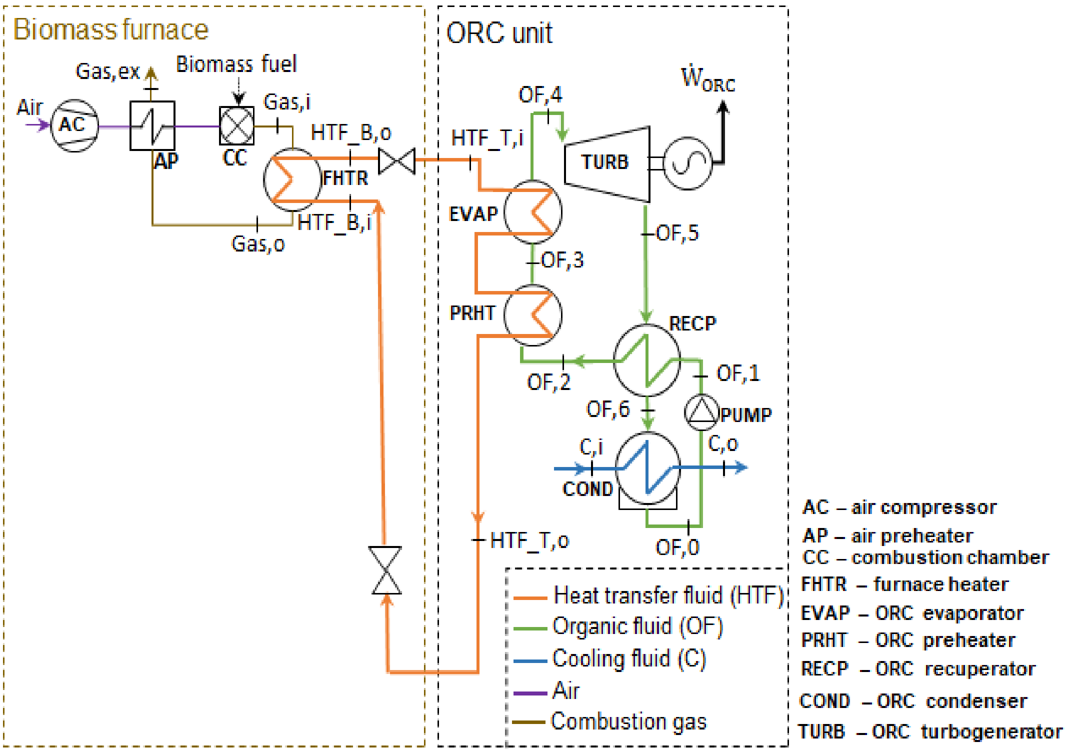

Figure 1. Interaction of the biomass heat source with the ORC unit.

2.2. Modeling of the Biomass and ORC Units

2.2.1. Biomass fuel and furnace modeling

The study employed an agricultural residue, palm kernel expeller (PKE), as the biomass fuel given its abundant availability in Nigeria and its favourable thermogravimetric characteristics for direct combustion [25]. A summary of the composition of the biomass fuel is highlighted in Table 1, in addition to the most relevant features of the combustion furnace. With an excess air value assumed to be 50%, the combustion gas temperature and mass flow rate were obtained by solving the combustion side balance equations for mass and energy, as follows:

$$\dot{m}_{Bio} + \dot{m}_{Air} = \dot{m}_{Gas} + \dot{m}_{Ash} + \dot{m}_{umb} \quad (1)$$

$$\dot{m}_{Bio}(LHV + h_{Bio}) + \dot{m}_{Air}h_{Air} = \dot{m}_{Gas}h_{Gas,i} + \dot{m}_{Ash}h_{Ash} + \dot{m}_{umb}LHV + \dot{Q}_{Loss} \quad (2)$$

The symbols $\dot{m}_{Gas}$, $\dot{m}_{Air}$, $\dot{m}_{Bio}$, and $\dot{m}_{Ash}$ denote mass flow rates of combustion gases, air, biomass fuel, and ash residue from the combustion of the biomass fuel, respectively, while $\dot{Q}_{Loss}$ and $\dot{m}_{umb}$ represent the insulation-induced heat losses in the furnace and mass flow rate of the unburned fuel, respectively. In this study, the sum of $\dot{Q}_{Loss}$ and $\dot{m}_{umb}$ was assumed equal to 1% of the useful part of the total biomass thermal energy.

It should be mentioned explicitly here that the aforementioned model-control mechanism of the biomass system means that the mass and energy balance equations of the combustion boiler are preserved not only at nominal conditions but also at off-design conditions. In this regard, the mass flow rate of biomass fuel consumed by the boiler is regulated depending on the thermal power required by the ORC per time. However, the temperature of the combustion gas is preserved by assuming the air-fuel ratio constant even under off-design conditions, to preserve the efficiency and other technical features of the modular biomass combustion boiler.

As stated earlier, the heat transfer side of the biomass boiler comprises a liquid-gas shell and tube heat exchanger configuration. The specific heat capacity of the HTF is obtained at the average temperature of the inlet and exit sides, and depending on the thermal duty required of the biomass system, the HTF mass flow rate is determined from the energy balance equation defined by the First Law of Thermodynamics. The effectiveness-NTU method is employed to simulate the behaviour of the liquid-gas heat exchanger under off-design conditions. Beginning with the thermal duty required of the biomass boiler, the change in the heat transfer by convection is computed based on the mass flow rate variation. Consequently, the real heat exchanger effectiveness and the temperature of the gas at the heat exchanger exit are determined.

2.2.2. ORC modeling

The ORC plant was designed to satisfy the zero-dimensional mass and energy balance models defined by the First Law of Thermodynamics. These models were implemented in MATLAB on a component basis for each of the ORC configurations studied. The mass and energy balance equations are defined respectively as follows:

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

$$\sum \dot{m}_i h_i + \dot{Q} = \sum \dot{m}_o h_o + \dot{W} \tag{4}$$

The symbol $\dot{m}$ denotes the mass flow rate of a working substance (kg/s), h represents the specific enthalpy (kJ/kg), $\dot{Q}$ is the flow of thermal energy, and $\dot{W}$ denotes the flow of work. The subscript 'i' indicates a flow into a component/system, while 'o' indicates an outward flow. The mass balance equation applies to all the system components as shown in eq. 3. For the energy model in eq. 4, the term $\dot{W}$ is null in all the heat exchangers, assuming zero pressure drop. In the pump, $\dot{W}$ is at the inlet side of the equation, and $\dot{Q}$ was taken as zero, assuming perfect thermal insulation of the component. Similarly. $\dot{Q}$ is taken as zero in the turbine for the same reason (perfect thermal insulation), and $\dot{W}$ is an outward flow representing the gross electrical power produced by the plant. Both $\dot{W}$ and $\dot{Q}$ were taken into account in the fan. The specific mathematical models applied to the plant components are exemplified in a previous study [44] for a regenerative subcritical ORC configuration. The net power output is obtained by subtracting the auxiliary power (for pump and fan) from the gross turbine power obtainable directly from eq. 4. Additionally, thermal efficiency was computed for the different case studies, defined as follows:

$$\eta = \frac{\dot{W}_{net}}{\dot{Q}_{ORC,in}} \qquad (5)$$

2.3. Optimization Approach of the ORC Systems

The optimization models which were also programmed in MATLAB, defined as the objective function, the maximization of the net power output of the ORC plant. For each of the ORC configurations considered, the optimization tools require the following input parameters:

- The temperature of the HTF (heat source) leaving the ORC and entering the biomass boiler;
- The minimum cycle (condensation) temperature; and
- HTF mass flow rate at the ORC inlet.

Additionally, other cycle parameters were fixed in the optimization tools as independent variables, as follows:

- Pinch point temperatures of the heat exchangers (evaporator, pre-heater, condenser, and recuperator in the case of the SUBORC-REGEN and SUPERORC-REGEN);
- Isentropic and electromechanical efficiencies of the pump;
- Isentropic and electric generator efficiencies of the turbine; and
- Mechanical efficiency of the fan.

The values assigned to these fixed variables are highlighted in Table 1. The decision variables optimized by the tool to maximize net output power are as follows:

- Maximum pressure and temperature of the ORC;
- ORC working fluid mass flow rate;
- Degree of superheat; and
- Minimum cycle pressure.

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Table 1. Characteristics of the biomass ORC plant.

Biomass combustion unit		**ORC unit**	
Furnace thermal duty	Decision variable	Working fluid	Toluene, n-Pentane, and n-Butane
Fuel composition (dry basis, % by weight)	53.6 % C, 5.1 % H, 0.5 % N_2, 40.8 % O_2,	Heat sink	Air
Volatiles (dry basis, % by weight)	76.1	Net electrical power	Optimized
Ash (dry basis, % by weight)	2.6	Nominal input thermal power	Decision variable
Higher heating value (dry basis)	21 MJ/kg	Nominal HTF flow rate	Decision variable
Moisture content (after drying)	8.9 %	Isentropic efficiency - pump	0.80
Stoichiometric air-fuel ratio	5	Motor efficiency - pump	0.98
Excess air	150 %	Isentropic efficiency - turbine	0.85
		Electromechanical efficiency	0.92
		Mechanical efficiency – cooling fan	0.60
		Pinch point temperature difference	5 ^{o}C

2.4. Sensitivity Analyses

Sensitivities of the objective function (net output power) to inlet temperature of the biomass heat source and cycle minimum (condensation) temperature were also investigated in the study. Additionally, ORC thermal efficiency that corresponds to each output power was computed during the sensitivity analysis for all the ORC configurations. Suffice it to mention that the optimization models were used for the sensitivity analysis, such that the results obtained remain the optimal choices for each of the working fluids and ORC configurations.

3. RESULTS AND DISCUSSION

3.1. Optimal Parameters of The Biomass ORC Plant Based on The Different Configurations

The main results of the optimization studies are presented in this section for the different configurations and organic working fluids considered.

3.1.1. Subcritical ORC without regeneration (SUBORC)

Table 2 highlights the optimal design of subcritical ORC plants without regeneration for the three working fluids investigated in this study. As can be seen, n-pentane would yield about 1 MW of electrical power from the biomass SUBORC plant, the highest among the working fluids compared in this study. Specifically, results showed that toluene would yield about 0.16 MW less and n-butane

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about 0.18 MW less, relative to n-pentane. The optimal thermal efficiency of the SUBORC plant followed a similar trend for the three working fluids; n-pentane showed the best performance at about 14%, followed by toluene at about 11.9%, and n-butane at about 11.6%. More so, the optimal parameters recorded for the auxiliary cycle power, ORC working fluid, minimum and maximum cycle temperature, and minimum and maximum cycle pressure follow different patterns for the different working fluids. For instance, for the n-pentane which recorded the highest net power and thermal efficiency, the evaporation temperature is only in the middle of the other two working fluids; greater than that of n-butane but less than that of toluene. The main significance of this is that the net power and thermal efficiency recorded by n-pentane take into account all the important cycle parameters highlighted in the table, rather than optimizing based on just a single or a few sets of parameters.

Table 2. Optimal parameters of the SUBORC plant utilizing biomass energy.

Parameter	Toluene	n-Pentane	n-Butane
Net Work (W)	8.3706e+05	1.0072e+06	8.1649e+05
Pump Work (W)	23398	44063	50081
Fan Work (W)	2.7001e+05	2.6339e+05	2.7238e+05
Max Pressure (Pa)	1.5625e+06	3.033e+06	3.4164e+06
Max Temperature (^oC)	246.39	196.08	167.94
Min Pressure (Pa)	1e+05	1.1567e+05	3.7849e+05
Min Temperature (^oC)	110.13	40	40
Superheat Degrees (^oC)	1	6.3931	22.384
ORC WF mass flow rate (kg/s)	12.791	12.076	13.18
Thermal Efficiency (%)	11.91	14.33	11.62

3.1.2. Subcritical ORC with regeneration (SUBORC-REGEN)

Table 3 reports the optimal design of subcritical ORC plants with regeneration for the three working fluids. Here too, n-pentane would yield the highest net electrical power of about 1.9 MW. However, the use of a regenerator would shore up significantly the performance of n-butane, making it outperform toluene. Specifically, results showed that while toluene would yield just about 1 MW of net electrical power, n-butane would yield 50% more at about 1.5 MW. Moreover, juxtaposing the results of the SUBORC and the SUBORC-REGEN shows that the use of regeneration would increase net power production for all the working fluids employed, but at varying degrees. In this regard, results showed that toluene would yield about 21% more power with the use of a regenerator relative to the SUBORC configuration; n-pentane would yield about 86% more power, and n-butane about 89% more power. Additionally, the trend of thermal efficiency for the three working fluids is similar to that of the net power; n-pentane recorded the highest efficiency at about 27%, followed by n-butane at about 22% and toluene at about 14%. As would be expected, regeneration also increased significantly the thermal efficiency for all the working fluids analyzed in the study, also at varying degrees. Specifically, regeneration would improve the ORC thermal efficiency by only about 2.5 percentage points using toluene as the working fluid, followed by n-butane with an increase of about 10.4 percentage points, and n-pentane with an increase of about 12.3 percentage points.

Table 3. Optimal parameters of the SUBORC-REGEN plant utilizing biomass energy.

Parameter	**Toluene**	**n-Pentane**	**n-Butane**
Net Work (W)	1.0088e+06	1.8699e+06	1.5453e+06
Pump Work (W)	21291	49617	56236
Fan Work (W)	2.0067e+05	1.7217e+05	1.8366e+05
Max Pressure (Pa)	1.1833e+06	3.033e+06	3.4164e+06
Max Temperature (^{o}C)	228.21	294	258.72
Min Pressure (Pa)	1e+05	1.1567e+05	3.7849e+05
Min Temperature (^{o}C)	110.13	40	40
Superheat Degrees (^{o}C)	1	104.31	113.17
ORC WF mass flow rate (kg/s)	15.714	13.598	14.8
Thermal Efficiency (%)	14.36	26.61	21.99

3.1.3. Supercritical ORC without regeneration (SUPERORC)

Results of the optimal design of the supercritical ORC plant without regeneration for biomass energy exploitation are highlighted in Table 4. In this case, toluene showed a high level of incompatibility with the characteristics of the biomass heat source under investigation, basically due to the need to increase the cycle maximum pressure beyond the critical pressure of the working fluid. Thus, only n-pentane and n-butane were assessed for the SUPERORC configuration as defined in this study. As can be seen, n-pentane would also outperform n-butane in this case study, yielding about 1.22 MW of electrical power from the biomass system as against about 1.14 MW achievable with the use of n-butane. Again, optimal thermal efficiencies of the SUBORC plant followed a trend similar to the net power output from the respective working fluids; n-pentane showed the best performance at about 17%, followed by n-butane at about 16%. Furthermore, results showed that increasing the cycle maximum pressure above the working fluid critical pressure would increase net output power and thermal efficiency for all working fluids. Results revealed specifically that for non-regenerated ORC configurations, SUPERORC increased net output power by about 210 kW for n-pentane and about 324 kW for n-butane, relative to the SUBORC case study.

Table 4. Optimal parameters of the SUPERORC plant utilizing biomass energy.

Parameter	**n-Pentane**	**n-Butane**
Net Work (W)	1.2172e+06	1.1409e+06
Pump Work (W)	1.2715e+05	1.288e+05
Fan Work (W)	2.563e+05	2.6056e+05
Max Pressure (Pa)	1.1e+07	1.1e+07
Max Temperature (^{o}C)	295	273.73
Min Pressure (Pa)	1.1567e+05	3.7849e+05
Min Temperature (^{o}C)	40	40
Superheat Degrees (^{o}C)	98.45	121.75
ORC WF mass flow rate (kg/s)	9.3396	9.6956
Thermal Efficiency (%)	17.32	16.23

3.1.4. Supercritical ORC with regeneration (SUPERORC-REGEN)

Table 5 highlights the results of the optimal design of the supercritical ORC plant with regeneration with n-pentane and n-butane as working fluids. It was obtained that n-pentane for the SUPERORC-REGEN case study would yield the highest power among all the configurations compared in this study, at about 1.98 MW. However, its increase over output power with n-butane for the same case study is only marginal, estimated at slightly above 8 kW. Additionally, juxtaposing the results in Tables 4 and 5 corroborate the earlier analysis that the addition of a regenerator would increase net output power. Here, integration of a regenerator to the supercritical ORC plant would yield about 63% more net output power for n-pentane and about 73% more for n-butane. Similarly, comparing the regenerated ORC for the subcritical and supercritical configurations (SUBORC-REGEN vs. SUPERORC-REGEN) corroborate the earlier analysis that the application of maximum pressure higher than the working fluid critical pressure would increase performance. Here, about 113 kW more power is generated by n-pentane and about 429 kW by n-butane, when the supercritical configuration is adopted in place of the subcritical one for the regenerative ORC plant. Furthermore, the trend of thermal efficiency for the working fluids is equally similar to that of the net power under this case study; n-pentane recorded a thermal efficiency of about 28.22%, slightly higher than what obtains in n-butane, 28.10%. As would be expected, regeneration also increased significantly the thermal efficiency for the working fluids analyzed in the supercritical ORC configurations. Specifically, regeneration would improve the supercritical ORC thermal efficiency by about 11 percentage points using n-pentane as the working fluid, and by approximately 12 percentage points with n-butane as the working substance. Moreover, switching from subcritical to supercritical configuration for the regenerative ORC would also improve the thermal efficiency by 1.61 percentage points for n-pentane and 6.11 percentage points for n-butane working fluids.

Table 5. Optimal parameters of the SUPERORC-REGEN plant utilizing biomass energy.

Parameter	**n-Pentane**	**n-Butane**
Net Work (W)	1.983e+06	1.9746e+06
Pump Work (W)	1.0022e+05	1.7979e+05
Fan Work (W)	1.6939e+05	1.722e+05
Max Pressure (Pa)	6.1532e+06	1.1e+07
Max Temperature (^{o}C)	295	295
Min Pressure (Pa)	1.1567e+05	3.7849e+05
Min Temperature (^{o}C)	40	40
Superheat Degrees (^{o}C)	98.45	143.02
ORC WF mass flow rate (kg/s)	13.272	13.533
Thermal Efficiency (%)	28.22	28.10

3.2. Sensitivity of the Optimal ORC Parameters to Biomass Inlet Temperature

3.2.1. Net power output and thermal efficiency variations for the SUBORC configuration

The effects of change in biomass temperature at the ORC inlet on the system performance are reported in this section for the SUBORC configuration. As can be seen in Fig. 2, net output power increases linearly with an increase in heat source inlet temperature for all the working fluids. The highest net power output is recorded by n-pentane over all the range of biomass inlet temperatures analyzed in this study. For n-butane and toluene, performance depends strongly on the exact biomass temperature at the ORC inlet. Specifically, results showed that n-butane outperforms toluene only at lower heat source temperatures. About equal net output power is produced by the two working fluids up to around 294 ^{o}C, beyond which toluene would yield higher net output power than n-butane. Additionally, thermal efficiencies of ORC using both n-pentane and n-butane are obtained to be insensitive to a change in biomass inlet temperature, while the efficiency increases also linearly with biomass inlet temperature for toluene.

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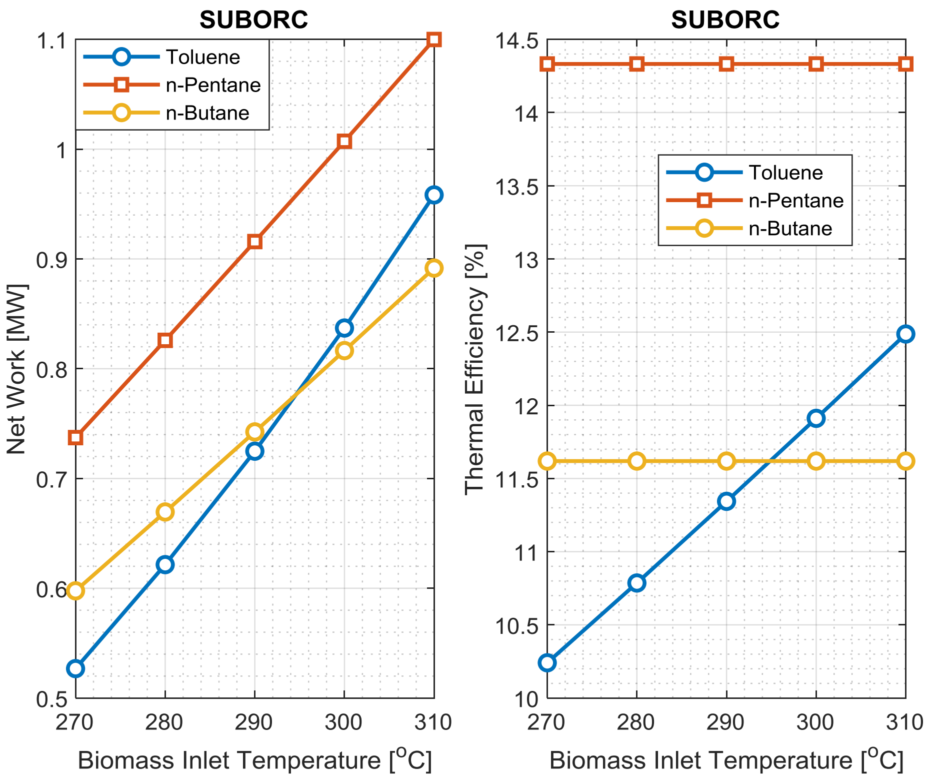

Figure 2. Variations of the net output power and thermal efficiency with heat source temperature for the SUBORC.

3.2.2. Net power output and thermal efficiency variations for the SUBORC-REGEN configuration

Sensitivity analysis results for the SUBORC-REGEN configuration (Fig. 3) also show that the high net output power recorded by n-pentane is across a wide range of biomass temperatures at the ORC inlet. Here too, the net output power increases linearly with an increase in the heat source temperature for all the working fluids considered. However, it is worth noting that there is no overlap of net output power in the case study as observed in the SUBORC; n-butane yielded more net power than toluene irrespective of the temperature of the heat source. Moreover, results showed that the plant thermal efficiency would increase initially with an increase in biomass inlet temperature up to around 300 ^{o}C for n-pentane, beyond which it remains fairly constant. Again, n-butane showed insensitivity to thermal efficiency with varying heat source temperatures, and toluene showed a linear increase in thermal efficiency as the biomass temperature increased.

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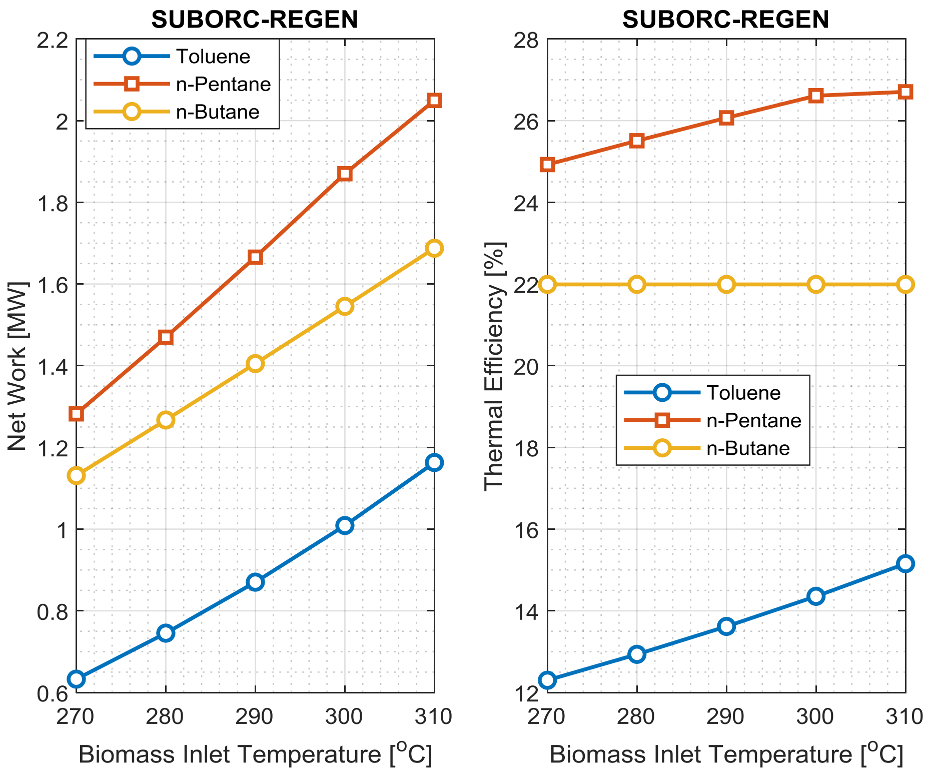

Figure 3. Variations of the net output power and thermal efficiency with heat source temperature for the SUBORC-REGEN.

3.2.3. Net power output and thermal efficiency variations for the SUPERORC configuration

The results of the sensitivity of net power output and thermal efficiency to variation in biomass inlet temperature are shown in Fig. 4 for the SUPERORC configuration. As can be seen, net output power increases with an increase in heat source temperature for the two working fluids. Also, n-pentane showed higher net power output than n-butane across the range of biomass temperature considered, although at a lower degree compared to the SUBORC configuration. Additionally, the thermal efficiency of the SUPERORC configuration increases non-uniformly with an increase in biomass temperature at the ORC inlet for n-pentane. For n-butane, there is only a slight increase in efficiency between 270 ^{o}C and 280 ^{o}C biomass temperature; thermal efficiency remains constant with a further increase in heat source temperature.

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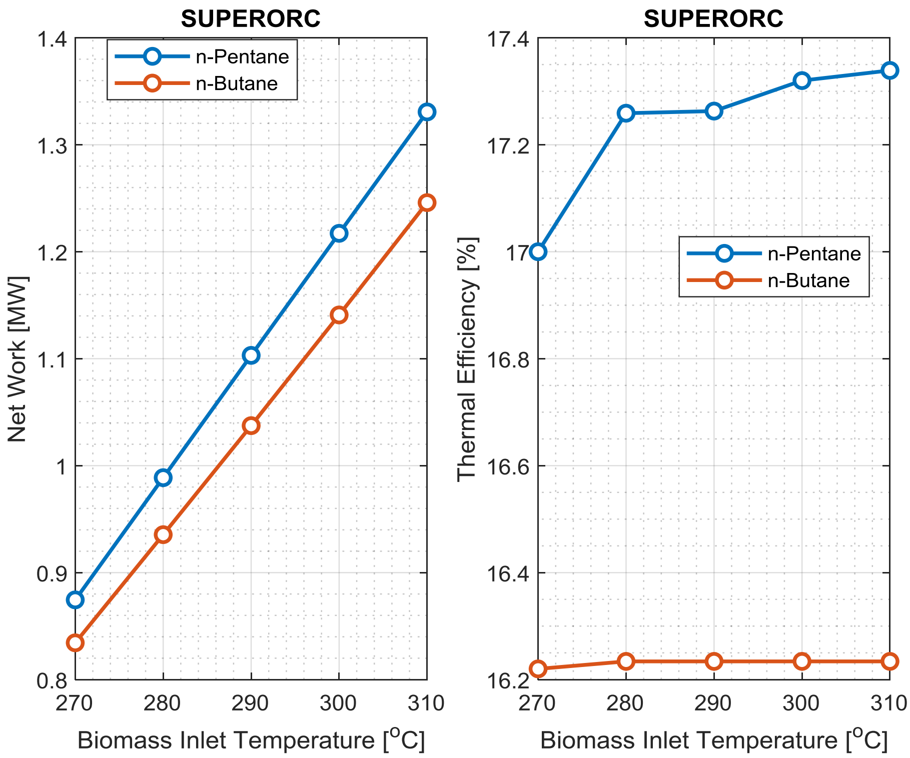

Figure 4. Variations of the net output power and thermal efficiency with heat source temperature for the SUPERORC.

3.2.4. Net power output and thermal efficiency variations for the SUPERORC-REGEN configuration

As can be seen in Fig. 5, net power output equally increases with an increase in biomass temperature for both n-pentane and n-butane. However, the margin of the net output power between n-pentane and n-butane is quite small throughout the range of temperatures investigated, implying that the two working fluids would perform at about the same level for the SUPERORC-REGEN configuration. In like manner, the thermal efficiency increases linearly with an increase in heat source temperature for the two working fluids.

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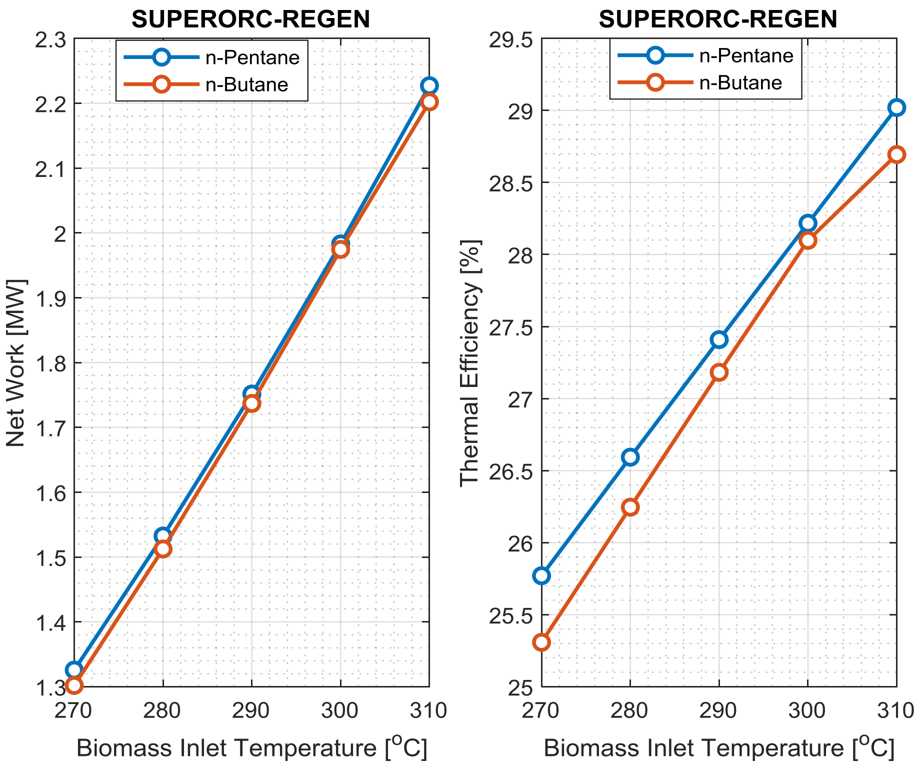

Figure 5. Variations of the net output power and thermal efficiency with heat source temperature for the SUPERORC-REGEN.

3.3. Sensitivity of the Optimal ORC Parameters to Minimum Cycle (Condenser) Temperature

3.3.1. Net power output and thermal efficiency variations for the SUBORC configuration

Effects of the cycle minimum temperature (condenser temperature) on net output power and thermal efficiency are reported here for the SUBORC. As can be seen in Fig. 6, increasing the condenser temperature led to a linear decrease in net output power for n-pentane and n-butane, while toluene showed no sensitivity to a change in condenser temperature. More so, the same trend was obtained for the thermal efficiency; an increase in condenser temperature decreases thermal efficiency linearly for n-pentane and n-butane, while toluene remains constant over the range of the condenser temperature considered.

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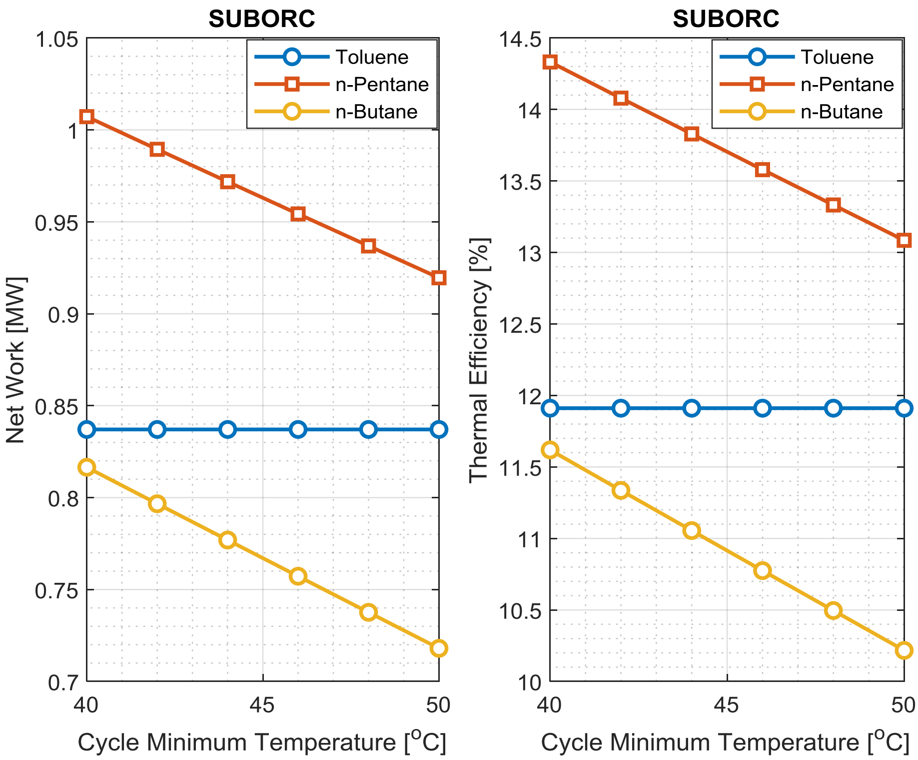

Figure 6. Variations of the net output power and thermal efficiency with condenser temperature for the SUBORC.

3.3.2. Net power output and thermal efficiency variations for the SUBORC-REGEN configuration

Furthermore, Fig. 7 shows that net power output and thermal efficiency decrease linearly with an increase in the cycle minimum temperature for n-pentane and n-butane, while toluene shows no sensitivity with a variation in condenser temperature.

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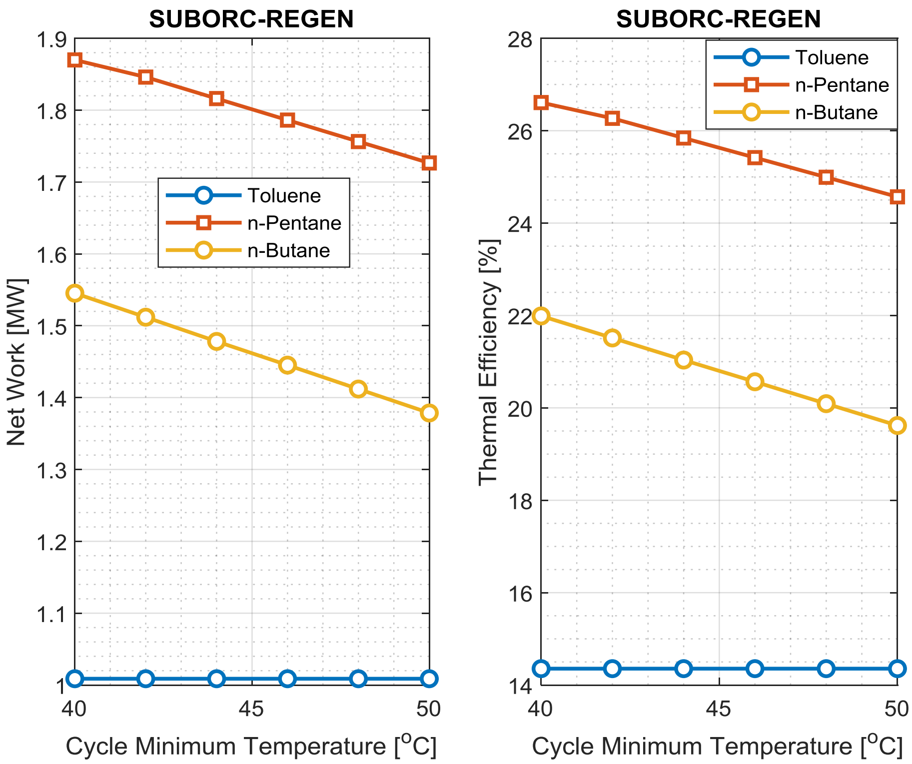

Figure 7. Variations of the net output power and thermal efficiency with condenser temperature for the SUBORC-REGEN.

3.3.3. Net power output and thermal efficiency variations for the SUPERORC configuration

For the supercritical ORC without regeneration, Fig. 8 shows that both n-pentane and n-butane resulted in a decrease in both the net power output and thermal efficiency with an increase in condenser temperature. However, n-pentane still showed a better performance across the range of condenser temperatures considered in the study.

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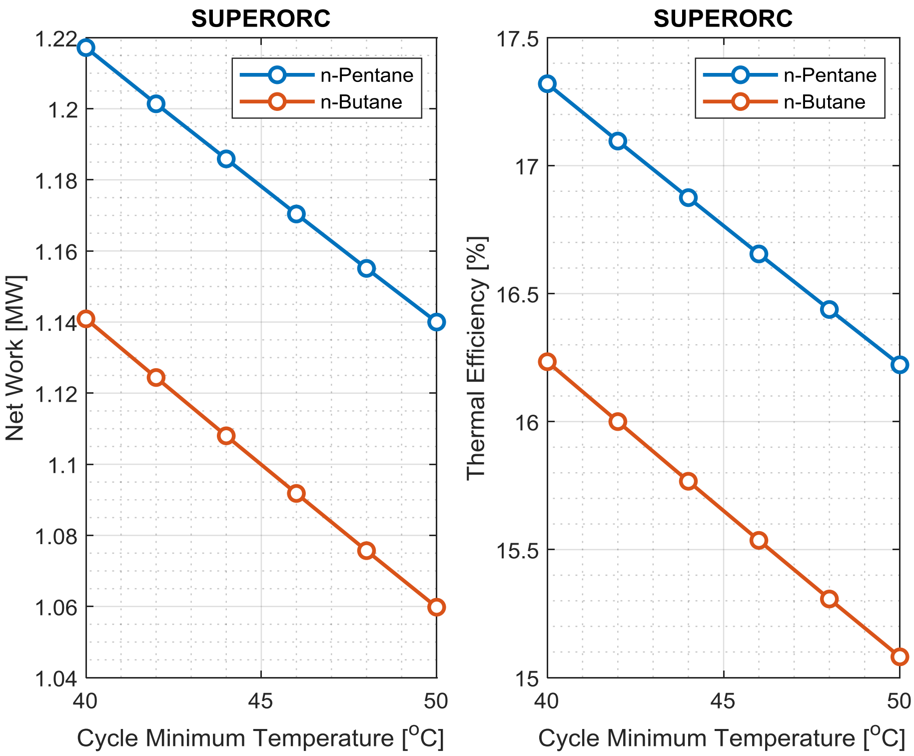

Figure 8. Variations of the net output power and thermal efficiency with condenser temperature for the SUPERORC.

3.3.4. Net power output and thermal efficiency variations for the SUPERORC-REGEN configuration

The sensitivity analysis results which are shown in Fig. 9 also revealed that the lower the cycle minimum temperature, the higher the net output power and thermal efficiency for both n-pentane and n-butane. It can however be seen here also that the magnitude of the difference between the two working fluids is quite marginal over the range of condenser temperatures considered, with both the net power and efficiency of n-butane almost matching those of n-pentane when the condenser temperature of around 50 ^{o}C is considered.

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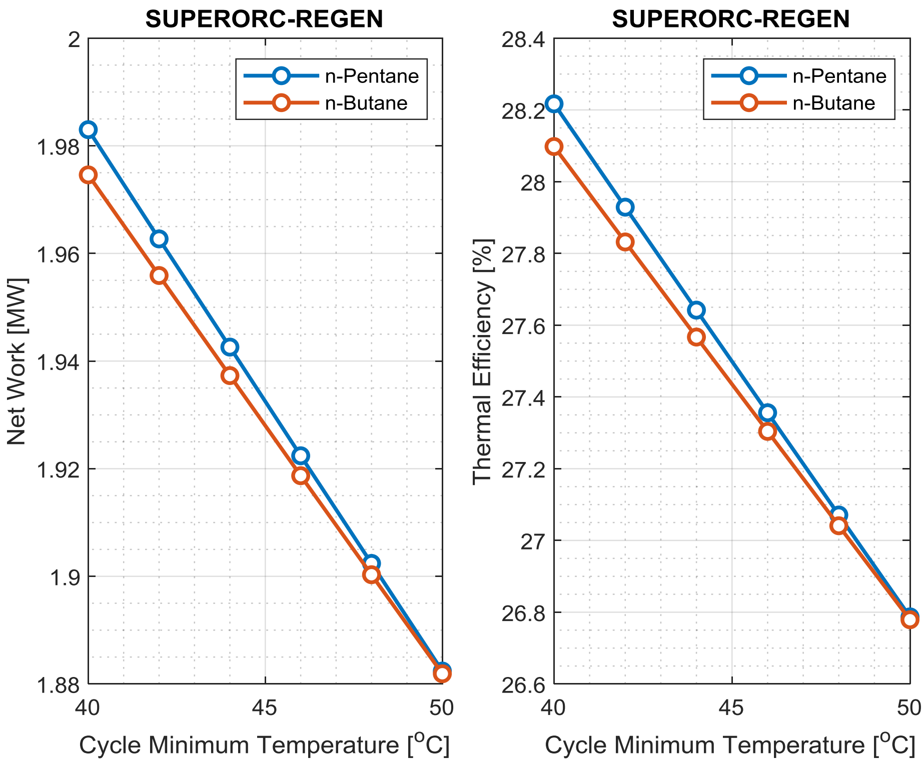

Figure 9. Variations of the net output power and thermal efficiency with condenser temperature for the SUPERORC-REGEN.

4. CONCLUSIONS

An attempt has been made in this study to investigate several ORC configurations to select one that would optimize electricity production from the combustion of a typical solid biomass fuel available abundantly in Nigeria. Although several authors have reported in the literature that there is vast potential for energy generation from biomass in Nigeria, no known large-scale biomass power plant exists in the country due to the limitation of technical know-how relating to conversion technologies. To bridge this gap, characteristics of a PKE, an agricultural waste available all over Nigeria, were employed in this study for the optimal design of ORC plants. A model-control biomass boiler was used to analyze the direct combustion of the solid biomass fuel to provide the thermal energy required for the ORC plant operation. For the ORC specifically, optimal designs of four different configurations were compared: the SUBORC, the SUBORC-REGEN, the SUPERORC, and the SUPERORC-REGEN. Furthermore, the effects of the temperature of the biomass heat source at the

ORC inlet and the minimum cycle temperature on the optimal performance of the various configurations were assessed. The main results obtained from the study are:

- The supercritical ORC type is capable of generating higher electrical power than the subcritical type. Taking for instance the regenerative ORC configuration, results showed that supercritical ORC would generate 113 kW and 429 kW more net power than the subcritical ORC, respectively for n-pentane and n-butane working fluids. Similarly, it was reiterated in the study that the adoption of regeneration improves ORC performance. Exemplarily, the SUPERORC-REGEN yielded 63% and 73% more power than the SUPERORC respectively for n-pentane and n-butane working fluids. Overall, it was obtained that the SUPERORC-REGEN would be the preferred choice amongst the options compared in this study for optimal exploitation of typical solid biomass in Nigeria;

- The working fluid n-pentane yielded the highest net power output and thermal efficiency for all the configurations examined. Specifically for the preferred SUPERORC-REGEN configuration, it yielded net power of about 1.98 MW and thermal efficiency of 28.22%;

- Increasing the biomass temperature at the ORC inlet led to an increase in net power output for all the configurations and working fluids considered in the study. Again, n-pentane outperformed n-butane and toluene across the range of heat source temperature considered, but only marginally concerning n-butane for the preferred SUPERORC-REGEN configuration;

- Increasing the minimum cycle temperature resulted in a linear decrease in net power output and thermal efficiency for n-pentane and n-butane working fluids in all the configurations considered, as would be expected.

In sum, deploying a supercritical ORC plant with regeneration portends an optimal choice for sustainable exploitation of solid biomass fuels which are abundant in Nigeria, for energy production. Future studies should focus on the economic assessment of the various ORC configurations to spur investment to achieve practical implementation of such plants in the country. Additionally, an exergy-based analysis should be conducted to investigate further optimization potentials of the ORC plant on a component basis.

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