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Special Issue
A Themed Issue in Honour of Professor Onukwuli Okechukwu Dominic (FAS).

This special issue is dedicated to Professor Onukwuli Okechukwu Dominic (FAS), marking his retirement and celebrating a remarkable career. His legacy of exemplary scholarship, mentorship, and commitment to advancing knowledge is commemorated in this collection of works.

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Cascade Organic Rankine Cycle (ORC) Power Production Systems Using a Low-Temperature Heat Source

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Abstract
The Organic Rankine Cycle (ORC) is a thermodynamic cycle that uses organic working fluids to transform heat into electricity through mechanical work. The performance of the ORC employing five working fluids namely, R123, R245ca, R601a, R601 and R610 was analyzed. It was demonstrated that the selected organic fluids could produce power from a low-temperature heat source. These working fluids were selected for solar heat usage based on their boiling points which were carefully selected to fall close to the reference ambient temperature of 25 ^oC-32 ^oC to avoid problems with condensation. The system performance indices (system efficiency, work output, and power output) were calculated using a commercial software named IPSEpro, which adopted an expander model and took pipe and heat exchanger pressure drops into account. R123 as the only working fluid in the three-stage system gave a power output 33.3% higher than that of the two-stage cycle which was 26.7% higher than the single-cycle system, this was the general trend for the two-stage and the three-stage systems. For the four-stage system, however, there was a significant drop in power output The highest power output of 1.68 KW came from the three-stage cascade cycle using R245ca as the only working fluid. The best working fluid combinations for two-stage and three-stage systems were shown to be R123+R245ca and R123+R245ca+R601a respectively.

Keywords: Rankine cycle, cascade, power, low temperature, heat source

1.0 Introduction

The Rankine cycle system is made up of basically an evaporator, a turbine (expander) to receive the vapor and power a generator, a condenser, and a pump to return the condensed fluid to the evaporator. Water is frequently used as the working fluid hence, steam is used to power the turbine. An organic Rankine cycle (ORC) system functions similarly to a practical steam engine but uses a hydrocarbon fluid instead of water (Bamorovat and Kim, 2017; Chen et al., 2017) In generating power from alternative sources instead of fossil fuels, a very popular system that has gained the attention of researchers is the organic Rankine cycle (ORC) since it has many advantages over the conventional steam Rankine cycle, the main one being that it can employ low- and medium-temperature as well as low-grade heat sources which are not amenable to the conventional steam Rankine cycle (Zhai et al., 2016; Ma et al., 2018). The need for sustainability and proper energy conversion and management methods has made energy conservation a top global priority. To preserve the environment and promote both human and animal health, the world's energy landscape is quickly evolving and moving away from the usage of fossil fuels toward various green and clean energy sources. The integration of solar energy with ORC has been investigated experimentally and theoretically (White, 2015; Zhai et al., 2016; Mehrpooya et al., 2017).

The Rankine cycle has been in use for many years with water as the working fluid. Since it is a thermodynamic cycle involving phase changes of the fluid from liquid to vapor and then back to liquid, heat is absorbed at the evaporator and rejected at the condenser with a consequence of work production at the turbine for power generation in accordance with the first and second laws of thermodynamics. The boiling point of the working fluid determines the operating temperature range of the cycle which is usually narrow. High-temperature heat sources are employed in steam cycles to achieve vaporization and sufficient superheat for significant efficiency of the system (Babalola and Adelaja, 2022).

Low-temperature heat sources (like industrial waste heat, engine exhaust heat and solar heat) are in abundance and constitute a huge energy waste but are inadequate for vaporizing the conventional Rankine cycle working fluid (water). This has given birth to the deployment of organic fluids with relatively low boiling points (Yufei et al., 2016). Solar heat being abundant in tropical regions like Nigeria, constitutes a huge waste in low-grade energy (heat) that can be harnessed for the production of high grade-energy (electricity) via the ORC system. Single-cycle ORC systems have paved the way for researchers to explore cascaded (multistage) ORC systems for increased efficiency (Jie and Hulin, 2016), optimization of working fluids (Babalola and Adelaja, 2022) and greater power output (Yun et al., 2015). Sung et al. (2016) showed that by introducing a second cycle with appropriate working fluids, the system efficiency could be increased by up to 25%. The challenge of selecting suitable working fluids for each cycle of a multistage system has come to the focus of some researchers. It has been shown that the chemical and physical properties of working fluids strongly affect the performance of each cycle (Read et al., 2014; Kaya et al., 2015; White and Sayma, 2018).

In this study, cascaded two-stage and three-staged ORC systems were investigated using a solar heat source. By carefully choosing the working fluids based on some key factors (boiling point, critical temperature, critical pressure, density, molecular weight, molecular complexity, safety and environmental friendliness), the first goal was to determine the cycle performance in terms of power output, thermal efficiency, and exergy efficiency under different heat-source temperatures and turbine inlet pressures. Secondly, water was used as a reference fluid to compare the properties of the working fluids. The analysis of the thermal efficiency of single and cascade systems was the third objective and fourthly to determine the best combinations of fluids for two-stage and three-stage cascade systems. The working fluids chosen have boiling points between 25 and 32 ^{o}C in order to easily condense them without difficulty in the condenser. These studies offer the needed information and data to optimize the number of cycles for efficient ORC system operations with different working fluid combinations which have not yet been addressed by researchers. More research work is yet to be done with respect to the interactions of different working fluids when employed in different cycles of an ORC system which is partly addressed here. Also, optimizing the number of cycles for best performance remains a challenge which is also frayed into by this work with a leap in extending the number of cycles to four

2.0 Methodology

The five selected working fluids for the simulation of the thermodynamic analysis of the process were, R123, R245ca, R601a, R601 and R610. A commercial software IPSEpro which uses a straightforward expander model was used to analyze the performance of the two-stage, three-stage, and four-stage ORC systems while accounting for the heat exchange and pipe pressure drops. The working fluids were assessed for safety, reduced environmental impact, and thermophysical properties. Tables 1 and 2 show the safety and physical properties of the selected working fluids. The operating fluid flowrate was set to 1 kg/s; the pump and turbine isentropic efficiency was set to 80% and the equation of state model used was SRK for each of the working fluids.

Table 1: Environmental, Safety and Health Impact Properties of the Working Fluids

working fluid	Safety group	Lower Flammability Limit (LFL) (%)	Ozone Depletion Potential (ODP)	Global Warming Potential (GWP)	Atmospheric life time (years)
R123	B1 (high toxicity and non-flammable)	6.3 excellent	0.02 (excellent)	77 (good)	1.3
R601a	A3 (low toxicity and highly flammable)	1.32 fair	0 (excellent)	1300 (fair)	12
R245ca	A1 (non-toxic and non-flammable)	7.1 excellent	0 (excellent)	726 (good)	7.6
R610	A1 (non-toxic and non-flammable)	1.9 fair	0 (excellent)	4 (Excellent)	1
R601	A3 (low toxicity and highly flammable)	1.4 fair	0 (excellent)	4 (Excellent)	3

Table 2: Physical Properties of the Working Fluids

Parameters	R123	R245ca	R601	R610	R601a	Water
Name	2,2-Dichloro-1,1,1-trifluoroethane	1,1,2,2,3-Pentafluoropropane	n-Pentane	Diethyl ether	Isopentane	Water
Molecular Formula	$C_2HCl_2F_3$	C3H3F5	C_5H_{12}	$(C_2H5)2$ O2	C_5H_{12}	H_20
Molecular Weight (g/mol)	152.93 (good)	134.05 (good)	72. 15 (very good)	74.12 (very good)	72.15 (very good)	18
Normal Boiling Point, t_{nbp} (ºC)	27.82	25.13	36.06	34.5	27.83	100
Critical Pressure, p_{cr} (MPa)	3.66	3.39	3.36	3.64	3.38	22.12
Critical Temperature, t_{cr} (ºC)	183.68	174.42	196.68	192.5	187.2	373.946
Critical density (g/cm^3)	0.55	0.523	0.232	0.26	0.63	1.00
Viscosity (poise)	1.08	0.000042	0. 00023	0.000224	0.00014356	0.01
Type of fluid	Isentropic	Dry	Dry	Dry	Dry	Wet
Specific Volume of liquid at 25ºC (m^3/kg)	0.17460	0.1682	0.1183	0.1064	0.19863	1.0030
Specific Volume of vapor at 25ºC (m^3/kg)	43.742	47.6758	24.2517	24.0756	28.274	1694
V_v/V_l	251	284	205	226	142	1700
Thermal conductivity (W/m.K)	0.075862	0.1043	0.0186	0.075862	0.02620	0.598
Specific heat (J/kg.K)	1022	1011.26	1730	1022	1010.345	4200

2.1 Process Description for the Cascade System

The feed pump, evaporator, turbine, and condenser are the major components of the ORC. A most simplified description for a cascaded system with a number of cycles (N) would look thus: The working fluid in Cycle-1 absorbs heat ($Q1_A$) from the low-temperature source (e.g. Solar heat) at Evaporator-1, expands at Turbine-1 to produce work (W1) and rejects heat ($Q1_R$) at Condenser-1 from where it returns to Pump-1 as a liquid. The heat ($Q1_R$) is harnessed in a heat exchanger to vaporize the second working fluid in Evaporator-2 of Cycle-2 (more heat could be added from the heat source) which thus absorbs heat ($Q2_A$) and flows to Turbine-2 where it expands to produce work (W2) and then rejects heat ($Q2_R$) at Condenser-2 from where it returns as liquid to Pump-2. This heat, ($Q2_R$) is again harnessed to vaporize the third working fluid in Evaporator-3 of Cycle-3 (more heat could also be added from the heat source) which then absorbs heat ($Q3_A$) and flows to Turbine-3, where it expands to produce work (W3) and so on. The work output for each cycle (W1, W2, W3, etc.) is converted to electricity via a generator. Figure 1 shows a temperature-specific entropy(T-s) diagram which is one of the best ways to represent the thermodynamic cycle of working fluids undergoing phase changes in an ORC system. Cascade cycles are taken in pairs, comprising the Top or High-temperature (HT) Cycle and the Bottom or Low-temperature (LT) Cycle. Each number in the cycle (1-2-3-4-1) indicates the end of a process step and the beginning of the next process while the letters ‘t’ and ‘b’ indicate top and bottom cycles respectively

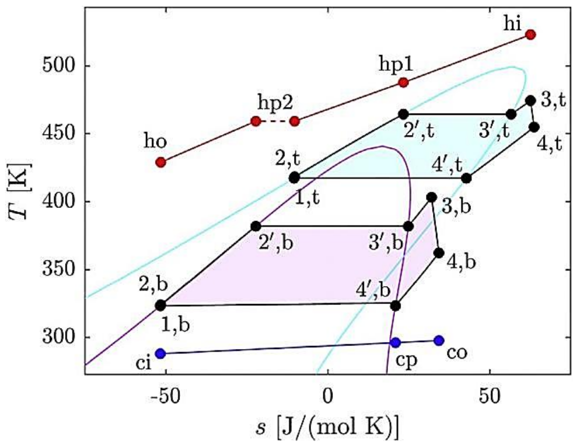

Figure 1: Temperature(T)-Specific Entropy(s) Diagram of the Cascade ORC System.

The steps comprising the processes across the four major components of each cycle are given below:

Step 1–2: The working fluid as a low-pressure subcooled liquid is pressurized with a pump and fed to the evaporator from the condenser.

Step 2–3: The working fluid is vaporized in the evaporator at approximately constant pressure by the externally supplied heat source (solar energy) and undergoes phase change from subcooled liquid to superheated vapor at the inlet of the turbine.

Step 3–4: The high-pressure superheated vapor expands in the turbine where its thermal energy is converted into mechanical shaft work as it expands to a lower pressure and temperature.

Step 4–1: The vapor is then condensed in the condenser using a cooling medium. The superheated vapor rejects heat and is returned to a subcooled liquid state.

Assumptions

The following assumptions were taken into account for the computation and analysis of system efficiencies, specific work and power output.

(1) The working fluids are in a saturated liquid state at the pump inlet and a saturated vapor state at the expander inlet.

(2) The cycles operate at steady state conditions.

(3) Pressure drops and heat losses to the environment in the pipes evaporator and condenser are negligible.

(4) Expander and pump operate adiabatically.

(5) Under such relatively low temperature and pressure working conditions, the ideal gas model is assumed.

2.2 Mathematical Model Equations

The mathematical model equations for various components of the cycle are given in this section. These equations were employed in the IPSEpro simulation using the parameters shown in Table 3.

2.2.1 Turbines

$$W_{T1} = m_1(h_1 - h_2) = \eta_E m_1(h_1 - h_{2s}) \quad (1)$$

$$W_{T2} = m_2(h_5 - h_6) = \eta_E m_2(h_5 - h_{6s}) \quad (2)$$

$$W_{T3} = m_3(h_{12} - h_{13}) = \eta_E m_3(h_{12} - h_{13s}) \quad (3)$$

The Volume Ratio (VR) for each turbine is given by:

$$VR = \frac{V_{out}}{V_{in}} \quad (4)$$

2.2.2 Pumps

The required pump work is defined by:

$$W_{P1} = m_1(h_4 - h_3) = \frac{m_1}{\eta_p}(h_4 - h_{3s}) \quad (5)$$

$$W_{P2} = m_2(h_8 - h_7) = \frac{m_2}{\eta_p}(h_7 - h_{8s}) \quad (6)$$

$$W_{P3} = m_3(h_{10} - h_9) = \frac{m_3}{\eta_p}(h_{10} - h_{9s}) \quad (7)$$

2.2.3 Heat Exchangers

Heat balance equations in heat exchangers are given by:

$$m_3(h_{11} - h_{10}) = m_2(h_6 - h_7) \quad (8)$$

$$m_2(h_5 - h_8) = m_1(h_2 - h_3) \quad (9)$$

2.2.4 System efficiency

System efficiency is given as:

$$\eta_s = \frac{W_{net}}{Qa} \quad (10)$$

therefore, η_s can be written as

$$\eta_s = \frac{W_{net}}{m_1(h_1 - h_4)} \quad (11)$$

$$W_{net} = (W_{E1} + W_{E2} + W_{E3})\eta_s - (W_{P1} + W_{P2} + W_{P3}) \quad (12)$$

2.2.5 Cold energy efficiency

Cold energy efficiency is given as follows

$$\eta_C \frac{W_{net}}{E_{Working\ fluid}} \quad (13)$$

$$E_{working\ fluid} = (h_9 - T_0\ S_9) - (h_{13} - T_0\ S_{13}) \quad (14)$$

where $E_{working\ fluid}$ is the maximum available exergy of a given mass of working fluid.

Table 3: Fixed Parameters for IPSEpro Simulation Software.

Isentropic efficiency of pumps	0.80
Condensation temperature	298 K
Turbine inlet temperature	333K
Environmental temperature	298 K
Supplied pressure for working fluid	0.4 MPa
Evaporation Temperature for working fluids	298K
Evaporation Pressure for Working Fluids	3MPa
Isentropic efficiency of turbines	0.80
Mass flow rate of working fluid	1Kg/S
Pinch point temperature difference	5 K
Temperature of Heat source	298 K
Pressure drop in each heat exchanger	10 kPa
Turbine efficiency	0.95

2.3 Response Surface Methodology

Single fluids were employed for the single ORC as well as for all Cycles in the cascaded ORC systems using the IPSEpro Simulator. For a combination of fluids in different cycles, this was achieved using the Response Surface Methodology (RSM) for the two- and the three-stage cascaded systems. This was not necessary for the 4-stage system because the single fluid case had already indicated a maximum at the 3-stage system with an obvious decline in performance at the 4-stage system. Optimization analysis was carried out on the best combination of working fluids for the two-stage and three-stage cascade systems. The results obtained are shown in Tables 5 and 6 respectively. This was done using Response Surface Methodology (RSM). This showed the relationship between different system performance indices namely, specific work output, system efficiency and power output. The Box-Behnken design was used in the software to show the responses of the different combinations of the five working fluids (R123, R245ca, R601a, R610 and R601). The Modelling equation for the cascaded ORC systems for two-stage and three-stage systems using response surface methodology typically used regression analysis to develop a mathematical model that relates the input variables (such as specific heat capacity, boiling points and the critical conditions of the working fluids) to the output variables (such as power output, system efficiency and specific work output). The general form of the response surface model for this cascaded ORC systems with a combination of working fluids can be expressed as:

$$Y = \beta_O + \sum(\beta_i X_i) + \sum(\beta_{ii} X_{i^2}) + \sum\sum\sum((\beta_{ij} X_i X_j) + \varepsilon \quad (15)$$

where: Y is the response variable (power output, system efficiency and specific work)

X_i and X_j are the input variables representing different working fluid properties or operating conditions.

β_0 is the intercept term

β_i, β_{ii} and β_{ij} are the regression coefficients for linear, quadratic, and interaction terms respectively.

ε is the error term

3.0 Result and Discussion

This section presents the results of the performance analyses of the single-stage, two-stage, three-stage and four-stage ORC systems with the selected working fluids and the comparison of their performances.

3.1 Results

The values obtained for specific work output, efficiency and power output are given in Table 4 for the single-stage and cascade (two-stage, three-stage and four-stage) ORC systems with R123, R245ca, R601a, 601 and 610 as working fluids.

3.1.1 Single Cycle System

For the single-stage system, it was observed that the system efficiency, power output and specific work were the lowest when compared with two- and three-stage systems and R123 had the highest values among all five working fluids for specific work, system efficiency and power output. Thus, it can be inferred that R123 is the best working fluid for a single stage ORC system (Jie and Hulin, 2016).

3.1.2 Two-Stage System

For the Two-stage system, it was observed that R245ca had the highest power output when used as the only working fluid, while R123 had the highest system efficiency and specific work. The thermodynamic efficiency and power output for R245ca and R123 when used as the only working fluids are significantly higher compared to those of R601, R610 and R601a. This is likely because R245ca and R123 have much higher molecular mass values than R601a, R601 and R601 Also, the combinations of working fluids for the two-stage system gave lower power output, system efficiency and specific work than using each fluid as a single working fluid for all cycles in the cascade. The power output, specific work and system efficiency of a 2-stage system were higher than those of a single-stage system and R245ca gave the highest power output here.

3.1.3 Three-Stage System

Similarly, for the 3-stage system, the combinations of working fluids gave lower power output, system efficiency and specific work than using each fluid as a single working fluid for all cycles in the cascade. The power output, specific work and system efficiency of the three-stage system were higher than those of the two-stage system for all five fluids also, R245ca gave the highest power output here.

3.1.4 Four-Stage System

Obviously, for the 4-stage system, the same trend was seen in the performance of the working fluids but with a significant drop in values relative to the two- and three-stage systems but higher than the single-stage system values. These observations could be attributed to the fact that R123 and R245ca perform optimally when used alone in all the cascaded cycles than when used in combination with other less efficient working fluids. This is because different working fluids have different properties and behaviors such that combining them in different cycles of the cascade can lead to issues with compatibility, performance and efficiency. Using a single working fluid ensures that all components of the system are designed to work optimally with that specific fluid.

3.2 Discussion

With the decline observed in the four-stage system, it can be concluded that for the fluids considered here, the three-stage cascade is optimum. R245ca was shown to have the best performance as a single working fluid for the two-, three- and four-stage systems. Both the two-stage and the three-stage systems, require more heat exchangers and expanders than the single-stage system; as a result, neither the two-stage nor the three-stage ORC system is economically advantageous for very small power-generating systems. This should, however, serve as a model for medium-sized power plants.

Optimization analysis was carried out to determine the best combinations of working fluids for the two-stage and three-stage systems. This was done using Response Surface Methodology (RSM). The combination of

R123+R245ca with a power output of 1.06 KW and R123+R245ca+R6010 with a power output of 0.85 KW emerged as the best for the two-stage and the three-stage systems respectively. The best combinations from the RSM optimization program are shown in Table 4 while the combinations with very poor performance were excluded. Some special combinations of two fluids in the three-stage cascade system were also observed. Of particular interest is No. 6 with R123 in the first and second cycles while R245ca was employed in the third cycle (R123+R123+R245ca), giving a relatively high power output of 1.34 KW.

For the two-stage ORC system, R123+R245ca, which was the best working fluid combination, had a predicted R^2 of 0.9770. This is in good agreement with the Adjusted R^2 of 0.9887 as it is required that the difference be less than 0.2. Also, the noise ratio of 40.807, which is required to be greater than 4.0 indicates a very good signal and confirmed that the model can be used to navigate the design space. For the three-stage ORC system, R123+R245ca+R610, as the best working fluid combination, had a predicted R^2 of 0.9234 which is also in good agreement with the Adjusted R^2 of 0.9840 and a noise ratio of 41.321 indicates a very adequate signal showing that this model can be used to navigate the design space.

The effect of the number of cascaded cycles on power output, system efficiency and specific work are shown for single working fluids in Figures 2, 3 and 4 while the performance of the 2-stage and the 3-stage systems using various fluid combinations are shown in Figures 5 and 6 respectively. As shown in Figure 2, the effect of the number of cascaded stages on specific work output is more significant for R245ca and R123 than for R610a, R601 and R610, while it is minimally impactful on system efficiency for all five fluids as seen in Figure 3. However, number of stages has a significant impact on specific work output for aal five working fluids (Figure 4).These observed effects are direct consequences of the interplay of the inherent thermodynamic properties of the working fluids which are clearly exhibited by their unique phase diagrams (ASRAE,2017).

Table 4: System Performances of Single and Cascaded ORC Systems.

N-Stage ORC	Fluid No.	Organic Working Fluids	Specific Work Output (KJ/Kg)	System Efficiency (%)	Power Output (KW)
Single stage	1	R123	29.80	11.62	0.71
	2	R245ca	21.17	9.7	0.70
	3	R601a	20.65	9.52	0.67
	4	R601	20.14	8.73	0.60
	5	R610	21.43	8.21	0.62
Two-stage	1	R123	36.86	12.68	0.90
	2	R245ca	35.82	12.3	1.4
	3	R601a	34.66	10.53	0.86
	4	R601	29.77	9.67	0.88
	5	R610	26.78	9.32	0.85
	6	R123+R245ca	35.23	10.02	1.06
	7	R245ca+R601a	33.24	10.001	0.83
	8	R123+R601a	33.13	10.0005	0.828
	9	R123+R601	33.04	10.00	0.83
	10	R245ca+R601	32.23	9.87	0.81
	11	R123+R610	31.34	10.01	0.80
	12	R245ca+R610	31.23	9.76	0.79
Three-stage	1	R123	41.26	14.76	1.2
	2	R245ca	40.54	14	1.68
	3	R601a	38.78	10.02	0.92
	4	R601	38.64	10.00	0.921
	5	R610	36.46	9.65	0.84
	6	R123+ R123+R245ca	39.77	10.32	1.34
	7	R245ca+R245ca+R601a	35.02	10.15	0.85
	8	R123+R601a+R601a	35.09	10.10	0.83

	9	R123+R245ca+R601a	33.86	9.89	0.83
	10	R123+R245ca+R601	33.76	9.87	0.84
	11	R123+R245ca+R610	32.98	9.89	0.85
	12	R245ca+R601+R610	31.87	9.67	0.82
	13	R245ca+R601a+R610	32.43	9.72	0.827
	14	R245ca+R601a+R601	32.45	9.75	0.80
	15	R123+R601a+R601	33.42	9.80	0.83
	16	R123+R601+R610	33.32	9.76	0.80
Four-Stage	1	R123	32.67	10.32	0.83
	2	R245ca	30.54	10.86	0.88
	3	R601a	28.97	9.98	0.76
	4	R601	26.89	9.06	0.68
	5	R610	28.76	9.08	0.70

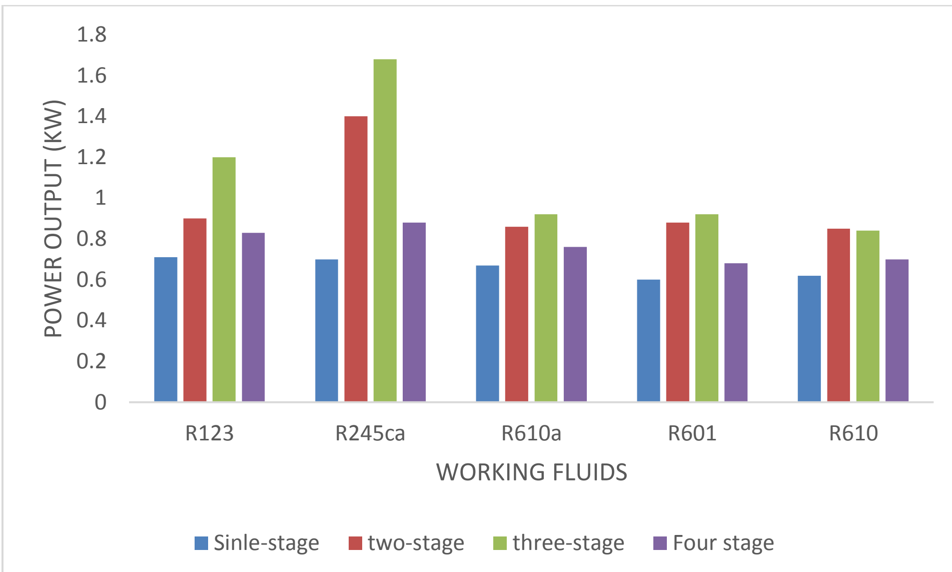

Figure 2: Variation of Number of Cascaded Stages with Power Output (KW) for Single Working Fluids

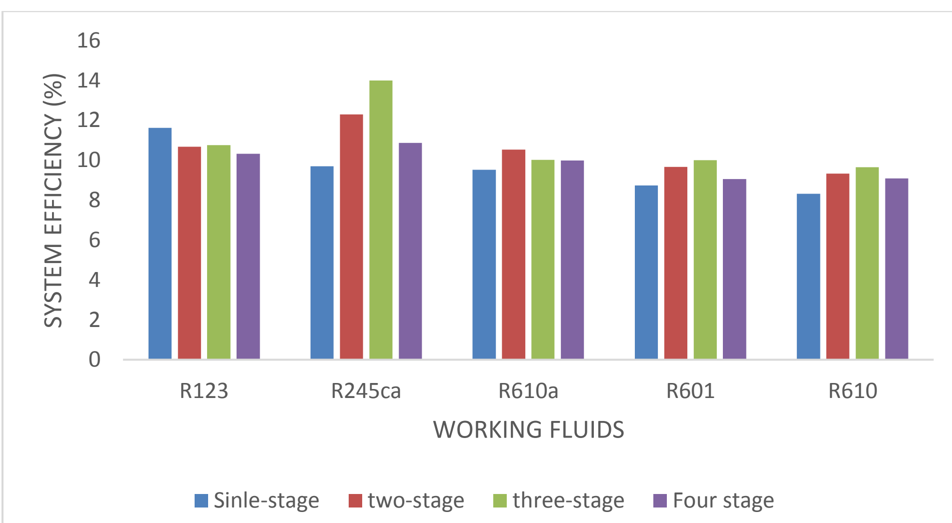

Figure 3: Variation of Number of Cascaded Stages with System Efficiency (%) for Single Working Fluids

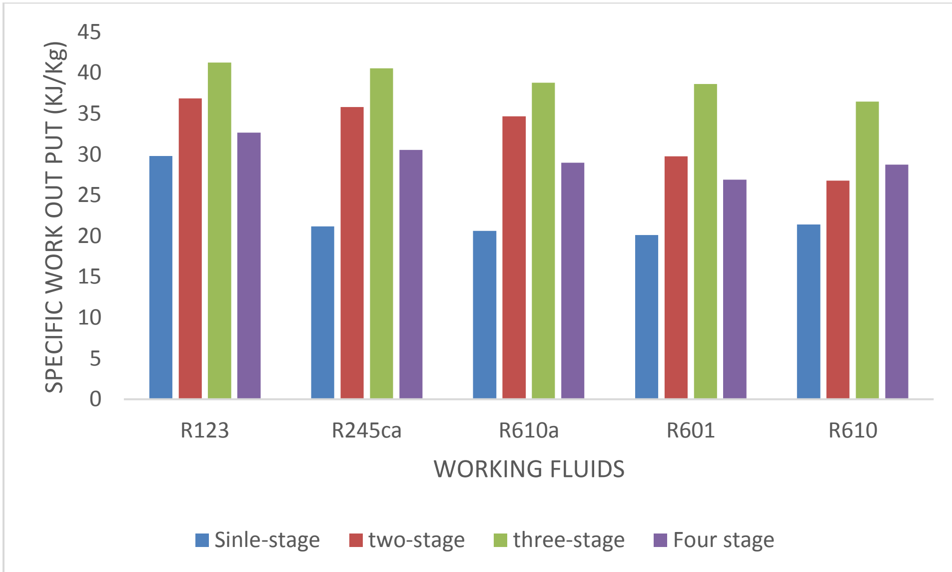

Figure 4: Variation of Number of Cascaded Stages with Specific Work (KJ/Kg) for Single Working Fluids

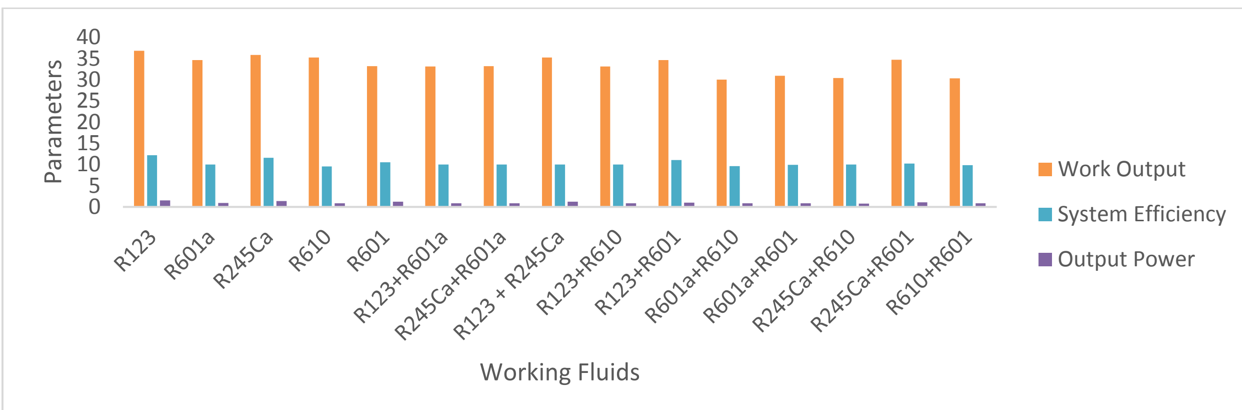

Figure 5: Performance of the Two-Stage System with Various Combinations of Working Fluids

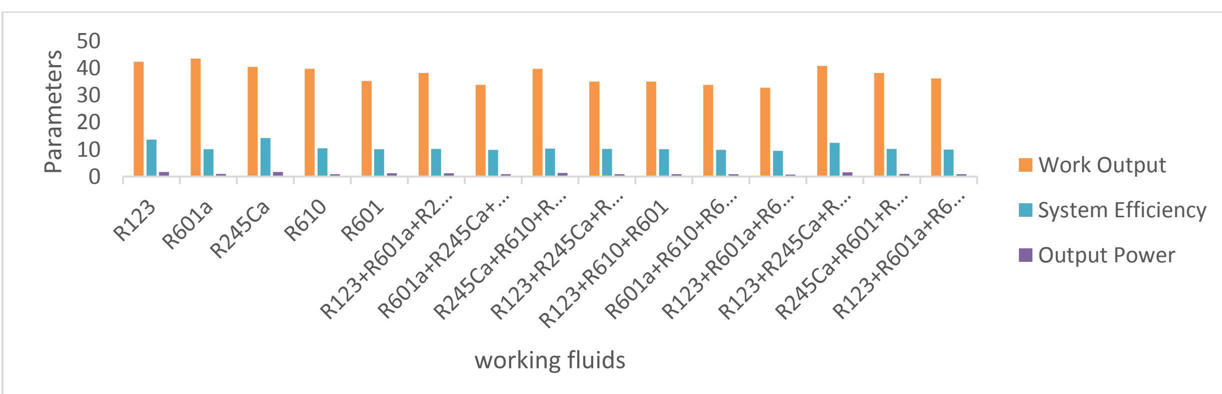

Figure 6: Performance of the Three-Stage System with Various Combinations of Working

4.0. Conclusion

This paper investigates the organic Rankine cycle system for power production from a low temperature heat source with specific application to solar heat. The focus was on cascading the ORC system into multiple cycles to improve performance parameters namely, specific work output, system efficiency and work output. Using the same working fluid for all cycles and alternatively using different working fluid combinations in a cascade were all explored. The challenge of finding the required number of suitable working fluids whose boiling points were amenable to the low temperature range of solar heat was also well addressed. The three-stage ORC system had the highest power output, system efficiency, and specific work output using a single working fluid for the three cycles. The two-stage cascade performed better than the four-stage system which in turn had a better performance than the single-cycle system which showed the poorest performance indices. Using a single working fluid throughout the cycles yields higher power output, system efficiency, and specific work output for the cascaded ORC systems than combining them.

R245ca emerged as the best single working fluid for two-stage and three-stage cascade systems. The best fluid combination for the two-stage system was R123+R245ca while R123+R245ca+R601a emerged as the best fluid combination for the three-stage cascade system. This highlights the importance of the interactions of the diverse properties of the combined working fluids. With these findings, the optimum number of cycles for best performance of cascade ORCs, based on currently available working fluids is now known and systems can be designed accordingly to harness the abundant solar heat for green power generation in tropical regions like Nigeria

5.0 Recommendation

Further work can be directed towards investigating the effect of employing working fluid blends in the cycles as well as developing new suitable and environmentally safe working fluids for the systems.

Nomenclature

h	specific enthalpy, kJ/kg
E	Exergy rate, kW
$\dot{m}$	Masse flow rate, kg/s
P	Pressure, bar
$\dot{Q}$	Heat rate, kW
$\dot{S}$	Entropy generation, kW/K
s	Specific entropy, kJ/kg.K
T	Temperature, °C
$\dot{W}$	Mechanical Power, kW
A	aperture area, m^2
g	generator
C	heat capacity, kJ/kg·K
v	specific volume, m^3 /kg
HT	High temperature cycle
LT	Low temperature cycle
T_b	Boiling point temperature, K
T_c	Critical temperature, K
P_c	Critical pressure MPa

Greek letters

η	Efficiency

Subscripts

C	Compressor
C	Condenser
E	Expander
in	Input
nbp	Normal Boiling Point
cr	Critical
out	Output
P	Pump
T	Turbine
Ⅰ, Ⅱ, III	cycle I, cycle Ⅱ, cycle III

Abbreviations

ORC	Organic Rankine Cycle
VR	volume ratio
PPTD	Pinch point temperature difference, K

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