EMS502U - Thermodynamic Cycles

Biomass Combined Heat and Power Organic Rankine Cycles

Name : Amir Mohammad Pousti

Introduction

Biomass Combined Heat and Power (CHP) systems are Organic Rankine Cycles (ORC) used to produce electricity and heat in a single, highly efficient process from biomass fuels, simultaneously. These systems are designed to efficiently convert organic materials into power, reducing waste and emissions in the process (Biomass CHP Technology Guide, n.d.). An ORC is fundamentally the same as Steam Rankine Cycles (SRC) as they are comprised of an evaporator, expansion device, condenser, and pump. The sole difference is that instead of water, an organic chemical is used as the working fluid (Rahber et al.,2017). The primary working organic fluids used for Biomass CHP's found in previous studies depend on the temperatures applied to the fluid including typically HFEs(Liu, Shao and Li, 2011), HCFC's, HFCs, Freon(Yamamoto et al., 2001) including HFE7000, HFE7100, n-pentane, R113, R123,R245a and R245fa(Ismail et al., 2016).

Hydrofluoroethers (HFEs) like HFE-7000 and HFE-7100 are employed as solvents and refrigerants due to their low toxicity, GWP, and ODP (TSAI, 2005). Both fluids have low boiling points, however HFE-7100's is somewhat higher, which is helpful for applications that require a wider temperature range. Compared to HFEs, n-pentane contributes more to ground-level ozone production and greenhouse gas emissions (*Pentane - an overview*, n.d). As transitional alternatives for more dangerous CFCs, HCFCs (Hydrochlorofluorocarbon) are refrigerants, solvents, and foam-blowing agents. HFCs (Hydrofluorocarbons) are valued for their low ozone depletion potential yet emit significant greenhouse gases.(Montzka, n.d.) R113 and R123 (both HCFCs) are being phased out due to their ozone-depleting properties, while R245fa and R245ca (HFCs) offer a compromise with their lower GWP than traditional Freons like R-19, which have been widely criticised and regulated due to their high GWP and ODP(Ismail et al., 2016).

The fluids were split into different types like they environmental impact and the type of fluid. The overall minimum and maximum ORC temperature was -107.2 °C and 326.9 °C, respectively. However, these are dependent on the different fluids used shown in table 3 (Ismail et al., 2016). However not all the fluids were considered due to environmental concerns, so for the fluids that are applicable the overall minimum and maximum ORC temperature was 20 °C and 140 °C, respectively (Liu, Shao and Li, 2011).

For the initial type of fluid which how a low environmental impact, the anticipated ORC. efficiency of the CHP system, when using selected primary working fluids for ORC, is projected to range from 9.2% to 16.6% (Liu, Shao and Li, 2011). This is mostly determined by variables such as the temperature of the hot water generated by the biomass boiler, the temperature of the cooling water in the ORC condenser, and the particular ORC fluid used. Furthermore, the system is expected to have an electrical output ranging from around 1.5-2.71kW (Liu, Shao and Li, 2011).

An analysis of Carnot cycles and SRC's will also commence for the purpose of comparing the working conditions and efficiencies to the Biomass CHP system. Additionally an evaluation of the advantages and disadvantages of ORC and SRC technologies will take place.

Carnot Cycle

The Carnot cycle represents maximum efficiency heat engines regardless of working fluid or operational conditions (Carnot Cycle - *an overview*, n.d.). The cycle undergoes four primary phases, as seen in Figure 1. Initially, water undergoes isothermal expansion, in which heat is absorbed from a heated reservoir by the fluid and expands at a constant temperature. Then adiabatic expansion occurs, which causes the fluid to cool down by expanding without sharing heat with its surroundings. Isothermal compression releases heat into a cool reservoir while the fluid is squeezed at a constant temperature. Finally, adiabatic compression compresses the

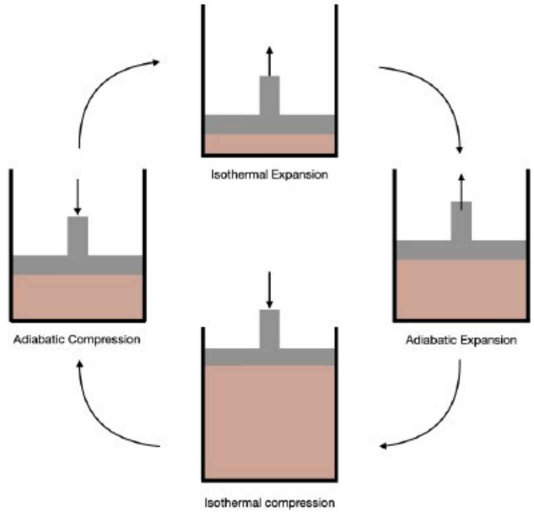

Figure 1 - Stages of Carnot cycle

steam to its initial condition without releasing heat, which raises the steam temperature(Carnot Cycle - *an overview*, n.d.). The Carnot cycle is completely reversible, and all irreversibilities, such as friction and heat losses, are neglected, resulting in the highest efficiency of any cycle of heat engines.

There are many reasons why the Carnot cycle is known as the ideal cycle. However, it is mainly known for the fact that it defines the maximum possible efficiency that any heat engine can achieve, as it is based on fundamental principles of thermodynamics. An example of this is the second law of thermodynamics, which states that the entropy of the universe increases over time for irreversible processes but remains constant for reversible processes like those in the Carnot cycle (Sekerka, 2015). The cycle includes two isothermal processes, where heat is added and expelled isothermally at a high or low temperature. The cycle also includes two adiabatic processes, where no heat is exchanged with the surroundings while insulated. These operations increase The cycle's efficiency, which changes the system's volume and temperature without transferring heat.

To be as efficient as possible, the ideal temperatures are needed. We also know to work out efficiency, we need a significant difference between the temperature of hot and cold fluid to maximize efficiency, as seen in the equation below :

$$\eta = 1 - \frac{T_{cold}}{T_{hot}} \tag{1.1}$$

<u>Steam Rankine cycle</u>

A fundamental thermodynamic cycle, the Steam Rankine Cycle (SRC), converts heat into work and electricity. It starts with boiler water. Burning fuel boils water, capturing heat energy and transforming it into steam's internal energy. Then it goes to a turbine. Steam expands and cools inside the turbine, turning the blades and converting internal energy into mechanical energy. Figure below shows how the cycle repeats: steam is cooled in a condenser until it condenses back into water and is pumped into the boiler. (Borgnakke et al., 2010) Phase transitions between liquid and vapour capture and release huge amounts of energy, making this cycle efficient for power generation. A closed cycle reuses water, making it more sustainable and cost-effective. Rankine cycles are commonly used with water or steam due to its large specific heat capacity, which allows it to absorb significant heat before boiling. Water is cheap and abundant, making it a good power generation fluid. Non-toxic and safe to handle, it poses few environmental and health dangers. Water is stable at many temperatures and pressures and has a high latent heat of vaporisation, absorbing heat when it evaporates. This facilitates efficient energy transfer during liquid-to-vapor phase shift. Water condenses back into liquid at condenser-friendly temperatures and pressures.

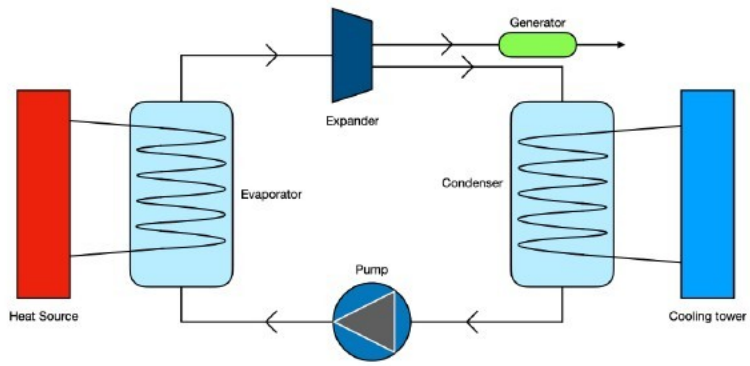

Figure 2- Schematic diagram of Stages of simple Rankine cycle

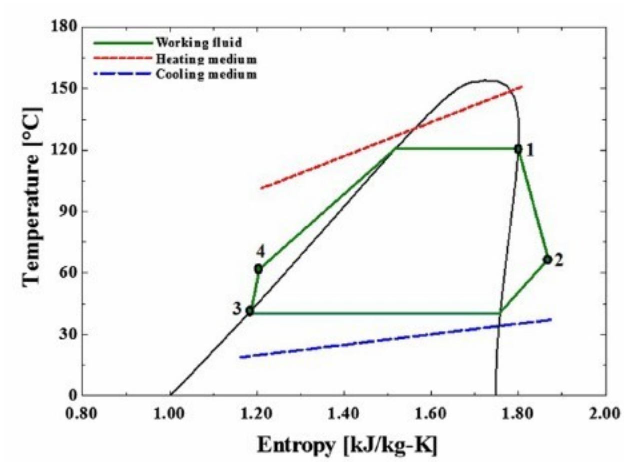

Figure 3- Temperature-entropy diagram of the simple ORC? (Rahber et al.,2017)

Steam Rankine cycle temperatures depend on design and operation. Cycle efficiency and functioning depend on temperatures. Figure 3 shows how entropy and temperature affect the cycle and how phases affect temperature. Temps are 150°C to 250°C before entering the evaporator and 600°C after entering the expander. High steam temperatures allow the turbine to extract more work, improving cycle efficiency. The steam temperature reduces from 150°C to 250°C after pumping and is cooled to below 100°C depending on the cooling water temperature and condenser efficiency (Çengel and Boles, 2015). The T-diagram shows that higher evaporator and lower condenser temperatures improve Rankine cycle efficiency.

Using the Steady Flow Energy Equation (SFEE),which characterizes the energy balance in a system when the process is steady and the mass flow is constant, the formula fo efficiency was derived. It provides a thorough understanding of energy conservation in fluid flow processes by taking into consideration the work done, heat transfer, and changes in kinetic, potential, and internal energy within the system.(Vakil and Green, 2011)

$$\dot{m}(h_{out} - h_{in} + \frac{V_{out}^2 - V_{out}^2}{2} + g(z_{out} - z_{in})) = Q - W \tag{1.2}$$

We also know to work out efficiency, we need a small difference between net work done and the heat input to maximize efficiency, with the heat input being the larger value as seen in the equation below (Palo, 2019):

$$\eta = \frac{W_{net}}{Q_{in}} \tag{1.3}$$

Carnot vs SRC

Comparing the Carnot cycle with the steam Rankine cycle reveals several key differences in different areas. The first is the implementation of these models. The Carnot cycle is a theoretical model that represents the maximum possible efficiency of a heat engine operating between two temperatures. However, the steam Rankine cycle is a practical thermodynamic cycle designed for real-world efficiency and operability. Efficiency is lower than the Carnot efficiency rather than SRCs due to irreversibility's and practical limitations, such as friction, heat losses, and the non-ideal behavior of working fluids. Lastly, the biggest difference between the Carnot Cycle and the steam Rankine cycle. The Carnot cycle can use any fluid without changing its maximum efficiency, while the steam Rankine cycle uses water as the working fluid due to its favorable thermodynamic properties.

During Xin, Xu and Yang research, they found general and simple method for evaluating the performance of the steam Rankine cycle (Xin, Xu and Yang, 2020). A peak temperature of 600°C and bottom temperature of 43.8 with pressures of 5.654 mPa and 0.026 mPa respectively was used to find the enthalpy values from the property tables (Rogers and Mayhew, 1995) at each point work out efficiently as shown below.

h_1	h_2	h_3	h_4
3660.74	1650.45	446.564	1199.82

Table 1- Enthalpy values at different stages of SRC

$$W_{net} = (h_1 - h_2) - (h_4 - h_3) = 1257.034 \tag{1.4}$$

$$Q_{in} = h_1 - h_4 = 2460.92 \tag{1.5}$$

$$\eta = \frac{W_{net}}{Q_{in}} * 100 = 51.08\,\%$$

With the variables provided, we achieve an efficiency of 51.08%. Below, we applied the same variables to the Carnot cycle.

$$\eta = (1 - \frac{316.95}{873.15}) * 100 = 63.70\,\%$$

The variations in the operations of the steam Rankine cycle and the Carnot cycle account for the disparity in efficiency between both. The Carnot cycle runs between two temperatures, achieving increased theoretical efficiency. It depicts an idealised, frictionless process with no irreversibilities. Conversely, the Rankine cycle exhibits reduced efficiency due to irreversibilities such heat loss and friction, making it more akin to actual steam power plant operations.

Fluid selection

A fluid can be chosen by analysing thermophysical properties and system performance. Higher thermal conductivity and heat capacity improve heat transfer and storage, increasing cycle thermal efficiency. For biomass boiler output temperatures, fluids with proper boiling points can improve heat exchange efficiency. Increased latent heat improves fluid heat transfer per mass. Through regulatory compliance, lower GWP and ODP improve environmental sustainability and economic efficiency. GWP compares CO2 and greenhouse gas heat over 100 years. ODP compares ozone layer damage to CFC-11, a popular refrigerant(Ismail et al., 2016).

HFE7000 and HFE7100 are popular for their chemical stability, low ODP and GWP, and near-room boiling temperatures. These qualities make them perfect for biomass CHP. System efficiency may increase due to N-Pentane's thermal conductivity and high latent heat of vaporisation(Liu, Shao and Li, 2011). System design must consider its flammability and safety. HCFCs like R113 and R123 were originally widely used in low-temperature heating due to their high thermal efficiency, but their moderate to high greenhouse gas footprint and some ODP(Montzka, n.d.). R245fa and R245ca HFCs are employed in Organic Rankine Cycles (ORC) in CHP systems and have low ODP but high GWP, making them advantageous in some cases(TSAI, 2005).

However, the fading out of HCFCs, current sustainability and environmental concerns, and the 191-nation agreement to accelerate phase-outs from 2009 with final phase-out in 2020 invalidate them in this research HFE7000, HFE7100, and n-pentane are rising because they are environmentally beneficial. (Liu, Shao and Li, 2011)They're the future, but less efficient.

The first fluid, HFE7000, simulated 20 times with an ORC efficiency of 9.2% to 16.0%. Simulation 16 produced the most electricity at 2.61 kW with a maximum fluid temperature of 140°C and a minimum of 20°C. It also indicated that the fluid with the lowest efficiency of 9.2% had a 1.50kW electrical output and a maximum and minimum temperature of 100°C and 20°C. (Liu, Shao and Li, 2011)

HFE7100 was simulated 18 times with ORC efficiencies from 9.2% to 15.4%. At 140°C and 20°C, simulation 16 produced 2.51 kW of electricity at peak efficiency. Simulation 9, with 140°C and 40°C temperatures and 1.50kW electrical output, had the lowest efficiency.(Liu, Shao and Li, 2011)

The last fluid simulated was N-Pentane, which had a peak efficiency of 16.6% at 140°C and 30°C with an electrical output of 2.71 kW after 4 runs. The least effect was simulated to have 13.3% efficiency at 120°C and 40°C. We measured 2.17kW of electrical output.(Liu, Shao and Li, 2011)

N-Pentane is the most efficient fluid under ideal conditions, possibly due to its chemical properties for the examined temperature ranges. Its temperature and efficiency variation are lower, suggesting it may be more stable or predictable under various working situations. Though comparable, HFE7000 and HFE7100 show how slight changes in the lowest temperature may affect output efficiency. HFE7100's worst-case efficiency is lower than HFE7000's while having the same maximum temperature.

Below, we applied the same variables to the Carnot cycle.

$$\eta = (1 - \frac{303.15}{413.15}) * 100 = 26.6\,\%$$

The discrepancy between the ORC efficiency at 16.6% and the Carnot cycle at 26.6% is due to the ORC's practical limitations, such as non-ideal fluid behavior and heat transfer losses, whereas the Carnot cycle represents an idealized maximum efficiency assuming no losses and reversible processes.

Advantages and Disadvantages

Regarding applications in Biomass Combined Heat and Power (CHP) systems, Organic Rankine Cycle systems provide several advantages over standard Steam Rankine Cycle systems.

Lower operational temperatures

One of the main benefits is the lower operational temperatures needed in ORCs as shown in table 3. (Zhang et al., 2016) With biomass CHP systems, where the heat source may come from combustion procedures that don't reach the high temperatures needed for effective steam production in SRC systems, this property is highly beneficial. Steam's thermal efficiency drops when's steams temperature drops below 370° C, however the maximum temperature needed in selected organic fluids is 140° C. This is due to the Carnot efficiency, which states that as the steam temperature decreases, this temperature difference narrows, leading to a lower theoretical maximum efficiency. (Carnot Cycle - *an overview*, n.d) This uneconomically increases the running cost of SRCs as more energy is needed to operate at high temperatures. Additionally, due to its versatility, ORCs may be used for both small-scale local biomass resources and larger-scale industrial biomass CHP applications. They work well in small configurations due to a higher fluid density than water in similar conditions. This means that a smaller volume of organic fluid is required for the same thermal energy input to produce the same amount of work as a larger volume of steam in SRC systems. This means Smaller Turbine and Equipment Size, leading to a lower capital cost. (Zhang et al., 2016)

High running cost

However, the running cost of ORCs can be seen as higher due to the high purchase price of organic fluids compared to the water needed in SRCs. (Rahber et al.,2017) Nonetheless, it can be argued that organic fluids in ORC systems are typically used in a closed loop, minimizing losses and eliminating the need for continuous water supply and treatment, thus reducing operational costs related to water management.

Low maintenance cost

The components used in ORC systems are generally simpler and more robust, leading to lower operation and maintenance costs than SRC systems. This is due to the organic working fluids used in ORC systems are less corrosive than water steam. This is because they are either dry or isentropic, meaning they stay at constant temperature. (Astolfi et al, 2023) This reduces corrosion damage and scaling on components, extending their service life and reducing maintenance frequency and costs. Lower pressures and temperatures involved in ORC systems while still attaining high efficiency levels meaning simpler designs can be used and less rigorous material requirements, which simplifies maintenance and operation (Zhang et al., 2016).

<u>High versatility</u>
Another advantage of ORCs is their high versatility in heat sources such as Biomass CHP systems, which directly affects the amount of different heat sources that can be used for ORC. However, due to water's high boiling point, only limited heating applications are applicable to SRCs. (Rahber et al.,2017)

<u>Low saturation temperatures</u>
We also know that ORCs run at low saturation temperatures due to the thermodynamic properties of the organic working fluids including a wide range of boiling points, high latent heat of vaporization and favorable vapor pressure characteristics at lower temperatures. These allow the condenser to work at atmospheric pressure maintaining low temperatures. (Astolfi et al, 2023) Also, during SRC operations, air removal is required within the condenser while it runs at sub-atmospheric pressure. This ensures steam can directly contact the cooling surfaces, making the cooling process more effective. (Rahber et al.,2017)

<u>Larger pump needed</u>
During a SRC operation, the amount of steam (mass flow rate) that needs to be moved through the system is relatively low. This means the pumps that circulate the steam don't have to work as hard, leading to lower power consumption for operating these pumps. On the other hand, ORC systems use organic fluids with higher densities compared to steam. To achieve the same energy output, ORC systems require moving a larger volume of this fluid through the system, resulting in a higher mass flow rate. Consequently, the pumps in ORC systems need to exert more effort to circulate this fluid, leading to higher power consumption for these pumps. (Rahber et al.,2017)

Conclusion
This research shows that Organic Rankine Cycles can replace Steam Rankine Cycles in biomass CHP systems. ORCs' adaptability makes them a promising technology for sustainable energy initiatives because they can convert low-grade heat into energy. The investigation revealed key differences and operating efficiency between these two thermodynamic cycles, which are vital for choosing the optimum energy system technology.ORCs work better at lower temperatures and with other fluids than water.This versatility is useful because biomass CHP heat sources cannot reach the high temperatures needed for SRC steam generation. ORCs can convert thermal energy to mechanical effort at lower temperatures to improve low-grade heat source thermal efficiency and sustainability by employing organic fluids with lower boiling points than water.A comparative study of working fluids like HFE7000, HFE7100, and N-Pentane in ORC systems shows that their superior thermal properties over conventional hydrofluorocarbons used in SRCs improve cycle efficiency and meet environmental regulations due to their low GWP and ODP. Closing the loop eliminates the need for regular replenishment, a major issue with water-based SRC systems, and minimises fluid losses, lowering operating costs. ORCs offer capital and operating cost advantages. Lower operating temperatures reduce system component material and design requirements, lowering initial investment and maintenance costs. ORC systems are more robust and corrosion-resistant than SRCs, which employ high-temperature water steam.For biomass-to-heat-and-power systems, the Organic Rankine Cycle is more effective and suitable. Its lower lifecycle costs, environmental benefits, and efficient use of low-grade thermal energy favour its adoption over the Steam Rankine Cycle. The ORC's fluid selection diversity and technological flexibility to varied heat sources enhance its performance and support sustainable energy goals. As the energy sector moves towards sustainability, Organic Rankine Cycle technology in biomass applications is expected

to grow due to its efficiency, cost, and environmental impact. This adjustment makes energy production systems more economically and environmentally sustainable and helps the world switch to renewable energy.

Appendix

Table 2 : Properties of steam used in investigation					
T_1	T_2	T_1	T_2	P_1	P_2
600	43.8	873.15	316.95	5.654	0.026

Table 3 : Properties of organic used in investigation							
Fluid	Boiling point	Temperature (C)	Pressure (mPa)	Density (kg/m^3)	Minium temperature	Maximum tempreture	Maximum pressure
R134a	-26.07	101.06	4.059	511.9	-103.3	180.0	70
R113	47.59	214.06	3.392	560.0	-36.2	251.9	200
R123	27.82	183.68	3.662	550.0	-107.2	326.9	40
R245ca	25.13	174.42	3.925	523.6	-73.2	226.9	60
R245fa	14.90	154.05	4.250	517.0	-73.2	226.9	60
HFE-7000	34	165.0	2.478	531.0	20	140	1.573
HFE-7100	61	2230.0	0.195	555.0	20	140	0.775
N-Pentane	36	196.5	3.364	429.9	30	140	1.329

Nomenclature

Sign	Name	Units
η	Efficiency	-
T	Tempreture	Kelvin or Celcius
P	Pressure	mPa
h	Enthalpy	kJ/kg
W	Work Output	kJ/kg
Q	Heat Input	kJ/kg

References

Biomass CHP Technology Guide. (n.d.). Available at: https://www.seai.ie/business-and-public-sector/business-grants-and-supports/support-scheme-renewable-heat/Biomass-CHP-Technology-Guide.pdf.

Rahber, K, Mahmoud, S, Al-Dadah,R K, Maozami, N and Mirhadizadeh, S A, (2017), Review of Organic Rankine Cycle for Small-Scale Applications, Energy Conversion Management, 134, pp 135-155. Available at: https://qmplus.qmul.ac.uk/pluginfile.php/3561103/mod_resource/content/4/Review%20of%20ORC.pdf

Liu, H., Shao, Y. and Li, J. (2011). A biomass-fired micro-scale CHP system with organic Rankine cycle (ORC) – Thermodynamic modelling studies. Biomass and Bioenergy, 35(9), pp.3985–3994. doi:https://doi.org/10.1016/j.biombioe.2011.06.025.

TSAI, W. (2005). Environmental risk assessment of hydrofluoroethers (HFEs). Journal of Hazardous Materials, 119(1-3), pp.69–78. doi:https://doi.org/10.1016/j.jhazmat.2004.12.018.

www.sciencedirect.com. (n.d.). Pentane - an overview | ScienceDirect Topics. [online] Available at: https://www.sciencedirect.com/topics/chemistry/pentane.

www.sciencedirect.com. (n.d.). Carnot Cycle - an overview | ScienceDirect Topics. [online] Available at: https://www.sciencedirect.com/topics/engineering/carnot-cycle.

Robert F. Sekerka. (2015). Thermal Physics. Elsevier eBooks. Available at: https://doi.org/10.1016/c2014-0-03233-9.

www.sciencedirect.com. (n.d.). Steam Rankine Cycle - an overview | ScienceDirect Topics. [online] Available at: https://www.sciencedirect.com/topics/engineering/steam-rankine-cycle.

Verschoor, M.J.E. and Brouwer, E.P. (1995). Description of the SMR cycle, which combines fluid elements of steam and organic Rankine cycles. Energy, 20(4), pp.295–303. Available at: https://doi.org/10.1016/0360-5442(94)00080-m.

Borgnakke, Moran, M.J., Shapiro, H.N., Boettner, D.D. and Bailey, M. (2010). Fundamentals of Engineering Thermodynamics. John Wiley & Sons Canada, Limited. Available at:

Çengel, Y.A. and Boles, M.A. (2015). Thermodynamics : an engineering approach. New York, Ny: Mcgraw-Hill Education.

Zhang, X., Wu, L., Wang, X. and Ju, G. (2016). Comparative study of waste heat steam SRC, ORC and S-ORC power generation systems in medium-low temperature. Applied Thermal Engineering, 106, pp.1427–1439. Available at: https://doi.org/10.1016/j.applthermaleng.2016.06.108.

Astolfi, M., Diego, M. E., Romano, M., et al. (2023). Integration of a novel Chemical Looping Combustion reactor into a thermochemical energy storage system. Energy Conversion and Management, Elsevier.

Palo, A. (2019). How to Calculate Thermal Efficiency of Rankine Cycle. [online] Medium. Available at: https://medium.com/@ashwinpalo/how-to-calculate-thermal-efficiency-of-rankine-cycle-37a7dbcadc12.

Xin, T., Xu, C. and Yang, Y. (2020). A general and simple method for evaluating the performance of the modified steam Rankine cycle: Thermal cycle splitting analytical method. Energy Conversion and Management, 210, p.112712. Available at :https://doi.org/10.1016/j.enconman.2020.112712.

Rogers, G.F.C. and Mayhew, Y.R. (1995). Thermodynamic and transport properties of fluids.

Vakil, A. and Green, S.I. (2011). Stagnation Pressure, the Bernoulli Equation, and the Steady-Flow Energy Equation. International Journal of Mechanical Engineering Education, 39(2), pp.130–138. Available at: https://doi.org/10.7227/ijmee.39.2.4.

Yamamoto, T., Furuhata, T., Arai, N. and Mori, K. (2001). Design and testing of the Organic Rankine Cycle. Energy, 26(3), pp.239–251. Available at: https://doi.org/10.1016/s0360-5442(00)00063-3.

Ismail, H., Aziz, A.A., Rasih, R.A., Jenal, N., Michael, Z. and Roslan, A. (2016). Performance of Organic Rankine Cycle Using Biomass As Source of Fuel. Journal of Advanced Research in Applied Sciences and Engineering Technology, [online] 4(1), pp.29–46. Available at: https://www.akademiabaru.com/submit/index.php/araset/article/view/1898/1456

Stephen A. Montzka (n.d.). NOAA Global Monitoring Laboratory - Halocarbons and other Atmospheric Trace Species. US Department of Commerce. [online] gml.noaa.gov. Available at: https://gml.noaa.gov/hats/about/hcfc.html.