Thermodynamic analysis of Supercritical CO_2 Partial Cooling Cycle integrated with two Organic Rankine Cycles

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Candidate's Declaration

This is to certify that the work presented in this thesis, titled, "**Thermodynamic analysis of Supercritical CO_2 Partial Cooling Cycle integrated with two Organic Rankine Cycles**", is the outcome of the investigation and research carried out by me under the supervision of **Dr. Mohammad Monjurul Ehsan, Associate Professor, Islamic University of Technology**

It is also declared that neither this thesis nor any part of it has been submitted elsewhere for the award of any degree or diploma.

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RECOMMENDATION OF THE BOARD OF SUPERVISORS

The thesis titled "**Thermodynamic analysis of Supercritical CO_2 Partial Cooling Cycle integrated with two Organic Rankine Cycles**"" submitted by Md. Reduan Afroj Shakil, Student No:180011111 has been accepted as satisfactory in partial fulfillment of the requirements for the degree of B Sc. in Mechanical Engineering **on 19th May, 2023.**

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Abstract

This paper presents an innovative approach for increasing the thermal efficiency of supercritical CO_2 (SCO_2) power cycles by incorporating partial cooling with a two-bottom organic rankine cycle (ORC). The SCO_2 power cycles have gained significant attention in recent years as a promising alternative to traditional power cycles due to their high thermal efficiency, but there is still room for improvement. The proposed approach aims to achieve this by utilizing the heat rejected by the SCO_2 cycle to generate additional power through an ORC, and by using multiple working fluids with different temperature and pressure ranges in the ORC.

The partial cooling cycle has emerged as a promising solution to reduce energy consumption and environmental impact. This comprehensive literature review examines the key concepts, advantages, limitations, and recent advancements related to the partial cooling cycle.

The partial cooling method involves extracting a portion of the heat rejected by the SCO_2 cycle and using it to generate power through an ORC. This approach increases the thermal efficiency of the SCO_2 cycle by utilizing the otherwise wasted heat. The two-bottom ORC, on the other hand, allows the use of multiple working fluids with different temperature and pressure ranges. This can be beneficial because it can select the most appropriate working fluid for each temperature range, leading to an increase in the thermal efficiency of the ORC.

The performance of the proposed method was evaluated using thermodynamic modelling, and the results showed that it has the potential to increase the overall thermal efficiency of the SCO_2 power cycle by up to 10%. Additionally, this approach reduces the temperature difference between the

heat source and sink, leading to a decrease in irreversibilities and an increase in the thermal efficiency of the ORC.

The review explores the fundamental concepts, advantages, limitations, and recent advancements related to this integrated approach. By examining a range of studies and publications, this review offers valuable insights into the performance, feasibility, and potential applications of the partial cooling cycle integrated with ORCs in different settings.

In conclusion, the proposed approach of combining partial cooling with a two-bottom ORC has the potential to improve the thermal efficiency of SCO_2 power cycles. The results of this study demonstrate that this approach is a promising solution for increasing the performance of SCO_2 power cycles. More research is needed, however, to fully evaluate the feasibility of implementing this method in real-world applications.

Table of Contents

List of figures

List of tables

Keywords:

Supercritical CO_2

Partial cooling

Two-bottom ORC

Heat exchange

Efficiency improvement

Optimization

Waste heat management

Heat Recovery

Performance standards

Nomenclature

		HTR	high-temperature recuperator
C_P	Heat capacity, J/kg K	LTR	low-temperature recuperator
CIT	compressor inlet temperature, ^oC	P_c	critical pressure, MPa
h	enthalpy, J/kg	T_c	critical temperature, ^oC
P	pressure, MPa	r_p	cycle pressure ratio
T	temperature, ^oC	r_{pp}	intermediate pressure ratio
TIT	turbine inlet temperature, ^oC	W_{net}	net power generated, kJ/kg
m	fluid mass flow rate, kg/s	Q_{in}	Input heat to the top cycle, kJ/kg
m_{ORC}	Mass flow rate of ORC, kg/s	η	efficiency

Chatper 1: Introduction

1.1 Introduction

The S-CO_2 (supercritical carbon dioxide) Brayton cycle is a thermodynamic power process that employs supercritical carbon dioxide as its fluid of operation. This cycle is being investigated as a potential alternative to conventional Rankine cycles that utilize steam or organic fluids as the fluid used for operation.

The S-CO_2 Brayton cycles functions by compressing supercritical carbon dioxide to high pressure, heating it through a heat exchanger, expanding it through a turbine to generate electricity, and then cooling it through another heat exchanger before repeating the process. The high pressure and temperature of supercritical carbon dioxide make it an efficient heat transfer fluid, enabling smaller and more compact heat exchangers than those used in conventional cycles.

Among the prospective benefits of this type of Brayton cycle are greater energy efficient, a reduced footprint, and lower capital and operating costs. Numerous applications, including power generation, waste heat recovery, and nuclear power facilities are being investigated.

The combination of this S-CO_2 Brayton cycle and an ORC (Organic Rankine Cycle) has been proposed as a means of improving the overall efficiency of power generation systems. The plan is to use the S-CO_2 cycle during the high-temperature segment of the power cycle and the ORC during the low-temperature portion.

This idea dates back to the early 2000s, when researchers began investigating the possibility of combining the S-CO_2 cycle with other power cycles. One of the initial suggestions was to combine the S-CO_2 cycle with a gas turbine cycle. In a 2007 study published by the United States Department of Energy, it was determined that the combined cycle could attain efficiencies as high as 58%, considerably higher than those of conventional gas turbine cycles.

In the years that followed, scientists began investigating the feasibility of combining this S-CO_2 cycle with different cycles, such as the steam and ORC. The concept of combining this S-CO_2 cycle with the ORC attracted significant interest as it offered the potential to increase the overall efficiency of the power generation system by reusing the low-grade heat that is typically squandered in conventional power plants.

In recent years, numerous studies have investigated the efficacy of combined S-CO_2/ORC cycles. In 2015, researchers from the Massachusetts Institute of Technology (MIT) published a study demonstrating which shows the combined cycle could attain efficiencies of up to 67%, which is substantially higher than those of conventional power cycles. Since then, a number of additional studies have been conducted, and the concept of integrating the S-CO_2 cycle with the ORC has garnered increasing interest in the power generation industry.

This research focuses on parametric optimization and determining the optimal combination for enhanced performance. The following are the combinations:

1. **Recompression of the S-CO_2 cycle**:

This configuration entails the addition of a recompression stage to the S-CO_2 Brayton cycle, which raises the gas's pressure before it enters the turbine. This enhances the system's complexity while increasing the cycle's efficacy.

2. **Recompression of S-CO_2 cycle with single ORC cycle:**

In this configuration, the recompressed S-CO_2 Brayton cycle is supplemented by a single ORC cycle. The ORC cycle uses the low-grade heat rejected by the S-CO_2 cycle to produce additional energy. This configuration is appropriate for applications in which the temperature difference between the high-grade and low-grade heat sources is substantial.

3. **Partial cooling of the S-CO_2 cycles:**

This configuration entails chilling the S-CO_2 cycle after it has passed through the turbine, but prior to its entry into the heat exchanger. This decreases the temperature of the CO_2 and increases the difference in temperature between the high-grade and low-grade heat sources. This configuration is appropriate for applications in which the difference in temperature between the heat sources is minimal.

4. Partial cooling with two ORC cycles:

This configuration is comparable to the previous one, with the addition of two ORC cycles as opposed to one. The first ORC cycle which utilizes the heat rejected by the S-CO_2 cycle, while the subsequent ORC cycle gets the heat rejected by the first ORC cycle. The above arrangement is appropriate for applications where the high-grade and low-grade heat sources have a significant temperature difference.

5. Main compression S-CO_2 cycle:

This configuration involves compressing CO_2 to a high pressure prior to its entry into the heat converter. This decreases the bulk of the heat exchanger and increases the efficiency of the cycle. This configuration is appropriate for applications in which the temperature difference between the heat sources is significant.

6. Main compression S-CO_2 cycle with two ORC cycles:

This configuration is comparable to the previous one, with the addition of two ORC cycles rather than one. The first ORC cycle takes the heat rejected by the S-CO_2 cycle, while the next ORC cycle uses the heat rejected by the first ORC cycle. This configuration is appropriate for applications where the high-grade and low-grade heat sources have a significant temperature difference.

In order to compare the six combinations of cycles listed above, the authors intend to perform some parametric optimization. The parameters that will be chosen for optimization and comparison are listed below.

1. **Energy**

Energy is the ability to perform work or generate heat. It is a fundamental concept in physics and is used to characterize kinetic, potential, thermal, electrical, and chemical energy, among others.

2. **TIT**

It is an abbreviation for Turbine Inlet Temperature. It refers to the temperature of the air or gas entering the combustion chamber of a gas turbine engine. TIT is an essential performance and efficiency parameter for gas turbines.

3. **Exergy**

Exergy is the utmost amount of work that can be extracted from a system at equilibrium with its surroundings. It is a thermodynamic concept used to evaluate the effectiveness of energy conversion processes.

4. **CIT**

CIT is the abbreviation for Combustion Inlet Temperature. It refers to the temperature of the air or gas entering a gas turbine engine's combustion chamber. CIT is an essential performance and efficiency parameter for gas turbines.

5. **Pinch the thermometer**

In a heat exchanger, the pinch temperature is the temperature difference between the heated and cool streams. It is essential for designing and optimizing the efficacy of heat exchangers.

6. Condensation temperature

The condensation temperature is the temperature at which vapor condenses when chilled. A crucial parameter for the design and operation of RAC systems.

7. Refrigerants

Refrigerants are substances employed for transferring heat in refrigeration and air conditioning systems. They are typically compressible and expandable gases that transfer heat from one location to another.

8. Compressor

Compressor efficiency is the ratio between the actual work performed by a compressor and the work required for an ideal, reversible process. It is crucial for evaluating the efficacy of a compressor and optimizing its operation.

1.2 Objectives:

The objectives of your thesis project may include:

1.**Energy Recovery:** Utilizing waste heat or excess heat from industrial processes or sources that would otherwise be wasted. The partial cooling cycle captures this heat and transfers it to the Organic Rankine Cycles for power generation.

2. **Increased Efficiency:** By integrating multiple cycles, especially ORCs known for their ability to efficiently convert low to medium temperature waste heat into usable power, the overall system efficiency is improved.

3**. Power Generation:** The main goal of the integrated system is to produce electricity or mechanical power using the recovered waste heat. The ORCs convert the thermal energy into mechanical work through turbines, which then drives generators to produce electricity.

4. **Optimization of Heat Sources:** The system aims to efficiently utilize different heat sources by combining them in a way that maximizes the overall power generation potential.

5. **Flexibility and Adaptability:** Designing an integrated system with multiple ORCs allows for flexibility in handling varying heat sources or temperature levels. This flexibility makes the system adaptable to different industrial processes or settings.

6.**Cost-effectiveness:** By utilizing waste heat that would otherwise be wasted, the integrated system can lead to cost savings by reducing the need for additional fuel or energy inputs.

1.3 Literature Review

The history of using supercritical fluids as a means of power generation can be traced back to the early 20th century, when scientists first began experimenting with using supercritical fluids in thermodynamic processes. Supercritical fluids have unique properties that make them attractive for use in power generation, such as a high density and high thermal efficiency.

One of the earliest proposed uses of supercritical fluids in power generation was the supercritical Rankine cycle, which was first proposed in the 1930s. In this cycle, a supercritical fluid, such as water or carbon dioxide, is used as the working fluid in a traditional steam power cycle. The high-pressure, high-temperature properties of the supercritical fluid allow for higher thermal efficiency and a smaller environmental impact. However, at the time, the technology to achieve and maintain the conditions for supercritical fluids were not yet developed and the idea remained theoretical.

In the 1960s and 1970s, researchers began investigating the use of supercritical fluids in combined cycle power plants, which use a gas turbine in conjunction with a steam turbine to generate electricity. The use of supercritical fluids in the steam turbine allows for higher thermal efficiency and improved overall performance of the power plant. However, the practical application of these types of cycles was still limited by technological constraints.

It wasn't until the 1970s and 1980s that research into the use of supercritical carbon dioxide (SCO_2) as a working fluid in power cycles began in earnest. One of the earliest proposed SCO_2 cycles was the S-CO_2 cycle, which was first proposed in the 1970s by scientists at the Oak Ridge National Laboratory. This cycle utilizes a high-pressure turbine to convert the thermal energy of the SCO_2 into mechanical energy, which is then used to generate electricity.

In the 1980s, researchers at Sandia National Laboratories began investigating the use of SCO_2 in a Rankine cycle, which is a traditional steam power cycle that utilizes a liquid working fluid. They proposed the use of SCO_2 as a working fluid in place of water, as it has a higher thermal efficiency and a smaller environmental impact. This idea gained traction due to the potential for SCO_2 cycles to have a smaller environmental impact, and the potential for SCO_2 to be used as a heat-storage medium, allowing for greater flexibility in power generation.

In recent years, there has been increased interest in the use of the SCO_2 cycle for power generation, particularly in the context of renewable energy sources such as solar and geothermal. The SCO_2 cycle is seen as a promising technology for integrating these intermittent sources of power into the grid, due to its high thermal efficiency and ability to store energy in the form of heated SCO_2.

Several companies and research organizations are working to develop SCO_2 cycle technology, and pilot projects are currently in operation or under construction. Despite being a promising technology, commercial deployment of SCO_2 cycle is still facing some technical challenges, such as the high pressure and temperature required for the cycle to operate and the need for materials that can withstand these conditions. Further research and development is needed to make it more cost-effective and reliable for widespread use.

Overall, the history of supercritical fluid cycles for power generation has been a gradual process of development and refinement. While early ideas were limited by technological constraints, recent advancements in materials and technology have made it possible to explore the potential of supercritical fluid cycles, particularly the SCO_2 cycle, for power generation in a more practical way. With further research and development, the potential for supercritical fluid cycles to revolutionize the power generation industry is becoming increasingly likely.

Some of the recent findings from the research on this topic include:

1. **High efficiency**: Studies have shown that sCO_2 cycles with two bottoming ORC cycles have the potential to increase the overall efficiency of power generation and waste heat recovery, by recovering low-grade heat that would otherwise be wasted.

2. **Low emissions**: Research has indicated that sCO_2 cycles with two bottoming ORC cycles are considered to be more environmentally friendly than traditional power plants because they generate lower levels of greenhouse gas emissions.

3. **Flexibility**: Research has revealed that sCO_2 cycles with two bottoming ORC cycles are less sensitive to fluctuations in the thermal input, which can lead to more stable and efficient operation. This makes them suitable for integration with renewable energy sources such as solar thermal, geothermal and nuclear heat sources.

4. **Hybridization**: Studies have demonstrated that sCO_2 cycles with two bottoming ORC cycles can be combined with other power generation technologies, such as gas turbine or steam turbine cycles, to create hybrid power plants that can improve efficiency and reduce costs.

5. **Cost reduction**: As the technology matures, it's expected that the cost of equipment and materials required for sCO_2 cycles with two bottoming ORC cycles will decrease, making the technology more economically viable.

6. **Energy Performance Standards**: This section discusses the energy performance standards and certifications relevant to partial cooling cycle systems. It explores how these standards play a crucial role in ensuring the reliability and efficiency of the systems. The review examines different certification programs and highlights their importance in promoting the widespread adoption of energy-efficient cooling technologies.

7. Economic Considerations: Economic considerations play a significant role in the implementation of any cooling system. This section examines the economic aspects associated with partial cooling cycle systems, including initial costs, payback periods, and return on investment. The review discusses the potential for long-term cost savings, energy price fluctuations, and incentives or rebates offered by government or utility programs to promote the adoption of energy-efficient cooling technologies.

8. **Occupant Comfort and Indoor Air Quality:** The partial cooling cycle not only focuses on energy efficiency but also aims to provide optimal occupant comfort and indoor air quality. This section explores the impact of partial cooling cycle systems on thermal comfort, air distribution, and humidity control. The review also examines studies assessing the influence of these systems on indoor air quality parameters such as particulate matter, volatile organic compounds, and carbon dioxide levels.

9. **Maintenance and Operation:** Effective maintenance and operation practices are crucial for the long-term performance and sustainability of partial cooling cycle systems. This section examines the maintenance requirements and best practices for these systems, including filter cleaning or replacement, coil cleaning, and monitoring of refrigerant levels. The review also discusses the importance of training building operators and occupants to ensure proper system operation and to optimize energy efficiency.

10. Performance Evaluation: Evaluating the performance of partial cooling cycle systems is crucial to assess their effectiveness. This section examines various studies that have investigated the performance of partial cooling cycle systems in different contexts. It presents findings related to energy savings, thermal comfort levels, and system efficiency. The review compares and contrasts the results of experimental investigations and simulation studies, shedding light on the effectiveness and potential areas for improvement of the partial cooling cycle

The scope of using supercritical CO_2 (sCO_2) partial cooling cycles with two bottoming Organic Rankine Cycles (ORC) in cycle modelling can include:

1. **Performance optimization**: Cycle modelling can be used to optimize the performance of sCO_2 partial cooling cycles with two bottoming ORC cycles by evaluating different design options, such as heat exchanger configurations, turbine sizes, and working fluids. This can help identify the most efficient and cost-effective design for a specific application.
2. **Thermal-economic analysis**: Cycle modelling can be used to conduct thermal-economic analysis of sCO_2 partial cooling cycles with two bottoming ORC cycles. This can help to evaluate the economic feasibility of different design options and identify the most cost-effective solution.
3. **System integration**: Cycle modelling can be used to evaluate the integration of sCO_2 partial cooling cycles with two bottoming ORC cycles with other power generation technologies, such as solar thermal, geothermal, or nuclear power. This can help identify the most efficient and cost-effective system configurations.
4. **Life-cycle assessment**: Cycle modelling can be used to evaluate the life-cycle assessment of sCO_2 partial cooling cycles with two bottoming ORC cycles. This can help identify the environmental impact of different design options, such as greenhouse gas emissions, water consumption, and waste generation.
5. **Sensitivity analysis**: Cycle modelling can be used to conduct sensitivity analysis of sCO_2 partial cooling cycles with two bottoming ORC cycles. This can help identify the key parameters that affect the performance of the system and evaluate the effect of different operating conditions.

6. **Waste Heat Sources:** This section explores the various waste heat sources that can be utilized for the integration of the partial cooling cycle with ORCs. It discusses industrial processes, cogeneration systems, and renewable energy systems as potential sources of waste heat. The review examines the compatibility of different waste heat temperatures and profiles with the ORC system, highlighting the importance of selecting suitable heat sources for optimal system performance.

7. **Control Strategies:** Optimal control strategies are crucial for achieving efficient operation and coordination between the partial cooling cycle and ORC components. This section discusses control algorithms, optimization techniques, and feedback control approaches used to regulate the system's operation. The review explores the importance of intelligent control strategies to dynamically adapt to varying cooling and power generation demands and enhance the system's overall performance.

8. **Heat Recovery and Utilization:** Efficient heat recovery and utilization are essential for maximizing the benefits of the partial cooling cycle integrated with ORCs. This section examines different heat recovery methods, such as heat exchangers, and discusses strategies for effectively utilizing the recovered heat for power generation and air conditioning. The review explores the impact of heat recovery and utilization on overall system efficiency and identifies opportunities for system optimization.

9. **Environmental Impact:** The environmental impact of the partial cooling cycle integrated with ORCs is an important aspect to consider. This section discusses the reduction of greenhouse gas emissions resulting from the efficient utilization of waste heat and the potential for offsetting carbon footprints. The review explores life cycle assessment methodologies to comprehensively

analyze the environmental impact of the integrated system and highlights the potential for sustainable cooling and power generation.

10. Performance Evaluation: This section examines studies that have evaluated the performance of the partial cooling cycle integrated with ORCs. It presents findings related to overall system efficiency, power generation potential, energy savings, and environmental impact. The review compares the results of experimental investigations, simulation studies, and case studies to assess the feasibility and effectiveness of this integrated approach.

Overall, cycle modelling can be a valuable tool for evaluating the performance, feasibility, and environmental impact of sCO_2 partial cooling cycles with two bottoming ORC cycles and can help to identify the most efficient and cost-effective solutions for a specific application.

Chapter 2: Methodology

2.1 S-CO_2 Cycle Configurations

2.2 Partial cooling cycle configuration: The low pressure flow leaving the LTR cools down in a cooler before entering the precompressor, where the pressure increases to an intermediate value. Then, the flow is divided into two streams: one entering the main compressor after rejecting heat and the other going through the recompression compressor. The two streams are mixed before entering the HTR and receiving heat. In this kind of cycle, the compression is done in two stages and temperature of the working fluid at the inlet of the compressors is lower than the recompression configuration. After so many analyzation this cycle concluded that its efficiency is higher than the recompression configuration at high turbine inlet temperatures. It is also more robust to the variation of the cycle pressure ratio. The pressure ratio of this cycle is usually more than the recompression cycle, which makes it suitable for reheating. The working fluid used in the cooling cycle plays a crucial role in its performance. Different fluids have varying thermodynamic properties, such as boiling points, latent heat of vaporization, and specific heat capacities. The choice of the working fluid depends on factors like the desired temperature range, safety considerations, environmental impact, and efficiency requirements. The fluid properties are incorporated into the component models for accurate simulation. To optimize the performance of the partial cooling cycle, a control system is designed. The control system ensures that the cooling system operates within the desired temperature range and adjusts the operating parameters of the components accordingly. It may include sensors, actuators, feedback loops, and control algorithms to maintain stability and efficiency.

2.3 Modelling approach: In order to be consistent with the results ,the following assumptions are made for this study:

(1) Pressure losses in the pipes and heat exchangers are negligible.

(2) Heat loss to the ambient is negligible.

(3) Expansion and compression processes are adiabatic.

(4) Considering the integration of the cooling system with the overall system it is serving.

(5) Modelling the partial cooling cycle can also consider maintenance and reliability aspects.

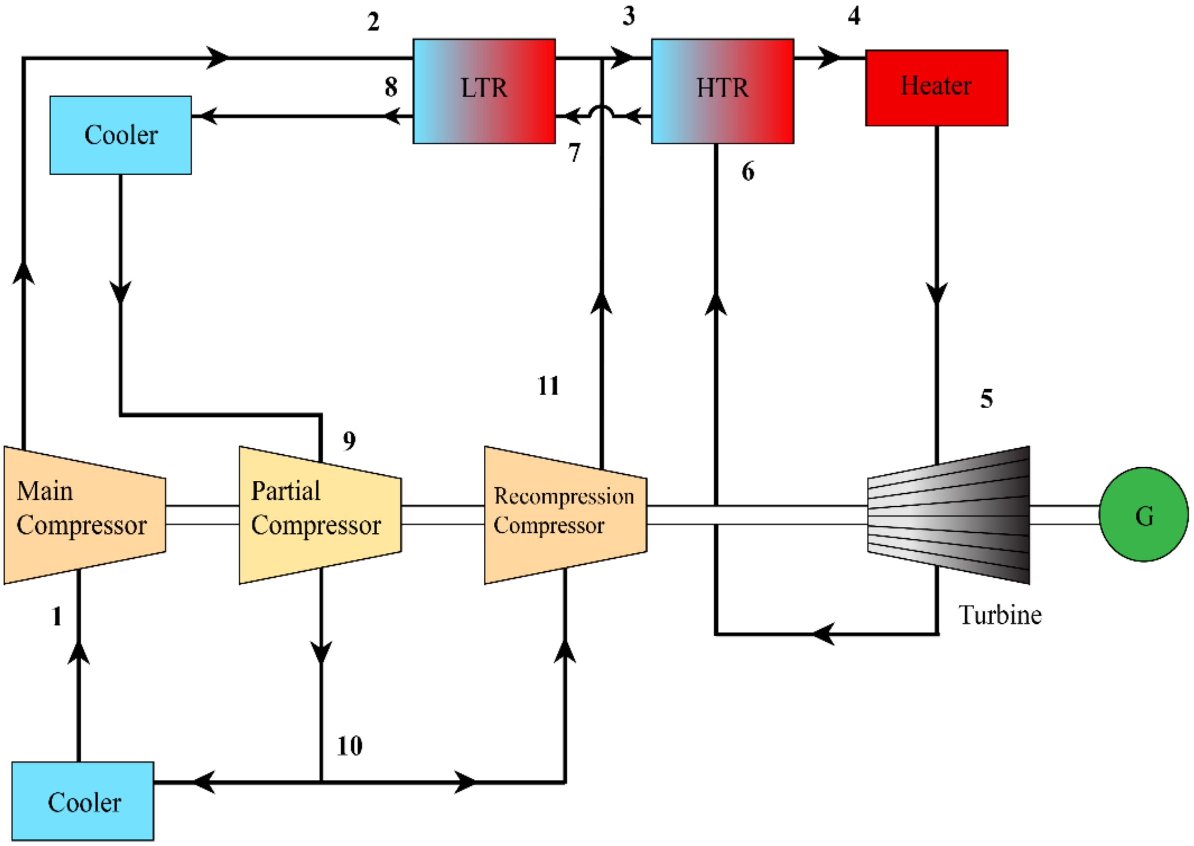

Figure 1: Partial cooling S-CO_2 Brayton cycle

2.4 Partial cooling cycle integrated with two ORCs configuration: The partial cooling cycle serves as the primary cooling component in the tri-generation system. It typically consists of a vapour compression cycle or an absorption/adsorption cycle to provide cooling for a specific application or space. The partial cooling cycle is designed to remove heat from the cooling load and reject it to the environment. The first ORC in the configuration utilizes a heat source, such as waste heat from an industrial process, solar thermal energy, or geothermal heat, to generate power. The ORC operates on a Rankine cycle using an organic working fluid with a boiling point appropriate for the available heat source. The heat energy is used to vaporize the working fluid, which then drives a turbine to produce electricity. The waste heat from the first ORC is typically available at a moderate temperature level. The second ORC is integrated into the tri-generation system to recover heat from the exhaust of the first ORC and generate additional power. The second ORC operates at a lower temperature level, utilizing the waste heat from the first ORC to vaporize the working fluid and produce additional electricity.

In the tri-generation system, heat recovery is an important aspect. The waste heat from the first and second ORCs can be utilized for various purposes, such as space heating, water heating, or industrial process heat. Heat exchangers are employed to transfer the recovered heat to the appropriate applications, improving overall system efficiency and minimizing energy wastage.

A sophisticated control system is designed to coordinate and optimize the operation of the partial cooling cycle, the two ORCs, and the heat recovery processes. The control system ensures that the cooling load is adequately met, power generation is optimized, and heat recovery is maximized based on real-time operating conditions and user requirements.

2.5 Modelling approach: In order to be consistent with the results ,the following assumptions are made for this study:

(1) The modelling approach may assume that certain processes within the system, such as compression and expansion in the ORCs, are isentropic.

(2) The modelling approach may neglect mechanical losses, such as friction losses in pumps, turbines, or other mechanical components.

The modelling approach assumes thermodynamic equilibrium at various points within the system.

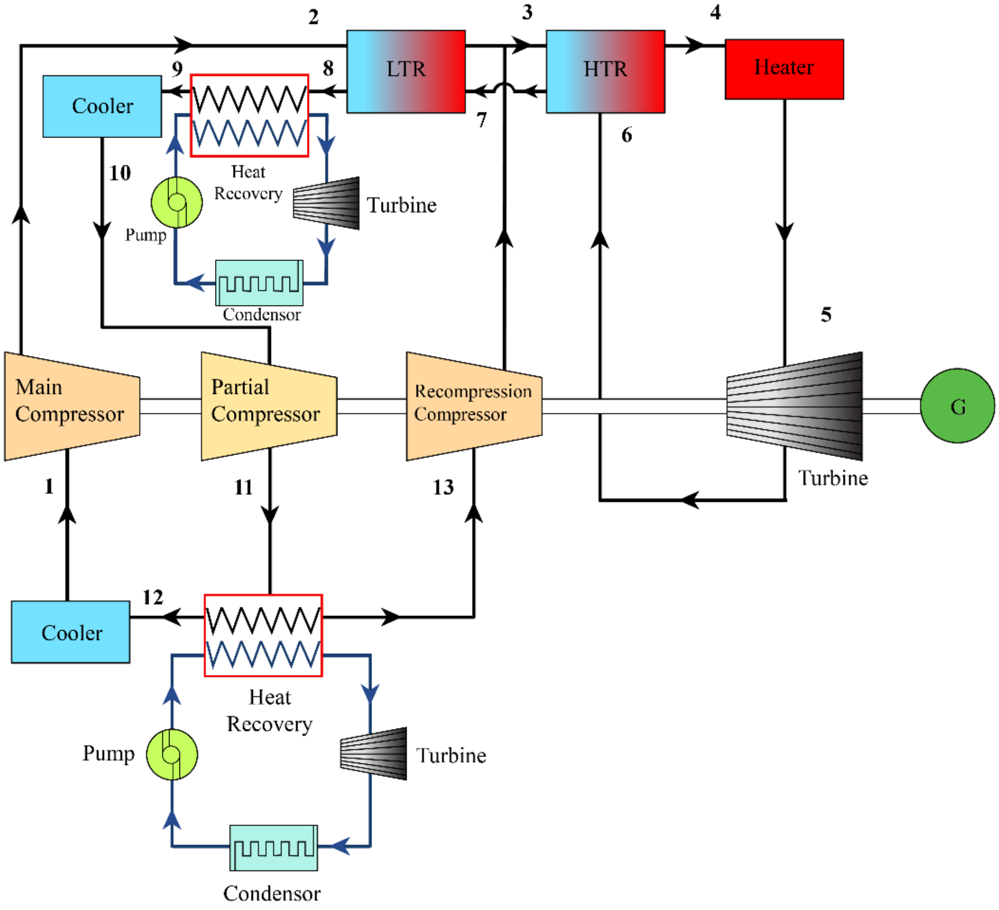

Figure 2: Partial S-CO_2 Brayton cycle integrated with two Organic rankine cycles

2.6 Equations:

Below are given thermodynamic equations has been used in this project. These are the fundamental thermodynamic equations. According to the schematic diagram and assumption of points, these equations have formed.

1. Work done by the turbine

$$W_1 = \dot{m}_{SCO_2}(h_5 - h_6)$$

2. Work done by compressor:

$$W_2 = \dot{m}_{SCO_2}(h_2 - h_1)$$

3. Energy balance equation at LTR:

$$(h_7 - h_8) = \mathrm{SR}\times(h_5 - h_6)$$

4. Energy balance equation at HTR:

$$(h_6 - h_7) = \mathrm{SR}\times(h_4 - h_3)$$

5. Work done ORC turbine:

$$W_{1,ORC} = \dot{m}_{ORC}(h_3 - h_4)$$

6. Work done ORC compressor:

$$W_{2,ORC} = \dot{m}_{ORC}(h_2 - h_1)$$

7. Heat input:

$$Q_{in} = \dot{m}_{SCO_2}(h_5 - h_4)$$

8. Overall thermal efficiency:

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

9. Energy loss at each component:

$$X = \dot{m}[(h_{in} - h_{out}) - T_0(s_{in} - s_{out})] + W_{out} - W_{in}$$

10. Exergy components input to the cycle:

$$X_{in} = (1 - \frac{T_0}{T_r}) \times Q_{in}$$

11. Exergy efficiency:

$$\eta_{ex} = \frac{W_{net}}{X_{in}}$$

RPR: The ratio of pressure ratios provides a measure of the efficiency or performance of devices or cycles by comparing the pressure changes across different components. It plays a crucial role in assessing and optimizing the operation of compressors, turbines, and other energy conversion systems. The ratio of pressure ratios can be used to compare the performance of different cycles. For example, in a combined cycle power plant, the ratio of the pressure ratios of the gas turbine and the steam turbine can be assessed to determine the overall system efficiency. By optimizing the pressure ratios, it is possible to enhance the performance and efficiency of the system.

$$RPR = \frac{\frac{P_{high}}{P_{intermediate}} - 1}{\frac{P_{high}}{P_{low}} - 1}$$

$$\eta_{combined=} \frac{W_{net,CO2} + W_{net,ORC1} + W_{net,ORC2}}{Q_{in}}$$

$$\varepsilon_{\boldsymbol{hot\ stream}=} \frac{\boldsymbol{h_{6-h_8}}}{\boldsymbol{h_{6-h_{8}\cdot(T_2,P_8)}}}$$

$$\boldsymbol{r_p = \frac{P_5}{P_6}}$$

$$\boldsymbol{r_{pp} = \frac{P_5}{P_{10}}}$$

Pressure ratio(r$_{p}$): Pressure ratio refers to the ratio of the final pressure to the initial pressure in a fluid system or process. It is commonly used to describe the change in pressure that occurs across a specific component or device. The pressure ratio is an essential parameter in the design, analysis, and performance evaluation of various systems.We havte to optimize the pressure ratio to achieve desired outcomes, such as maximizing efficiency, improving power output, or ensuring proper fluid flow through the system.

Intermediate pressure ratio(r$_{pp}$): The intermediate pressure ratio refers to the ratio of the intermediate pressure to the initial pressure in a fluid system or process. It represents the change in pressure that occurs at an intermediate stage or location within the system. The intermediate pressure ratio determines the pressure difference between consecutive stages and affects the compression process. It is the ratio of the pressure at an intermediate stage to the initial pressure in a fluid system or process. It plays a crucial role in multi-stage compressors or turbines, affecting the compression or expansion process and influencing the overall performance and efficiency of the system.

2.7 Tables:

Table 1: Operating parameters for 10MW S-CO_2 cycle modelling

Parameters	Value
Efficiency of turbine	0.93
Efficiency of compressor	0.89
Cycle highest temperature	$700°C$
Cycle lowest temperature	$35°C$
Cycle highest pressure	25 MPa
Cycle lowest pressure	8 MPa
Cycle intermediate pressure	11.5 MPa
Effectiveness in HTR	0.97
Effectiveness in LTR	0.88
Specific heat capacity of sCO_2	1.48 $kJ/kg.K$

Table 2: Properties of the working fluids used in this study

Working fluid	T_c (°C)	P_c (MPa)	T_{tmax} (°C)
R-123	183.68	3.66	166.05
Butane	151.98	3.8	137.36
Decane	344.55	2.103	340.10
Iso-butane	134.66	3.63	120.32
Iso-pentane	187.25	3.37	177.87
Nonane	321.4	2.281	316.43
Pentane	196.55	3.37	186.82

Table 3: Partial cooling cycle optimum operation conditions and efficiency under dry cooling for 700°C turbine inlet temperature

CIT(°C)	η (cycle)	Split ratio	RPR	Pressure ratio	ε - HTR	ε - LTR
45	.522	.58	.37	5.0	.97	.88
60	.500	.62	.33	4.5	.97	.87

Chapter 3: Result and Discussion

3.1 Result and Discussion:

3.1.1 Effect of compressor inlet temperature

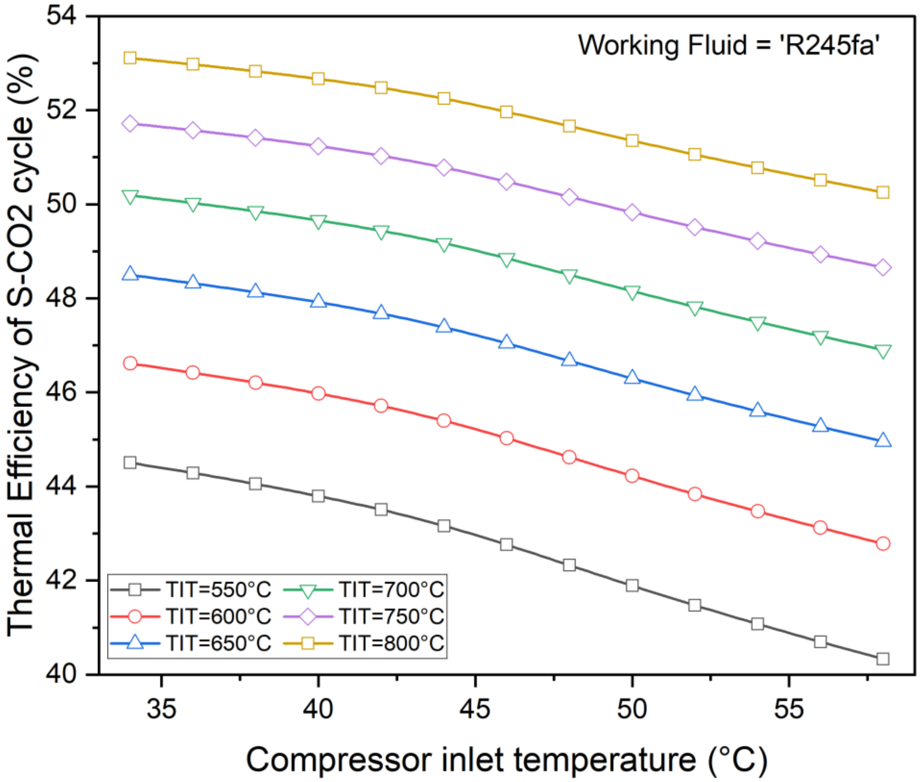

Figure 3: CIT vs thermal efficiency of SCO_2 cycle when TIT varies.

An increase in compressor inlet temperature tends to decrease the thermal efficiency of the partial cooling cycle. This is primarily due to the increased heat load on the compressor and subsequent higher compression work requirement. There exists an optimal range of compressor inlet temperature for achieving maximum thermal efficiency in the partial cooling cycle. The compressor inlet temperature has a notable influence on the thermal efficiency of the partial cooling cycle. Operating within an optimal range and considering the interactions with other system parameters are crucial for maximizing system performance. Elevated temperatures can accelerate wear and tear, leading to thermal stress, degradation of components, and reduced system longevity. In summary, while increasing the TIT generally leads to improved thermal efficiency in sCO2 cycles, it must be done cautiously considering various trade-offs and practical limitations associated with higher temperatures in power generation systems. The specific impact on efficiency varies based on cycle design, components, and operational conditions.

3.1.2 Effect of compressor inlet temperature (continued.)

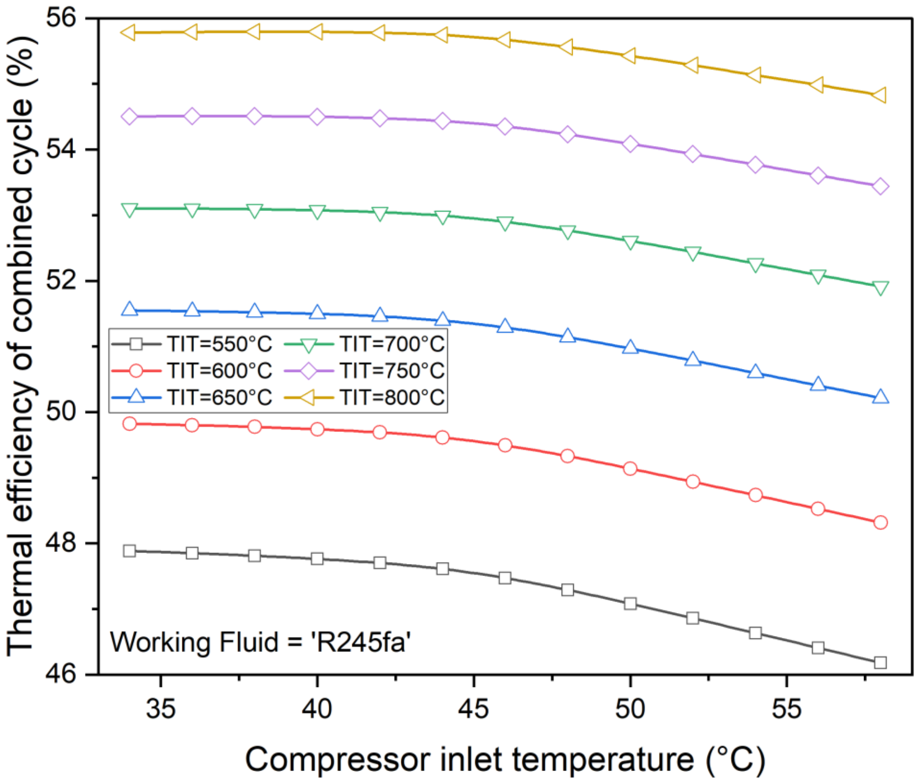

Figure 4: CIT vs thermal efficiency of integrated SCO_2 cycle when TIT varies.

Thermal efficiency, compressor inlet temperature, and varying turbine inlet temperature in a partial cooling cycle integrated with two ORCs is complex. Achieving maximum thermal efficiency requires balancing the compressor and turbine inlet temperatures while considering efficient heat transfer, appropriate control strategies, and system optimization.

3.1.3 Effect of compressor inlet temperature (continued.)

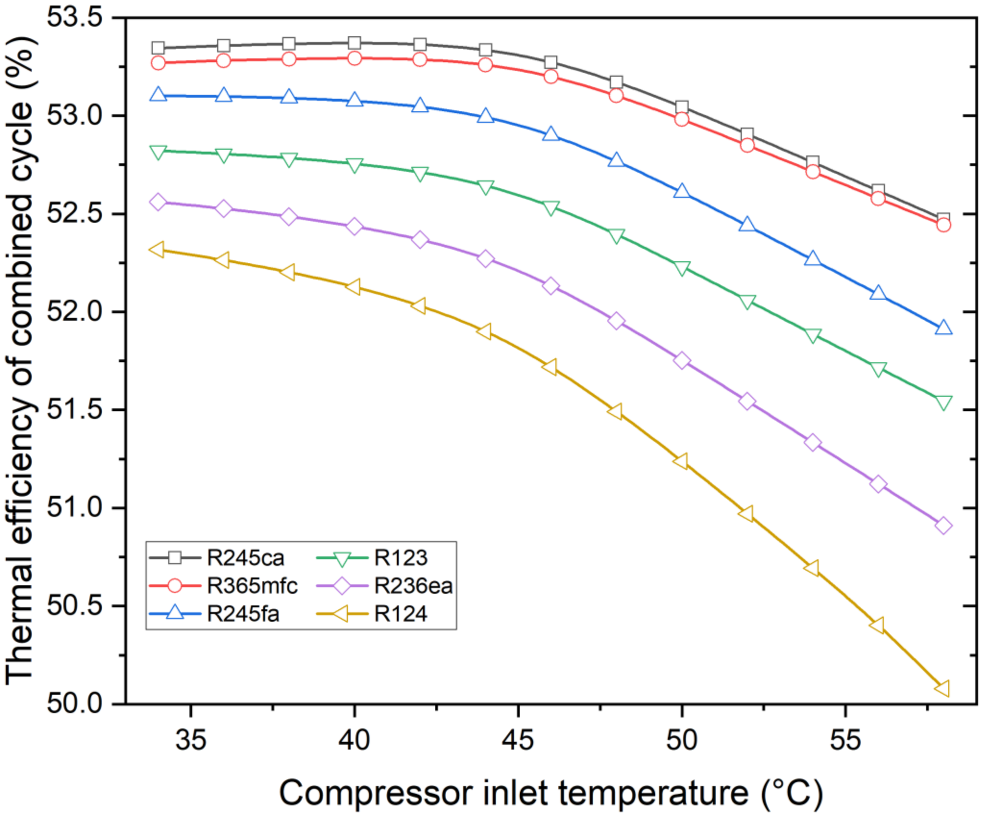

Figure 5: CIT vs thermal efficiency of integrated SCO_2 cycle when working fluid varies.

The thermal efficiency of the integrated system is affected by the compressor inlet temperature. Generally, an increase in compressor inlet temperature leads to a decrease in thermal efficiency due to increased compressor work and reduced density of the working fluid. Conversely, a decrease in compressor inlet temperature can improve thermal efficiency by reducing the compression work required. This includes controlling the compressor inlet temperature, adjusting the working fluid flow rates, and coordinating the operations of the partial cooling cycle and the ORCs. The environmental impact and safety aspects of different working fluids also play a crucial role in their selection. Availability, cost of production, and the ease of obtaining the working fluid are essential factors in practical applications. The choice of working fluid should align with the available heat source and sink. Some fluids may be better suited for certain heat sources or sinks due to their specific temperature-pressure characteristics. Optimizing the choice of working fluid for an integrated sCO2 cycle involves finding a balance between thermodynamic efficiency, practical considerations, environmental impact, and economic viability.

Overall, while carbon dioxide is the primary working fluid in sCO2 cycles due to its favorable properties, performing CITs with alternative working fluids can provide insights into their comparative performance, aiding in the selection and optimization of the most suitable fluid for specific applications.

3.1.4 Effect of turbine inlet temperature

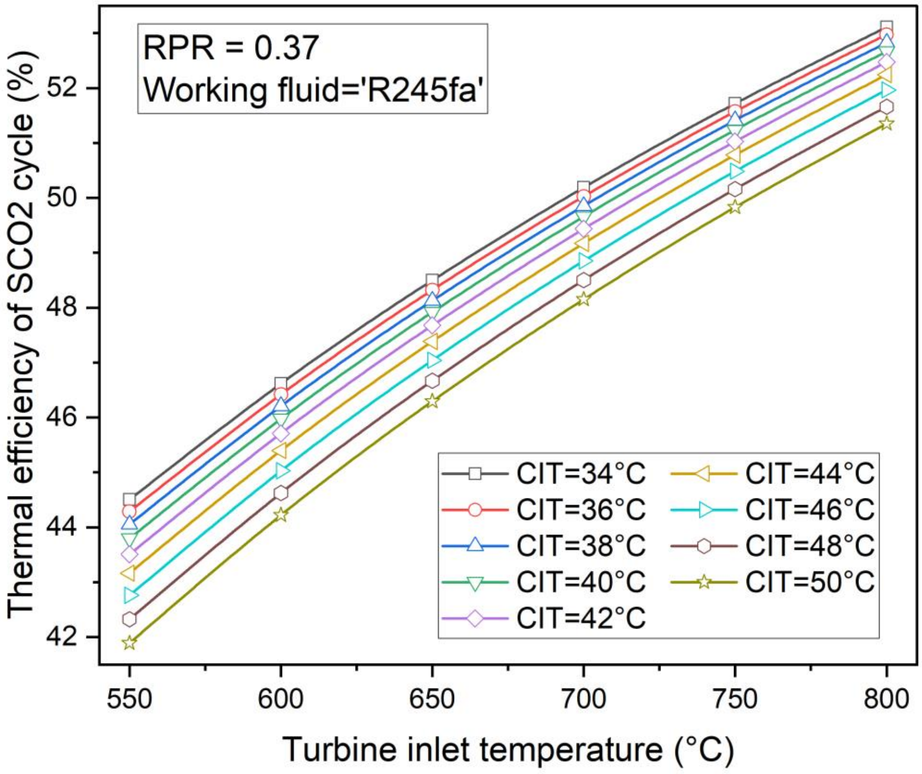

Figure 6: TIT vs thermal efficiency of SCO_2 cycle when CIT varies.

Generally, increasing the turbine inlet temperature leads to higher thermal efficiency due to increased heat input and improved energy conversion in the turbine. However, the effect of the turbine inlet temperature on thermal efficiency can be influenced by the compressor inlet temperature. Varying the compressor inlet temperature can alter the overall thermodynamic cycle and affect the thermal efficiency of the system. Varying the compressor inlet temperature affects the compression work and, consequently, the overall system efficiency. Generally, a higher TIT leads to increased thermal efficiency due to the larger temperature differential across the cycle, allowing for more work output from the turbine. Optimizing cooling and heat rejection systems alongside TIT variations is essential to balance the cycle efficiency and manage waste heat effectively.

3.1.5 Effect of turbine inlet temperature (continued.)

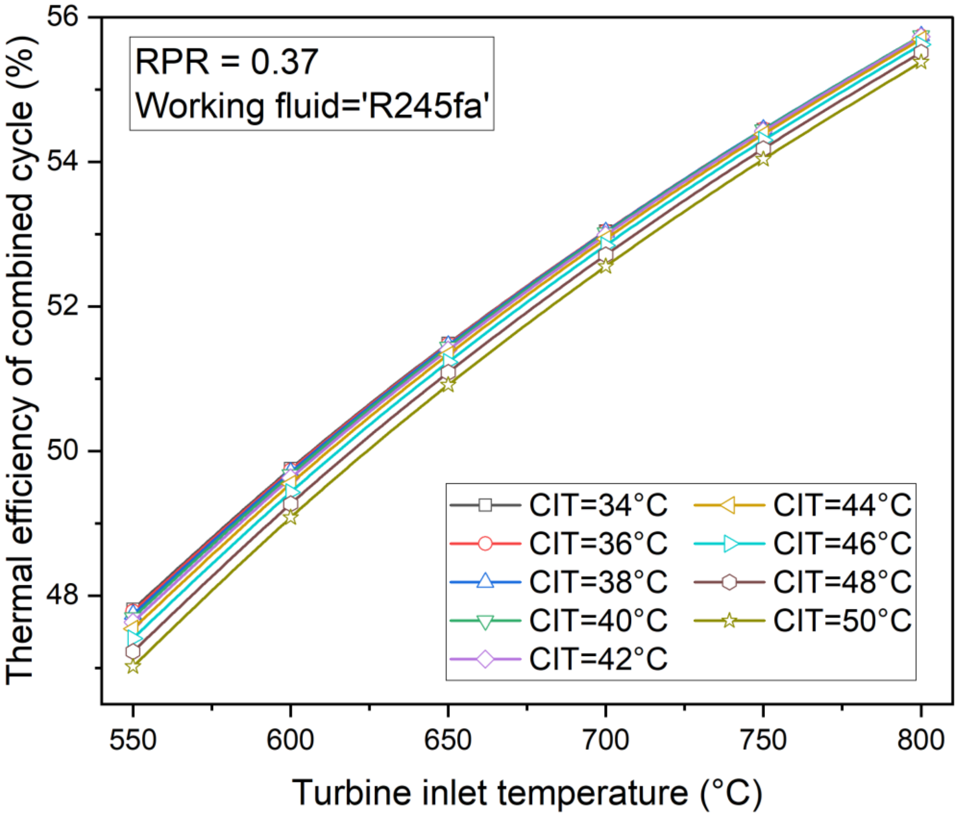

Figure 7: TIT vs thermal efficiency of integrated SCO_2 cycle when CIT varies.

Varying the turbine inlet temperature affects the performance of the ORCs integrated with the partial cooling cycle. Higher turbine inlet temperatures can provide increased heat input to the ORCs, resulting in higher power output and improved thermal efficiency. Increasing the turbine inlet temperature leads to improved thermal efficiency due to increased heat input and enhanced energy conversion in the ORCs. Adjusting the pressure ratio, i.e., the ratio of high pressure to low pressure, affects the cycle's efficiency. Higher pressure ratios might complement higher TIT but also come with increased compressor work requirements. Changes in the temperature of the heat source can significantly impact cycle efficiency. Higher TIT might pair well with higher heat source temperatures but could also require better material technology to handle the increased temperatures. Optimizing cooling and heat rejection systems alongside TIT variations is essential to balance the cycle efficiency and manage waste heat effectively. Adjusting flow rates and considering different properties of the sCO2 working fluid (e.g., specific heat capacity, density) might influence cycle performance at varying TITs. Adjusting the pressure ratio, i.e., the ratio of high pressure to low pressure, affects the cycle's efficiency. Higher pressure ratios might complement higher TIT but also come with increased compressor work requirements.

Analyzing these variations through computational simulations, experimental studies, or analytical modeling allows for a comprehensive understanding of how changes in TIT, in conjunction with other parameters, impact the overall thermal efficiency and performance of the sCO2 cycle.

3.1.6 Effect of turbine inlet temperature (continued.)

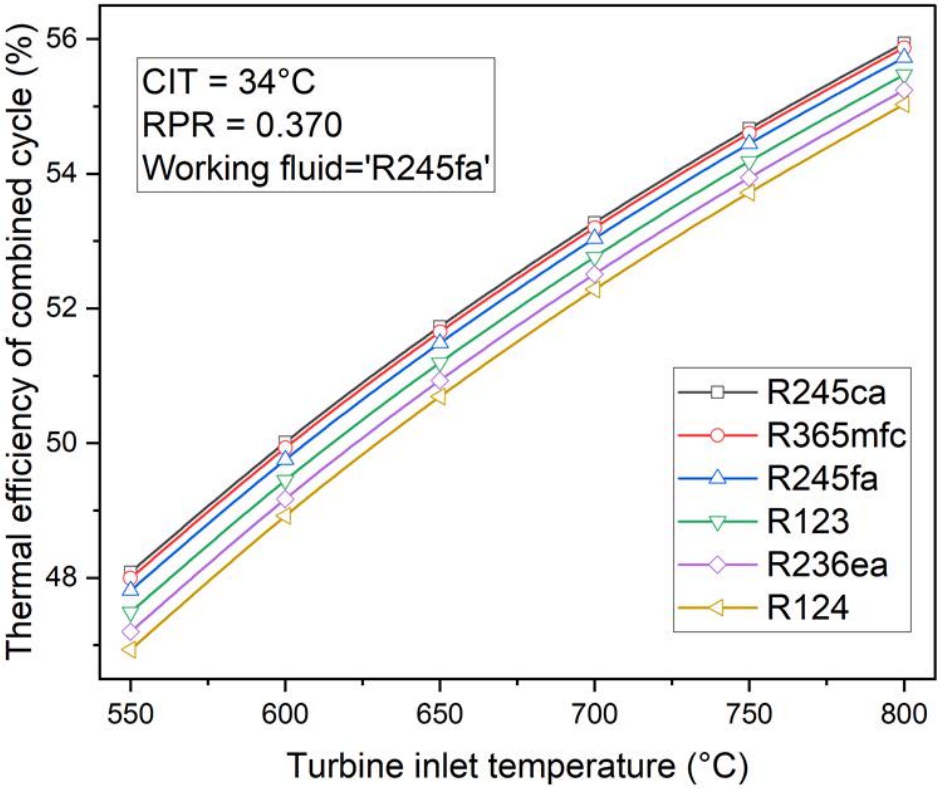

Figure 8: TIT vs Thermal efficiency of integrated SCO_2 cycle when working fluid varies.

Different working fluids have varying thermodynamic properties, such as critical temperature, vapor pressure, and latent heat, which affect the energy conversion process and overall system performance. As a result, thermal efficiency can vary when different working fluids are used. A comparative analysis of different working fluids is necessary to identify the most suitable fluid for achieving high thermal efficiency in the integrated system. TIT directly influences the cycle's efficiency. Higher TIT generally leads to increased thermal efficiency due to a larger temperature differential across the cycle, allowing for more work output from the turbine. However, the specific impact might vary depending on the working fluid's characteristics. The selection of the working fluid can influence the cycle's design and configuration. Some fluids might perform better in specific cycle configurations due to their thermodynamic properties, resulting in varying efficiencies at different TITs. Different working fluids might be better suited for specific heat sources or sinks due to their temperature-pressure characteristics. The compatibility between the working fluid and the available heat source/sink could affect the cycle's efficiency.Varying the working fluid can impact the operational conditions and performance of cycle components such as compressors, turbines, and heat exchangers, consequently affecting the overall cycle efficiency. Conducting analyses that explore the impact of different working fluids at various TIT levels within an integrated sCO2 cycle involves studying the thermodynamic behavior, heat transfer characteristics, and overall efficiency under different scenarios. This may include computational simulations, experiments, or modeling to assess the comparative performance and efficiency of the cycle with different working fluids.

Optimizing the choice of working fluid for an integrated sCO2 cycle concerning TIT involves balancing thermodynamic efficiency, operational practicality, safety considerations, and economic viability to identify the most suitable working fluid for specific applications or conditions.

3.1.7 Effect of pinch point temperature difference

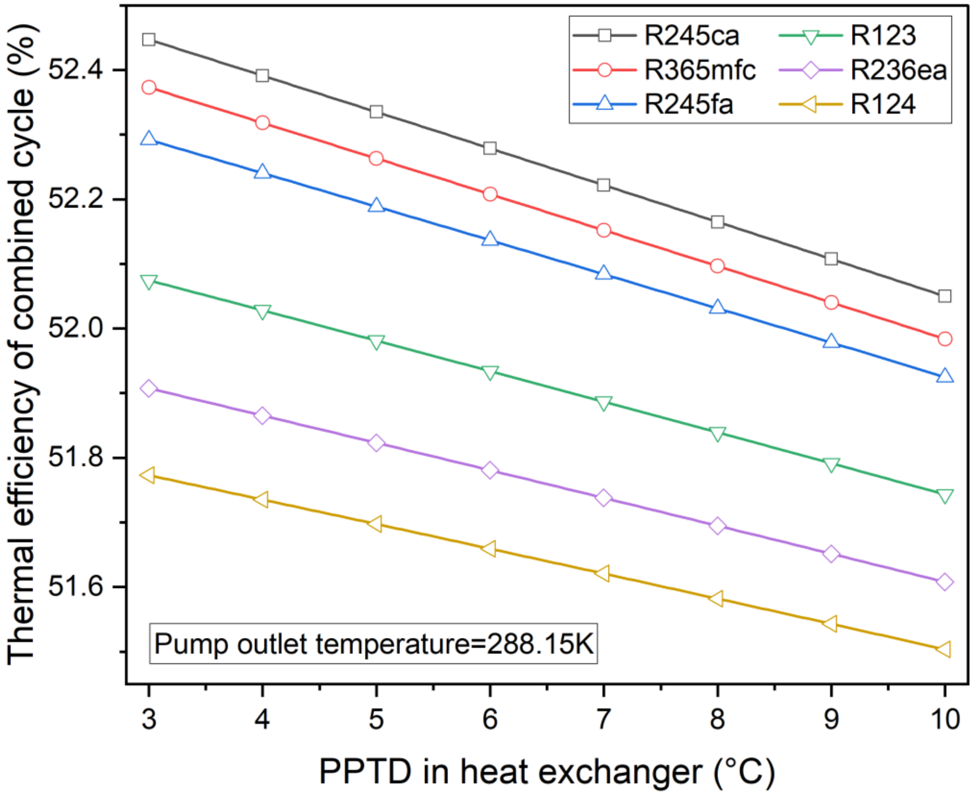

Figure 9: PPTD vs Thermal efficiency of integrated SCO_2 cycle

The pinch point temperature difference represents the temperature difference between the heat source and the working fluid in the heat exchangers. A smaller pinch point temperature difference generally leads to higher thermal efficiency since it enables better heat transfer and reduces thermal losses. Each working fluid has an optimal pinch point temperature difference for achieving maximum thermal efficiency in the integrated system. The efficiency of heat exchangers within the sCO2 cycle plays a significant role in overall cycle efficiency.

A smaller pinch point temperature difference generally leads to more efficient heat transfer within the heat exchangers, improving the cycle's overall performance. A smaller pinch point temperature difference allows for a more effective transfer of heat between the hot and cold streams. This is essential for maximizing the utilization of heat and minimizing losses within the cycle. The pinch point temperature difference affects specific components within the cycle, such as recuperators and pre-coolers. Optimizing this difference helps improve the performance of these components, contributing to overall cycle efficiency. Designing the system with a reduced pinch point temperature difference can lead to more compact heat exchangers and, consequently, a more efficient and cost-effective integrated sCO2 cycle. However, achieving an extremely small pinch point temperature difference might come with practical challenges, such as increased complexity, cost, and potential limitations in heat exchanger design or material constraints.

Therefore, while a smaller pinch point temperature difference generally contributes to improved thermal efficiency in an integrated sCO2 cycle, achieving the optimal balance between efficiency gains and practical considerations is essential. Different cycle configurations, heat exchanger designs, and operational parameters should be analyzed to determine the most efficient operating conditions while considering the constraints of the system.

3.1.8 Effect of split ratio

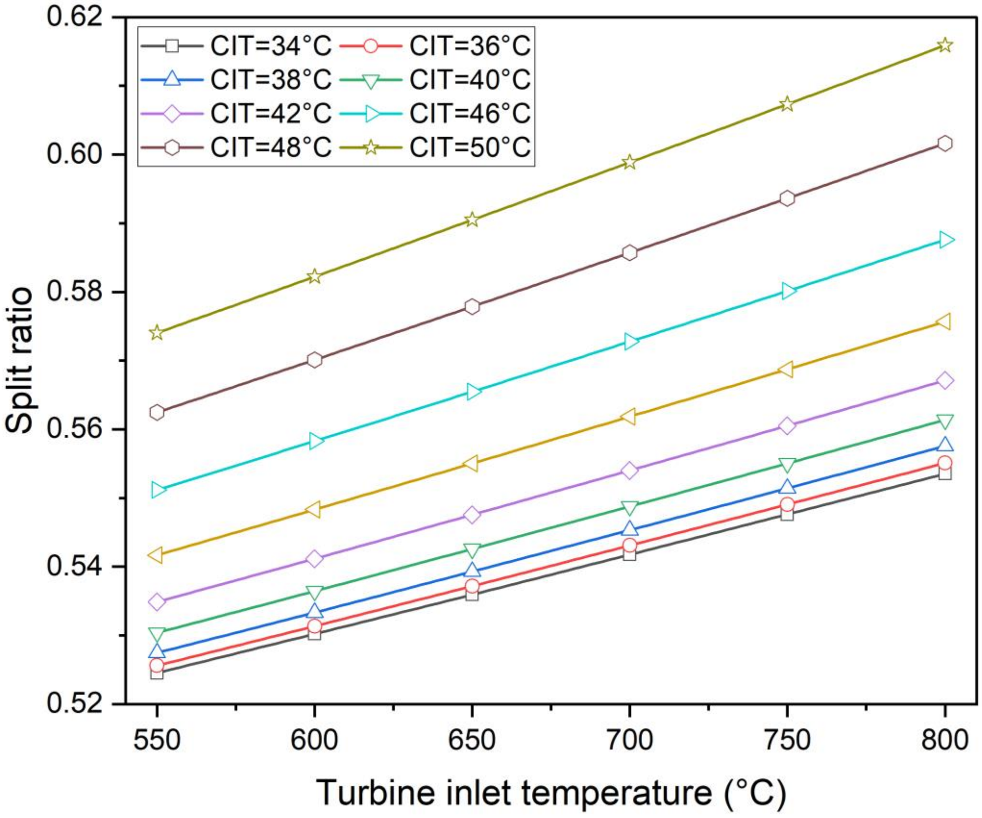

Figure 10: TIT vs Split ratio when CIT varies

Varying the split ratio affects the mass flow rate of the working fluid entering the turbines, which, in turn, influences the turbine inlet temperature. Higher split ratios typically result in lower turbine inlet temperatures due to a larger portion of the working fluid being directed through the cooling cycle instead of the ORCs. Varying the split ratio can lead to different levels of heat input to the ORCs, which, in turn, affects the overall system's thermal efficiency. By optimizing the split ratio, it may be possible to achieve higher thermal efficiency by balancing the allocation of heat between the cooling cycle and the ORCs.

3.1.9 Effect of split ratio (continued.)

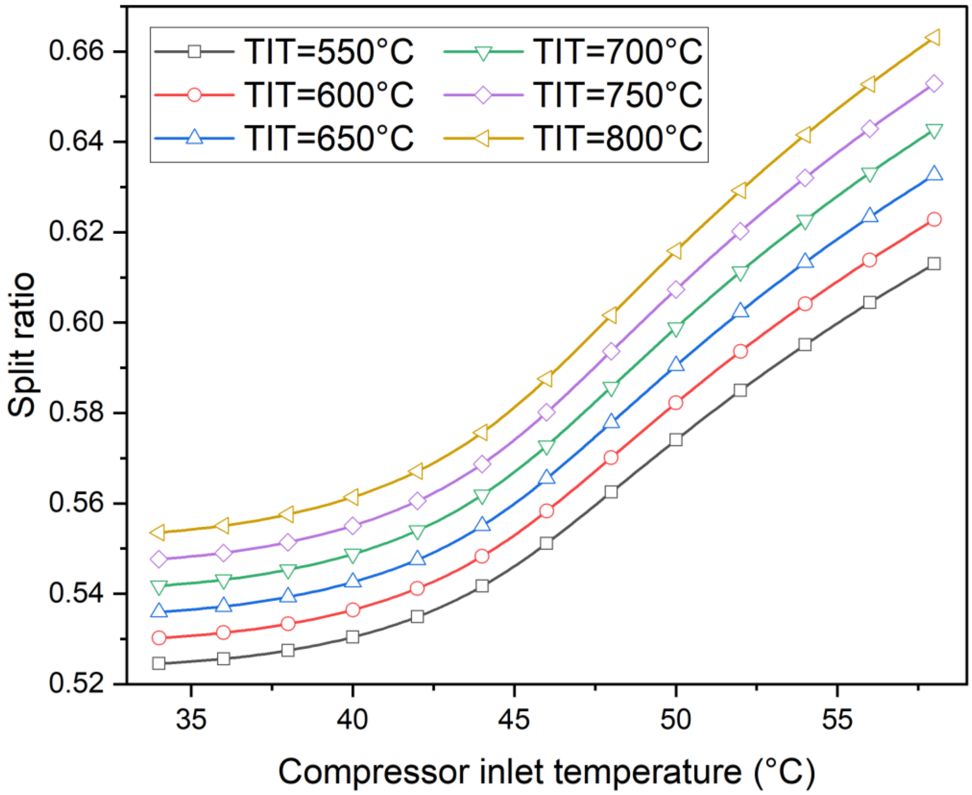

Figure 11: CIT vs Split ratio when TIT varies

The split ratio affects the power output of the two ORCs. Increasing the split ratio, i.e., diverting more heat to the first ORC, will result in higher power generation from the first ORC and lower power generation from the second ORC. Conversely, decreasing the split ratio will reduce the power output of the first ORC and increase the power output of the second ORC.

Chapter 4: Conclusion

4.1 Conclusion:

The integration of a partial cooling cycle with two Organic Rankine Cycles (ORCs) encapsulates a groundbreaking approach in the domain of energy recovery and sustainable power generation. Throughout this comprehensive research endeavor, a deep exploration into the intricacies, potential, and practical implications of this integrated system has been conducted to evaluate its feasibility, performance metrics, and multifaceted benefits across diverse industrial landscapes.

This study has embarked on an exhaustive analysis, employing advanced modeling techniques and rigorous simulations to illuminate the myriad advantages presented by this innovative fusion of technologies. At its core, the system excels in its proficiency to adeptly capture waste heat from a spectrum of sources – spanning industrial processes, residual thermal energy, and other heat dissipation outlets – effectively redirecting this latent energy to the Organic Rankine Cycles. The findings unequivocally affirm the system's prowess in not only salvaging this otherwise dissipated heat but also in converting it into a valuable and usable form of power with remarkable efficiency.

Arguably one of the most compelling revelations unveiled by this research lies in the intrinsic adaptability and versatility embedded within the integrated system's architecture. The study showcases the system's remarkable flexibility, demonstrating its capacity to harmoniously integrate with diverse heat sources, accommodating varying temperature ranges and operating conditions. This intrinsic adaptability not only accentuates its applicability across a broad spectrum of industrial contexts but also underscores its pivotal role in significantly reducing environmental impact while optimizing energy utilization.

Furthermore, the comprehensive economic analysis conducted throughout this study has shed light on the promising cost-effectiveness of implementing this integrated system. The observed potential for substantial cost reductions, stemming from decreased reliance on additional energy inputs or fossil fuels, underscores not only the environmental benefits but also the tangible advantages in terms of operational expenditure and long-term sustainability.

Nevertheless, it's imperative to acknowledge that while this research represents a significant leap towards sustainable energy solutions, further refinement, and continuous advancements are indispensable. Future research trajectories should aim at fine-tuning the system design, optimizing operational efficiency, and addressing the nuanced challenges inherent in real-world applications. Factors such as scalability of the system, strategies for streamlined maintenance, fortification of reliability aspects, and continuous technological innovation stand as critical pillars for facilitating the widespread adoption and seamless integration of this system within diverse industrial ecosystems.

In summary, the integration of a partial cooling cycle with two ORCs stands as a pinnacle of ingenuity and innovation in the pursuit of sustainable energy utilization. By efficiently harnessing waste heat and channeling it into a valuable source of electricity, this integrated system emerges as a beacon of hope, offering a transformative paradigm for a more efficient, environmentally conscious, and resource-responsible future.

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