The 8th International Supercritical CO_2 Power Cycles Symposium
February 27 – 29, 2024, San Antonio, Texas
Paper #22

sCO_2 Waste Heat Recovery System for Turbofan Engine – System Optimization and Component Design

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ABSTRACT

The aviation industry accounts for part of the CO_2 emissions contributing to climate change. The industry has established a target to reduce 2050 net aviation carbon emissions by 50 % relative to 2005 levels. Decarbonization of the aviation industry can be done via several pathways. The waste heat recovery is one of the key pathways to achieving reduced emissions and improved system efficiency. Waste heat can be converted to electric power by using bottoming cycle. One of the potential bottoming cycles for aircraft application is a Supercritical CO_2 (sCO_2) power system. The sCO_2 power system has advantages because of the component compactness, which is a key factor for aircraft integration. The present work focuses on integration of the supercritical CO_2 power system into the aircraft propulsion system (current and next-generation aircraft engines with use of different fuels, such as sustainable aviation fuel (SAF), hydrogen, natural gas, ammonia, or dual fuels) and evaluation of its performance. Detailed optimization of the sCO_2 waste heat system will be evaluated with a focus on cycle efficiency and net power under different operating conditions (idling on the ground, cruise, landing, and takeoff). The primary heat exchanger (PHX) and cooler are the critical components of the system. The PHX and Cooler design are optimized to highest effectiveness. The results show that the WHR unit may generate an additional 100 - 300 kW with sCO_2 cycle efficiency approximately 33 %.

I. NOMENCLATURE

sCO_2	=	Supercritical carbon dioxide
H_2	=	Hydrogen
TIT	=	stagnation temperature at combustion chamber exit
TIT_{sCO2}	=	Turbine inlet temperature – sCO_2 power system
CIT_{sCO2}	=	Compressor inlet temperature
C	=	Compressor
T	=	Turbine
RHX	=	Recuperative heat exchanger
PHX	=	Primary heat exchanger
HX	=	Heat exchanger
G	=	Generator
LPT	=	Low pressure turbine
HPT	=	High pressure turbine
APU	=	Auxiliary Power Unit
WHR	=	Waste heat recovery systems
ECS	=	Environmental control system
CFD	=	Computational fluid dynamics

II. INTRODUCTION

Reducing emissions poses significant challenges when designing new energy systems based on fossil fuels. In 2021, the global anthropogenic CO_2 emissions amounted to around 35 billion tons. Asia was the largest contributor, accounting for roughly 60% of total CO_2 emissions, while Europe and the US jointly contributed about 17% [1]. The need to lower emissions necessitates design and process modifications across various sectors, including industrial production, gas turbine-based power plants, and transportation, encompassing both automotive and aviation [2]–[5]. Notably, the transportation sector is a major CO_2 emitter, accounting for approximately 27% of emissions, with the aviation industry responsible for about 3% of the total [6]. To mitigate CO_2 emissions in these sectors, there are several approaches available, encompassing both direct and indirect methods. A direct approach involves substituting current hydrocarbon fuels with those having lower life cycle emissions. The International Civil Aviation Organization (ICAO) has noted substantial improvements in air transport operations, achieving an 80% increase in fuel efficiency and a 75% reduction in noise levels compared to fifty years ago [7]. Sustainable aviation fuels (SAF) have gained attention as a potential alternative to fossil fuels, offering the promise of lower carbon emissions from production to combustion [8]. There is also growing interest in carbon-free fuels like hydrogen (H2) [10], [11], and ammonia [12].

An indirect approach focuses on harnessing waste heat from processes or exhaust streams [13]–[17] to enhance the overall efficiency of systems. In the case of aircraft, waste heat can be converted into electricity for onboard consumption [2], [13], [17]–[19] through various power cycles, such as the steam Rankine cycle [20], organic Rankine cycle [21], or supercritical CO_2 Brayton cycle [5], [22]. These thermodynamic cycles operate at different temperatures and efficiencies [23], which influence their suitability for specific applications. Implementing heat recovery in aircraft presents challenges due to strict weight and volume constraints, demanding operating conditions (e.g., vibration), and the need for safe and reliable operation. Nevertheless, a waste heat recovery (WHR) system offers an alternative avenue to enhance propulsion performance and reduce emissions in aircraft [2], [13], [17]–[19].

The power generated by an aircraft engine's bottoming cycle has the potential to supply energy to various systems, such as environmental control, hydraulics, pneumatics, and more, which have traditionally relied on engine power extraction, often through an accessory gearbox. For modern twin-engine single-aisle commercial aircraft, the rated power extraction typically amounts to approximately 125 kW per engine [24]. Importantly, this power output falls within the capacity of a supercritical CO_2 waste heat recovery (sCO_2 WHR) system [5], [19].

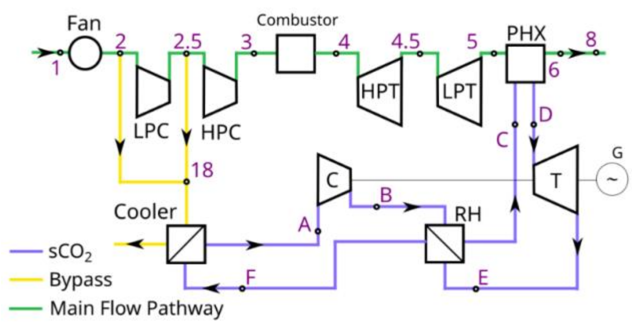


FIGURE 1: SCHEMATIC OF THE SCO_2 WHR SYSTEM FOR TURBOFAN ENGINE [37].

Nevertheless, a distinctive challenge for a waste heat recovery (WHR) system in aircraft engines lies in the integration of the primary heat exchanger (PHX) and Cooler into the engine's flow path, as illustrated in Figure 1. To ensure a net benefit, such as reduced specific fuel consumption (SFC), these heat acquisition (PHX) and heat rejection (Cooler) heat exchangers must exhibit low air-side pressure drops and conformal form factors. Numerous studies have been conducted on the design and implementation of heat exchangers for WHR systems in aircraft engines [2], [5], [25], [26]. For instance, Saltzman et al. [27] conducted a comparative analysis of conventionally constructed plate-fin air-to-liquid cross-flow heat exchangers (similar to aircraft oil coolers) and additively manufactured heat exchangers with a comparable geometry. This approach can also be applied to PHX and Cooler heat exchangers. In a similar vein, Misirlis et al. [28] optimized the recuperation system by employing computational fluid dynamics (CFD), experimental measurements, and thermodynamic cycle analysis, spanning a wide range of engine operating conditions.

III. AIRCRAFT ENGINE SYSTEM DESCRIPTION

The engine selected for this study is a high bypass ratio turbofan engine (i.e., most of the air bypasses the core of the engine and is exhausted out of the fan nozzle) with a bypass ratio of 5.2:1, generating 27,236 N (6,123 lbf) of thrust at 10,668 m (35,000 ft) altitude and a Mach number of 0.74. The engine is a two-shaft (or two-spool) engine, where each shaft is powered by its own turbine section (the high-pressure and low-pressure turbines, respectively). The fan and booster (commonly called the low-pressure compressor, LPC) are mounted on the low-pressure shaft. The overall pressure ratio is 35.496 and the fan pressure ratio is 1.7. The maximum cycle temperature is 1,460 K [5]. The T-s diagram of the engine is shown in Fig. 2.

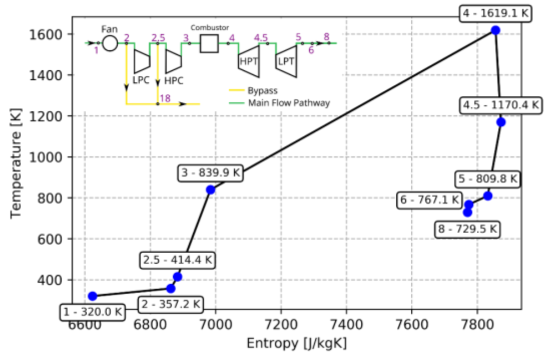


FIGURE 2: SCHEMATIC AND T-S DIAGRAM OF THE TURBOFAN ENGINE [37].

Engine cycle analysis is performed for 10 cases that address ground, takeoff, cruise, and landing operations. The sCO_2 WHR unit was analyzed for each case to assess feasibility for a wide range of operating conditions. The standard operating parameters and design point of the WHR unit for the engine are listed in Table 1, where the ground operation is at an altitude of 0 m and the cruise operation is at an altitude of 10,668 m. The study is done, and the cycle are analyzed under steady-state cruise operating condition at case 10.

TABLE 1: TURBOFAN ENGINE PARAMETERS [37].

Case	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**unit**
Altitude	0	0	0	0	0	0	1,668	9,668	10,668	10,668	m
Ambient temperature	320	315	310	300	290	288.15	277.31	225.31	218.81	218.81	K
Mach Number	0.00	0.00	0.00	0.00	0.00	0.00	0.30	0.50	0.64	0.74	-
Inlet parameters for PHX/Core (sCO_2 heater)											
T_5	865.3	856.7	848.0	830.9	816.2	813.5	792.4	684.3	684.1	679.8	K
P_5	124.13	125.02	125.967	128.03	130.47	130.96	111.28	47.74	45.38	47.29	kPa
Mass flow $_5$	59.25	60.45	61.69	64.33	67.21	67.77	59.95	28.56	27.16	28.4	kg/s
Inlet parameters for Air cooler/Fan (sCO_2 cooler)											
T_{18}	355.91	351.01	346.11	336.29	326.73	324.95	318.46	275.71	275.85	280.58	K
P_{18}	140.41	141.26	142.13	143.95	145.89	146.26	127.22	51.68	49.19	52.81	kPa
Mass flow rate $_{18}$	23.49	23.97	24.46	25.51	26.67	26.89	23.80	11.34	10.78	11.28	kg/s

IV. WASTE HEAT RECOVERY CYCLE

A. Main Flow Pathways Parameters

In the overall engine baseline configuration, the WHRS extracts the waste heat from the exhaust via the primary heat exchanger and rejects it at the bypass via the cooler as shown in Figures 1 and 4. Figure 3 displays the typical mission profile for an aircraft that uses the type of engine suitable for a WHR system implementation. The cycle calculations are done using assumptions, constraints, and boundary conditions from Tables 2 and 3.

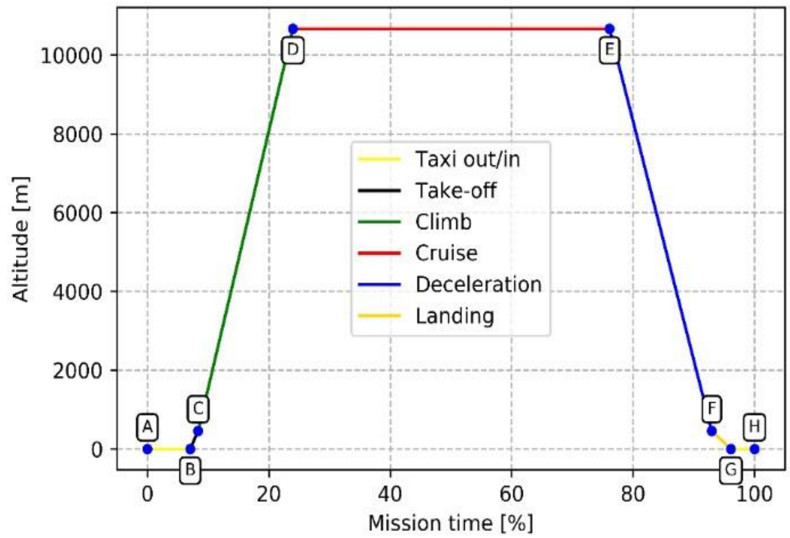


FIGURE 3: TYPICAL MISSION PROFILE BASED ON FLIGHT TIME [38].

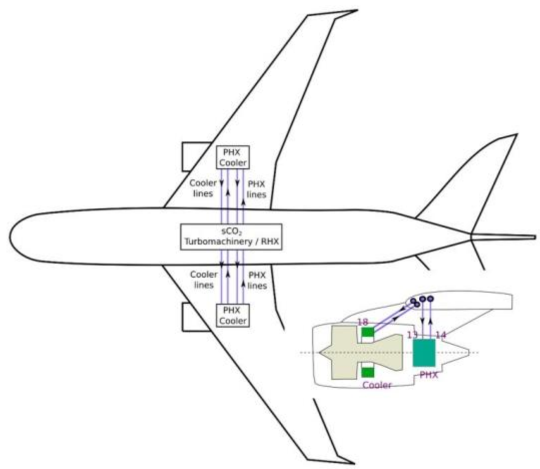


FIGURE 4: PLACEMENT/INTEGRATION ON ENGINE.

TABLE 2: sCO_2 WHR CYCLE INLET ASSUMPTIONS AT PRIMARY HEATER AND COOLER [37].

Case	ADP (Cruise)	unit
Altitude	10,668	m
Ambient temperature	218.81	K
Mach Number	0.74	-
Inlet parameters for PHX/Core (sCO_2 heater)		
T_5	722.42	K
P_5	42.74	kPa
Mass flow $_5$	28.4	kg/s
Inlet parameters for Air cooler/Fan (sCO_2cooler)		
T_{18}	306	K
P_{18}	59.29	kPa
Mass flow rate $_{18}$	11.28	kg/s

TABLE 3: BOUNDARY CONDITIONS FOR OPTIMIZATION [38].

Parameter	Assumptions	unit
Minimum compressor inlet temperature (CIT)	Air temperature + 5.0 K*	K
ΔT_{PHX}	10	
WHR unit compressor inlet pressure	7.4	MPa
Recuperator (RH) effectiveness	90	%
***Turbine isentropic efficiency**	90	
***Compressor isentropic efficiency**	75	
sCO_2 mass flow rate	Variable	kg/s
Net power	492	kW

*Assumed efficiency for preliminary analysis which will change with detailed design of the turbomachinery.

B. Definition of Required Power

The Waste Heat Recovery System (WHRS) plays a pivotal role in the electrical power generation of an aircraft, necessitating a defined baseline for its minimum power output. This baseline is crucial for consistent performance across various operational phases of the aircraft, such as take-off, cruise, landing, and taxiing. For the WHRS, a minimum power production of 492kW has been established, ensuring that the system meets the power demands in all these conditions. This benchmark is particularly relevant when considering the performance of engines like the Leap1B by Safran, which operates within a power transfer range of 310 to 450 kW with 22 kRPM shaft speed according to its Accessory Gearbox (AGP) Specifications [39]. The EASA (European Aviation Safety Agency) reports an electric power extraction of 125 kW per engine for a typical single aisle 250 passenger aircraft [24].

C. Comparison Metrics

The process of cycle selection hinges on a comprehensive evaluation of several critical criteria. The cycle performance, characterized by its ability to generate the necessary net power while effectively utilizing incoming waste heat, is of utmost importance. The system weight and size are considered to ensure practicality and efficiency. Additionally, the complexity of cycle integration plays a pivotal role in decision-making, as it directly impacts the system's feasibility and maintenance requirements. Furthermore, minimizing adverse effects on the heat source, such as maintaining pressure drops within permissible limits, is a key consideration. Lastly, striving for maximum overall engine performance underscores the overarching goal of achieving optimal efficiency and functionality in the selected cycle. These criteria collectively guide the selection process, ensuring that the chosen cycle aligns with the project's objectives and constraints.

- Cycle performance- producing required net power with incoming waste heat
- System weight and size
- Cycle and integration complexity
- Minimum effect on heat source such as lower than allowable pressure drops
- Maximum overall engine performance

V. sCO_2 POWER CYCLE SELECTION

A. Considered cycles

With the aim of maximizing power to heat transferred, the cycles that were considered are simple and recuperated Brayton, recompression, split expansion, precompression, precooling, preheating and cascade which is a mixed configuration of other cycles. As per the comparison metrics the final selected cycle aims to have relatively low cycle weight, integration complexity, and effect on heat source. As per Table 4, precooling, cascade, and preheating cycles have two primary heaters or coolers. Therefore, those cycles were no longer considered for analysis because the heat exchangers will carry higher percentages in terms of system weight, and they would introduce more complexity to the overall system integration. The schematics and Ts diagrams showing the mass flow rate path of the analyzed cycles are shown in Figures 5-14. The variations include a combination of turbine(s), compressor(s), primary heater(s), cooler(s), and recuperator(s).

TABLE 4: CYCLES UNDER CONSIDERATION AND THEIR COMPONENTS.

Components	Simple Brayton	Recuperative	Re-compression	Split expansion	Pre-compression	Pre-cooling	Cascade	Preheating	
Compressor	1	1	2	2	2	3	1	1	
Turbine	1	1	1	2	1	1	2	1	-
RHX	0	1	2	2	2	2	2	1	
PHX	1	1	1	1	1	1	2	2	
Cooler	1	1	1	1	1	2	1	1	

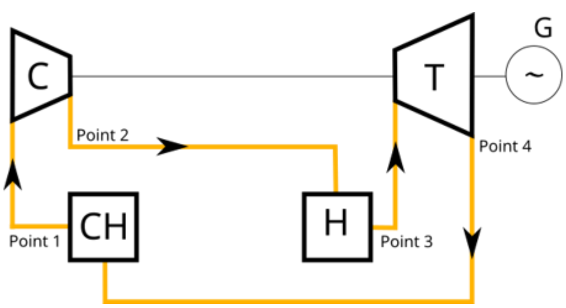


FIGURE 5: SCHEMATIC OF SIMPLE BRAYTON CYCLE.

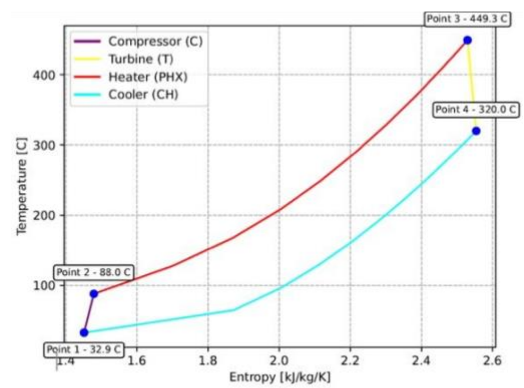


FIGURE 6: TS DIAGRAM OF SIMPLE BRAYTON CYCLE.

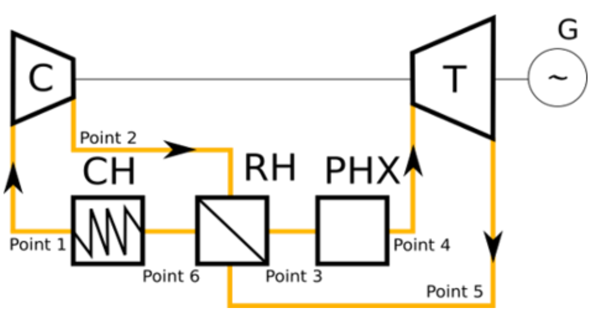


FIGURE 7: SCHEMATIC OF RECUPERATED BRAYTON CYCLE.

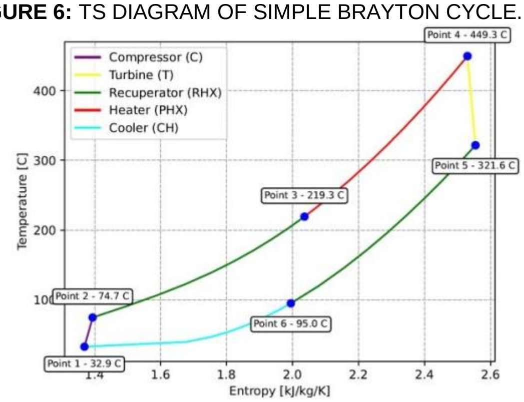


FIGURE 8: TS DIAGRAM OF RECUPERATED BRAYTON CYCLE.

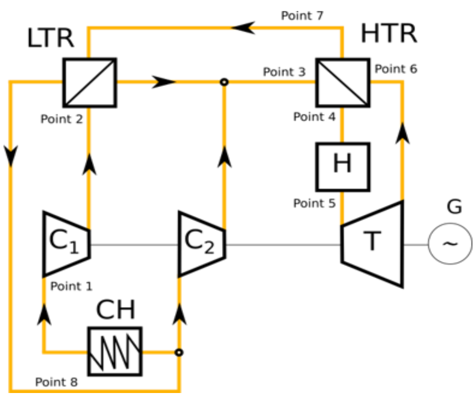


FIGURE 9: SCHEMATIC OF RECOMPRESSION CYCLE.

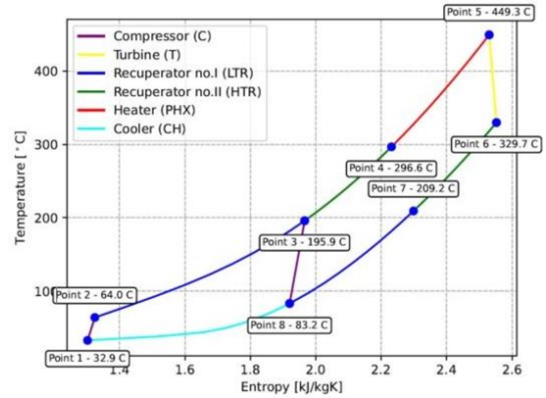


FIGURE 10: TS DIAGRAM OF RECOMPRESSION CYCLE.

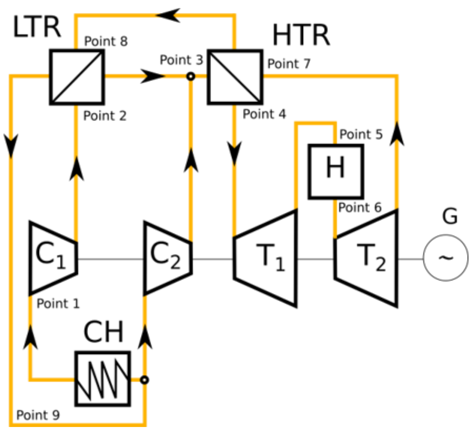


FIGURE 11: SCHEMATIC OF SPLIT EXPANSION CYCLE.

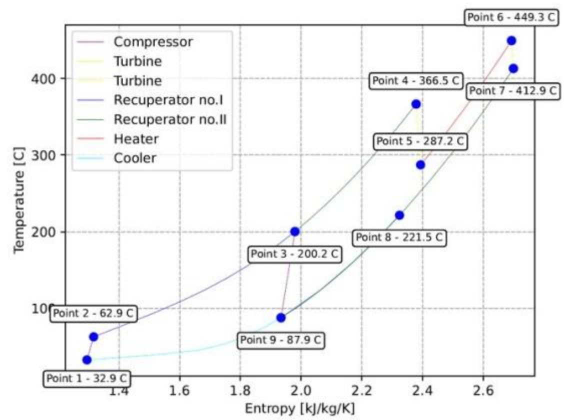
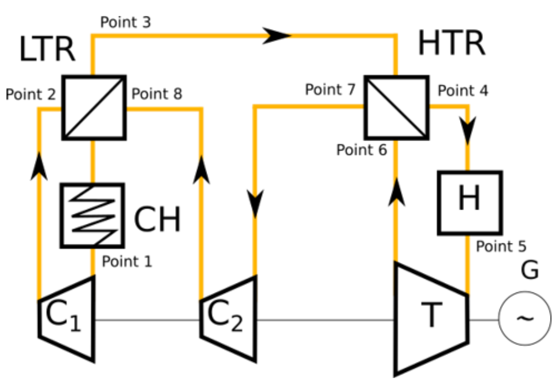
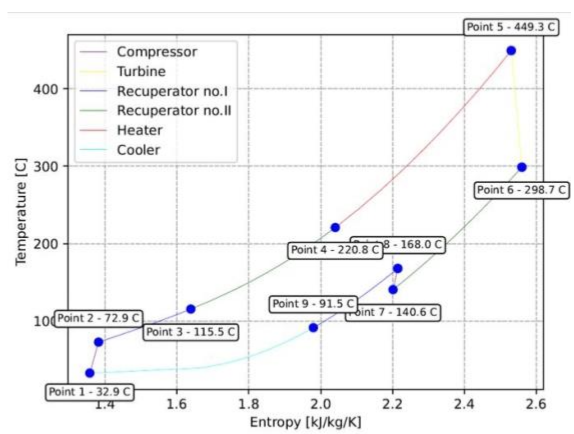


FIGURE 12: TS DIAGRAM OF SPLIT EXPANSION CYCLE.



FIGURES 13: SCHEMATIC OF PRECOMPRESSION CYCLE.



FIGURES 14: TS DIAGRAM OF PRECOMPRESSION CYCLE.

B. Cycle Analysis Results

The following results in Table 5 contains the summary of the thermodynamic results on the analyzed cycles. When examining the five cycle configurations while holding the power output constant, key insights can be gained. The Simple Brayton cycle demonstrates the lowest cycle efficiency at 17.11%, indicating a significant demand for added heat (2.88 MW) to achieve the target power output. In contrast, the Recuperative cycle stands out with a notably higher cycle efficiency of 31.84%, signifying efficient utilization of added heat (1.55 MW) to maintain the same power output. Similarly, the Re-compression cycle exhibits impressive thermal performance, boasting a cycle efficiency of 36.18% and requiring only 1.36 MW of added heat.

TABLE 5: CYCLE CALCULATION RESULTS, COOLER AND HEATER INLET PARAMETERS AND WHRS MASS.

	Simple Brayton	Recuperative	Re-compression	Split expansion	Pre-compression	
Cycle efficiency	**17.11**	**31.84**	**36.18**	**32.36**	**31.96**	%
Turbine power output	0.71	0.67	0.85	0.89	0.79	MW
Compressor input power	0.21	0.18	0.36	0.40	0.30	
Added heat	**2.88**	**1.55**	**1.36**	**1.52**	**1.54**	
Removed heat	**2.38**	**1.05**	**0.87**	**1.03**	**1.05**	
Regenerative heat	0.00	1.38	2.08	3.06	1.41	
Net power	0.492					
mass flow - max	5.44	5.23	7.08	7.97	5.25	kg/s
Cooler/fan						
sCO_2 flow – cooler	5.44	5.23	4.38	5.00	5.25	kg/s
sCO_2 pressure	7.69	7.81	8.47	8.63	7.86	MPa
sCO_2 inlet temperature	320	95	83.2	87.9	91.5	C
sCO_2 outlet temperature	32.85					C
Heater/Core						
sCO_2 flow – heater	5.44	5.23	6.45	7.19	5.25	kg/s
sCO_2 pressure	25	25	25	25	25	MPa
sCO_2 inlet temperature	88	219.3	296.6	287.2	220.8	C
sCO_2 outlet temperature	449.27					C

C. WHRS Heat Exchangers Designs

The main challenge for a sCO_2 waste heat recovery system is integration between the sCO_2 power cycle and the turbofan engine. Based on turbofan engine and sCO_2 power system design, the main components which may affect engine performance are the Cooler/fan and primary/core heat exchangers. These heat exchangers are installed between points 5 and 6 (PHX/Core) and point 18 (Cooler/Fan), see Fig. 3. The PHX and Cooler must be installed in the engine flow path and are directly connected to the engine structure. The size and internal flow passage designs of these heat exchangers will impart pressure drop penalties in the engine core and fan streams, which are important propulsion system design factors. The disposition of the PHX and cooler in the structure of turbofan engine is shown in Fig. 15. The sCO_2 compressor and turbine located in the fuselage [5] for the WHR architecture described in this paper.

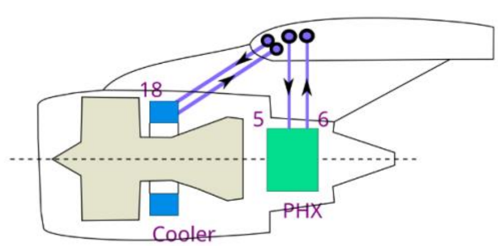


FIGURE 15: COOLER AND PHX INTEGRATION IN THE ENGINE AND WHR SYSTEM [37].

The following Figures 16-18 show the configuration for each heat exchanger found in the

WHRS- primary heater, cooler and recuperator. They have been all designed to be plate-fin. Table 6 shows the performance of the heat exchangers where the inlet conditions on the sCO_2 side were based on the Recuperated Brayton cycle. The heat exchangers were sized using recuperated Brayton cycle design parameters and scaled for other cycles using the energy density value. For the effectiveness, the maximum heat that can be transferred through the recuperator was calculated to be much lower than the heat required to be regenerated through the WHRS.

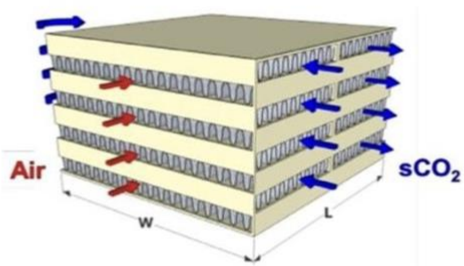


FIGURE 16: PRIMARY HEATER DIAGRAM [37].

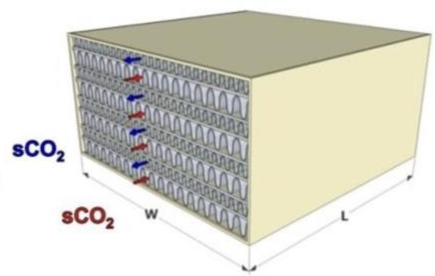


FIGURE 17: RECUPERATOR DIAGRAM

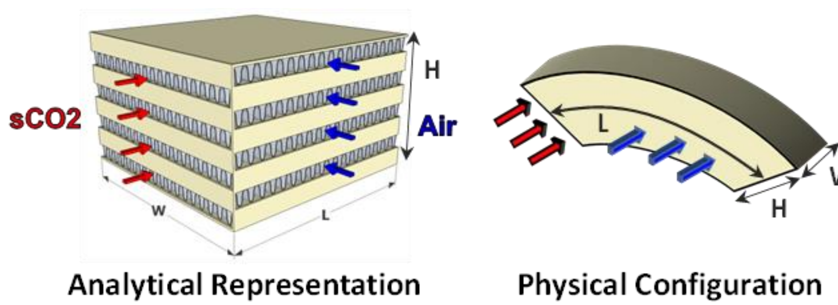


FIGURE 18: COOLER DIAGRAM [38].

TABLE 6: HEAT EXCHANGER DESIGN AND PERFORMANCE RESULTS. [37], [38]

HEX	Fluid	Type	Material	Energy Density	e	DP/ P_hot	DP/ P_cold
[-]	[-]	[-]	[-]	[kW/Kg]	[%]	[%]	[%]
Heater	Air/sCO_2	Plate/Fin	Titanium	12.25	95	5.85	0.1
Cooler	sCO_2/Air	Plate/Fin	Titanium	17.13	95	2.5	0.94
Recuperator	sCO_2/sCO_2	Plate/Fin	Titanium	21.64	80	0.07	0.005

D. Waste Heat Recovery System Mass

The system mass was estimated using the energy density of the heater, cooler and recuperative heat exchangers from Table 6. The inlet conditions of the recuperative Brayton cycle were used to define the problem statement for the components. The performance targets were respectively set to constrain the designs for the given application. It is important to note that Turbine and Compressor mass are negligible for these calculations. The components were designed using RBC design parameters and scaled for other cycles using the energy density value. The estimated system mass for the considered cycles is shown in Table 7.

TABLE 7: WASTE HEAT RECOVERY SYSTEM MASS.

	Simple Brayton	Recuperative	Re-Compression	Split expansion	Pre-Compression	
PHX	234.73	126.15	111.01	124.13	125.68	kg
Cooler	139.14	61.49	50.67	60.04	61.15	
Recuperator	-	63.57	96.14	141.29	65.33	
WHRS Mass	**373.87**	**251.20**	**257.82**	**325.46**	**252.16**	

E. Cycle Selection Analysis

In selecting the optimal cycle for aircraft power systems, as define by key metrics, the recompression cycle stands out due to its high efficiency of 36.18% and compact size of 251.2 kg, making it ideal for retrofitting existing engines. This choice is driven by its ability to effectively generate required power while efficiently using waste heat. The recompression cycle presents a balanced solution that meets the critical criteria of efficiency and power generation.

CONCLUSION AND FUTURE WORK

The research presented here offers a comprehensive and detailed analysis of cycle performance and the integration of heat exchanger designs into aircraft engines, marking a significant contribution to sustainable aviation. Centered on the use of Supercritical CO_2 (sCO_2) power systems for waste heat recovery, this study provides a path forward for reducing the carbon footprint of the aviation industry. The investigation into various cycle configurations, particularly under steady-state cruise operating conditions, underscores the efficacy of sCO_2 systems in enhancing the efficiency and reducing emissions of aircraft propulsion systems. Key findings from the results section of the study include the potential of the sCO_2 cycle to generate an additional 100 - 300 kW of power, with an efficiency of approximately 33%. This demonstrates the tangible benefits of integrating sCO_2 systems into aircraft engines. The design of the primary heat exchanger (PHX) and cooler, crucial components of the sCO_2 system, shows promising results in terms of effectiveness and integration within the engine architecture.

Future studies will delve into the impact of the waste heat recovery system on overall engine performance. This includes evaluating the advantages of using the bypass as a heat sink compared to utilizing the fuel line, a consideration that could further optimize the system's efficiency and environmental benefits.

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ACKNOWLEDGEMENTS

The research is funded by the NASA University Leadership Initiative program through grant number 80NSSC22M0067. Any findings, and conclusions in this paper are those of the authors and do not necessarily reflect the views of the supporting institution.