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Parametric Study of Supercritical Carbon Dioxide (sCO_2) Cycles for Waste Heat Recovery from Jet Engines [*]

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ABSTRACT

This study will focus on technologies and applications that have excelled in many other industries but yet to be applied in aviation, which is waste heat recovery technology with supercritical carbon dioxide (sCO_2) as the cycle's working fluid. In this case, this technology can help to reduce the jet engines' fuel consumption, and minimize fuel expenses and also carbon dioxide (CO_2) emissions. The analysis of sCO_2 cycle that is thermodynamically integrated into a turbofan jet engine is conducted via simulation within the Aspen Plus software and the Microsoft Excel is used for the post-processing of the results. Moreover, a quantitative analysis is done to select the best performing sCO_2 cycle configuration based on the jet engine's performance increment after the cycle's integration as its waste heat recovery system. All in all, the obtained results show that recuperation cycle (42.46%, 2197.67 kW) performs much better than basic Brayton cycle (18.53 %, 2555.84 kW) in terms of thermal efficiency and network. As for jet engine performance, integrating the basic Brayton cycle has generated greater thrust specific fuel consumption (TSFC) savings of 13.91% with improved value of 1.7474 kg/s/kN compared to the recuperation cycle savings of 7.06% and improved value of 1.8865 kg/s/kN.

Keywords: Jet engine, Waste heat recovery, Thrust specific fuel consumption, Supercritical carbon dioxide, Basic Brayton cycle.

I. INTRODUCTION

Recently, issues of global warming and the resulting climate change have become a major talking point in terms of mankind's future. Among the key contributors to global warming is greenhouse gas emission, especially the carbon dioxide (CO_2) [1]. At the moment, though the contribution of aviation emissions to climate change can be considered as small, it is also growing at higher rate than other sources of emissions [2-3]. To reduce or completely eradicate the aviation emissions, alternative electric and hybrid engines have been proposed and studied. However, many of these technologies will not be available for commercial use until many years ahead [4]. With current limited options, waste heat recovery can provide a short-term solution and long-term application to the issue. In short, waste heat is defined as unused heat released to the surrounding environment by any forms of heat engine in a thermodynamic process [5], which could be converted to useful work. In aviation field, typical turboshaft engines may generate as large as 30% of waste heat when in operation, which has a big potential to be recovered as useful energy [6]. Previous studies on the integration of organic Rankine cycle (ORC) with jet engine have shown good potential in reducing thrust specific fuel consumption (TSFC) of the engines. However, possibility of using other working fluids to further reduce the TSFC should be also explored [7-8].

Supercritical carbon dioxide (sCO_2) is a state of CO_2 in which its temperature and pressure is either at or above its critical point, where the distinct liquid and gas phases do not exist. With a critical condition of 30.98˚C and 7.38 MPa, it is highly likely that CO_2 can achieve supercritical condition with ease. Generally, high values for the specific heat can be achieved at constant pressure and isothermal compressibility. sCO_2 typically possesses a higher density than other working fluids such as steam and water, and this

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will enable the engine system components to be downsized to a large degree. In comparison, sCO$_2$ is 100 to1000 times denser (encompassing liquid properties) and 5 to 10 times more viscous (gas properties) than other gas counterparts with a smaller diffusivity by 0.01 times only. With these properties in hand, mechanical work required to pressurize the fluid is greatly reduced, indirectly increasing the cycle efficiency and power output [9]. Moreover, sCO$_2$ cycle can also guarantee a compact turbomachinery. When the cycle is operated above its critical point, its minimum pressure is higher (i.e. around 7,400 kPa) as compared to the steam Rankine cycle (i.e. a few kPa) and the jet engine Brayton cycle (i.e. around 100 kPa). The working fluid of sCO$_2$ will remain dense throughout the cycle and this directly lowers its volumetric flow rate. As a result, by rough comparison, the required turbomachinery size will be 10 times smaller than that for the steam Rankine cycle [10].

This objective of the presented study in this paper is to quantitatively analyze the performance of recuperation and basic Brayton cycle in terms of thermal efficiency, net generated work and heat recovery efficiency. This is done to determine which sCO$_2$ cycle is the best performing. The resultant performance improvement of turbofan jet engine after being fitted with the best performing sCO$_2$ cycle can also be estimated in terms of TSFC.

II. SETUP AND METHODOLOGY

A background study is conducted to identify the most suitable configuration of sCO$_2$ cycles to be applied on jet engines for optimum efficiency by utilizing the advantages of sCO$_2$ and waste heat recovery applications. Among the main focused aspects of sCO$_2$ cycles for this background study include the application or uses, which ranging from power generation [11-12] to marine turbines [13], and also the configuration's performance, mostly their recuperation cycles. Furthermore, the available methods to analyze the configuration including MATLAB REFPROP, Aspen Plus and Engineering Equation Solver (EES) [14-18] have been covered as well. Based on the findings, two different sCO$_2$ cycles are further analyzed for the jet engine's waste heat recovery system application. As illustrated in Figure 1 and Figure 2 respectively, they are recuperation cycle and basic Brayton cycle. The latter mostly acts as the control system for comparison.

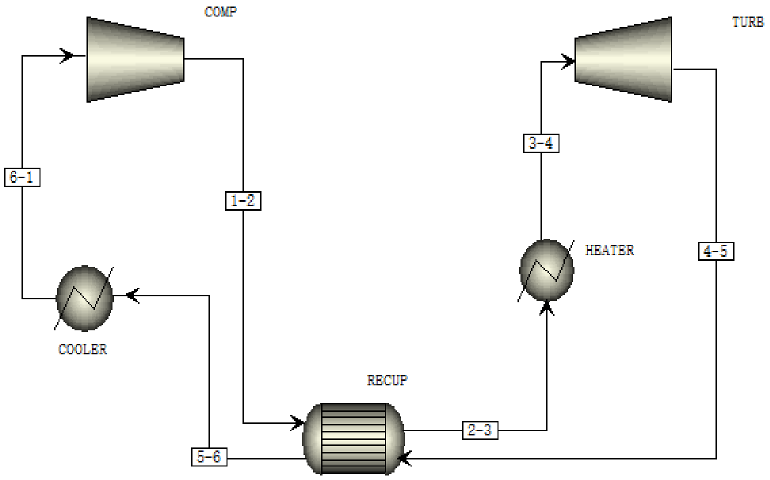

Figure 1 Schematic diagram for a recuperation cycle system simulated on Aspen Plus

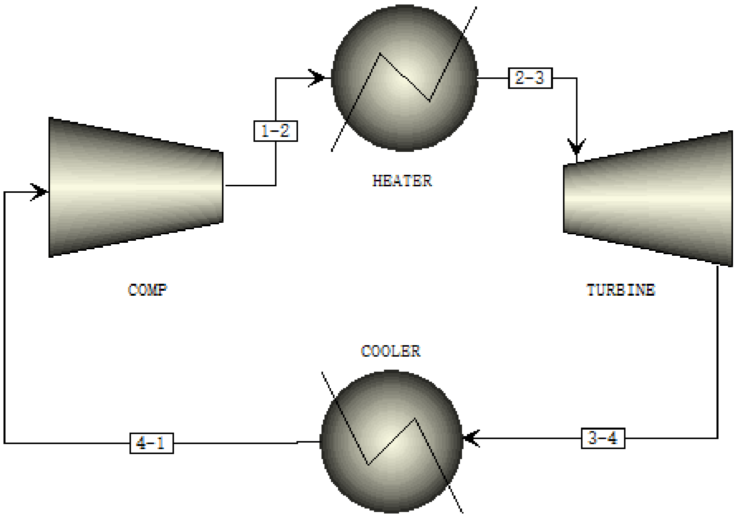

Figure 2 Schematic diagram for a basic Brayton cycle system simulated on Aspen Plus

In the meantime, CFM International LEAP turbofan engine is applied in this study as the base reference model. This engine is selected since it is the fastest selling engine in aviation history, which means that it is among the most common aircraft engines in the world. Specifically, LEAP-1A engine variant is used. According to its manufacturer's website (www.cfmaeroengines.com), it has TSFC of 14.4 g/s/kN and also maximum continuous thrust of 140.96 kN. Moreover, since sCO_2 cycle is a form of thermodynamics cycle, it can be mathematically expressed in accordance to thermodynamics laws. In view of this, the thermodynamic equations related to recuperation and basic Brayton cycles are tabulated in Table 1 and Table 2, respectively.

For performance analysis, two main thermodynamic parameters are analyzed in deciding the best sCO_2 cycle as the optimum waste heat recovery system, which are output power generated and thermal efficiency. These parameters are respectively assessed by Equation (1) and Equation (2). Additionally, TSFC can also be calculated using Equation (4) for the comparison, which has been modified from the original Equation (3) to account for fuel savings achieved via integration of a waste heat recovery cycle.

Table 1 Thermodynamic equations at each stage of a recuperation cycle

Component	**Energy Relation**
Compressor	$\dot{W}_C = \dot{m}(h_2 - h_1) = \frac{\dot{m}(h_{2s}-h_1)}{\eta_C}$
Recuperator	$\dot{Q}_R = \dot{m}(h_3 - h_2) = \dot{m}(h_5 - h_6)$
Heater	$\dot{Q}_H = \dot{m}(h_4 - h_3)$
Turbine	$\dot{W}_T = \dot{m}(h_4 - h_5) = \dot{m}(h_4 - h_5)(\eta_T)$
Pre-cooler	$\dot{Q}_{PC} = \dot{m}_{PC}(h_6 - h_1)$

Table 2 Thermodynamic equations at each stage of a basic Brayton cycle

Component	**Energy Relation**
Compressor	$\dot{W}_C = \dot{m}(h_2 - h_1) = \frac{\dot{m}(h_{2s}-h_1)}{\eta_C}$
Heater	$\dot{Q}_H = \dot{m}(h_3 - h_2)$
Turbine	$\dot{W}_T = \dot{m}(h_4 - h_3) = \dot{m}(h_4 - h_{3s})(\eta_C)$
Pre-Cooler	$\dot{Q}_{PC} = \dot{m}_{PC}(h_4 - h_1)$

$$\dot{W}_{net,Brayton}\ (\text{in kW}) = \dot{W}_{net,Recuperation} = \dot{W}_T - \dot{W}_C \tag{1}$$

$$\eta_{th,Brayton}\ (\text{in }\%) = \eta_{th,Recuperation} = \frac{\dot{W}_{net}}{\dot{Q}_{total}} = \frac{\dot{W}_T - \dot{W}_C}{\dot{Q}_H} x\ 100\ \% \tag{2}$$

$$TSFC\ (\text{in kg/s/kN}) = \frac{\dot{m}_f}{T} \tag{3}$$

$$TSFC\ (\text{in kg/s/kN}) = \frac{\dot{m}_f - \dot{m}_{rec}}{T} \tag{4}$$

However, since there is no open source that directly shows the fuel mass flow rate value of the chosen engine, it is still necessary to utilize the original TSFC formula as shown at Equation (3). For the LEAP-1A engine variant, by conducting reverse calculation from the data obtained for T = 140.96 kN and TSFC = 0.0144 kg/s/kN (converted to SI unit), the estimated value of the fuel mass flow rate is 2.0298 kg/s. On the other hand, for the value of recovery mass flow rate, it is estimated using Equation (5), in which *HV* equates to the heating value of kerosene fuel. Jet-A1 fuel, which is the most common aviation fuel used within the industry, has a value of HV = 43 MJ / kg. Furthermore, Equation (6) to Equation (8) are used to estimate the heat recovery efficiency. This parameter acts as an indicator to gauge the effectiveness of the cycle designs in recovering the heat inputted, regardless of its heat source. In terms of its specific heat capacity at constant pressure, because the exhaust gas is often released to the atmosphere as a waste material, it is assumed to follow ideal-gas properties of air. Meanwhile, for waste heat or exhaust gas mass flow rate, a reference value is obtained from the Wärtsilä 18V50DF engine that is four-stroke internal combustion (IC) engine that can produce 17.55 MW power with engine efficiency of 47 %, which is comparable to a jet engine [19-20]. Thus, the value obtained for waste heat or exhaust gas mass flow rate is 28.2 kg/s [20].

$$\dot{m}_{rec} = \frac{\dot{Q}_H}{HV} \tag{5}$$

$$\eta_{HR,Brayton} = \eta_{HR,Recuperation} = \eta_{HR,Regeneration} = \frac{\dot{Q}_H}{\dot{Q}_{rec}}\ x\ 100\ \% \tag{6}$$

$$\dot{Q}_{rec} = \dot{m}_e c_P \theta \tag{7}$$

$$\theta = T_{e1} - T_{e2} \tag{8}$$

For this research, the software utilized for modelling the system designs is called Aspen Plus. This software is a Chemical Process Simulator, widely used in the Chemical Engineering field. It allows users to build a process model and simulate it using the complex calculations (i.e. models, equations, math calculations, regressions). Some example similar studies to this research that also used this software include Ref. [14] and Ref. [17]. The obtained simulation results are n post-processed using Microsoft Excel. Table 3 lists all input parameters to the software for the analysis. It should be noted that for this analysis, sCO_2 mass flow rate of basic and recuperative cycles simulations are taken as 19.0 kg/s and 21.5 kg/s, respectively [19]. Moreover, for the sensitivity analysis that is also conducted in this study, the range of the varied parameters is tabulated in Table 4.

Table 3 Input parameters for cycle analysis

Component	Parameters	Values
Compressor	Inlet Temperature	32 °C [9]
	Inlet / Outlet Pressure	7.5 MPa / 25 MPa [9]
	Pressure Ratio	3.33 or 10:3 [9]
Heater	Temperature (Waste Heat)	550 °C (www.easa.europa.eu)
	Pressure (Working fluid)	25 MPa [9]
Turbine	Expansion Ratio	3.33 [9]
	Inlet / Outlet Pressure	25 MPa / 7.5 MPa [9]
Precooler	Coolant Temperature	25 °C (Assumption)
Recuperator	Approach Temperature / Hot Outlet – Cold Inlet Temperature Difference	5 °C [21]

Table 4 Range of operating variables used for sensitivity analysis

Parameters	Range	Increment
Maximum cycle pressure	10 – 30 MPa	0.1 MPa
Waste Heat Temperature (WHT)	400 – 700 °C	1 °C

In obtaining thermodynamic properties of sCO_2, the Peng-Robinson method within the Aspen software is used. This method is the latest development among other cubic Equations of State (EOS), from the earliest ideal gas law and Vaan der Waal equation, and through Peng-Robinson's predecessors, Redlich-Kwong and Soave-Redlich-Kwong. In general, Peng-Robinson provides pretty accurate value of the calculated state variable (i.e. temperature, pressure, volume) for liquid as well as for non-polar gases. Hence it is often set as the default selection for running simulations in Aspen Plus.

III. RESULTS AND DISCUSSION

For model validation of the software and most of the input parameters, a basic Brayton cycle has been modelled and simulated. The parameters are primarily based on Ref. [19] and Ref. [20], which relate to the Wärtsilä 18V50DF engine. The simulation findings are compared with results from the two references and they are tabulated in Table 6 and graphically shown in Figure 3. It can be observed from Figure 3 that the mean absolute percentage error (MAPE) is computed as 5.3%. The maximum and minimum error difference respectively occurs at the highest and the lowest waste heat temperature utilized, with values of 12.31 % (at 300 °C) and 0.71% (at 600 °C). The model validation with variation of waste heat temperature is applied because the change in network output is quite significant depending on the level of this heat source temperature.

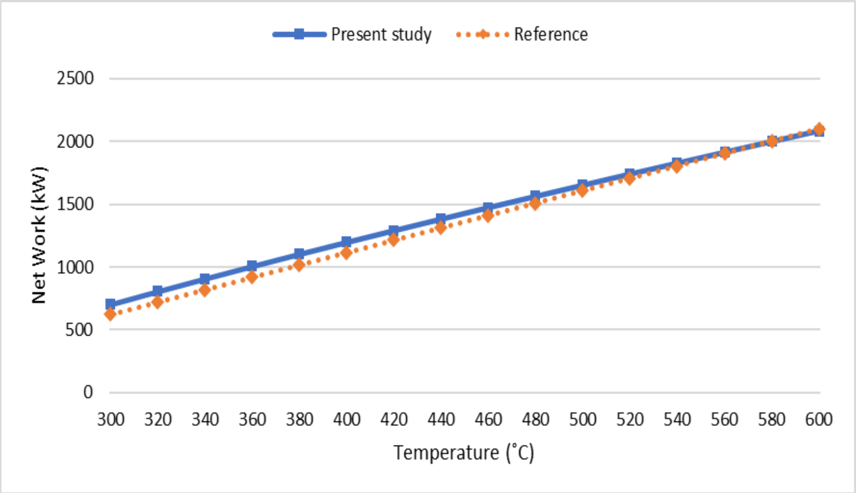

Figure 3 Model validation of optimized network output with variation of waste heat temperature

Table 6 Input parameters for model validation

Component	**Parameters**	**Values**
Compressor	Inlet Temperature	32 °C
	Outlet Pressure Ranges	7.5 / 30 MPa
	Isentropic Efficiency	75 %
	Pressure Ratio	4
Heater	Inlet Temperature (Waste Heat)	300 – 600 °C
	Approach Temperature	10 °C
Turbine	Expansion Ratio	4
	Isentropic Efficiency	80 %
Precooler	Coolant Temperature	10 °C
	Approach Temperature	10 °C
Recuperator	Approach Temperature	10 °C
Working fluid (sCO_2)	Mass flow rate	19 kg/s

Once the validation is deemed acceptable, simulation for the recuperation cycle can be conducted. Table 7 shows the comparison between the simulation results of the basic Brayton cycle and recuperation cycle. It can be noted that the recuperation cycle has a better performance in terms of both thermal efficiency and also net generated work than the basic Brayton cycle. However, the basic Brayton cycle is shown to be more efficient with regards to heat recovery. In general, this difference in performance can be explained by the presence of recuperator(s). Recuperator functions to harvest the high temperature sCO_2 fluid exiting the turbine and transfer this high capacity of heat into preheating the sCO_2 fluid leaving the compressor. Hence, the temperature of sCO_2 will be much higher when entering the heater in comparison to a cycle without any recuperators. Less heat is required to be input into our heater as to attain a similar or even higher turbine inlet temperature than basic Brayton cycle, leading to higher cycle performance efficiency. This is evident by much lower heat input measured at the heater of a recuperation cycle (6018.95 kW), almost half of the heat energy required for basic Brayton (11861.12 kW). In the meantime, the same trend can also be observed at the cooler, with the recuperation cycle (3463.11 kW) needing three times lesser energy to cool down the working fluid compared to the basic Brayton cycle (9602.47 kW). The temperature of the incoming hot stream to the cooler in the basic Brayton cycle is much higher, as the recuperator has acquired part of the heat energy exiting the turbine before reaching the cooler, thus a much lower temperature of hot stream cooler input. On the whole, it is deduced that, even though a basic Brayton cycle can retain most of its cycle's input heat (i.e. high heat recovery efficiency), the absence of a recuperator to recycle heat outlet from the turbine and thus higher amount of heat energy dissipated at cooler and rejected to the surroundings instead of being reutilized has caused its network and thermal efficiency to be lower than the recuperation cycle.

Table 7 System design results of waste heat recovery sCO_2 cycle

Parameter	**Basic Brayton**	**Recuperation**
Compressor work, $\dot{W}_c$ (kW)	790.26	894.24
Turbine(s) work, $\dot{W}_T$ (kW)	2987.93	3450.08
Heat input at heater, $\dot{Q}_H$ (kW)	11861.12	6018.95
Heat output at cooler, $\dot{Q}_{PC}$ (kW)	9602. 47	3463.11
Heat input at recuperator(s), $\dot{Q}_R$ (kW)	-	7402.85
Net work, $\dot{W}_{net}$ (kW)	2197.67	2555.84
Thermal efficiency, η_{th} (%)	18.53	42.46
Heat recovery efficiency, η_{rec} (%)	86.58	43.94

In Figure 4, the thermal efficiency of a basic Brayton cycle is shown to exhibit a near plateau as the waste heat temperature increases since the network done is increasing parallel with the increment of waste heat temperature. The maximum and minimum values are 18.79 % at 400 °C and 18.10 % at 700 °C. This is noted to be much less effective than the recuperation cycle's thermal efficiency, which is observed to increase proportionally with increasing waste heat temperature, with values within ranges from 34.34 % and 48.46 %. Moreover, in Figure 5, the net produced work by the recuperation cycle is higher in overall compared to that of the basic Brayton cycle, although both sets of data exhibit a similar proportional trend with increasing waste heat temperature. Basic Brayton cycle fares within a range of 1552.75 kW and 2804.28 kW for the net generated work while recuperation cycle produced a range of 1811.17 kW and 3256.28 kW, which is slightly higher.

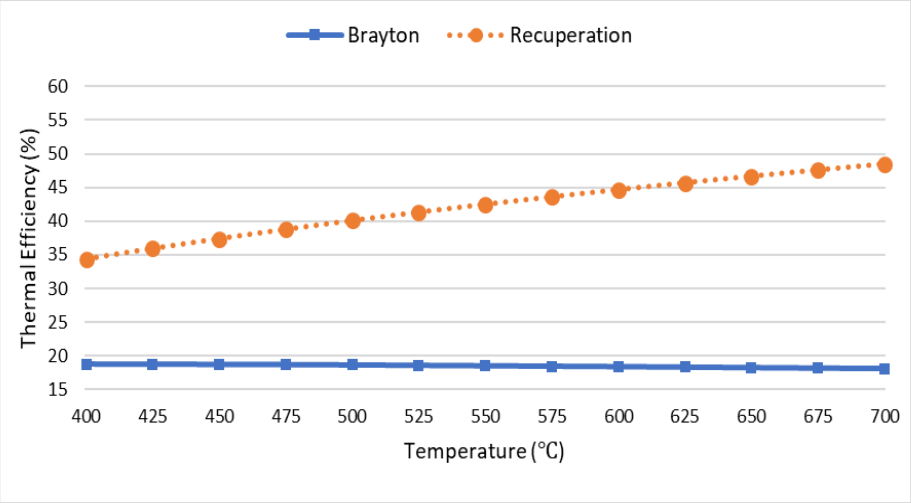

Figure 4 Effect of waste heat temperature variation on thermal efficiency for the sCO_2 cycles

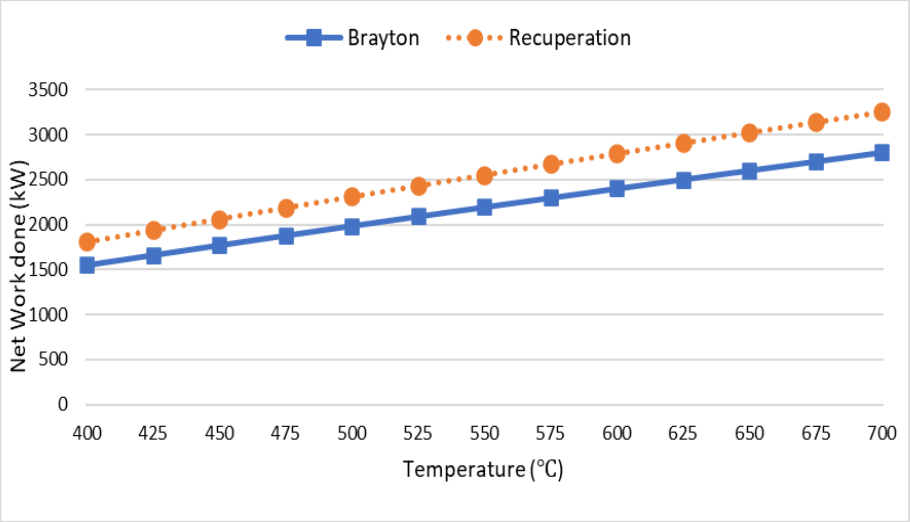

Figure 5 Effect of waste heat temperature variation on net work done for the sCO_2 cycles

Meanwhile, for variation of maximum cycle pressure, the basic Brayton cycle is still the lower performing cycle in Figure 6. It exhibits near plateau trend that is similar to previous Figure 4, with values ranging between 12.04% to 18.26%. This is still a very large margin when compared to the recuperation cycle. However, this time around, both cycles experienced a decreasing trend as the cycle pressure is increased. The recuperation cycle's thermal efficiency drop from 65.37% to 38.32% as maximum cycle pressure is increased from 100 MPa to 300 MPa. Furthermore, the effects of maximum cycle pressure variation on network generated is shown in Figure 7. It shows the recuperation cycle has produced greater network compared to the basic Brayton cycle. It should be noted that this time around, the margin in performance is greater than that shown in Figure 5 (when the waste heat temperature is varied). However, unlike Figure 5, both cycles exhibit proportional decrease in net work done as pressure increases. Recuperation cycle produced a network in the range between 2347.95 kW and 3294.53 kW while the basic Brayton cycle generated a net work in the range between 1323.48 kW and 2160.00 kW.

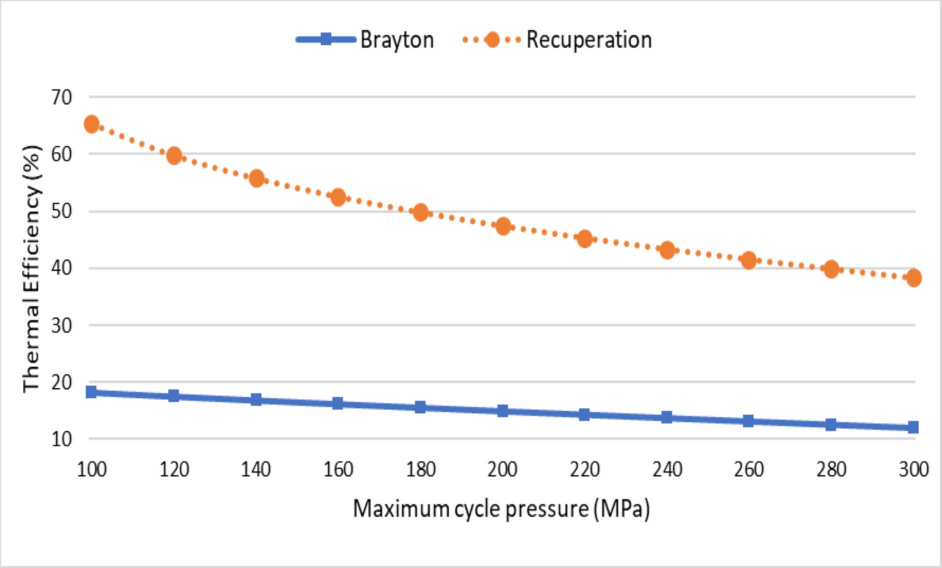

Figure 6 Effect of maximum cycle pressure variation on thermal efficiency for the sCO$_2$ cycles

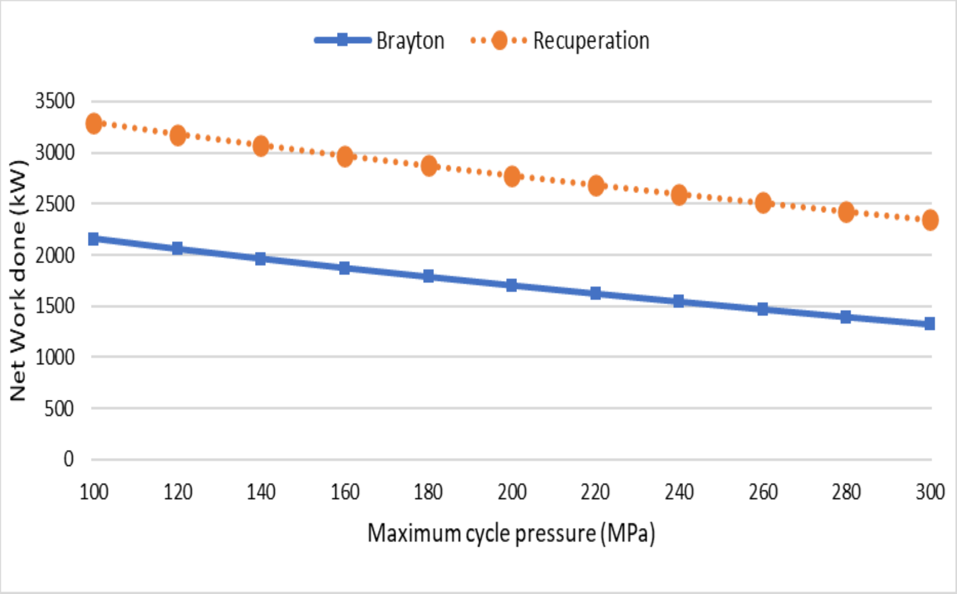

Figure 7 Effect of maximum cycle pressure variation on net work done for the sCO$_2$ cycles

Furthermore, by installing sCO$_2$ waste heat recovery system to an aircraft engine, the fuel consumption required will also be substantially reduced. As tabulated in Table 8, the Brayton cycle is capable of reducing TSFC to a value of 1.7474 kg/s/kN, or a 13.91% in reduction of its original value. In the meantime, the recuperation cycle has smaller improvement than the basic Brayton cycle, with a value of 1.8865 kg/s/kN and a reduction of 7.06%. The variation of TSFC is plotted as a function of increasing engine thrust at Figure 8, with the range of thrust value taken from 0 kN up until 143 kN, which is the maximum take-off thrust of our engine, the CFM International LEAP. From the plot, it is observed that both sets of data are being extremely close. The decreasing exponential trend starts to plateau around 60 kN of engine thrust. As the only TSFC data obtained of the CFM International LEAP engine is at cruise phase and not all phases of flight or thrust variation, the trend line is extremely exponential graph, which is very different to the positive parabolic curve that is more common or supposed to be obtained as engine thrust increases.

Table 8 TSFC values for basic Brayton and recuperation cycles

Cycle	**$\dot{m}_{rec}$ (kg / s)**	**Improved TSFC (kg/s/kN)**
Brayton	0.2824	1.7474 (13.91 %)
Recuperation	0.1433	1.8865 (7.06 %)

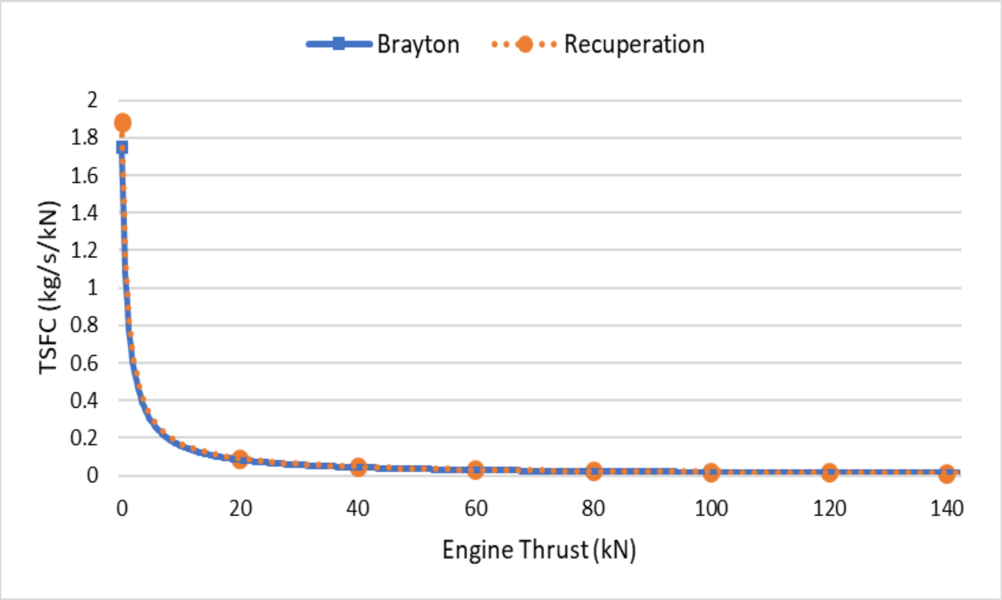

Figure 8 Variation of TSFC in terms of engine thrust for basic Brayton and recuperation cycles

Due to the similarity in TSFC values of both cycles, smaller range of thrust values is extracted and graphically shown in Figure 9. In this figure, it clearly depicts the basic Brayton has a lower TSFC value than recuperation cycle, thus more fuel efficient and energy effective. Numerically, the overall range of TSFC is 0.1942 to 0.0647 kg/s/kN for basic Brayton cycle and 0.2096 to 0.0699 kg/s/kN for the recuperation cycle.

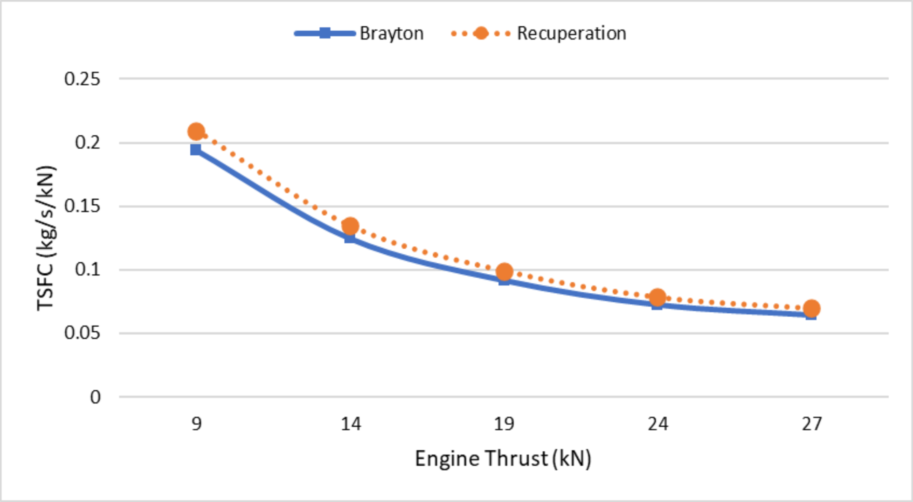

Figure 9 Variation of TSFC in terms of engine thrust for basic Brayton and recuperation cycles within engine thrust range of 9 – 27 kN

IV. CONCLUSIONS

This paper presents the performance analysis on the basic Brayton and also recuperation cycles for utilizing the advantages of sCO_2 and waste heat recovery applications. Overall, it is concluded that in terms of thermal efficiency, the recuperation cycle is better performing than the basic Brayton. Based on the sensitivity analysis, when the waste heat temperature is increased, both cycles experience an increase in thermal efficiency and net generated work. In contrast, when maximum cycle pressure is increased, both cycles show a decreasing trend in thermal efficiency. Even though the recuperation cycle requires an extra recuperator to be installed compared to the basic Brayton cycle, it has been shown to produce vast improvements in performance for the recuperation cycle. Nonetheless, the performances of the basic Brayton sCO_2 cycle is also very encouraging, which raises the possibility of utilization in low-grade (less than 100°C) and also medium-grade (100 to 400°C) waste heat recovery. All things considered, based on the obtained results from this study, optimum sCO_2 cycle for jet engine waste heat recovery system is taken as recuperation cycle. Although the TSFC found for recuperation cycle is slightly higher than that for basic Brayton cycle, the net work done is clearly higher, which implies that higher power output could be produced with this type of cycle. In future, study on impact of extra weight of the cycles to the conventional jet engines can be evaluated.

LIST OF ABBREVIATIONS

Nomenclature
C = compressor
CO_2 = carbon dioxide
c_P = specific heat capacity at constant pressure (kJ/kg. ℃)
f = fuel
F = engine thrust (kN)
h = specific enthalpy (kJ/kg)
H = heater
HTR = high temperature recuperator
HV = heating value of kerosene (MJ/kg)
LTR = low temperature recuperator
$\dot{m}$ = mass flow rate (kg/s)
MAPE = Mean Absolute Percentage Error
PC = precooler
$\dot{Q}$ = heat transfer rate (kJ)
RCP = recuperator
rec = heat recovery
s = specific entropy (kJ/kg)
sCO_2 = supercritical carbon dioxide
TB = turbine
T = temperature (℃)
TSFC = Thrust Specific Fuel Consumption
$\dot{W}$= power output (kW)
WHT = waste heat temperature
x = flow split ratio

Greek Symbols
η_C = compressor efficiency
η_{th} = thermal efficiency
η_T = turbine efficiency
$\theta =$ change in temperature (K)

Subscript
C = compressor
C1 = main compressor
C2 = recompressing compressor
e1 = exhaust gas / waste heat
e2 = maximum allowable exhaust gas / waste heat to be released to the surroundings

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