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# Analysis of Recuperation Supercritical Carbon Dioxide Cycle for Heat Recovery of an Aircraft Engine

Chong Zhi Ken[1], Syamimi Saadon[1,*]

[1] Department of Aerospace Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia

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**ABSTRACT**

Reducing fuel consumption and maximizing thrust power are both critical factors for aircraft engine. Various technologies have been discovered and developed to achieve these goals. One of them is perhaps by integrating a waste heat recovery system to the engine. Therefore, this study will focus on waste heat recovery technology for aircraft engine, by applying a recuperation-supercritical carbon dioxide ($sCO_2$) cycle in order to reduce jet engines' fuel consumption and minimizing fuel expenses. The analysis will be conducted by modeling and simulation using Aspen Plus software. A quantitative analysis is done in order to compare the new modified recuperation $sCO_2$ cycle with the conventional basic Brayton-$sCO_2$ cycle in terms of their performance. The results stated that for both thermal efficiency and network done, recuperation-$sCO_2$ cycle performs much better with 42.46% of efficiency and network done at 2197.67 kW, than basic Brayton cycle at only 18.53 % of thermal efficiency and 2555.84 kW of network done. When integrating both cycles to aircraft engine, each of the cycle exhibits greater Thrust Specific Fuel Consumption (TSFC) savings, with up to 13.91 % and improved value of 1.7474 kg/s/kN for basic Brayton- $sCO_2$ cycle, and savings of 7.06 % and improved value of 1.8865 kg/s/kN for recuperation-$sCO_2$ cycle.

## 1. Introduction

Recently, global warming and resulting climate change has become a major talking point in terms of mankind's future. In general terms, the main contributor to global warming are greenhouse gas emissions, with carbon dioxide ($CO_2$) being the best known [1]. In year 2016 alone, global $CO_2$ emissions have reached a total of 49.4 billion tonnes, with the aviation sector (excluding manufacturing) contributing around 1.9 % of it or around 938.3 million tonnes, which is a sizable amount [2].

Understandably, to reduce, or eradicate emissions completely, alternatives like electric and hybrids engine may seem like the future, with no less than 80 new electric aircraft projects within 2016 - 2018 according to consultancy firm Roland Berger. However, it does caution that commercial service are forecasted not before early 2030s for short-haul routes (1100 – 1500 km), with all-

* *Corresponding author.*
*E-mail address: mimisaadon@upm.edu.my*

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electric aircraft not expected before 2045 [3]. Thus, with limited options, one option may provide a short-term solution, and long-term application to this issue – waste heat recovery. Waste heat is the unused heat released to the surrounding environment by any forms of heat engine in a thermodynamic process that converts heat to useful work [4, 5, 6, 7]. In the aviation field, typical turboshaft engines may generate as large as 30% of waste heat too whenever in operation, in which there is immense potential to be recovered as useful energy [8].

Supercritical carbon dioxide ($s\mathrm{CO}_2$) is a state of $\mathrm{CO}_2$ in which its temperature and pressure is either at or above its critical point, where distinct liquid and gas phases do not exist. With a critical condition of 30.98 ˚C and 7.38 MPa, it is very likely that $\mathrm{CO}_2$ can achieve supercritical condition with ease. High values for specific heat can be achieved at constant pressure and isothermal compressibility. Supercritical carbon dioxide also typically possesses a higher density than other working fluids like steam and water, enabling the engine system components to be downsized to a large degree. As a comparison, $s\mathrm{CO}_2$ is 100–1000 times denser (encompassing liquid properties) and 5–10 times more viscous (gas properties) than its 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 cycle efficiency and power output [9].

A $s\mathrm{CO}_2$ cycle can also guarantee compact turbomachinery. When the cycle operates above its critical point, its minimum pressure is much higher, (around 7,400 kPa), compared to a steam Rankine cycle (a few kPa). The working fluid of $s\mathrm{CO}_2$ will remain dense throughout the cycle, and directly decrease its volumetric flow rate. By rough comparison, its resulting turbomachinery size required will be 10 times smaller than a steam Rankine cycle [10].

One of the main criteria in order to consider which type of waste heat recovery technology to be applied for aircraft engine is to identify the evaporation temperature of the working fluid. This is crucial since this condition could minimize the difference in temperature of the waste heat and the working fluid when the heat is exchanged within the evaporator. This will result in lower heat transferred required between the hot and cold fluid in the evaporator, and eventually will lead to a higher thermal efficiency. Therefore, supercritical carbon dioxide is chosen as the working fluid for this application. To the best of authors' knowledge, no research has been executed yet to explore the possibility of integrating this $s\mathrm{CO}_2$as waste heat recovery of aircraft engine compared to other technologies available.

As a consequence, the research objective is to analyze the performance of recuperation and basic Brayton $s\mathrm{CO}_2$ cycles quantitatively, mainly via thermal efficiency and network generated to determine whether a recuperation-$s\mathrm{CO}_2$ cycle will perform better than a basic Brayton-$s\mathrm{CO}_2$ cycle. The performance improvements made to an aircraft engine will eventually be measured, in terms of Thrust Specific Fuel Consumption (TSFC).

## 2. Methodology

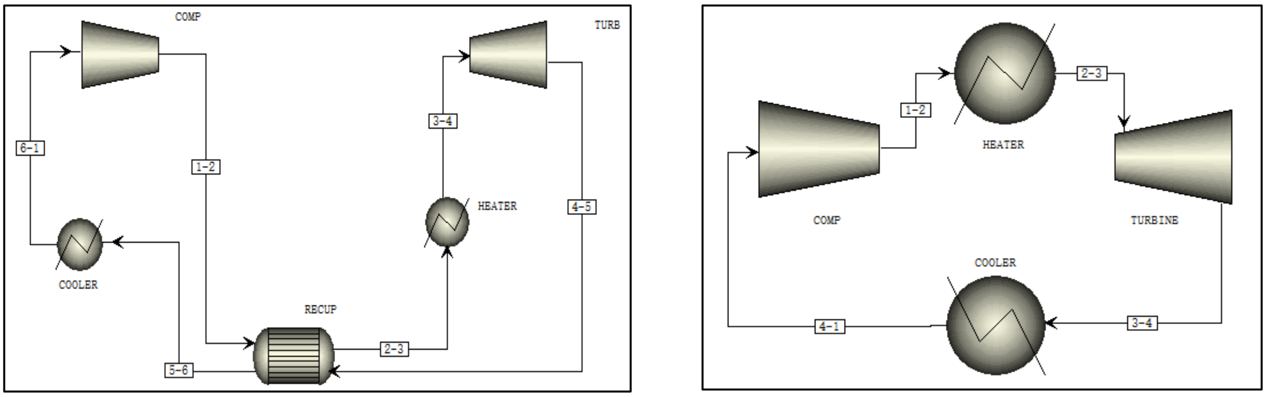
### *2.1 Basic and Recuperation Supercritical Carbon Dioxide ($sCO_2$) Cycles*

Background research is conducted to identify the most suitable configuration of $s\mathrm{CO}_2$cycles to be applied on jet engines to achieve optimum efficiency by utilizing the advantages of supercritical carbon dioxide and waste heat recovery applications. We can also observe the numerous analysis methods conducted so that we can shortlist the most important parameters that can best express the engine's performance.

The research encompasses several aspects, include: (i) its application or uses, ranging from power generation [11, 12], to marine gas turbines [13], and offshore oil rig installations; (ii) its best performing $s\mathrm{CO}_2$ configurations, mostly recuperation cycles; and (iii) its analyzing method, like

MATLAB REFPROP, Aspen Plus, and Engineering Equation Solver (EES) [14, 15, 16, 17, 18]. Therefore, two different $sCO_2$ cycles were selected to gauge the best performing configuration for jet engine's waste heat recovery system, which are

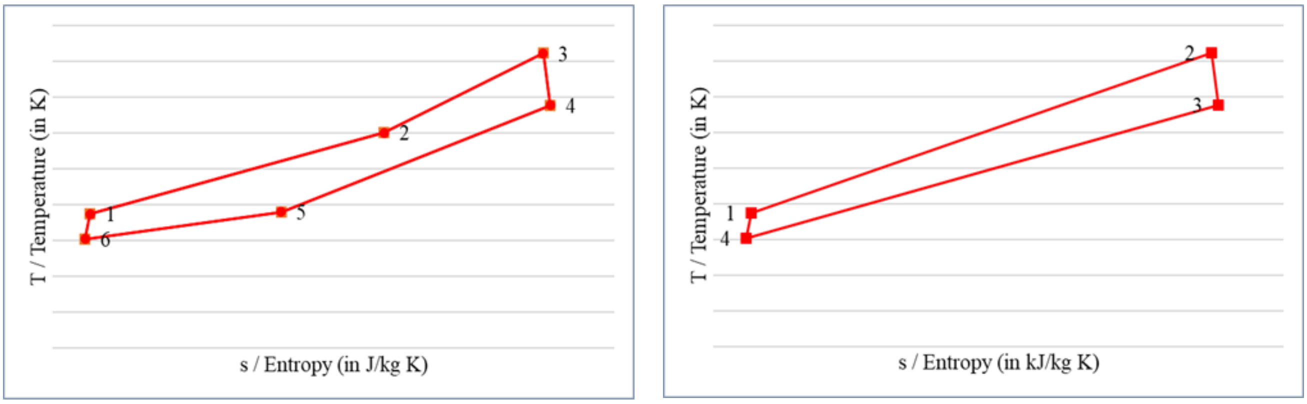
i. Recuperation cycle as shown in Figure 1(a); and
ii. Basic Brayton cycle, as a control shown in Figure 1(b).




(a) (b)

**Fig. 1.** Schematic diagram for a (a) recuperation cycle and (b) basic Brayton cycle systems simulated on Aspen Plus

Since supercritical carbon dioxide ($sCO_2$) cycle is a form of thermodynamics cycle, in accordance with the thermodynamics laws, we can mathematically express the cycles with temperature-entropy graphs as shown in Figure 2.




(a) (b)

**Fig. 2.** Absolute T-s diagram for a (a) recuperation cycle and (b) basic Brayton cycle

## *2.2 Methodology of The Modelling and Simulation*

For this research, the software utilized is called Aspen Plus (Version 11) to conduct modelling of system designs. This software is a Chemical Process Simulator, widely used in the Chemical Engineering field. It allows users to build a process model and then simulate it using complex calculations (models, equations, math calculations, regressions) and some papers of similar objectives to this research has been using it too [19] [20]. The results obtained is then post-processed at Microsoft Excel, a spreadsheet software with calculation, graphing tools, pivot tables, and a macro programming language called Visual Basic for Applications. A flow diagram of modelling a thermodynamic cycle is shown at Figure 3.

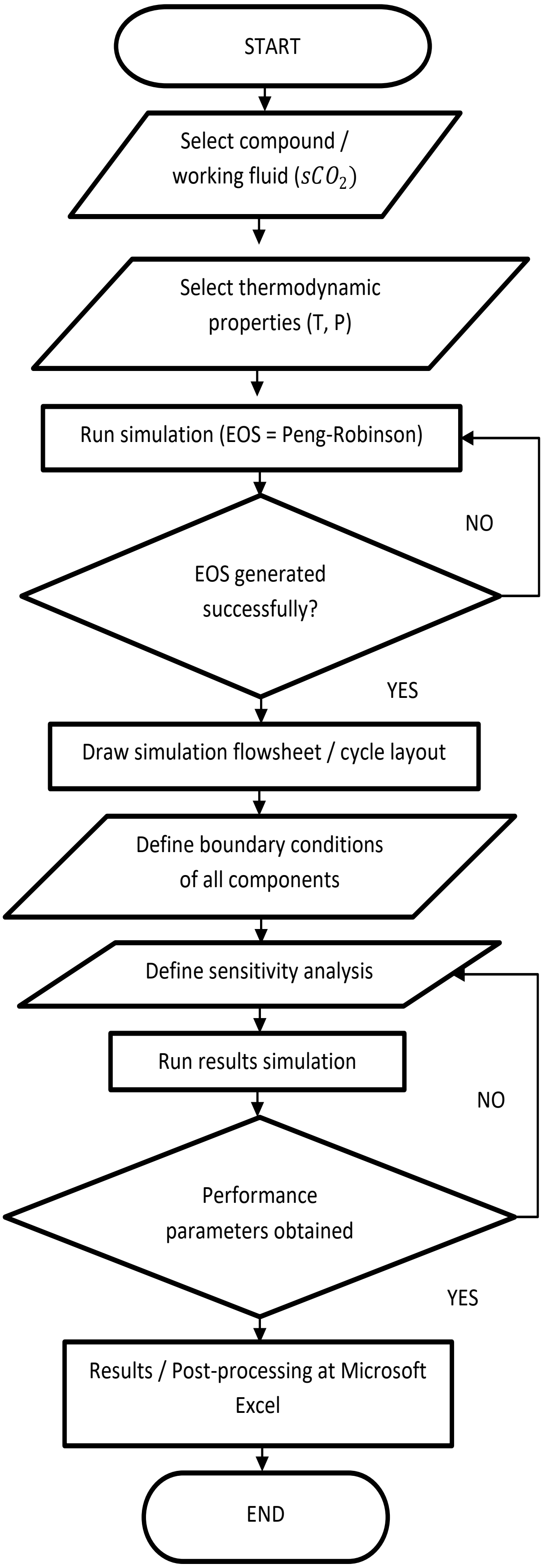



**Fig. 3.** Software simulation flow chart for Aspen Plus and Microsoft Excel

## 3. Results and Discussions

### *3.1 Model Validation*

As a precautionary measure, model validation of the software and most of the input parameters must be done. Thus, a basic Brayton cycle has been modelled and simulated using parameters pre-determined from reference sources [21, 22]. Most of the parameters are according to the Wärtsilä 18V50DF engine. The simulation findings are compared with the sources' result, graphically shown in Figure 4.

An MAPE of 6.14 % is obtained, and its maximum and minimum error difference appearing at WHT of 514°C (7.64 %) and 300°C (3.75 %), well within the pre-set value of 10 %. Waste heat temperature parameter is utilized, as one of the research's parameters.

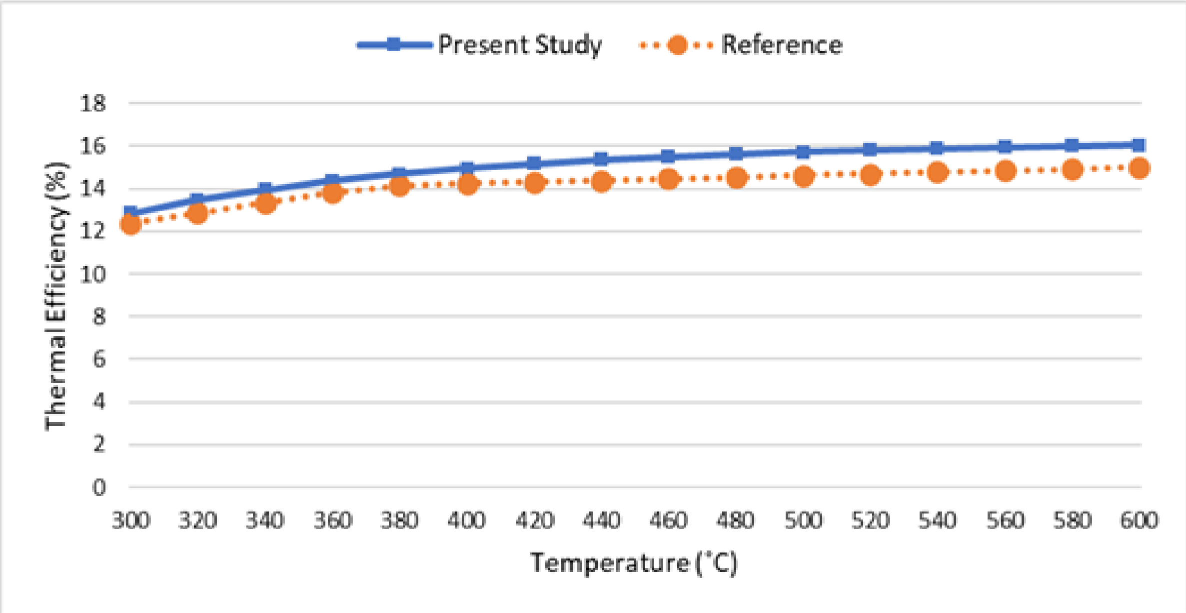



**Fig. 4.** Model validation of optimized thermal efficiency with variation of waste heat temperature

### *3.2 Analysis of The Waste Heat Temperature Effect on the $sCO_2$ Cycles*

Once the model created is validated, the performance analysis of both of the cycles can be executed. In Figure 5 below, the thermal efficiency of the basic Brayton cycle exhibited a near plateau as waste heat temperature increases, with a maximum and minimum values of 18.79 % (at 400 °C) and 18.10 % (at 700 °C), which is much less effective than recuperations', which increased proportionally as waste heat temperature increases, with values within ranges of 34.34% and 48.46%.

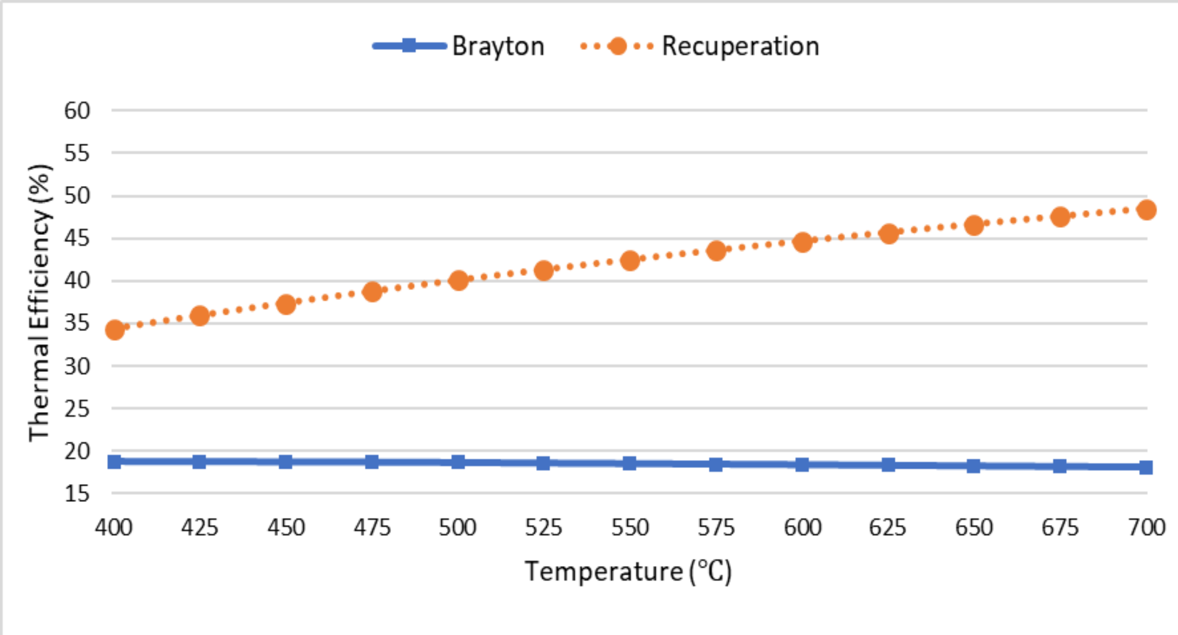



**Fig. 5.** Effect of waste heat temperature variation on thermal efficiency for all $sCO_2$ cycles

For Figure 6, the network produced by a recuperation cycle is higher in overall compared to a basic Brayton cycle, although both sets of data exhibit the same graph trend in increasing proportionally as waste heat temperature increases. Basic Brayton cycle fare within a range of 1552.75 kW and 2804.28 kW, whereas recuperation cycle produced a range of 1811.17 kW and 3256.28 kW, slightly higher than basic Brayton.

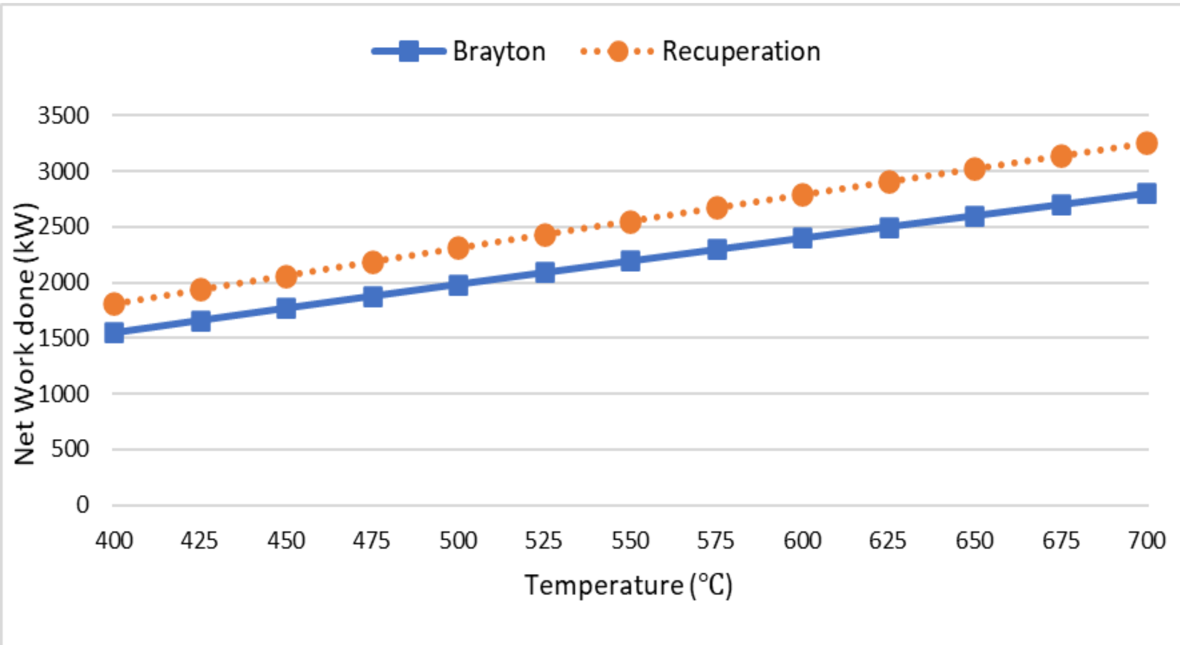



**Fig. 6.** Effect of waste heat temperature variation on net work done for all $sCO_2$ cycles

Therefore, it is deduced that although a basic Brayton cycle can retain most of its input heat within the cycle, as evidenced by the high heat recovery efficiency at, its lack of a recuperator to recycle heat outlet from the turbine and thus higher amount heat energy cooled down at cooler and rejected to the surroundings instead of being reutilized, causes its network and thermal efficiency to be lower than that of a recuperation.

### *3.3 Effects on The Thrust Specific Fuel Consumption (TSFC) Of the Aircraft Engine*

By installing a $sCO_2$ waste heat recovery system to an aircraft engine, the fuel consumption required will be substantially reduced. Results from simulation show that the Brayton cycle is capable of reducing the TSFC to a value of 1.7474 kg/s/kN, or a 13.91 % in reduction from its original value, whereas 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 %. Therefore, the variation of TSFC is plotted as a function of increasing engine thrust as in Figure 7. Numerically, ranges of TSFC are 0.1942 – 0.0647 kg/s/kN for basic Brayton and 0.2096 – 0.0699 kg/s/kN for the recuperation cycle.

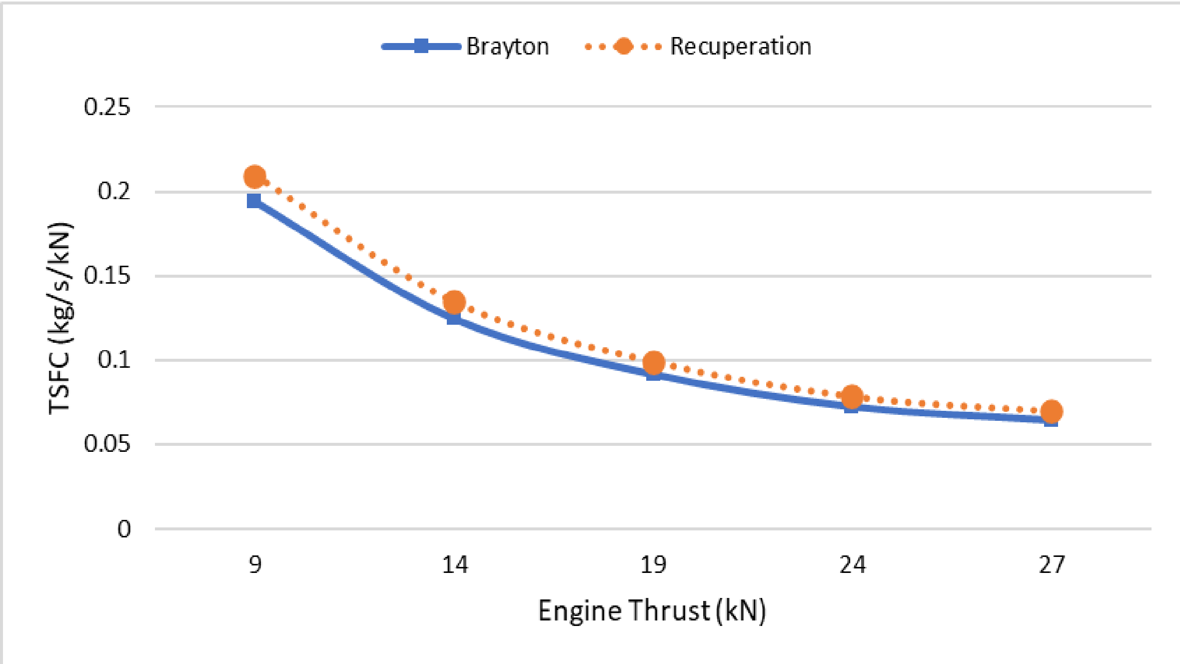



**Fig. 7.** Variations of TSFC with engine thrust for basic Brayton and recuperation cycles

## 4. Conclusions

From this study, one could conclude that the recuperation $sCO_2$ cycle is better-performing than basic Brayton cycle. Although a recuperation cycle requires an extra recuperator to be installed, it produced vast improvements in terms of performance.

On another note, the impact of integrating $sCO_2$ cycle to an aircraft engine is recorded by calculating the thrust specific fuel consumption (TSFC) value, which shows quite impressive results, of 7 to 13 % of reduction in TSFC, for both of the cycles. This provides a positive insight that a $sCO_2$ cycle might be a good option of waste heat recovery system for aircraft engines.

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