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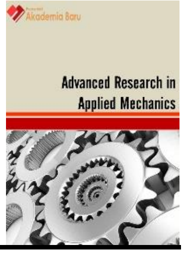

Performance Analysis of Supercritical Carbon Dioxide-Brayton Cycle for Waste Heat Recovery using Aspen Plus

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ABSTRACT

This study will focus on technologies and applications that has excelled in other industries, but yet to be explored in aviation, which is waste heat recovery technology, with supercritical carbon dioxide (sCO_2) as the cycle's working fluid, in reducing jet engines' fuel consumption and minimizing fuel expenses and carbon dioxide (CO_2) emissions. Research on the analysis of a sCO_2 cycle thermodynamically to be integrated into a turbofan jet engine will be highlighted in this paper. The analysis will be conduct ed via simulation within the Aspen Plus software and result's post-processing via Microsoft Excel. A quantitative analysis to select the best performing sCO_2 cycle configuration, as well as the jet engine's performance increment after the cycle's integration as its waste heat recovery system, are presented in this paper. The results stated that for both thermal efficiency and net work, recuperation cycle (42.46 %, 2197.67 kW) performs much better than basic Brayton cycle (18.53 %, 2555.84 kW).

Keywords:
Aspen Plus, Brayton cycle, waste heat recovery, supercritical carbon dioxide

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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-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]. In the aviation field, typical turboshaft

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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 [5].

Supercritical carbon dioxide ($s\mathrm{CO}_2$) is a state of 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 CO_2 can achieve supercritical condition with ease. High values for specific heat can be achieved at constant pressure and isothermal compressibility.$s\mathrm{CO}_2$ 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 [6].

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), and a jet engine Brayton cycle (around 100 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 [7].

Therefore, the research objective is to analyze each configuration's performance quantitatively, mainly via thermal efficiency, net work generated, and heat recovery efficiency, to determine which $s\mathrm{CO}_2$ cycle is the best performing. The performance improvements made to a turbofan jet engine can also be gauged, in terms of Thrust Specific Fuel Consumption (TSFC), after fitting the best performing $s\mathrm{CO}_2$ cycle.

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 [8, 9], to marine gas turbines [10], 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) [11, 12, 13, 14, 15]. Therefore, two different $s\mathrm{CO}_2$ cycles were selected to gauge the best performing configuration for jet engine's waste heat recovery system, which are: (i) Recuperation cycle (Fig.1 (a)); and (ii) Basic Brayton cycle, as a control (Fig. 1(b)).

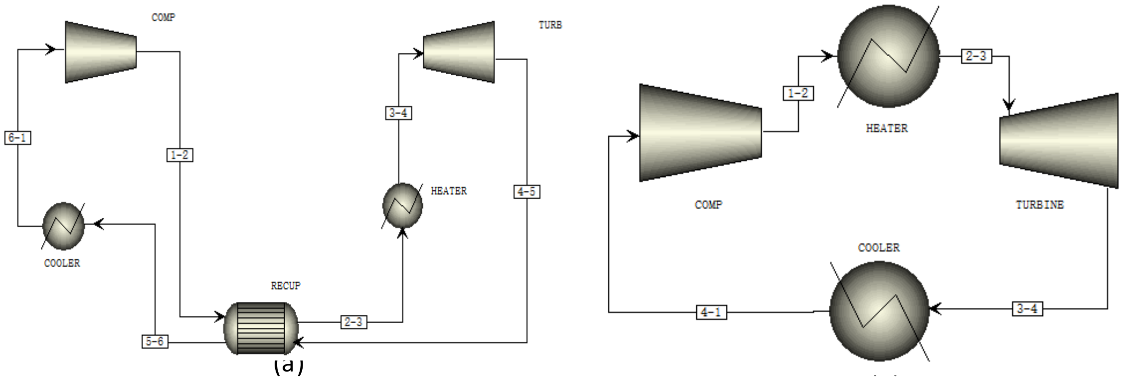

Fig. 1. Schematic diagram for a (a) recuperation cycle and (b) basic Brayton cycle systems simulated on Aspen Plus

3. Results and discussions

At Fig. 2, 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%.

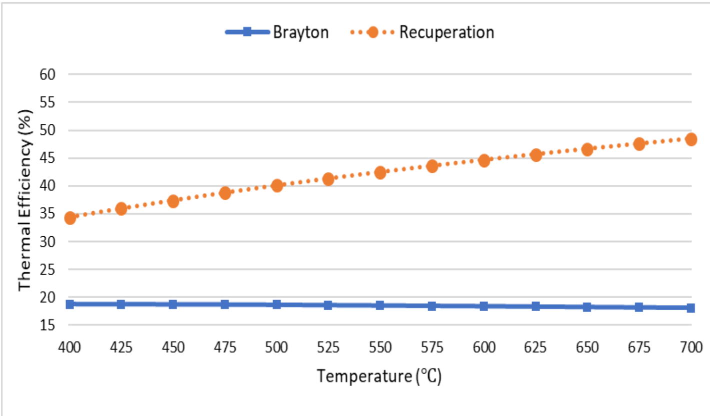

Fig. 2. Effect of waste heat temperature variation on thermal efficiency for all sCO_2 cycles

For Fig. 3, the net work 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.

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 net work and thermal efficiency to be lower than that of a recuperation.

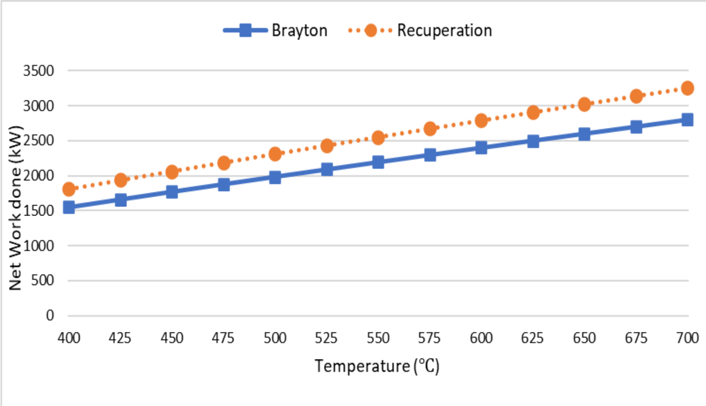

Fig. 3. Effect of waste heat temperature variation on net work done for all sCO_2 cycles

4. Conclusions

To summarize the results obtained from our research, it is concluded that in terms of thermal efficiency, the recuperation cycle is better-performing than basic Brayton's. In terms of sensitivity analysis, when waste heat temperature is increased, all cycles experienced an increasing in thermal efficiency and net work done. Although a recuperation cycle requires an extra recuperator to be installed to a basic Brayton cycle, it produced vast improvements in performance, compared to basic Brayton cycle. Nonetheless, the performances of a basic Brayton sCO_2 cycle is also very encouraging, which raises the possibility of utilization in low-grade (less than 100 ℃) and medium-grade (100 – 400 ℃) waste heat recovery, by which the increased efficiency in recuperation effect can be neglected.

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