Performance Analysis of Heat Recovery System for a Turbofan Engine using Intercooler and Recuperator via Aspen Plus

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Abstract: Global warming and climate change have been major problems in the present world. Greenhouse gas emissions contribute to global warming in which carbon dioxide being the best known. The aviation sector (excluding aerospace) has contributed to a total of 49.4 billion tons of carbon dioxide emission in 2016 alone. A solution to curb the increase of greenhouse gases has been proposed to temporarily solve this problem while future technological advancements occur. Having a heat recovery system by using heat exchangers in the engine helps to not only improves the performance of the engine but to also reduce temperature of the exhaust gases that will be eliminated as waste heat into the atmosphere. The main objective of the introduction of intercoolers and recuperators is to reduce the thrust specific fuel consumption whilst increasing the thrust and reducing emissions. This research thesis focuses on the analysis of intercooling and recuperation within the aspects of thermodynamics to be integrated into a typical turbofan engine. The analysis will be conducted via process simulation software – Aspen Plus V11 and the data from the software will be exported to Microsoft Excel for post-processing and graph visualization. Three main objectives of the study are to determine whether compression work will be reduced, studying the increase of thrust and performance of the engine with the positioning of heat exchangers and the improvement of TSFC with the integration of heat exchangers. For the first objective, it has been proven that there is a reduction in compression work for the recuperated engine of 7.64% but there is a 13.17% increase in compression work for the intercooled engine. For the second objective, thrust increased in both recuperated and intercooled cycles with 1.14% and 1.31% for the recuperated and intercooled cycles, respectively. Finally for the third objective, a decrease in TSFC for both recuperated and intercooled cycles show that both the heat recovery systems have an improvement of TSFC.

1 Introduction

For the past few decades, the main contributor of global warming has been carbon emissions. Especially in the region of Southeast Asia, which consists of Malaysia,
In the aviation sector, aircraft engines’ exhaust fumes are classified as high-grade waste heat due to the harnessing of exhaust heat from direct combustion processes to be recovered as useful energy. Four primary factors influence the selection criteria of various heat recovery technologies to have an acceptable waste heat recovery system. The four properties are the heat transfer method, waste heat carrier medium, equipment size, and operational temperature range [12]. Previous researchers have studied the possibilities to recover this waste heat using organic Rankine cycle and supercritical CO₂ cycle [13-15].
However, these methods would not really be cost effective and would give extra weight to the aero-engine.

Intercooling and recuperation along with reheating have been widely used in the gas turbine industry as it is an approach that is feasible and consumes less time to partially advance designs of gas turbines which are already pre-existing. It would usually take about ten or more years to complete the design of gas turbines from initial conceptual phase to the production stage. Westinghouse and Rolls-Royce proved this strategy of incorporating intercoolers, recuperators, or reheaters when they built the WR-21 marine gas turbine engine, which had intercooler and recuperator devices, enhancing efficiency by improving thermal performance [16]. Having an intercooled recuperated turbofan engine in civil airlines has the potential to reduce pollutant emissions and fuel consumption. This can be accomplished by enhancing the heat recovery system [17].

Therefore, it is suggested in this paper that by integrating an intercooler and a recuperator, the compressor work will be reduced due to the increase of density and pressure of the air entering the compressor. Emissions would be reduced due to the presence of the recuperator that utilises exhaust heat to preheat the turbine inlet. Besides that, correct positioning of heat exchangers would result in maintaining the effectiveness of the component.

1.2 Present studies on heat recovery

In order to conceptually optimise problems, Omar et al. [18] developed a mathematical model for calculating the mass of a compact heat exchanger in a conventional gas turbine cycle with a recuperator as heat recovery. The type of engine used was a dual-circuit, twin-shaft turbofan engine. It is found that when the heat exchanger effectiveness increases, the optimal values of compressor pressure ratio decrease significantly. Besides that, increasing the effectiveness of the heat exchanger will also decrease the optimal values of the bypass ratio. It is also stated found that the turbofan efficiency increases with an increase of heat exchanger efficiency. The variety of different parameters that respond to the heat exchanger was discussed and the mathematical model was used as a tool to optimise these parameters. The type of heat exchanger used is also an essential parameter that needs to be emphasised. Xu et al. [17] which utilised an intercooled recuperated turbofan engine states that the preliminary choice for heat recovery system would be the fin tube heat exchanger due to its high effective heat transfer performance and compact structure. A major problem of the installation of heat exchangers in jet engines is the bending flow path which would cause substantial pressure loss. The journal discusses on how the flow path design can be improved and the selection of heat exchangers with annular fins and circle tubes were proposed. Iterative calculations for the heat recovery system were also done to optimise the heat exchanger effectiveness. A program named Civil Engine Flow Path Design which isa new method of flow path design has been developed in order to conceptually estimate the size of the overall engine flow path. Sensitivity analysis was also discussed in the journal in which a major finding states that an increase of 8MW in the amount of heat transfer of the intercooler will lead to an improvement of 33.95% improvement in thrust. Meanwhile, an increase of 8 MW in the amount of heat transfer in the recuperator will lead to a 2.72% decrease in thrust. High amounts of heat transfer in the intercooler causes the HPC to use less work from the high-pressure turbine (HPT), improving exhaust velocity thus increasing the thrust. However, in the recuperator, high amounts heat transfer would cause a reduction in nozzle exit temperature, reducing the thrust. Besides that, an 8MW increase in heat transfer amount in the recuperator would lead to an increase by 16.53% decrease in specific fuel consumption (SFC) due to the increase in turbine inlet temperature (TIT) due to recuperation. An increase in thrust can be done by increasing the heat transfer amount in the intercooler. Likewise, increasing the heat transfer amount in the recuperator would decrease SFC and emissions. However, more research is needed to explore the performance
of the intercooled recuperated turbofan engine for an overall flight mission of the engine. Flow path design issues may also need further consideration. Salpingidou et al. [19] studied the effect of placing recuperators at different locations. They placed a recuperator after the power turbine (conventional recuperative, CR), before the power turbine (alternative recuperative, AR) and placing both before and after the power turbine (staged heat recovery, SHR). The journal compares these three different recuperative cycles in twin-spool gas turbine engines. Integrating heat exchangers right after the final turbine in the conventional recuperative configuration is done to exploit the high thermal energy content of the hot exhaust gases in which the heat will be fed to the compressor discharge air where it enters the combustion chamber with higher content of enthalpy, reducing the cycle fuel demand leading to increased thermal efficiency while reducing emission of pollutants. A thermodynamic model was developed with the aid of CAPE-OPEN/COCO, CyclePad and GasTurb11. Results have shown that the CR cycle was more preferable than AR cycle for low pressure ratio values while when the OPR is at higher values, the AR cycle would be preferred.

2 Methodology

The software used is Aspen Plus V11 to model to turbofan engine. Aspen Plus V11 is a software commonly used in chemical engineering, more accurately process simulating sectors. This software is capable of building a process model and then simulating it using complex calculations with different models, equations, regressions, etc. The sophisticated user interface of the software enables the user to directly obtain parameters from the processes such as temperature, pressure, enthalpy flow etc. and can easily be exported into Microsoft Excel where the next step will be carried out. Data processing will be carried out with Microsoft Excel in which simple calculations of work, thrust and, TSFC will be done.

The turbofan engine on Aspen Plus V11 was modelled after the CFM56-7B engine. The fan and exhaust are modelled as a compressor and a turbine respectively. A component known as a splitter is used after the fan to split the airflow into two — one is entering into the LPC and the other as bypass air. Figure 1 shows the general turbofan CFM56-7B engine modelling.

Fig. 1. Schematic flowsheet diagram of a basic turbofan Brayton cycle simulated.

In the intercooled cycle, the basic turbofan cycle was still used. However, an addition of a heat exchanger was introduced in between the LPC and the HPC, acting as an intercooler. Figure 2 shows the model.
Fig. 2. Schematic flowsheet diagram of an intercooled turbofan Brayton cycle simulated.

In the intercooled cycle, the basic turbofan cycle was still used. However, an addition of a heat exchanger was introduced after the LPT acting as a recuperator to harvest hot air from the turbine. Figure 3.

Fig. 3. Schematic flowsheet diagram of a recuperated turbofan Brayton cycle simulated.

3 Results and discussion

A turbofan engine has been modelled and simulated on the Aspen Plus V11 software using parameters from a reference source and the results were compared. Parameters for model validation are tabulated in Table 1. Ambient air is set at temperatures and pressures 288 K and 101.4 kPa respectively.

<table>
<thead>
<tr>
<th>Component</th>
<th>Location</th>
<th>Station number</th>
<th>Mass flow(kg/s)</th>
<th>Temperature(K)</th>
<th>Pressure (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fan</td>
<td>Inlet</td>
<td>1</td>
<td>361.0</td>
<td>288</td>
<td>100.4</td>
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<tr>
<td></td>
<td>Outlet (exhaust)</td>
<td>2</td>
<td>301.8</td>
<td>337</td>
<td>159.5</td>
</tr>
<tr>
<td></td>
<td>Outlet (LPC)</td>
<td>3</td>
<td>59.2</td>
<td>314</td>
<td>130.5</td>
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<tr>
<td>LPC</td>
<td>Inlet (fromfan)</td>
<td>4</td>
<td>59.2</td>
<td>314</td>
<td>130.5</td>
</tr>
<tr>
<td></td>
<td>Outlet</td>
<td>5</td>
<td>59.2</td>
<td>445</td>
<td>370.9</td>
</tr>
<tr>
<td>HPC</td>
<td>Inlet</td>
<td>6</td>
<td>59.2</td>
<td>445</td>
<td>370.9</td>
</tr>
<tr>
<td></td>
<td>Outlet</td>
<td>7</td>
<td>56.8</td>
<td>872</td>
<td>3338.0</td>
</tr>
<tr>
<td>Combustor</td>
<td>Inlet</td>
<td>8</td>
<td>56.8</td>
<td>872</td>
<td>3338.0</td>
</tr>
<tr>
<td></td>
<td>Outlet</td>
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<td>58.1</td>
<td>1624</td>
<td>3171.5</td>
</tr>
<tr>
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<td>Inlet</td>
<td>10</td>
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<td>1617</td>
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<tr>
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<td>Inlet</td>
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<td>59.3</td>
<td>1241</td>
<td>872.0</td>
</tr>
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<td></td>
<td>Outlet</td>
<td>13</td>
<td>59.3</td>
<td>897</td>
<td>200.7</td>
</tr>
<tr>
<td>Exhaust</td>
<td>Outlet</td>
<td>14</td>
<td>60.5</td>
<td>894</td>
<td>198.7</td>
</tr>
</tbody>
</table>
3.1 System design results

The system design results are obtained and tabulated in Table 2:

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Basic Brayton</th>
<th>Recuperation</th>
<th>Intercooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPC work $W_{LPC}$ (kW)</td>
<td>7,794</td>
<td>7,399</td>
<td>9,466</td>
</tr>
<tr>
<td>HPC work $W_{HPC}$ (kW)</td>
<td>25,405</td>
<td>23,262</td>
<td>28,106</td>
</tr>
<tr>
<td>HPT work $W_{HPT}$ (kW)</td>
<td>24,322</td>
<td>24,765</td>
<td>28,163</td>
</tr>
<tr>
<td>LPT work $W_{LPT}$ (kW)</td>
<td>22,431</td>
<td>22,704</td>
<td>25,063</td>
</tr>
<tr>
<td>Overall net power produced $W_{nett}$ (kW)</td>
<td>13,554</td>
<td>16,808</td>
<td>15,654</td>
</tr>
</tbody>
</table>

The data above can be represented graphically in Figure 4 which represents the power produced in turbines whereas Figure 5 representing power consumed in compressors. There is a 7.64% decrease in power consumed by compressor in the recuperation cycle but in the intercooled cycle, there is an increase of 13.73% in power consumed by compressor. [22,23]
With the results in Table 2, compressor power consumed has been reduced in relation to the baseline engine in the recuperation cycle but seen an increase in work in compressor in the intercooled cycle both relative to the baseline engine proposed by Aydin et al. [20]. However, even though the increase in compressor was seen in the intercooled cycle, the overall power output was increased because the turbines have also increased in power produced. The recuperation cycle has higher output power and also a reduction in compression work as hypothesised. Andriani et al. have found that the main intercooling effect reduces compression work leading to a greater enthalpy drop in the power turbine, causing an increase in power [21]. This corresponds to the higher drop in temperatures in the compressor in in the intercooled cycle. The cycle with recuperation gives the highest output power of 16,808 kW with an increase of about 24% to the reference engine which is 13,554 kW. The intercooled cycle also has a reasonably promising value of 15,654 kW, having an increase of about 15.49% with regards to the reference engine.

### 3.2 Thrust, propulsive efficiencies and thrust specific fuel consumption

In gas turbine engines, thermal efficiency quantifies the nett work output with the total heat input supplied to the working fluid. However, in aero-engines where production of thrust is considered, propulsive efficiency is used as an indication to quantify how efficient thermal efficiency is converted into useful propulsive energy. The propulsive efficiency is a function of the thrust, velocity and therate of fuel addition into the combustion chamber. Figure 6 shows the propulsive efficiency in all three cycles.

It is seen that the propulsive efficiency of the intercooled cycle is relatively the lowest among all three of the cycles with a propulsive efficiency of 32.03%. The recuperative and reference cycles both have propulsive efficiencies of 48.06% and 47.52% respectively. The low value of propulsive efficiency in the intercooled cycle with about a difference of 32.60% shows that it is underperforming with regards to the reference engine although in previous sections, we have seen that the intercooled cycle has shown some promising results in nett power output and in thrust production.

The thrust specific fuel consumption (TSFC) is a measure of how much thrust per unit fuel can be produced. Lower TSFC values are better as less amount of fuel is needed to produce a same unit of thrust. TSFC in the recuperative and intercooled cycles show lower results with 0.00541 kg/kNs and 0.00540 kg/kNs when compared to the reference TSFC value of 0.00547 kg/kNs. These differences have a reduction of about 1.10% and 1.28% for the recuperative and intercooled cycles respectively.

![Variation of Propulsive Efficiency](image_url)

**Fig. 6.** Propulsive efficiencies of each cycle
4 Conclusion

After carrying out the study, it is found that:

- The pressure and temperature before and after intercooling and recuperation had been carried out via simulation modelling on Aspen Plus V11. From these parameters, the required work input for the cycles have been identified in the software.
- Besides that, the intercooler seems to show poor performance in this case, therefore only a recuperator would be a feasible choice to be installed as a heat recovery system in the turbofan engine.
- Finally, lower fuel burn has been achieved in both intercooled and recuperated cycles in which the TSFC was computed to verify this objective in which the initial objective of the thesis was to develop a turbofan engine with lower fuel burn by evaluating its TSFC.
- To conclude, although the intercooled cycle has the highest nett power and thrust produced, the propulsive efficiency is lower than the reference engine. The recuperated cycle on the other hand might not have extremely high percentages of difference of nett power, thrust, propulsive efficiency and TSFC, it seems to be a better choice over the intercooled cycle.

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References


