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PARAMETRIC STUDY ON AIR BRAYTON CYCLE AS AN EXHAUST ENERGY RECOVERY METHOD

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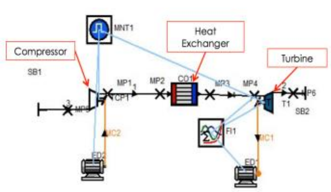
Graphical abstract



Abstract

Exhaust energy recovery is one of the ways to improve engine's fuel utilization. Parametric study of Air Brayton Cycle (ABC) as an exhaust energy recovery was done to see its feasibility. Parameters such as the mass flow rate, heat exchanger effectiveness, compressor and turbine efficiencies and heat exchanger pressure drop were analyzed to see their effects. It was found that the ABC can extract up to 3-4 kW of energy from the exhaust of a 5.9 liter diesel engine. This translates to about 3-4% of Brake Specific Fuel Consumption (BSFC) improvement. Careful integration of the main components is crucial to the success of the ABC as an exhaust energy recovery.

Keywords: Exhaust energy recovery, waste heat recovery, Brayton cycle, pressure ratio

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1.0 INTRODUCTION

Exhaust energy recovery is gaining more attention due to the increasing demand of a more efficient engine. The ever stringent emission regulations and fluctuating fuel prices further amplify this need. An internal combustion engine expels more than 30% of the fuel's energy in the exhaust as wasted heat [1, 2]. This wastage could be harvested via various exhaust energy recovery methods such as Air Brayton cycle (ABC), Rankine cycle, turbo compounding and thermoelectric generator (TEG). Many researches have been done using these methods [3-14]. For this study, the parametric study of ABC as a form of exhaust energy recovery is investigated.

2.0 AIR BRAYTON CYCLE

Brayton cycle is a thermodynamic cycle where a constant pressure heat addition process takes place such as in a gas turbine. It can either be a closed loop system where the working fluid in this case is air, is reused or an open loop where fresh air is drawn into the compressor. Figure 1 shows a Brayton cycle exhaust energy recovery system being integrated to an internal combustion engine (ICE).

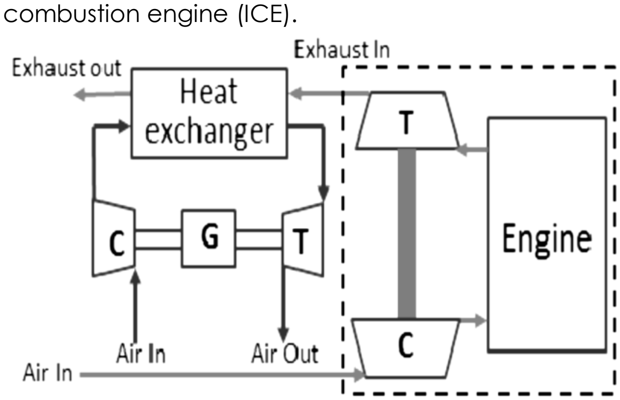

Figure 1 An example of Air Brayton cycle exhaust energy recovery configuration [3]

Brayton cycle generally consists of three main components which are the compressor, heat exchanger and turbine or expander. A compressor will first compress air into a heat exchanger. Exhaust gas from the engine will then pass through the heat exchanger which will transfer heat to the compressed air. After flowing through the heat exchanger, the hot air will then be expanded via a turbine or expander to produce work. The turbine can be coupled to a generator to produce electricity or, similar to mechanical turbo compound, be coupled to the engine to provide extra power.

Brayton cycle has a distinct advantage where the working fluid (air), is readily available, environmentally friendly and also cost effective. Besides that, another advantage is that the Brayton cycle can work as an add-on or retrofit unit and can be easily coupled to an existing system. This is highly desirable as major hardware changes on the existing engine are not needed.

Analytical study on the use of Brayton Bottoming System (BBS) on a diesel engine found that when compared to a normal turbocharged engine, the BBS can give up to 12% improvement in fuel economy. When compared with turbo compound system, it can still give an improvement of 4.4% in fuel savings. It was also suggested to pair the BBS with turbo compound to result in much better fuel economy [3].

In this paper, Brayton cycle for energy recovery was implemented by integrating it together with the turbocharger compressor [4]. This allows the system to only have one compressor instead of two. Results show that the fuel economy can be improved by 2.6% at high engine speeds and 4.6% at low engine speeds under full load operating conditions [4].

3.0 METHODOLOGY

Parametric study on Air Brayton Cycle (ABC) was done to see its feasibility as a form of exhaust energy recovery. The arrangement of components of the studied ABC is similar to what is shown in Figure 1. The recovered power from the ABC will be the main concern as that will translate to the amount of power recovered from the exhaust. In this study, various parameters were varied such as the mass flow rate of the system, heat exchanger effectiveness and pressure drop/loss as well as compressor and turbine efficiencies.

3.1 Governing Equations

The compressor power is given by Equation (1)

$$P_{Compressor} = \frac{\dot{m}_C C_p T_{inlet}\left(1 - PR^{\frac{k-1}{k}}\right)}{\eta_C} \quad (1)$$

Turbine power in Equation (2)

$$P_{Turbine} = \dot{m}_T C_p T_{inlet}\left(1 - PR^{\frac{k-1}{k}}\right)\eta_T \quad (2)$$

Air will be used as the working fluid for our Brayton cycle system. Specific heat of air is given by Equation (3)

$$C_{p\_air} = A_0 + A_1T_1 + A_2T_1^2 + A_3T_1^3 + A_4T_1^4 + A_5T_1^5 \quad (3)$$

Where,

A_0=0.10831165 x 10^4,
A_1=-0.68388122,
A_2=0.17875137 x 10^{-2},
A_3=0.113236565 x 10^{-5},
A_4=0.82943324 x 10^{-9},
A_5=0.11100191 x 10^{-11}

Power recovered will be the amount of power extracted at the turbine minus the power supplied to the compressor. This is shown in Equation (4)

$$P_{Recovered} = P_{Turbine} - P_{Compressor} \quad (4)$$

Heat exchanger effectiveness in Equation (5)

$$\varepsilon = \frac{(\dot{m}C_p)_g(T_{c,out} - T_{c,in})}{(\dot{m}C_p)_{\min}(T_{g,in} - T_{c,in})} \quad (5)$$

Engine Brake Specific Fuel Consumption (BSFC) is obtain from Equation (6)

$$BSFC = \frac{\dot{m}}{P} \quad (6)$$

1D simulation was also done to validate the result from the parametric study. The simulation was modelled in AVL BOOST which is part of AVL SIMULATION TOOLS [15].

The governing equations in AVL BOOST consist of energy, momentum and mass conservation, solved along mean path-line of the flow. Equations of mass and energy are solved for each volume and the momentum equation solved for each boundary between volumes. The equations are written in an explicitly conservative form in Equations (7) – (9).

Equation (7): Mass continuity equation

$$\frac{dm}{dt} = \sum_{boundaries} m_{flux} \quad (7)$$

Equation (8): Conservation of momentum equation

$$\frac{d(m_{flux})}{dt} = \frac{dpA + \sum_{boundaries}(m_{flux}u)}{dx} - \frac{4C_f\frac{pu^2dxA}{2D} - Cp(\frac{1}{2}pu^2)A}{dx} \quad (8)$$

Equation (9): Conservation of energy equation

$$\frac{d(me)}{dt} = p\frac{dV}{dt} + \sum_{bound} m_{flux} H - h_g A(T_{gas} - T_{wall}) \quad (9)$$

3.2 Selection of Engine

For this study, an engine was chosen as reference to obtain a realistic exhaust gas temperature. The engine chosen is a 5.9 liter six cylinder diesel engine from Cummins [16]. Table 1 shows the engine's specifications and performance characteristics.

Table 1 Engine specifications for Cummins 6B5.9 [16]

Parameter	Value
Capacity	5.9 L
Bore	102 mm
Stroke	119 mm
Compression ratio	17.3:1
Rated Power	90 kW @ 2800 RPM
Rated Torque	305 Nm @ 2800 RPM
Exhaust Temperature	950 K

The effect of mass flow rate of the system, heat exchanger effectiveness and pressure drop/loss as well as compressor and turbine efficiencies on the amount of power recovered was studied. The effects of each parameter were studied individually. Thus, while one parameter will be changed, the other parameters will be kept constant for analysis. The default value of each parameter is shown in Table 2.

Table 2 Default parameters for analysis

PARAMETER	VALUE
Air Brayton Cycle Mass Flow Rate	0.2 kg/s
Heat Exchanger Effectiveness	0.75
Compressor and Turbine Efficiencies	0.75
Pressure drop across heat exchanger	5 %

4.0 RESULTS AND DISCUSSION

4.1 Parametric Study Validation

The parametric study conducted was compared and validated with 1D simulation. The ABC system was modeled in AVL BOOST software as shown in Figure 2.

The default parameters in Table 2 were inserted into the simulation model to compare with our parametric study. Figure 3 shows the comparison of power recovered based on parametric study values and simulation values.

It can be seen that the parametric study values does not differ too much from the simulation values. The difference is about 0.5% in average. Thus, this shows that the parametric study is adequate enough for this analysis.

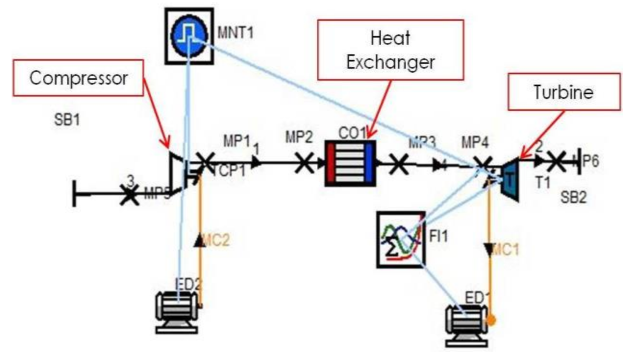

Figure 2 1D simulation model in AVL BOOST.

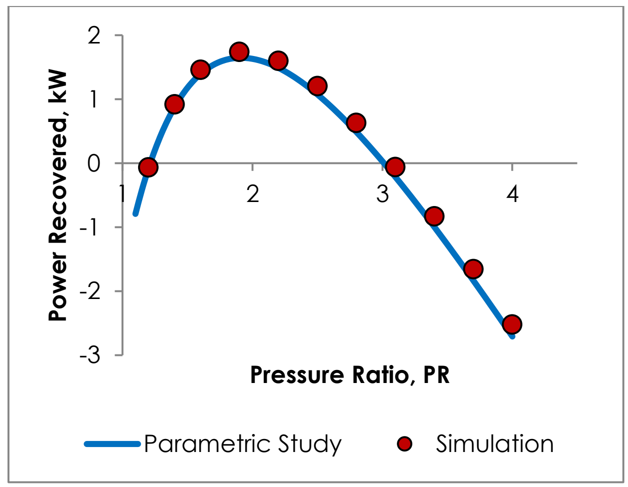

Figure 3 Comparison of parametric study and simulation

4.2 Effect of Mass Flow Rate of Air

For this study, the working fluid used was air. The first parameter of concern is the effects of varying the mass flow rate of air in the system. The results are shown in Figure 4. Mass flow rate of 0.1, 0.2 and 0.3 kg/s were used while the rest of the parameters are set as in Table 2.

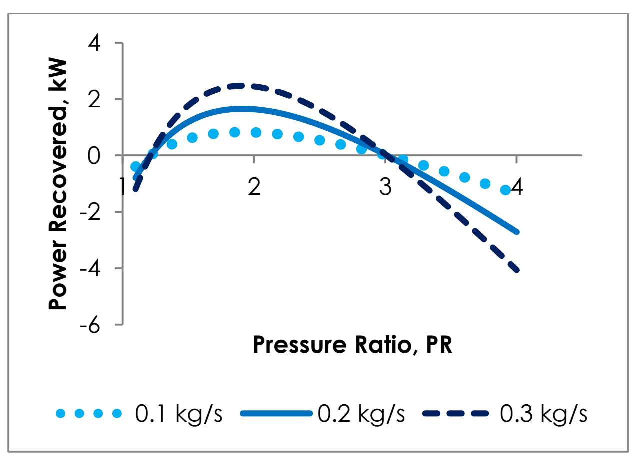

Figure 4 Power recovered with varying mass flow rate of air

Figure 4 shows that as mass flow rate of air in ABC increases, the power recovered also increases. The maximum powers that can be recovered are about 800 W, 1.6 kW and 2.5 kW for 0.1, 0.2 and 0.3 kg/s respectively. It can also be seen that the optimum pressure ratio for all cases is about PR=2. At higher pressure ratios (PR>3) however, negative improvement can be seen. This is because at higher pressure ratios, the compressor requires more work to compress the air and the power extracted by the turbine is not enough to compensate this requirement.

The effect of this power recovered to the engine's BSFC is then shown in Figure 5.

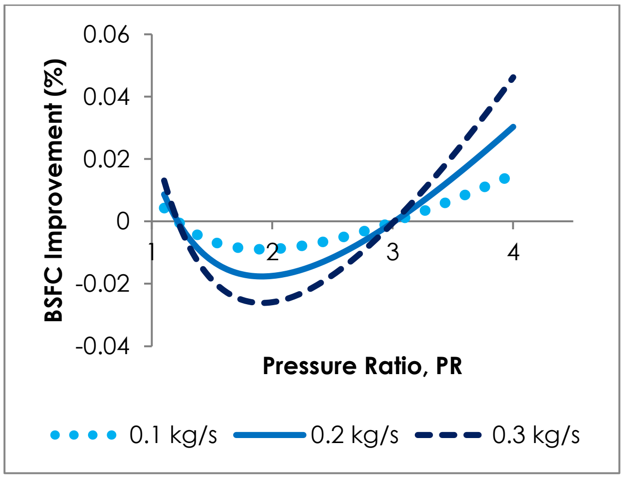

Figure 5 BSFC improvement with varying mass flow rate of air

From Figure 5, it can be seen that for 0.3 kg/s of air flow and PR=2, the system can produce almost 3% improvement is BSFC. At 0.2 kg/s the highest improvement in BSFC is about 2% and for 0.1 kg/s is about 1%. At higher pressure ratios (PR>3), Figure 5 shows that the BSFC increases which means an increase in fuel consumption. This is due to negative power recovered in that pressure ratio range.

4.3 Effect of Heat Exchanger Effectiveness

Next parameter investigated is the heat exchanger effectiveness. Heat exchanger effectiveness dictates the amount of energy that is extracted from the exhaust and transferred to the ABC. The effect of heat exchanger effectiveness is shown in Figure 6.

From Figure 6 it can be seen that as heat exchanger effectiveness increases, the amount of power that can be recovered increases as well. Up to 3.4 kW of power can be recovered using a heat exchanger with an effectiveness of 0.8. Another thing worth noting is that as heat exchanger effectiveness increases, the optimum pressure ratio increases as well. This is mainly due to the non-linear relationship of power recovered and pressure ratio. Thus to fully optimize the power recovery, the pressure ratio of the system must be selected properly.

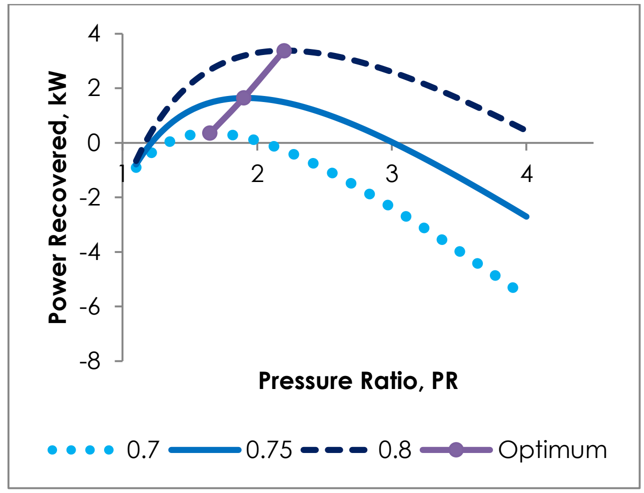

Figure 6 Power recovered with varying heat exchanger effectiveness

The effect of heat exchanger effectiveness on the BSFC of the engine can be seen in Figure 7. It can be seen that the BSFC improvement increases as the heat exchanger effectiveness increases. Almost 4% improvement in BSFC is possible if a heat exchanger with an effectiveness of 0.8 is used. It should be noted that at an effectiveness of 0.7, the BSFC improvement is almost negligible (less than 1%). Thus, an effectiveness of more than 0.7 is needed to make ABC work in this case as any lower value would render the ABC as an exhaust energy recovery method pointless.

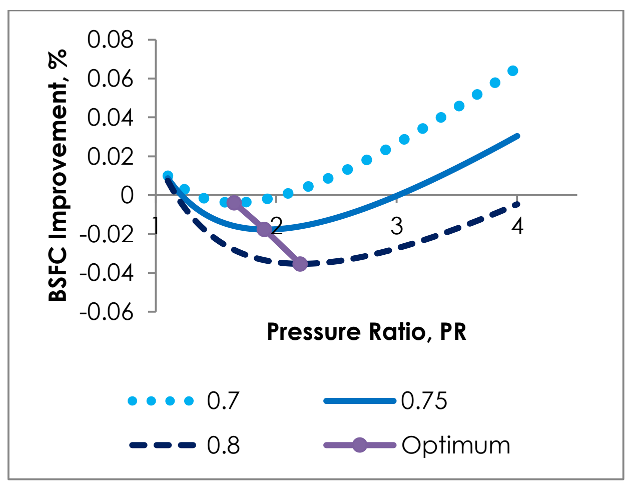

Figure 7 BSFC improvement with varying heat exchanger effectiveness

4.4 Effect of Turbo machines Efficiency

Another important parameter investigated is the efficiency of the compressor and turbine. Both the compressor and turbine efficiencies were set to be equal at 0.7, 0.75 and 0.8 to see their effects on power recovered. Figure 8 shows the power recovered at different compressor and turbine efficiencies with variations in pressure ratios.

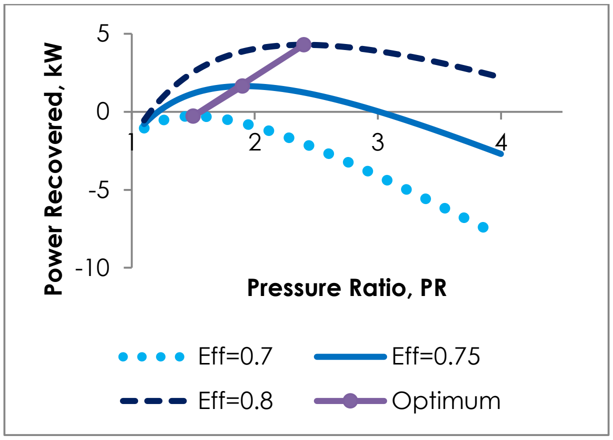

Figure 8 Power recovered with varying compressor and turbine efficiencies.

It can be seen that as the efficiency of the turbo machines increases, so does the power recovered. At an efficiency of 80% the maximum power recovered is about 4.3 kW whereas at 75% the maximum recovered power is about 1.6 kW. At efficiency of 70% however, there is negative work recovered which means that to make the ABC work, the efficiency of the turbo machines must be above 70%. Efficiencies of more than 70% are not uncommon for turbo machines [17].

Figure 9 shows the effect of varying turbo machines efficiencies on the BSFC.

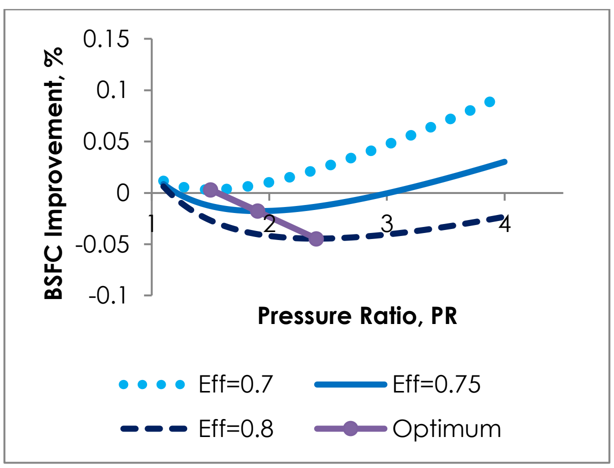

Figure 9 BSFC improvement with varying compressor and turbine efficiencies

It can be seen from Figure 9 that the BSFC improvement increases as the efficiency of both the compressor and turbine increases. More than 4% reduction in BSFC is possible when a compressor and turbine of 80% efficiency is used. It should be noted that similar to the power recovered value, there exist an optimum pressure ratio to extract exhaust energy using the ABC. Here we can see that at 75% efficiency, the optimum pressure ratio is about 1.9 whereas for 80% efficiency the optimum pressure ratio is 2.4. This again is due to the non-linear relationship of power recovered and pressure ratio.

4.5 Effect of Heat Exchanger Pressure Loss

The final parameter to look into is the effect of heat exchanger pressure loss on the ABC system. For this, 3 conditions will be tested which are 10%, 5% and no pressure loss. Figure 10 shows the effect of varying heat exchanger pressure loss on the power recovered from the ABC system.

Here in Figure 10, the effect of pressure loss can be seen quite clearly. As pressure loss increases, the amount of power recovered decreases. At no pressure loss condition, the maximum amount of power that can be recovered is around 3 kW. However, in reality, a heat exchanger with no pressure loss is quite hard to achieve maybe even impossible. At 5% pressure loss however the power recovered drops to about 1.6 kW and at 10% pressure loss the amount drops even further to only about 130W. This means that the pressure drop of the heat exchanger cannot be more than 10% otherwise the ABC system would not work efficiently.

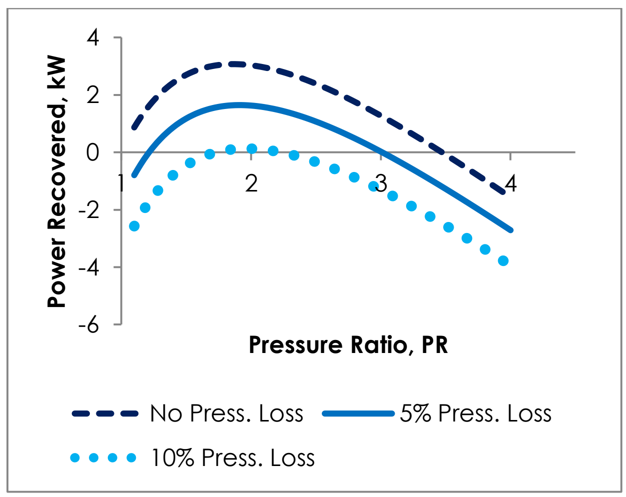

Figure 10 Power recovered with varying heat exchanger pressure loss

Figure 11 shows the effect of the heat exchanger pressure loss on the engine's BSFC. As heat exchanger pressure losses increase, the engine's BSFC increases as well. The maximum amount of BSFC improvement is about 3% at a pressure ratio of 2 when a heat exchanger with no pressure loss is used. At 5% the improvement is about 1.8% whereas at 10% pressure loss the improvement is only about 0.1% which is very small. This further stresses that a low pressure loss heat exchanger is needed and it should be less than 10% to make the ABC work.

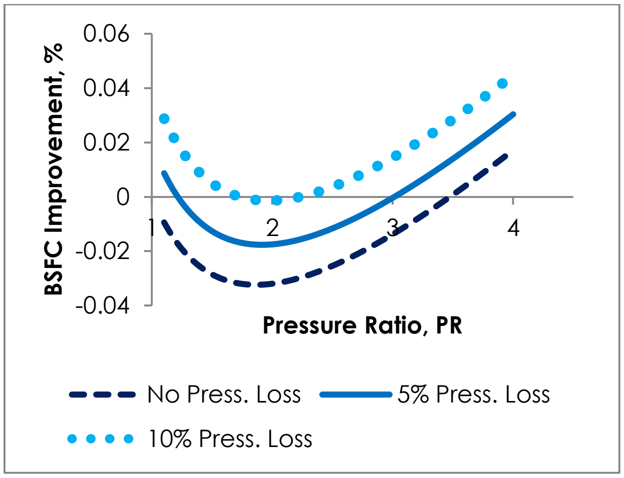

Figure 11 BSFC improvement with varying heat exchanger pressure loss

4.6 Further Discussion

From the parametric study conducted, it can be seen that the Air Brayton Cycle (ABC) has the potential to work as an exhaust energy recovery system. The possible power recovered from the exhaust of this engine is about 3-4 kW and this results in about 3-4% in BSFC improvement. Other researchers also reported similar fuel economy improvement of about 2-4% [3]. One of the main component that is crucial to the success of the ABC as an exhaust energy recovery method is the heat exchanger. One of the main parameter is the effectiveness of the heat exchanger. From this study, the effectiveness of the heat exchanger should be more than 70% to make the ABC feasible. Definitely a higher effectiveness would result in more power to be recovered from the exhaust and research has been done on developing heat exchanger with high effectiveness that can reach over 90%.

However, having a high effectiveness alone is not enough as the heat exchanger must also have low pressure drop of not more than 10%. Developing a heat exchanger that is both effective and at the same time impose low pressure drop is a challenge as both of these parameters are countering each other. An effective heat exchanger will usually impose quite high pressure drop and vice versa thus a compromise might be needed. Proper analysis needs to be done to develop a heat exchanger specifically for the ABC that has high effectiveness, low pressure drop as well as being compact enough in terms of size.

Besides the heat exchanger, the compressor and turbine are also important components that will contribute to the success of the ABC. This can only be realized by using compressor and turbine that has efficiency of 70% and above. This is definitely achievable as various researches have shown that efficiencies of above 80% are possible. A higher efficiency compressor and turbine would definitely increase the amount of power recovered. From the parametric study, it was found that an optimum pressure ratio exists at various turbo machines efficiency and heat exchanger effectiveness. If the ABC is required to work at only one point this would not be a problem as the optimum pressure ratio can be selected and a suitable compressor and turbine can be chosen to work at that point. However, if the ABC was to be installed in an engine that works at different speed and load, like in an automotive engine for example, this could prove a challenge as the exhaust temperature and mass flow would definitely fluctuate over time. For the ABC to work effectively in this condition, the compressor and turbine must be able to work efficiently at various mass flow and pressure ratio. A variable geometry compressor and turbine might be needed to take advantage of this.

5.0 CONCLUSION

Parameters such as air mass flow rate, heat exchanger effectiveness and pressure drop as well as turbo machines (compressor and turbine) efficiency were studied. Air Brayton Cycle (ABC) can be implemented as an exhaust energy recovery method. A recovered power of about 3-4 kW is possible and this translates to about 3-4% improvement in engine BSFC. This can be realized and improved by having a high efficiency turbo machines (more than 70%) as well as high effectiveness (70%) and low pressure drop (<10%) heat exchanger. There is also an optimum pressure ratio where the ABC can extract maximum power. Careful analysis is needed on each component especially on the heat exchanger and turbo machines if ABC is to work optimally and provide maximum energy recovery.

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Nomenclature

P	Power
$\dot{m}_c$	Mass flow rate of the compressor
$\dot{m}_T$	Mass flow rate of the turbine
η_c	Compressor efficiency
η_T	Turbine efficiency
T	Temperature
$BSFC$	Brake specific fuel consumption
ε	Effectiveness
C_p	Specific heat
PR	Pressure ratio
k	Specific heat ratio

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