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THE STUDY ON PERFORMANCE OF NATURALLY ASPIRATED SPARK IGNITION ENGINE EQUIPPED WITH WASTE HEAT RECOVERY MECHANISM

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ABSTRACT

The waste heat from exhaust gases represents a significant amount of thermal energy, which has conventionally been used for combined heating and power applications. This paper explores the performance of a naturally aspirated spark ignition engine equipped with waste heat recovery mechanism (WHRM). The amount of heat energy from exhaust is presented and the experimental test results suggest that the concept is thermodynamically feasible and could significantly enhance the system performance depending on the load applied to the engine. However, the existing of WHRM affects the performance of engine by slightly reducing the power.

Keywords: waste heat recovery, power turbine, exhausts gas.

INTRODUCTION

The number of motor vehicles continues to grow globally and therefore increases reliance on the petroleum and increases the release of carbon dioxide into atmosphere which contributes to global warming. To overcome this trend, new vehicle technologies must be introduced to achieve better fuel economy without increasing harmful emissions. For internal combustion engine (ICE) in most typical gasoline fuelled vehicles, for a typical 2.0 L gasoline engine used in passenger cars, it was estimated that 21% of the fuel energy is wasted through the exhaust at the most common load and speed range [1]. The rest of the fuel energy is lost in the form of waste heat in the coolant, as well as friction and parasitic losses.

Since the electric loads in a vehicle are increasing due to improvements of comfort, driving performance, and power transmission, it is therefore of interest to utilize the wasted energy by developing a heat recovery mechanism of exhaust gas from internal combustion engine. It has been identified in [2] that the temperature of the exhaust gas varies depending on the engine load and engine speed. The higher the engine speed the higher the temperature of the exhaust gas. Significant amounts of energy that would normally be lost via engine exhausts can thus be recovered into electrical energy. Theoretically, the energy from the exhaust gas can be harnessed to supply an extra power source for vehicles and will result in lower fuel consumption, greater efficiency, and also an overall reduction in greenhouse gas emission.

The recent technologies on waste heat recovery of IC engine is consists of low grade heat from cooling system and high grade heat from exhaust system. For low grade waste heat, the organic Rankine cycle is the favourite choice to recover waste energy [3] 4, 5, 6], whereas high grade heat, several techniques of recover the energy are applied such as thermoelectric generator [7, 8, 9, 10], turbocharger [11, 12, 13, 14], turbo-compound [15, 16, 17, 18], Rankine cycle system [19, 20, 21, 22, 23], heat pipe [24], air conditioning [25, 26], heat exchanger for thermal energy storage [27, 28], and heat exchanger for fuel conservation, emission reduction [29] and power turbine of waste heat recovery mechanism [30]. The approaches either by theoretical, simulation or experimental works it lead to improve the brake fuel consumption that generated better overall efficiency.

Based on the applications of waste heat recovery that are more attractive to be explored are turbocharger, and turbo-compound due to the simple construction and less cost. This is because the potential to produce output power and improves BSFC and efficiency are promising. To improve the performance of turbocharger, several studies [11, 31, 32, 33] used electrical motor assisted or integrated Starter Generator (ISG) to turbocharger or to parallel hybrid power system on a diesel engine [11]. The aim of this method is to improve the fuel economy of diesel homogeneous charge compression ignition (HCCI), and the results are the fuel economy, the soot emission and NOx emission are improved by 10.9%, 6%, and 12.1% respectively [11]. The electrical motor assisted turbocharger is the integration of a high-speed 7.5 kW electric motor-generator within a standard turbocharger of a heavy-duty vehicle, which the purpose of this system is to improve the fuel economy and turbo-lag. As a result, this system on an urban bus, the fuel economy can be improved by up to 6% or above depending on the actual driving cycle and an electrical assist motor can reduce turbo-lag by typically 50% [31, 32, 33].

Many studies on the turbo-compound in term of control strategy [16], parametric geometry [15], dynamic model and characteristic [17, 34], and behaviour of turbo-compound based on operating charts for turbocharger component and power turbine [35]. Sendyka and Soczówka [36] claimed that the application of a turbo-compound system is profitable, especially for heavy loaded engines, which can improve power, torque, and fuel consumption by 10-11%, 11%, and 5-11%, respectively.

In control strategy, Algrain, M. [16] describes control system developments for an electric turbo-compound system on heavy-duty diesel engines. The simulation results done by [16] indicate that at the rated power, the fuel consumption of a Class-8 on-highway truck engine would be reduced by almost 10%. Considering a typical road load for an on-highway truck, where the engine prevailing operating regime is at 1500 rpm, and loads fluctuated between 25% and 50%, overall reduction in fuel consumption is estimated to be around 5% [16]. Zhao *et al.* [15] presents a set of parametric studies of power turbine performed on a turbo-compound diesel engine by means of turbine through flow model. By using simulation model, the result is verified and validated with engine performance test data and attained reasonable accuracy. The parametric studies are conducted to analyse the influences of turbine parameters (blade height, blade radius and nozzle) on engine BSFC, power, expansion ratio, air mass flow rate and exhaust temperature. As results, the geometry parameters of turbine (blade height, blade radius, nozzle exit blade angle) have significant effects on engine BSFC and power [15].

For our concern, there is no application of turbo-compound without a turbocharger system in the internal combustion engine. Therefore, this condition is an opportunity to study on the power turbine (turbo-compound) at the naturally aspirated internal combustion engine that has not a turbocharger system.

In this study, a simple novel waste heat recovery mechanism (WHRM) is proposed. The WHRM is a device adapted from a turbocharger module, where the compressor part is replaced with a DC generator to produce an output current and voltage. This simple and low cost structure with straight forward energy recovery and with complexity-free control system is expected to be a great alternative application for an energy recovery system.

EXPERIMENTAL SETUP

The experiment was performed on a Toyota vehicle having 1.6 litre in-line four-cylinder gasoline engines. Table-1 shows the specification of the test engine. A schematic diagram of the experimental setup is shown in Figure-1. A 75 Watt bulb and 100 Watt bulb were used as a load causing the DC generator to produce an output current and voltage which were recorded in a computer through USB digital multimeter. The air duct to the intake manifold of engine was equipped with a pitot tube digital anemometer to measure the volume flow rate of the intake air. The engine speed and the WHRM turbine speed were continuously monitored using an optical tachometer allowing the digital data to be recorded in a computer through USB data acquisition module. This was also applied for the data of the throttle position for intake air captured using the existing throttle sensor in the experimental vehicle. The test was conducted on the road with variable vehicle speed up to 70 km/h with normal driving and full throttle driving to measure the performance of engine with and without WHRM. Some features of the instrumentation are summarized in Table-2. To determine the performance of engine on the full throttle driving, a simulation program is needed. This simulation is created under Matlab Simulink environment. The program is using demo Simulink program [37] with some modification to suit the target. From the simulation, we can get the power and torque of the engine experimental vehicle. The results are needed to compare between before and after implementation of waste heat recovery mechanism, which then can see whether these mechanisms affect the performance of engine or not. Figure-2 shows the original demo program Simulink and some modification had been made.

Table-1. Specification of the test engine.

Type	Specification
Valve train	DOHC 16 valves
Fuel system	Multi point fuel injection
Displacement	1587 cc (in-line)
Compression ratio	9.4:1
Bore	81 mm
Stroke	77 mm
Power	112Hp @ 6600 rpm
Torque	131Nm @ 4800 rpm

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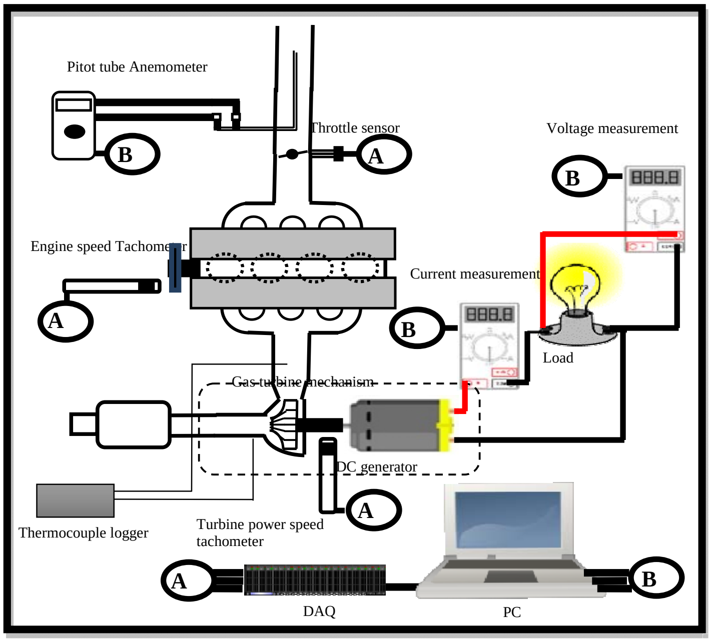

Figure-1. Schematic layout of the experimental setup of waste heat recovery mechanism.

Table-2. Details of the instrumentation used in the experiment.

Instrument	Range	Uncertainty
Extech Pitot tube anemometer for Air volume flow rate [m^3/min]	0 – 99 ,999	±3% rdg
Existing throttle sensor for Throttle angle [degree]	0 – 90º	-
Compact Optical tachometer for Engine speed [rpm]	100 – 60,000 rpm	±0.5%
Compact Optical tachometer for power turbine [rpm]	100 – 60,000 rpm	±0.5%
Pros'Kit USB multimeter for Voltage [V]	0 – 600 V	±(0.5%+4d)
Pros'Kit USB multimeter for Current [A]	0 -10 A	±(1.2%+10d)

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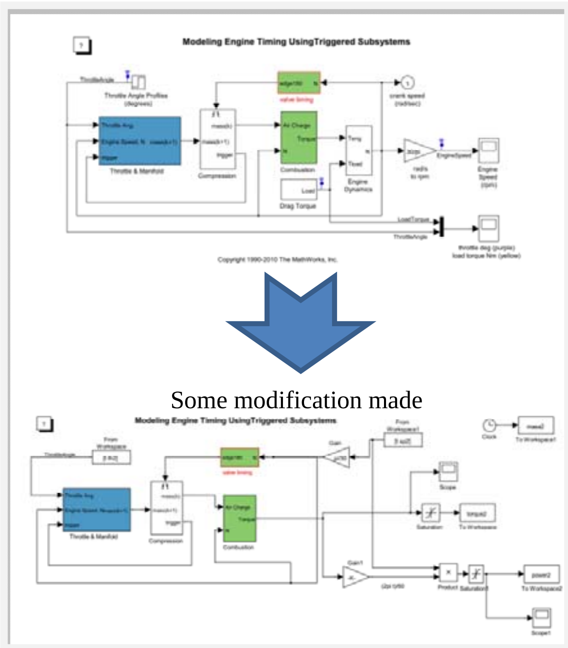

Figure-2. Modified Demo simulink program.

RESULTS AND DISCUSSIONS

Figure-3, Figure-4, and Figure-5 show the heat energy from the exhaust gas of experimental vehicle in terms of engine speed, exhaust temperature, air flow rate, and throttle angle.

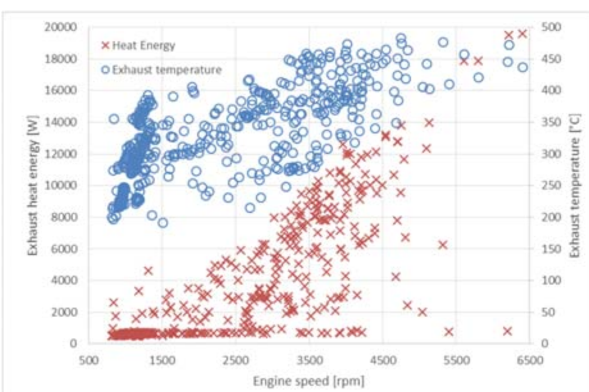

Figure-3. Heat energy from exhaust gas of experimental vehicle on engine speed and exhaust temperature.

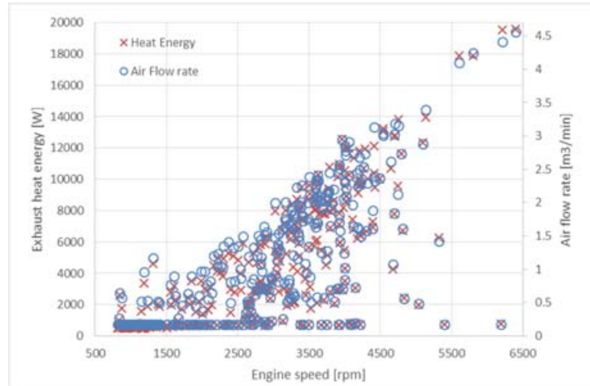

Figure-4. Heat energy from exhaust gas of experimental vehicle on engine speed and air flow rate.

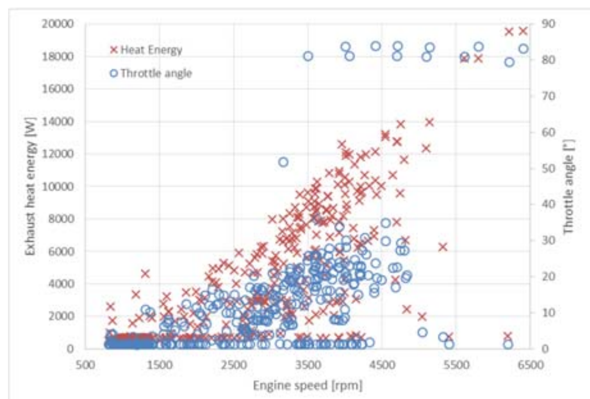

Figure-5. Heat energy from exhaust gas of experimental vehicle on engine speed and throttle angle.

The heat energy from exhaust is depending on the engine speed and exhaust temperature; however there are some behaviours that is not accomplish this argument. This is because the experimental work was conducted on the on-road test that no parameters were being controller. The measurement is based on the normal driving and full throttle driving on the road, resulting the dynamic and transient conditions. The heat energy from exhaust is various in the range of 500 W up to almost 20 kW, which is a good agreement with [38] where the heat energy is in the range of 5 kW and can reach up to 23 kW. Air flow rate give a significant effect on the heat energy that almost each single data of both parameters are match each other. Even though, engine speed and exhaust temperature are high, but air flow rate is low, the heat energy follows the air flow rate consistently.

In term of throttle angle, the increasing of throttle angle will increase the heat energy as shown in Figure-5. By applying around 10 to 30 degree on the normal driving, we can produce 2 kW to 12 kW of heat energy. However, at the full throttle driving where the throttle angles are almost 90 degree, not all the heat energy is on the

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maximum value. This is once again due to the actual driving on the road as dynamic and transient conditions. Therefore, to optimise the heat energy from exhaust, we need to increase the engine speed, exhaust temperature, throttle angle, and air flow rate. By combining all of these parameters on the optimum value, the heat energy from exhaust can be generated at the optimum condition. It is obviously seen that the waste heat energy is high. Therefore, to recover this waste heat energy from exhaust system is worthy.

Figure-6 shows the measured data of the parameters which have already combined between the normal driving test and full throttle test. Both tests are clearly differentiated by seeing the throttle angle curve, where showing the highest throttle angle achieved (around 87º - 88º) was a full throttle test.

As seen in Figure-6, correlations between all the parameters can be clearly observed for instance the air flow rate gives influence to the engine speed; the higher air flow rate can get a higher engine speed. The change of throttle angle also affects directly the air flow rate, engine speed, and WHRM turbine speed, which eventually changes the output current and voltage accordingly.

In full throttle test, two conditions were applied, which was 2nd gear position and 3rd gear position in an initial start. It is clearly shown that the turbine speed can get higher value at the 2nd gear position compare to the 3rd gear condition. This is due to the 2nd gear position for initial start will a higher torque to start moving and easily achieved 7000 - 8000 rpm of engine speed within a few second, however in the 3rd gear condition would have lower torque causing difficult to get engine speed of 7000 - 8000 rpm in few seconds.

In term of voltage and current that generated from generator, the higher voltage can be seen at the load of 100 W / 48 V as high as 42 volt, however the higher current at the load of 75 W / 24 V as high as 3.3 A. This is due to the torque of generator. The load of 100 W / 48 V generates lower torque for generator thus high rpm of turbine can be achieved resulting higher voltage can produce, however this load has less current to produce due to higher voltage of load. Correlation between torque and current is directly affected, which higher current will give a higher torque. Low voltage with higher wattage of load can create a higher current for generator.

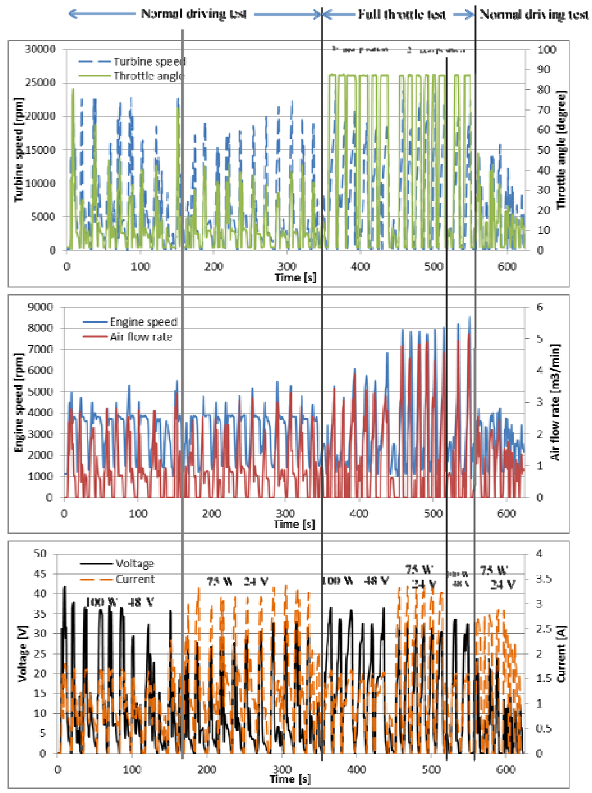

Figure-6. The measured data from the experimental vehicle with WHRM.

Figure-7 shows the power generated from WHRM. It is clearly shown that the load of 75 W / 24 V can generate higher power as high as 109 W than the load of 100 W / 48 V, even though the voltage produced from load of 75 W / 24 V is slightly less than the load of 100 W / 48 V. Figure-7 reveals that the performance of WHRM is significantly affected by the fluctuation of throttle angle, air flow rate and engine speed during the normal driving and full throttle driving, which results in the power of WHRM being fluctuant. This behavior also found in [39] that could be difficult to capture a consistent output power of WHRM.

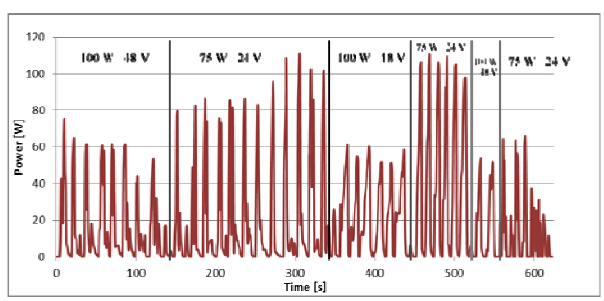

Figure-7. Power generated from WHRM.

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Figure-8 and Figure-9 show the power and torque of the experimental vehicle, respectively. It can be seen that the WHRM affects the performance of the experimental vehicle, which the vehicle without WHRM has slightly higher power that the vehicle with WHRM. This is because of the back pressure created from the turbine. The stream of gas exhaust that should be released through the exhaust pipe smoothly, was suddenly block with the existing of turbine causing the exhaust system being disturbed. Finally, the power of vehicle becomes slightly decrease from the original power. Another reason is that the experimental vehicle is a naturally aspirated engine, where by the design the higher back pressure created at the exhaust manifold cannot be catered by this kind of engine, where the turbocharger engine is more suitable for this circumstance.

The torque of both with and without WHRM show a similar value. Therefore the existing of WHRM in the experimental vehicle is not much affect the performance of vehicle in term of torque.

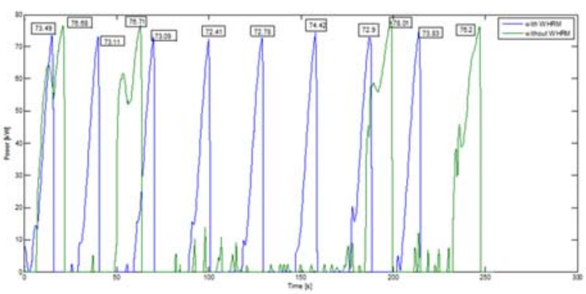

Figure-8. Power of the experimental vehicle with and without WHRM (value in kW).

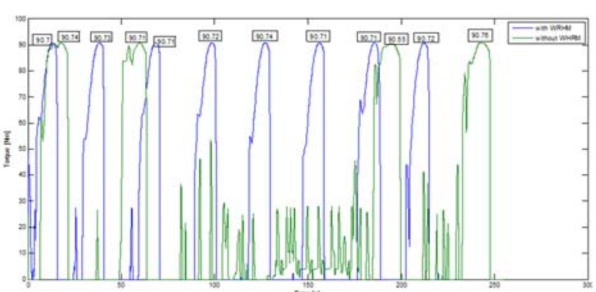

Figure-9. Torque of the experimental vehicle with and without WHRM (value in Nm).

CONCLUSIONS

Utilization of waste heat energy from the exhaust gas using a WHRM system in a spark ignition engine has been reported. The system has been proven to produce current up to 3.5 A and voltage up to 24 V at normal driving in rural environment. The proposed system could become a potential energy recovery that can be stored in the auxiliary battery to be used for electrical purposes such as air conditioning, power steering, or other electrical or electronic devices in an automotive vehicle. However, the existing of WHRM affects the performance of engine by slightly reducing the power.

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