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Exhaust Gases Energy Recovered from Internal Combustion Engine for Useful Applications

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Abstract : *The importance of this study is primarily to address the energy problem. The main contribution of this study, in addition to conserving energy through recovery technique, is reduction in the impact of global warming due to exhaust gas emission to the environment. The objective of the research is to recover exhaust gases energy from internal combustion engines for utilization. The experimental set-up consisted of a single cylinder, four-stroke, multi-fuel engine connected to eddy current dynamometer for loading. Thermocouple temperature sensors and transmitters were used to measure exhaust gas to calorimeter inlet temperature and exhaust gas from calorimeter outlet temperature. Exhaust gas mass flow rate and temperature measurements were used to determine the recovered energy. Recovered heat energy was 1.257% of fuel energy when the engine was operated on diesel at 1000 rpm and a torque load of 18 Nm. 3.153% of fuel energy was recovered at 1500 rpm and a torque load of 6 Nm when biodiesel was used. At a speed of 1000 rpm 22.6% and 23.004% of the thermal energy through exhaust was recovered when the engine used diesel and biodiesel at torque loads of 6 Nm and 14 Nm respectively.*

Keywords: *calorimeter, exhaust gas, fuel energy, global warming, recovered energy*

I. Introduction

Internal combustion engines are the greatest consumers of fossil fuel in the world [1]. From the total heat supplied to the engine in the form of fuel, approximately, 30 to 40% is converted into useful mechanical work. The heat which remains is expelled through exhaust gases to the environment and engine cooling systems, resulting in serious environmental pollution [2]. Fossil fuel reserves are getting depleted. With research on waste heat recovery of exhaust gas from internal combustion engines, energy supply will be increased and the impact of global warming due the emission of carbon dioxide would be reduced. Exhaust gases immediately leaving the engine can have temperatures as high as 450-600°C [3]. It is imperative that serious and concrete effort should be launched for conserving energy through exhaust heat recovery techniques. Such a waste heat recovery technique would ultimately reduce the overall energy requirement and also the impact on global warming. The internal combustion engine has been a primary power source for automobiles over the past century. Presently, high fuel costs and concerns about foreign oil dependence have resulted in increasingly complex engine designs to decrease fuel consumption. For example, engine manufacturers have implemented techniques such as enhanced fuel-air mixing, turbo-charging, and variable valve timing in order to increase thermal efficiency.

However, around 60-70% of the fuel energy is still lost as waste heat through the coolant and the exhaust [4]. Moreover, increasingly stringent emissions regulations are causing engine manufacturers to limit combustion temperatures and pressures lowering potential efficiency gains [5]. It is argued that the engine has consumed more than 60% of fossil oil, as the most widely used source of primary power for machinery, critical to the transportation, construction and agricultural sectors [6]. On the other hand, legislation of exhaust emission levels has focused on carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and particulate matter (PM). Energy recovery on engine exhaust is one of the ways to deal with these problems since it can improve the energy utilization efficiency and reduce emissions [7]. Given the importance of increasing energy conversion efficiency for reducing both the fuel consumption and emissions of engine, scientists and engineers have done lots of successful research aimed at improving engine thermal efficiency, including supercharge and lean mixture combustion. However, in all the energy saving technologies studied, engine exhaust heat recovery has been less emphasized. Many researchers recognize that waste heat recovery from engine exhaust has the potential to decrease fuel consumption without increasing emissions, and recent technological advancements have made these systems viable and cost effective [8, 9, 10]. Among the different technologies available for waste heat recovery applications to internal combustion engines, the Rankine cycle is traditionally regarded as one of the solutions [11]. Extensive work has been proposed in relation to the application of Rankine cycles in road transport [12], as well as in the maritime sector [13]. Road and maritime applications normally differ markedly in terms of their operative conditions. Waste heat recovery system design for application in international shipping focuses on steady state conditions, and often, on one individual operating point, due to typically stationary operations of such systems. On the other hand, road applications require focus on transient operations, which leads to the existence of extensive literature on waste heat recovery control systems [14, 15]. Even in the latter case, however, although observations from real operations are sometimes used to weight the selected operating points [16] the waste heat recovery system design still relies on steady state methods. Heating and cooling periods are sometimes considered [17] but this is mainly done in order to estimate the time of response rather than for optimising the heat recovery potential. Non-road machinery, particularly agricultural machines, and inland shipping vessels constitute a significant share of respectively land and sea based transportation. These vehicles generally follow clearly identifiable operating cycles which are significantly dynamic but follow a determinate, repeatable pattern. In addition, compared to cars and trucks, these applications show higher engine load coefficient and exhaust temperatures [16, 18, 19, 20]. Hence, being in between steady state generator and heavy transient road engines for both size and transient behaviour, heavy non road engines (marine or agriculture) should have specifically designed heat recovery systems [21]. Several studies are dedicated to the dynamic performance of single phase heat exchangers as well as to two-phase ones [14, 15, 22]. However, the subject of efficient designs of WHRS evaporator based on dynamic cycle performance still remains unclear.

II. Materials and Methods

The experimental set-up consisted of a single cylinder, four-stroke, multi-fuel engine connected to an eddy current dynamometer for loading at various engine speeds for diesel and biodiesel fuels. Experiments were conducted for the two fuels at engine speeds of 1000, 1250 and 1500 rpm in accordance with the manufacturer's recommendations. The engine was tested for torque loads of 6 to 22 Nm at intervals of 4 Nm for the speeds and fuels studied. The dynamometer was bidirectional. The shaft mounted finger type rotor ran in a dry gap. A closed circuit type cooling system permitted for a sump. Dynamometer load measurement was from a strain gauge load cell and speed measurement was from a shaft mounted three hundred sixty pulses per revolution rotary encoder. To control the speed, a set speed was given to the controller. If the measured speed of the shaft was less than that of the set speed, the load was decreased. If the measured speed of the shaft was greater than that of the set speed, then the load was increased. Since the engine had sufficient torque to attain the set speed, this maintained a constant speed. To control the load, a set load was given to the controller. If the measured load on the dynamometer was greater than that of the set load, the load was decreased. If the measured load on the dynamometer was less than that of the set load, then the load was increased. Since the engine had sufficient torque to attain the set load, this maintained a constant load while the speed varied.

2.1 Fuel Energy

In order to determine the fuel energy, the calorific value of the two fuels: diesel and biodiesel were used as 42000 kJ/kg and 37800 kJ/kg respectively. Croton nut biodiesel was used in this study. From (1) fuel energy was a product of fuel consumption data and calorific value for the two fuels when the engine was operated at different speeds and torque loads.

$$\dot{Q}_F = \dot{m}_f \times CV \tag{1}$$

Where:

$\dot{Q}_F$ = fuel energy (kJ/h)

$\dot{m}_f$ = fuel consumption (kg/h)

CV = calorific value (kJ/kg)

2.2 Recovered Exhaust Gas Energy

A pipe calorimeter with a volume of 0.06 m^3 was used to determine the changes in exhaust gases energy. Thermocouple temperature sensors and transmitters were used for temperature measurement. Data was obtained for: air and fuel consumption; exhaust gas to calorimeter inlet temperature; and exhaust gas from calorimeter outlet temperature. The specific heat capacity of exhaust gas was used as 1.006 kJ/kg·K. The quantity of energy recovered in the exhaust gas was determined as given in (2).

$$\dot{Q}_R = \left(\dot{m}_a + \dot{m}_f\right) \times C_p \times (T_i - T_o) \tag{2}$$

Where:

$\dot{Q}_R$ = energy recovered in exhaust gas (kJ/h)

$\dot{m}_a$= air consumption (kg/h)

$\dot{m}_f$= fuel consumption (kg/h)

C_p = specific heat of exhaust gas (kJ/kg·K)

T_i = exhaust gas to calorimeter inlet temperature (°C)

T_o = exhaust gas from calorimeter outlet temperature (°C)

III. Results and Discussions

Table 1 presents the calculated results of fuel energy, Table 2 presents the observed readings of exhaust gas to calorimeter inlet temperature, Table 3 presents the observed readings of exhaust gas from calorimeter outlet temperature and Table 4 shows the results of recovered energy from exhaust gases for diesel and biodiesel fuels at different engine speeds and torque loads.

Table 1: Fuel energy (kJ/h) for different engine speeds and torque loads

Fuel	Speed	Torque Load				
		6 Nm	10 Nm	14 Nm	18 Nm	22 Nm
Diesel	1000 rpm	50295	57435	46305	51870	56280
	1250 rpm	84945	76020	80010	68985	78225
	1500 rpm	64680	63315	69720	68040	64890
Biodiesel	1000 rpm	61520	59252	53109	54621	55472
	1250 rpm	79475	73805	75222	73332	74750
	1500 rpm	18900	25043	30240	35438	46683

Table 2: Exhaust gas to calorimeter inlet temperature (°C) for different engine speeds and torque loads

Fuel	Speed	Torque Load				
		6 Nm	10 Nm	14 Nm	18 Nm	22 Nm
Diesel	1000 rpm	226.9825	235.4933	265.2508	301.6185	317.7113
	1250 rpm	251.9720	265.8695	282.8140	311.8110	324.3443
	1500 rpm	286.3828	313.6878	321.2783	317.0655	309.5725
Biodiesel	1000 rpm	220.7150	229.8870	265.1768	305.5435	323.6478
	1250 rpm	245.0528	257.1550	287.6763	318.9543	327.7053
	1500 rpm	298.0313	326.7800	329.5810	323.6558	318.4850

Table 3: Exhaust gas from calorimeter outlet temperature (°C) for different engine speeds and torque loads

Fuel	Speed	Torque Load				
		6 Nm	10 Nm	14 Nm	18 Nm	22 Nm
Diesel	1000 rpm	181.0628	188.8180	208.9578	252.2200	280.1358
	1250 rpm	216.9143	223.4725	240.9443	275.0158	306.5290
	1500 rpm	239.9900	262.2458	298.9893	334.7343	357.4790
Biodiesel	1000 rpm	181.2850	187.1163	209.6405	249.0958	276.5935
	1250 rpm	203.4350	216.1705	239.4978	276.7233	316.3203
	1500 rpm	245.0060	278.8088	311.1170	342.1768	358.7660

Table 4: Recovered heat energy (kJ/h) for different engine speeds and torque loads

Fuel	Speed	Torque Load				
		6 Nm	10 Nm	14 Nm	18 Nm	22 Nm
Diesel	1000 rpm	223.7090	310.7696	557.2585	652.0935	505.7460
	1250 rpm	296.6622	361.0046	423.1053	483.0411	285.5740
	1500 rpm	505.0622	600.3571	348.6629		
Biodiesel	1000 rpm	196.4516	318.6234	682.1858	842.1567	639.4726
	1250 rpm	394.7314	409.3199	679.3241	723.2143	214.7649
	1500 rpm	663.8649	657.5995	341.8538		

In the case of diesel fuel, when the engine was operated at 1000 rpm and loaded at 6 Nm, the recovered energy was 0.445% of the fuel energy and 22.6% of heat energy entering the exhaust. This compares well with a study by [23] where 18% of heat energy entering the exhaust was recovered using a diesel engine. When the load was increased to 10 Nm, the recovered energy was 0.541% of the fuel energy and 22% of heat energy entering the exhaust. At 14 Nm the recovered energy was 1.203% of the fuel energy and 23.3% of heat energy entering the exhaust. The energy recovered at 1000 rpm for diesel fuel at a load of 18 Nm was 1.257% of the fuel energy and 17.8% of heat energy entering the exhaust. Loading the engine at 22 Nm showed that the recovered energy was 0.899% of the fuel energy and 12.8% of heat energy entering the exhaust. It can be concluded that torque loads between 6 Nm to 14 Nm had the same effect on the recovered energy since they gave percentages of heat energy entering the exhaust as: 22.6%, 22%, and 23.3%. In this study, the maximum recovered energy for the lowest engine speed of 1000 rpm was 0.181 kW while in a study by [23] the maximum recovered energy for the lowest engine speed of 1400 rpm was approximately 17 kW when the engine was fueled on diesel. [24] designed a medium temperature waste heat recovery system based on organic Rankine cycle to recover exhaust energy from a heavy duty diesel engine and achieved the highest exhaust waste heat recovery efficiency of 10% to 15% for the optimized heat exchanger design.

In the case of biodiesel fuel, when the engine was operated at 1000 rpm and loaded at 6 Nm, the recovered energy was 0.319% of the fuel energy and 20.024% of heat energy entering the exhaust. When the load was increased to 10 Nm, the recovered energy was 0.538% of the fuel energy and 20.753% of heat energy entering the exhaust. At 14 Nm the recovered energy was 1.285% of the fuel energy and 23.004% of heat energy entering the exhaust. Energy recovered at 1000 rpm for biodiesel fuel at a load of 18 Nm was 1.542% of the fuel energy and 20.029% of heat energy entering the exhaust. Loading the engine at 22 Nm showed that the recovered energy was 1.153% of the fuel energy and 15.688% of heat energy entering the exhaust. Torque loads of 6 Nm, 10 Nm, 14 Nm and 18 Nm had the same effect on recovered energy since the percentages of heat energy entering the exhaust corresponding to them were: 20.024%, 20.753%, 23.004% and 20.029%. In a related study, simulation work by [25] on energy recovery systems for engines showed that there were significant, potential, fuel economy advantages, between 6% and 31%, and high efficiencies could be achieved at practical operating pressures. [26] reported an improvement of 27% in recoverable exergy of flow at a heat exchanger outlet when the heat exchanger wall thickness was increased from 0.5 mm to 2.5 mm. In this study, the maximum recovered energy for the lowest engine speed of 1000 rpm was 0.2338 kW when the engine was fueled on biodiesel. Fig. 1 illustrates the variations of the recovered energy versus torque loads at an engine speed of 1000 rpm.

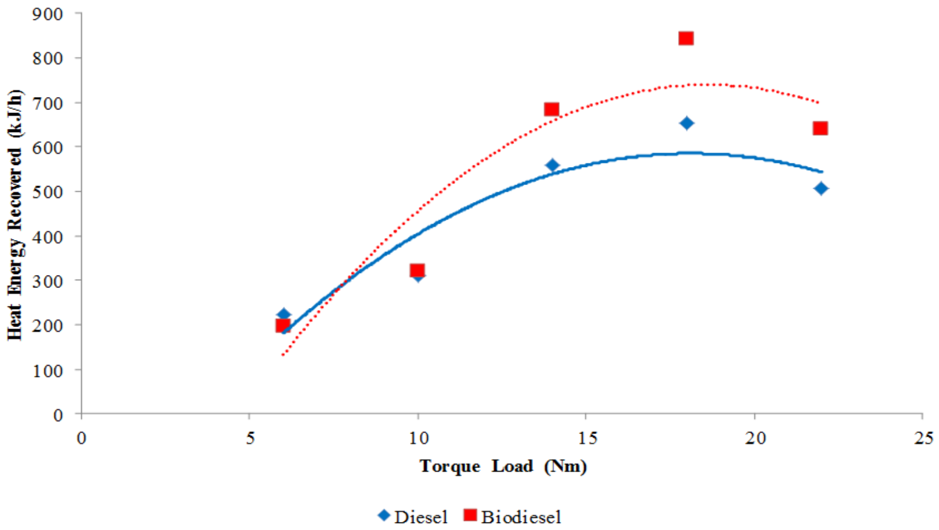

Figure 1: Recovered Energy against Torque Load at 1000 Rpm

Increasing the engine speed to 1250 rpm and loading at 6 Nm, in the case of diesel fuel, showed that the recovered energy was 0.349% of the fuel energy and 15.4% of heat energy entering the exhaust. This compares well with a study by [27] where a diesel engine integrated with a shell and tube exchanger was used to recover 10% to 15% of heat energy entering the exhaust. When the load was increased to 10 Nm, the recovered energy was 0.475% of the fuel energy and 17.5% of heat energy entering the exhaust. At 14 Nm the recovered energy was 0.529% of the fuel energy and 16.2% of heat energy entering the exhaust. The energy recovered at 1250 rpm for biodiesel fuel at a load of 18 Nm was 0.7% of the fuel energy and 12.8% of heat energy entering the exhaust. Loading the engine at 22 Nm reduced the recovered energy to 0.365% of the fuel energy and 5.9% of heat energy entering the exhaust. In this study, the maximum recovered energy for the medium engine speed of 1250 rpm was 0.1342 kW while in a study by [23] the maximum recovered energy for the medium engine speed of 1800 rpm was approximately 21 kW when the engine was fueled on diesel. In order to improve waste heat recovery, [28] modelled the combination of organic Rankine cycle (ORC) with thermoelectric generator (TEG) in an internal combustion engine (ICE). The authors found that by recovering the high and low temperature waste heat with the thermoelectric generator and the organic Rankine cycle respectively, the energy recovery capability could be as high as 13.1 kW from a thermal source of 773 K.

For biodiesel fuel, when the engine was operated at 1250 rpm and loaded at 6 Nm, the recovered energy was 0.497% of the fuel energy and 18.8% of heat energy entering the exhaust. When the load was increased to 10 Nm, the recovered energy was 0.555% of the fuel energy and 17.6% of heat energy entering the exhaust. At 14 Nm the recovered energy was 0.903% of the fuel energy and 18.3% of heat energy entering the exhaust. The energy recovered at 1250 rpm for biodiesel fuel at a load of 18 Nm was 0.986% of the fuel energy and 14.3% of heat energy entering the exhaust. Loading the engine at 22 Nm reduced the recovered energy to

0.287% of the fuel energy and 3.7% of heat energy entering the exhaust. In this study, the maximum recovered energy for the medium engine speed of 1250 rpm was 0.201 kW when the engine was fueled on biodiesel. [29] concluded that dual loop organic Rankine cycle while using R123 could generate 32.63 kW. In static gas turbine applications, [30] used Toluene as a working fluid to implement an organic Rankine cycle (ORC) system due to its good thermal stability and being less harmful to the environment. [30] found that as much as 26 kW could be recovered from a 1500 kW gas turbine electric generator. Fig. 2 illustrates the variations of the recovered energy versus torque loads at an engine speed of 1250 rpm.

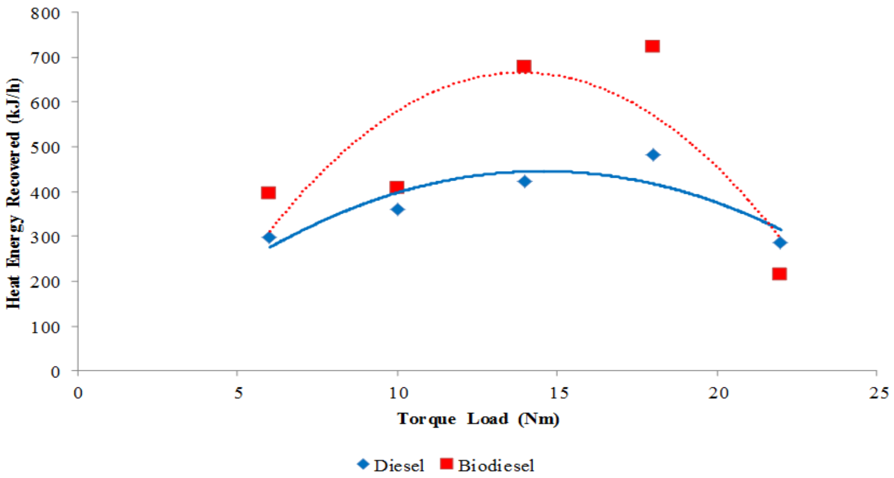

Figure 2: Recovered Energy against Torque Load at 1250 Rpm

In this study, the highest engine speed used was 1500 rpm. For diesel fuel, at the lowest load of 6 Nm, the recovered energy was 0.781% of the fuel energy and 17.66% of heat energy entering the exhaust. The energy recovered at 1500 rpm for diesel fuel at a load of 10 Nm was 0.948% of the fuel energy and 17.74% of heat energy entering the exhaust. At 14 Nm the recovered energy was 0.5% of the fuel energy and 7.49% of heat energy entering the exhaust. Torque loads of 6 Nm and 10 Nm had the same effect on recovered energy since the percentages of the total exhaust energy corresponding to them were: 17.66% and 17.74%. In this study, the maximum recovered energy for the highest engine speed of 1500 rpm was 0.1667 kW while in a study by [23] the maximum recovered energy for the highest engine speed of 2200 rpm was approximately 23 kW when the engine was fuelled on diesel. [31] conducted experiments to measure the available exhaust heat from a 40 kW diesel engine generator set and reported 10%, 9% and 8% additional power by using water, ammonia and hydrofluorocarbon-134a as the working fluids respectively. In the case of biodiesel fuel, the energy recovered at 1500 rpm for at a load of 6 Nm was 3.513% of the fuel energy and 19.3% of heat energy entering the exhaust. When the load was increased to 10 Nm, the recovered energy was 2.626% of the fuel energy and 15.8% of heat energy entering the exhaust. A load of 14 Nm reduced the recovered energy to 1.13% of the fuel energy and 6% of heat energy entering the exhaust. In this study, the maximum recovered energy for the highest engine speed of 1500 rpm was 0.1844 kW when the engine was fueled on biodiesel. Fig. 3 illustrates the variations of the recovered energy versus torque loads at an engine speed of 1500 rpm.

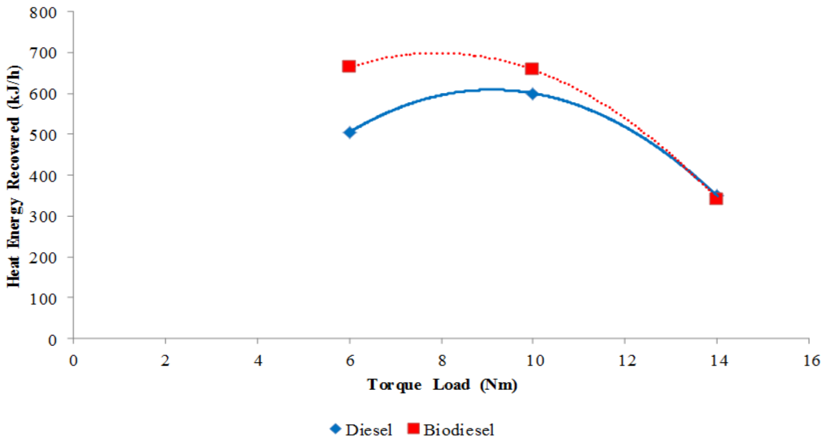

Figure 3: Recovered Energy against Torque Load at 1500 Rpm

IV. Conclusion

Considering the peak recovered energy at the three engine speeds: energy recovered at 1000 rpm for diesel fuel at a load of 18 Nm was 1.257% of the fuel energy and 17.8% of heat energy entering the exhaust, energy recovered at 1000 rpm for biodiesel fuel at a load of 18 Nm was 1.542% of the fuel energy and 20.029% of heat energy entering the exhaust, energy recovered at 1250 rpm for biodiesel fuel at a load of 18 Nm was 0.7% of the fuel energy and 12.8% of heat energy entering the exhaust, energy recovered at 1250 rpm for biodiesel fuel at a load of 18 Nm was 0.986% of the fuel energy and 14.3% of heat energy entering the exhaust, energy recovered at 1500 rpm for diesel fuel at a load of 10 Nm was 0.948% of the fuel energy and 17.74% of heat energy entering the exhaust, and lastly for biodiesel fuel, the energy recovered at 1500 rpm for at a load of 6 Nm was 3.513% of the fuel energy and 19.3% of heat energy entering the exhaust.

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