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Performance Evaluation of a Prototype Engine for Generation of Power from Exhaust Gas of a Gasoline Generator

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Abstract: *The use of waste heat associated with exhaust gas of internal combustion engine for electricity generation are abound in literature. However, the use of pressure energy in the exhaust gas to generate electricity is just gaining attention and the need to ascertain the feasibility of any device or engine that can use the pressure energy for the aforementioned purpose has become necessary. So in this research, performance evaluation of a developed prototype engine to generate power from the pressure energy associated with exhaust gas of gasoline generator was carried out. Minimum power of 58.1W and maximum power of 90.2W were developed by the prototype engine at exhaust gas velocities of 9.5m/s and 4.8m/s, backpressures of 109600 and 113800N/m^2, temperatures of 279^{0}C and 198 ^{0}C and at turbine speed of 401 and 640 rpm respectively. The maximum efficiency of the prototype engine was found to be 43.4% at the gasoline generator speed of 4000rpm while the minimum efficiency was found to be 40.6% when the gasoline generator speed was 1000rpm. The determination of the efficacy of employing the built porotype engine to generate electricity using pressure energy from gasoline generator exhaust gas, which is frequently wasted, in this research, is a significant contribution to knowledge.*

Keywords: *Prototype Engine, Gasoline Generator, Exhaust Gases, Thermoelectric Generators (TEGs), Power Generated*

INTRODUCTION

The problem of global warming has prompted researchers to focus their efforts not only on finding alternative renewable energy sources, but also on improving machine energy efficiency, which includes converting waste energy into useable energy (Kamarulhelmy *et al.*,2017). When compared to heat rejected through coolant and lubricating oil, exhaust gases of internal combustion engines carry away a greater amount of heat at high temperatures (Rajpoot, *et al.*,2017).

Many researchers have noticed the necessity to conserve waste heat or energy in the exhaust gas of internal combustion engines powered by fossil fuels (gasoline and diesel). As a result, these researchers have devised a number of methods for generating electricity from waste heat. A review of exhaust gas heat recovery for I.C. engines was conducted by Jadhao and Thombare (2013). Their research demonstrated that there is a lot of heat accessible from internal combustion engines and also described how much energy is lost through exhaust gas. Sawant *et al.* (2017) created a thermoelectric power generation system that might be used in a car engine. Based on their findings, they concluded that the thermoelectric generator's electric power is proportional to the exhaust gas flowrate and input exhaust temperature. In their work, Rahman *et al.* (2015) used MiF-EGR (micro-facet exhaust gas recirculation) to retain the intake temperature at 70^{0}C by keeping exhaust flow to the engine cylinder chamber and boost the engine volumetric efficiency. They claimed that the TEG generated electrical power from heat flow over an exhaust temperature gradient and transferred DC electrical power to the vehicle's electrical system, reducing the alternator's load by up to 10%. Adavbiele (2013) looked into a typical total waste heat recovery system that included thermoelectric generators (TEGs) and a gasoline engine. Although the TEGs' overall efficiency was low due to significant irreversibilities, the output power of the TEGs established a level of electrical power that could be generated from engine waste heat, according to the researcher.

For internal combustion engine autos, including gasoline and hybrid electric vehicles, Christopher and Shameer (2013) devised and implemented a thermoelectric waste heat energy recovery system. Their findings showed that the proposed technology may perform well in a variety of environments and is promising for the automotive industry. Kunt (2017) developed an air-cooled thermoelectric generator to recycle waste heat energy from internal combustion engines' exhaust systems. He assessed the performance by measuring voltage, current, and power values under various heat circumstances based on load resistance changes. The resulting results were compared to those of analysis and experiments. Maximum voltage was 11.03 V (experiment) and 11.22 V (analysis) at load resistance of 45, while maximum current was 0.42 A at load resistance of 5 (experiment). Bobba and Rajesh (2016) developed a 7X7 cm Bismuth Tellurium (Bi2Te3) Thermo Electric Generator that uses heat energy from automobile exhaust emissions to charge the battery of a hybrid vehicle and improve its performance. They claimed that the output voltage generated from this configuration was around 12V for a 6-minute engine operation during performance evaluation. Changxin and Wei (2013) designed a novel prototype for TEG made from vehicle exhaust, constructed an experimental structure, and tested it. They claimed that the prototype may be used for exhaust heat recovery based on the results of theoretical analysis and experiment. When the hot side temperature was 473K and the system thermal efficiency was 4.04 percent, the prototype could provide a maximum power output of roughly 202W. Goncalves *et al.* (2010) proposed employing heat pipes in conjunction with thermoelectric generators to recover heat from exhaust. Standard heat pipes are inserted into a square exhaust duct to gather heat and send it to a rectangular prism shaped metallic block on which the TEGs are mounted to generate electricity, according to the researchers. Anchal and Saikhedkar (2015) conducted an experimental study on waste heat recovery for an internal combustion engine utilizing TEG. They discovered that at a speed of 1300 RPM and a load of 20 kg, the greatest quantity of heat transported away by hot exhaust gases was 2597.61 J/s. The maximum power obtained from the TEG module was 29.94 J/s when it was sandwiched between the hot and cold junctions and the engine speed was maintained at 1300 RPM with a load of 20 kg and cold-water flows at a temperature of 16 °C. Dongxu *et al.* (2017) investigated the use of thermoelectric generators in marine engines for waste heat recovery (WHR) (TEG). At various design and operational settings, they discovered that the TEG can collect 2–4 KW electrical power from exhaust gas. Deok- In and Hyung- Lee (2013) used a numerical simulation to look into the possibility of waste heat recovery utilizing thermoelectric generation with an internal combustion engine. In the exhaust system, physical factors such as exhaust temperature and mass flow rate were examined, and the best position for installing a thermoelectric generator (TEG) was established. Numerical analysis was used to determine the optimal position of the temperature distribution and TEG performance. The power output of the TEG increases dramatically with the temperature differential between the cold and hot sides, according to the experimental data.

According to Talape *et al.* (2016), employing a thermo-electric generator, a motorcycle exhaust system may provide power without modification (TEG). As a result, they adopted a simple square clamp approach that eliminated the requirement for a heat exchanger and simplified the design. They also stated that the energy generated by TEG from vehicle exhaust gas can be stored in a battery for later use. They believe that if their project is implemented on a wide scale, such as in the automotive industry, fuel consumption will be greatly decreased. According to Jinkyu *et al.* (2013), utilizing exhaust gas energy and converting it to mechanical or electrical energy can significantly enhance the efficiency of internal combustion engines. They installed a thermo-Electric Generator (TEG) in the exhaust system to take advantage of an energy flow between the hotter exhaust gas and the ambient air. The researchers discovered that the power output of a thermoelectric generator grows dramatically when the temperature difference between the cold and hot sides increases. Chandan *et al.* (2016) investigated the use of exhaust gas to drive the piston of an internal combustion engine and determined that an exhaust gas driven IC engine converts waste energy into usable work. They stated that an internal combustion engine's fuel consumption and exhaust pollutants were reduced significantly. The engine's fuel efficiency can be improved, and the valve timing can be better adjusted to extract more work each cycle. It is because the exhaust from the first and third cylinders becomes the entrance for the second cylinder, that better scavenging is possible. This improvement is a step toward engines that are greener, cleaner, and more fuel efficient. Tahani *et al.* (2018) explored the various waste heat resources in a 12-liter compression ignition engine, and then implemented two distinct Rankin cycle topologies for simultaneous heat recovery from the engine coolant and exhaust gases. They added that the power generated by these systems is converted to electricity and can be used to eliminate parasitic loads from the engine. Aranguren *et al.* (2018) stated that they developed a thermoelectric generator prototype that produced 21.56 W of net power (thermoelectric power minus auxiliary equipment consumption) on a 0.25 m2 (about 100 W/m^2) surface. The prototype was installed near the combustion chamber's exhaust and included 48 thermoelectric modules as well as two types of heat exchangers: finned heat sinks and heat pipes.

Migliaccio and Jankowski (2015) developed a system-level model for thermoelectric generator (TEG)-based vehicle engine exhaust waste heat recovery (WHR) and assessed the impact of using high effective thermal conductivity devices to load level the hot side of the TEG array spatially. They claim that load levelled WHR systems generate more power at a higher efficiency than standard WHR systems because TEG material qualities are particularly temperature sensitive. Rui *et al.* (2018) built an automobile exhaust thermoelectric generator (AETEG) into a prototype military SUV, analyzing its temperature distribution, output voltage, output power, system efficiency, and inner resistance, as well as testing several important influencing factors such as vehicle speed, clamping pressure, engine coolant flow rate, and ambient temperature on its output performance. They reported that higher vehicle speed, greater clamping pressure, quicker engine coolant flow rate, and lower ambient temperature all improved overall output performance, but ambient temperature and coolant flow rate were less significant. AETEG had a maximum output power of 646.26 W, with a conversion efficiency of 1.03 percent. Pohekar *et al.* (2018) gave a review of the current state of the art in exhaust waste heat recovery systems using thermoelectric generators (TEGs). When considering vehicle exhaust waste heat, they claimed that such systems provide direct heat-to-electric energy conversion and allow creating exhaust energy recovery systems without adding moving elements to the vehicle. Although pressure energy is connected with waste heat in internal combustion engine exhaust gases, little or no attempt has been made to save and utilise the pressure energy associated with waste heat in exhaust gases to generate electricity. In this regard Zubair (2022) developed a prototype engine that can use pressure energy of exhaust gas of gasoline generator to produce electricity. Nevertheless, the evaluation of the performance of the developed prototype engine is lacking in literature. Hence the aim of this research is to carry out the performance analysis of the developed prototype engine, with a view to ascertaining the feasibility of its usage.

MATERIALS AND METHODS

2.1 Materials and Equipment

The following materials and equipment were used to carry out the research.

i. A developed prototype engine by Zubair (2022) shown in Fig. 1. The prototype engine comprises of the following:

- Single phase ELEPAQ Gasoline generator with the following specifications;
  Model no = SV7800E2
  Rated voltage = 230V
  Rated frequency = 50Hz
  Rated output = 2.5KVA
  Maximum output = 2.8KVA
- Turbine
- Ki Tech. Alternator having the following specifications
  Model no= LBDC24Z45-954
  Output power = 100W
- SK Bridge Rectifier having the following specification;
  Diode = 5amps
  Capacitor = 4800microfarad
  Voltage= 35V
- Two pieces of 12V battery

ii. Pressure gauge.
iii. K-Type Digital Thermocouple
Range: 0- 1300^{0}C
Model no= C900FK02-M-AN
iv. CE Contact/Surface speed digital Tachometer
Model no = DT-2235B+ S417108
v. CE Digital Multimeter

Model no= DT 9205A

Fig. 1. The developed prototype engine by Zubair (2022)

2. Experimental Procedure

The gasoline generator of the prototype engine was run on the speed of 1000, 2000, 3000, 4000 and 5000rpm. The speed of the gasoline generator was varied to see how different speeds will affect the exhaust flow characteristics that determine the prototype engine's developed power. The pressure of exhaust gas passing through the prototype engine was measured using Hannu (2007) and Abhisket *et al.* (2017) techniques, with a pressure gauge installed after the turbine to the exhaust gas flow line. Another pressure gauge was installed at the turbine intake to measure the inlet pressure of the exhaust gas flowing into the turbine, and another at the muffler outlet to measure the pressure of exhaust flow through the muffler. The average pressure of exhaust gas flow through the prototype engine was determined by averaging the results of the three pressure gauges attached to the engine. After evaluating the change in piezometric head, using equation (1), the velocity of flow of the exhaust gas in each section of the prototype engine where the manometers were fitted were evaluated using equation (2).

$$\Delta h = \left(\frac{\rho_m}{\rho_e} - 1\right) h \qquad (1)$$

Where Δh is the change in piezometric head, ρ_m is the density of the manometric fluid, ρ_e is the density of the exhaust gas and h is the manometric deflection. After evaluating the change in piezometric head, the velocity of flow of the exhaust gas in each section where the manometers were fitted were evaluated using the expression stated as

$$V = \sqrt{2g\Delta h} \qquad (2)$$

The exhaust gas temperatures were measured by Type-k thermocouples. This was achieved by inserting one thermocouple probe into the exhaust pipe before the turbine to obtain initial temperature of the exhaust gas and second thermocouple probe was inserted into the exhaust pipe after the turbine and the third thermocouple was inserted in the tail pipe of the exhaust that is after the muffler to measure the outlet temperature of the exhaust gas. The speed of the turbine of the prototype engine was measured with Tachometer and the current and voltage generated were measured with multimeter and the product of measured current and voltage were evaluated to get the generated power by the prototype engine. All the measurements were carried for five minutes for a period of thirty minutes and average values were considered. Type-k thermocouples were used to measure the exhaust gas temperatures. This was accomplished by inserting one thermocouple probe into the exhaust pipe before the turbine to obtain the initial temperature of the exhaust gas, a second thermocouple probe into the exhaust pipe after the turbine, and a third thermocouple probe into the exhaust pipe after the muffler to measure the exhaust gas outlet temperature. The prototype engine's turbine speed was measured using a tachometer, and the current and voltage generated were measured with a multimeter, and the product of the recorded current and voltage was analyzed to determine the engine's generated power. For a period of five minutes, all measurements were carried out and average values were considered. The efficiency of the prototype engine was evaluated using the relation stated by Xu *et al.* (2021) as

$$\eta_{PE} = \frac{P_e + P_t + P_g}{M_e H_u} \qquad (3)$$

where,
P_e is the effective power of the generator (Elepaq generator) (W)
P_g is the output power of the alternator (Dynamo)(W)
M_e is the mass fuel consumed in unit time (Kg/s)
H_u is the calorific value of gasoline used (J/Kg)
P_t is the output power of the turbine(W)
And P_t was evaluated using equation given by Nonthakarn et al. (2019) as;

$$P_t = G_s \times l_o \times \eta_t \qquad (4)$$

Where, G_s is the intensity of exhaust gas flow, η_t is the isentropic efficiency of the turbine which is typically between 70-90% (Nuclear power for everybody, 2021) and l_o is the theoretical work by energy per mass of exhaust gas which is expressed according to Nonthakarn *et al.* (2019) as;

$$l_o = \frac{K_1}{K_{1-1}} \times \ R_{sp} \times \ (T_{S'} - T_S) \qquad (5)$$

Where K_1 is the value of adiabatic exhaust gases, R_{sp} is the constant value of the exhaust gases relative to the gas constant to the molecular weight of the exhaust gas. T_s is the temperature of exhaust gases flowing into the turbine and $T_{S'}$ is the temperature of exhaust gases flowing out from the turbine.

RESULT AND DISCUSSION

The variation of the power generated by the prototype engine with the velocity of its exhaust gas is shown in Fig. 2.

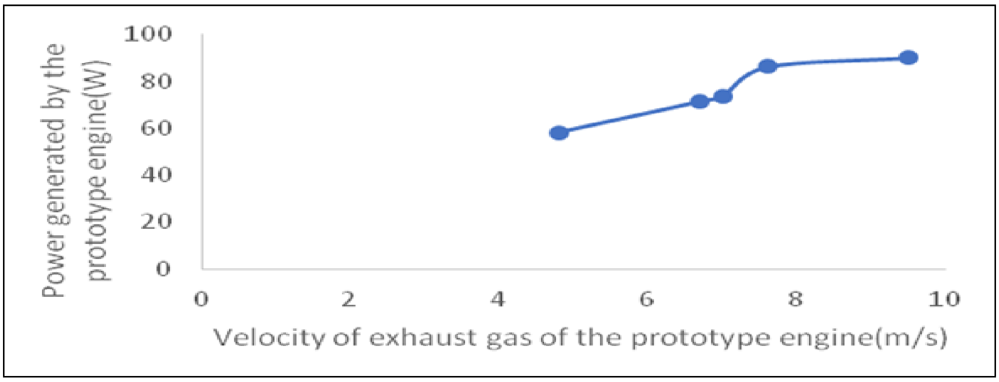

Fig. 2. Variation of power generated by the prototype engine with the velocity of exhaust gas of the prototype engine

It can be seen from Fig. 2, that as the velocity of exhaust gas from the prototype engine increases, power generated by the prototype engine increases. This trend is similar to the trend of results of Guduru (2015). Moreso this observation collaborated the observations of Kiran *et al.* (2019) in his work which showed that there is a remarkable trend of increase in the output power with regard to increase in flow rate of exhaust gases. This is because as more gases impact on the turbine blades, the speed of rotation of the turbine increases, giving a higher power output in this case power generated by the prototype engine. Maximum power of 90.2W and minimum power of 58.1W were generated by the prototype engine at exhaust gas velocities of 9.5m/s and 4.8m/s respectively. The variation of power generated by the prototype engine with its exhaust gas backpressure is depicted in Fig.3.

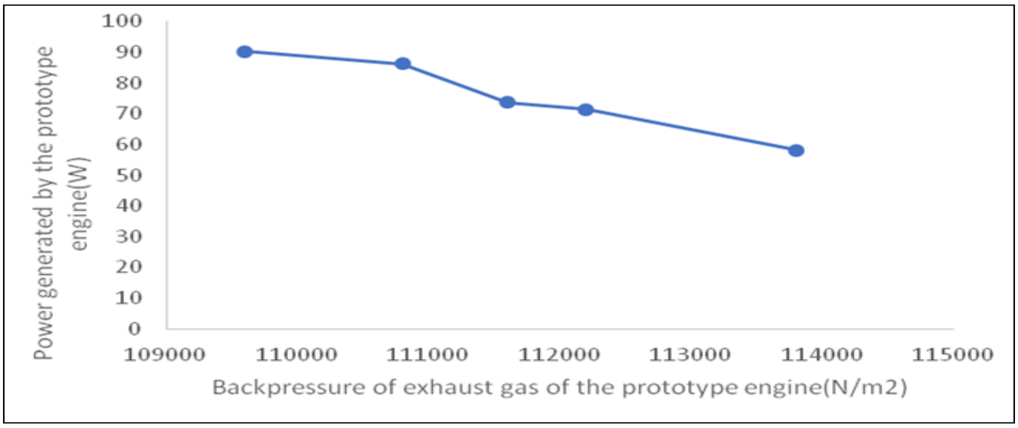

Fig. 3. Variation of power generated by the prototype engine with its exhaust gas backpressure

It can be seen from Fig.3, that as back pressure of the prototype decreases, the power generated by the prototype engine increases. Maximum power of 90.2W and minimum power of 58.1W were generated by the prototype engine at backpressures of 109600 and 113800N/m² respectively. Fig. 4 shows the variation of power generated by the prototype engine with its exhaust gas temperature.

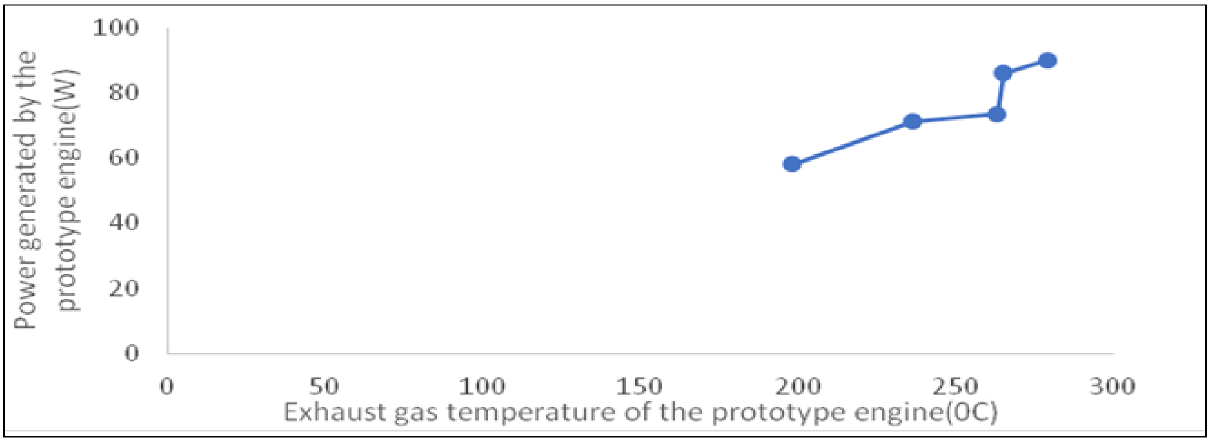

Fig. 4. Variation of power generated by the prototype engine with its exhaust gas temperature

It can be seen from Fig. 4, that as the exhaust gas of the prototype engine increases the power generated by the prototype engine increases. According to Lungu *et al.* (2021) based on his work remarked that as exhaust gas temperature increases, the power and torque of an engine also increases. Maximum power of 90.2W and minimum power of 58.1W were generated by the prototype engine at exhaust gas temperatures of 279⁰C and 198 ⁰C respectively. The variation of power generated by the prototype engine with generator speed is shown in Fig. 5.

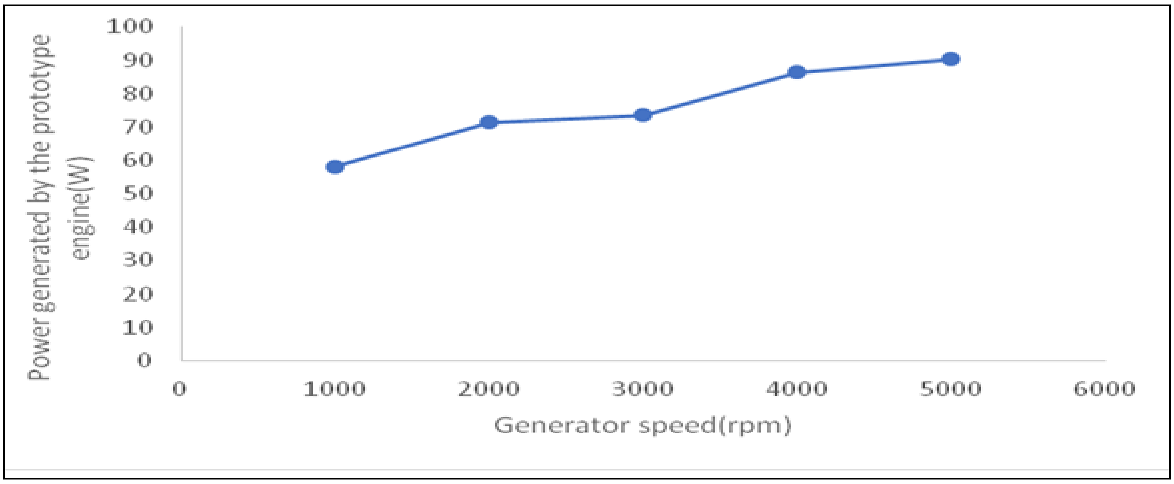

Fig. 5. Variation of power generated by the prototype engine with generator speed

It can be seen from Fig. 5 that as the generator speed increases the power generated by the prototype engine increases. This finding is line with the finding of Kiran *et al.* (2019) in their works. The authors remarked that the increasing trend in power generated as the engine speed increases is because the flow rate of exhaust gases is proportional to the engine speed, which increases the power output of the turbine. The prototype engine generated the least power of 58.1W and greatest power of 90.2W at the generator speed of 1000 and 5000 rpm respectively as evident in Fig. 5. The variation of power generated by the prototype engine with generator load is shown in Fig. 6.

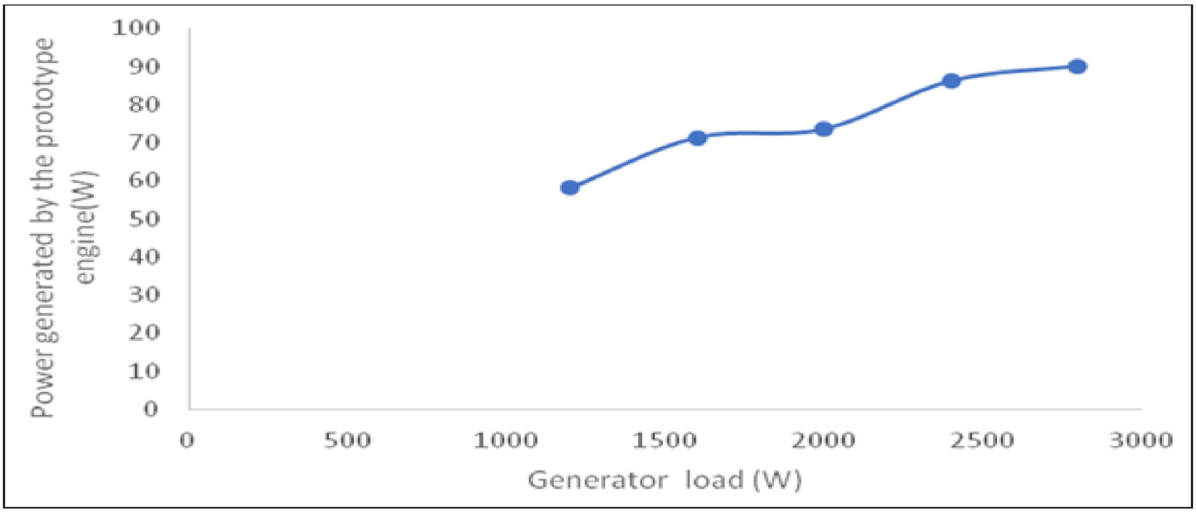

Fig. 6. Variation of power generated by the prototype engine with generator load

It is evident in Fig. 6 that as the generator load increases, the power generated by the prototype engine increases. As the generator load increases, there is corresponding increase in flow rate of the exhaust gases. According to Kiran *et al.* (2019), this is a result of more gases impacting the turbine blade and the speed of the turbine increases thereby making the porotype engine to generate high power. The prototype engine generated the least power of 58.1W and greatest power of 90.2W at generator loads of 1200 and 2800W respectively as seen from Fig. 6. The variation of power generated by the prototype engine with its turbine speed is shown in Fig. 7.

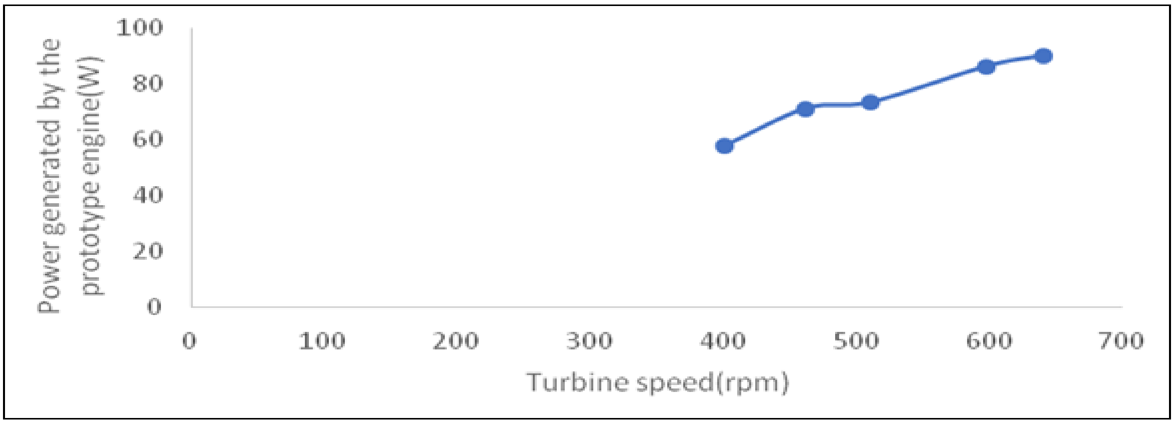

Fig. 7 Variation of power generated by the prototype engine with its turbine speed

It can be seen from **Fig.7** that as the turbine speed increases, the power developed by the prototype engine increases. This trend is line with the trend of result obtained by Shaikh *et al.* (2017) and Guduru and Ipak (2015) in their works. The aforementioned authors remarked that the power generated is directly proportional to the speed of the turbine. Minimum power of 58.1W and maximum power of 90.2W were developed by the prototype engine at turbine speed of 401 and 640 rpm respectively as evident in **Fig.7.** The variation of prototype engine turbine speed with generator speed is shown in Fig. 8.

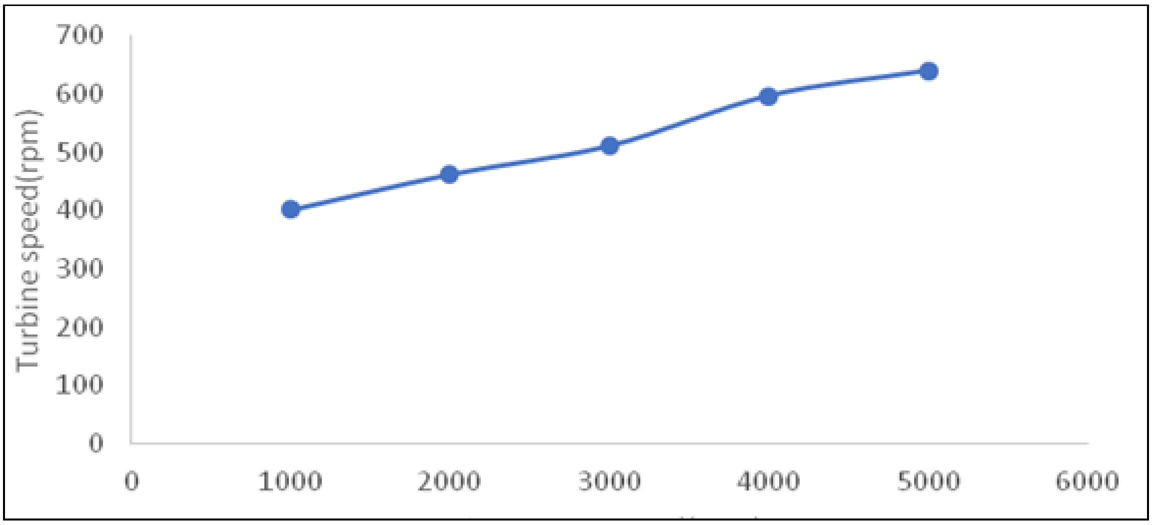

Fig. 8 Variation of prototype engine turbine speed with generator speed

It can be seen from Fig. 8 that as the generator speed increases, the turbine of the prototype engine speed increases. This observation is in line with the observation in the works of Hountalas *et al.* (2012). When the generator speed was 1000rpm the turbine attained the speed of 401rpm and when the generator speed was 5000rpm, the turbine attained its maximum speed of 640rpm as evident in Fig. 8. The variation of the efficiency of the prototype engine with generator speed is shown in Fig. 9.

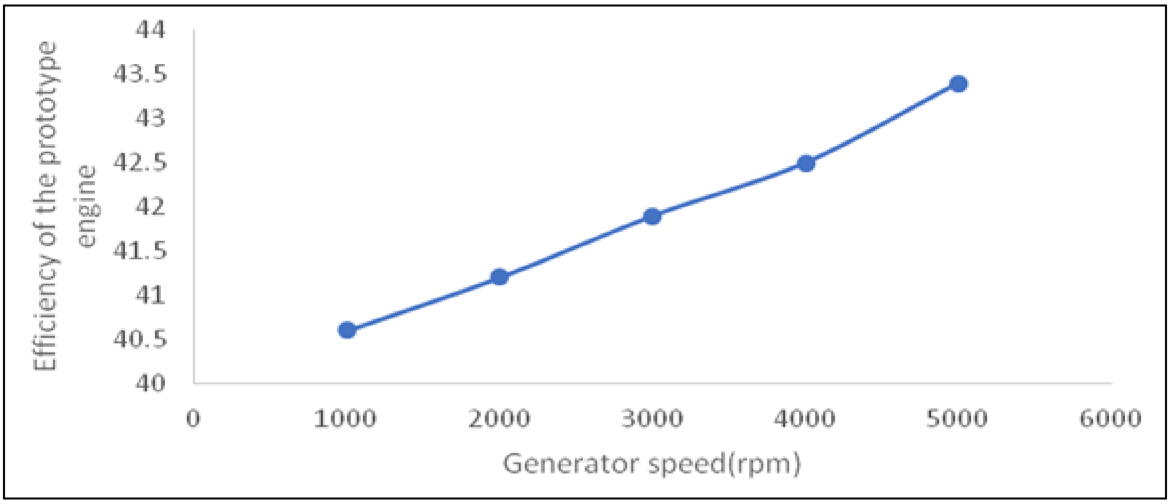

Fig. 9 Variation of the efficiency of the prototype engine with generator speed

It can be seen from Fig. 9 that as the generator speed increases that is from 12000rpm to 5000rpm, the prototype engine efficiency increases from 40.6 % to 43.4%. The maximum efficiency of the prototype engine was found to be 43.4% at the generator speed of 4000rpm. This trend of observation is somewhat similar to the one observed by Xu *et al*. (2021) in their research where they obtained maximum efficiency of 42.8% at engine speed of 3000rpm. The increase in efficiencies of the prototype engine and the one developed by Xu *et al*. (2021) is as result of more power output of the turbine and the alternator of the engines. The prototype engine and the one created by Xu *et al*. (2021) have higher efficiency as a result of the turbine and alternator of the engines producing more power.

CONTRIBUTION TO KNOWLEDGE

The study established the efficacy of employing the designed porotype engine to generate electricity using the pressure energy of gasoline generator exhaust gas, which is frequently wasted.

CONCLUSION

From the study, it has been identified that there are large potentials of energy savings through the use of pressure energy recovery technologies. Waste pressure energy recovery entails capturing and reusing the waste pressure energy from internal combustion engine and using it for electricity generation. On the basis of the overall result and in line with the stated aim of this research, the following conclusions can be made. The exhaust gas velocity and temperature increase with increase in generator speed and load for the prototype engine. The power generated by the prototype engine and the prototype engine efficiency increase with increase in exhaust gas velocity, temperature and turbine speed. It is highly feasible to use pressure energy associated with exhaust gas of gasoline generator and internal combustion engine in general, to generate electricity.

CONFLICT OF INTEREST

There is no conflict of interest for this research work.

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