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Research paper

Performance of Free-Piston Linear Generator by Using Compressed Air

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Abstract

Free-piston linear generator (FPLG) engine combines a linear engine coupled to a permanent-magnet assembly. High Pressure UTP FPLG engine was invented as a new source of green power generation. The working principle of expansion of compressed air in a two-stroke dual piston engine was used to convert kinetic energy into electrical energy via electromagnetic induction. Electric power generated directly from the moving piston-rod-magnet assembly forced by the expansion of compressed air. Excess electricity from renewable energy sources can be converted into energy stored as compressed air. The expansion process of compressed air in the power stroke is examined by varying the parameters such as air injection supply pressure, valve injection timing and air flowrate. It was observed through expeimentally higher supply pressure gives higher power generation but results in lower efficiency.

Keywords: *Free-piston linear generator; power generation; kinetic energy; electrical energy; electromagnetic induction.*

1. Introduction

Renewable energy sources grew strongly in recent years. From a discussion in World Energy Outlook 2016, there will be 37% of power generation from renewable sources in 2040 compared with 23% in 2016. The excessive electricity from these renewable sources is stored in energy storage. In Denmark, a Compressed-Air-Energy-Storage (CAES) has been proposed to utilize the excess electricity and control the fluctuating level wind-production [1]. In this project, a linear generator engine (Figure 1) is based on a free- piston engine where it is crankless and freely moves inside two chambers. It has no mechanical output and has less friction due to the absence of side load to the piston skirt. The simple design with fewer parts makes it less costly, less maintenance and makes it more reliable. Due to its compact design, it has a high power to weight ratio [2]. The objectives of the project are to study the performance of FPLG engine by expansion of compressed air in the power stroke and to analyze the results obtained in term of power generation and engine efficiency by varying parameters such as supply pressure, injection valve timing and air flowrate.

The prototype is composed of two crucial parts which are the linear engine and linear generator. There are three main assembly of the engine which is the piston-rod assembly, the stator and permanent magnet assembly and the chamber assembly. The piston-rod assembly, which encompasses two pistons where one connected to each end of the rod. The chamber assembly consists of one cylinder liner, one cylinder holder and one cylinder head at each part. The permanent magnet is located at the translator shaft which is made of stainless steels with a Quasi Halbach arrangement while the stator consist of four coils of silicon steel laminations in set of coil bracket is located at the center of the engine. Sensors such as pressure transducer, linear position sensor and fast switching solenoid valves attached to record and analyse experimental data.

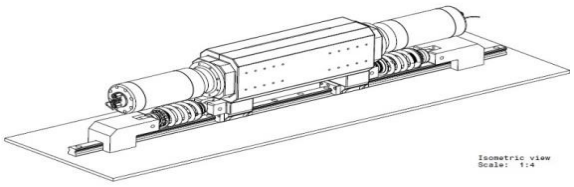


Fig. 1: UTP two-stroke High Pressure FPLG engine prototype

The prototype shown in Figure 1 has a working principle of two-stroke engine where exhaust and intake stroke is completed within 1 cycle and the compression and power stroke is 1 cycle. The expansion of compressed air in the power stroke is used to generate electricity. Compressed air with specified pressure value is injected into the chambers through pneumatic fitting air inlet so the expansion energy of the compressed air in the chamber pushes the piston back and forth. The magnetic field from the moving translator cuts the magnetic fields of the coils externally placed in the middle section of the engine to produce electricity as shown in Figure 2 and Figure 3.

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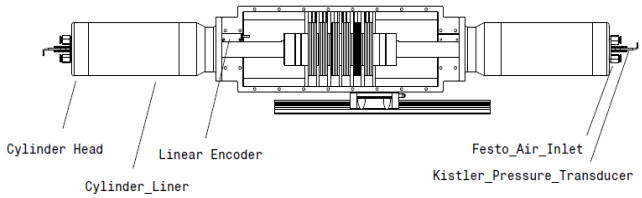


Fig. 2: FPLG front view cross-sectional view

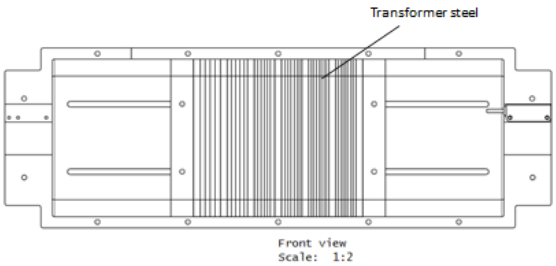


Fig. 3: FPLG front view of middle component with transformer steel

Several developments have been done regarding free-piston engines with compressed air as the working fluid. A new small-scale Free Piston Expander (FPE) engine that operates using low temperature waste heat sources to produce electrical power output [3]. It is based on sliding-piston design. The parameters varied for the FPE engine cycle are piston mass external load and heat input to identify conditions and trends of optimum performance. Its basic design is based on the concept of mechanical or electrical power output from an external thermal source.
It is a sliding expander type of mechanical work. The results from this FPE are shown in Table 1 below. The thermal efficiency is low due to small heat input and operating temperature gradients associated with waste heat. It was revealed that the key design features that reveal the FPE efficiency and power output are dependent on piston mass, external load, input heat-rate and duration of heat input.

Table 1: Output power for various loading condition for fixed input heat

Piston mass (g)	Efficiency (%)	Operating freq. (Hz)	Output power (mW)
0.34	0.13	102.1	137
0.68	0.15	99.2	145
1.02	0.16	93.4	148
1.36	0.17	85.7	146
1.70	0.18	79.0	141
2.04	0.19	73.5	138
2.38	0.20	68.9	134
2.72	0.20	65.0	130
3.06	0.21	61.7	127
3.40	0.21	58.8	123

An experimental study of an oil-free steam piston expander for micro-combined heat and power systems was conducted by Bouvier et al. [4].This study describes the performance of an oil-free steam piston expander. This expander produced electrical power between 740 and 2400W with a significant range of supply temperature between 260 and 340 degree Celsius and pressure between 20 and 34 bar. In the single-cylinder steam expander, there are four phases been identified which are compression process, intake process, expansion process and exhaust process. The first process which is the intake stroke, the intake valve is opened and steam enters into the expander. Next, the expansion stroke where the intake valve is closed and the fluid start to expand. Here, the pressure is high. Then, the exhaust valve opens during the exhaust stroke while the steam exits the expander causing the decreasing of pressure. There is still part of the fluid trapped inside the cylinder after the exhaust valve is closed and it is compressed again in the next cycle. From the expander, the results also show that higher supply pressure gives higher overall efficiency. This study also gives the result of the expander overall isentropic efficiency including electrical generator efficiency was between 19% and 40%.

The compressed air technology (CAT) is used to control the movement of the second generation pistons and single crankshaft [5]. The pistons work in two phases which are the first is motor phase and the other one is intermediate phase of either compression or expansion. The engine consists of 4 two-stage pistons where four compression and four expansion chambers. This engine has two functions which are to compress ambient air and refill in the air storage tanks and also to make it successive by approaching isothermic expansion. In India, a company TATA has invented a compressed air technology with a Mini CAT car which is operated by compressed air concept.

2. Methodology

Two set of experiments were conducted. Firstly, one valve with 4,6 and 8 bar of injection pressure experiment and secondly two valves with 4,6 and 8 bar experiments. A control and data acquisition (DAQ) system based on National Instrument (NI) hardware and software is used to control the injection supply pressure timing and to log data during experimentation (Figure 5). The setup for the experiment includes the compressor, pressure regulator, air receiver tank, FPLG engine, NI control system and a host PC. The compressor and air receiver tank is prepared to give supply pressure to the FPLG engine. All the fittings required is fulfill and set up before the experiment is run. A pressure regulator was placed at both compressor and air receiver tank to control and maintain supply pressure to FPLG. Before the experiments were run, numerous tests were done to determine the optimum injection timing (valve timing) which gives the best injection timing for the piston to reach the maximum displacement of the piston travel in the cylinder. The Host PC is connected to the control system to control the prototype. The controller constist of a National Instrument cRIO which all input and output signals are controlled and logged. The data collected is further analysed in Microsoft Excel. Several cycles for each run of experiments was conducted and average cycle was determined and was used for further analysis. The analysis was focused on single side of the cylinder, which is the left cylinder as the assumption of both side of the cylinder gives same results in term of P-V diagram. Six experiments gives several P-V diagram constructions and same pattern was obtained.

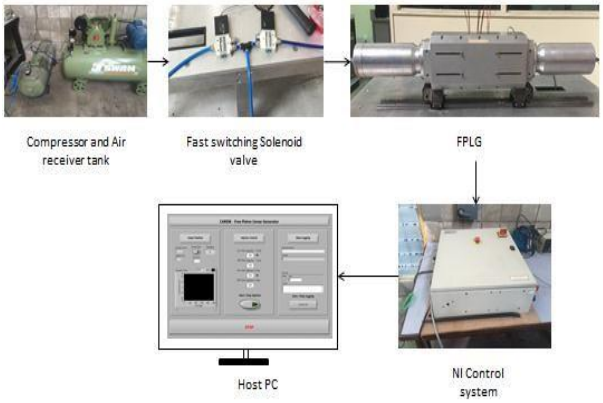


Fig. 4: Experimental setup for FPLG

3. Results and Discussion

Experiments for 8 bar pressure with different flowrate which is with one valve and two valves was conducted and shown in Figure 6. The graph start with zero pressure where the piston is at far left means at its TDC position and the pressure increase by the injection of compressed air and reach the peak pressure while at the same time the expansion moves the piston to the far right means at its BDC position. Then the valve is closed and pressure starts to drop. It can be seen that the piston move earlier and reach pressure at 1.3 bar earlier for two valves compared to one.This

indicates higher flowrate pushes the piston faster as the peak pressure develop faster.

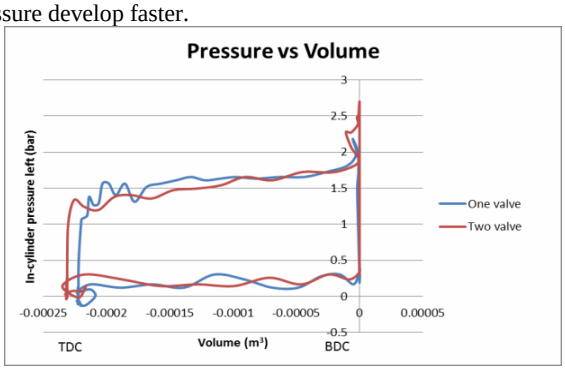


Fig.6: P-V diagram of 8 bar pressure with different flowrate

A comparison of injection pressure for two valves experiment can be seen in Figure 7 where the highest injection pressure which is at 8 bar shows the highest peak pressure and have higher volume difference determined by the area under the graph. The graph constructed is not in a smooth line due to pressure wave in the cylinder as there were still pressure from the another side during the expansion in the left side of the cylinder. The area of the diagram represents the net work output of the engine. As being calculated, the highest net work output is produced from the two valve with 8 bar of pressure at approximately 36 Joule (J).

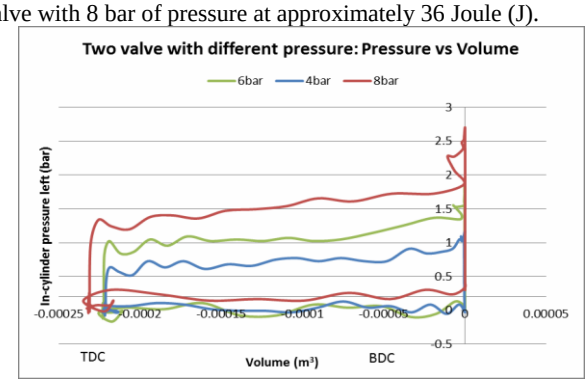


Fig. 7: P-V diagram of two valve with different pressure

A velocity profile is constructed for one complete circle including the negative values to determine when the highest velocity is. The velocity profile shown in Figure 8 is for the two valve with different pressure experiment. It was observed that 8 bar pressure gives the highest velocity due to higher flowrate and higher pressure. When pressure is higher, there is more air coming into the cylinder and this gives faster speed thus significantly more power output generated. Beginning of the cycle, the curve has greater gradient as the piston accelerated rapidly and then decelerated slowly over the rest of the cycle.

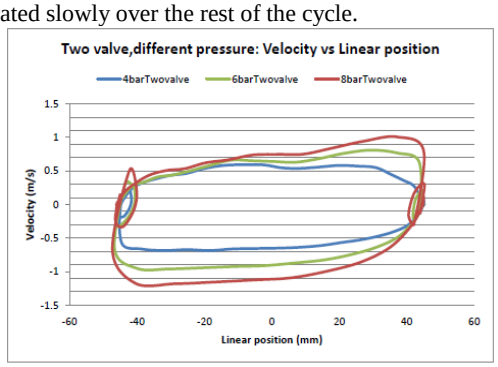


Fig. 8: Velocity profile of two valve with different pressure

Current generated versus piston displacement is constructed in Figure 9 from the two valve with different pressure experiment. The graph apparently shows sinusoidal wave as the generator produced alternating current (AC). It was once again observed that 8 bar pressure gives higher current compared to 6 bar and 4 bar pressure. The same trend can be seen in Figure 10 which shows the voltage versus linear position. 8 bar pressure gives the higher peak of voltage compared to 6 bar and 4 bar pressure.

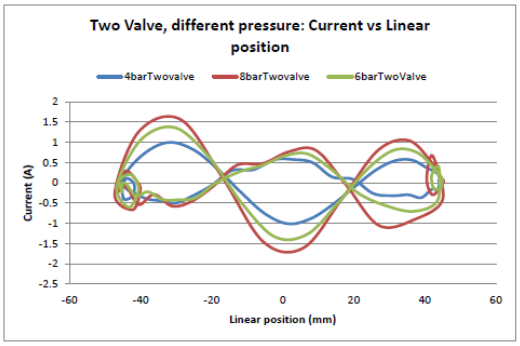


Fig.9: Current profile of two valve with different pressure

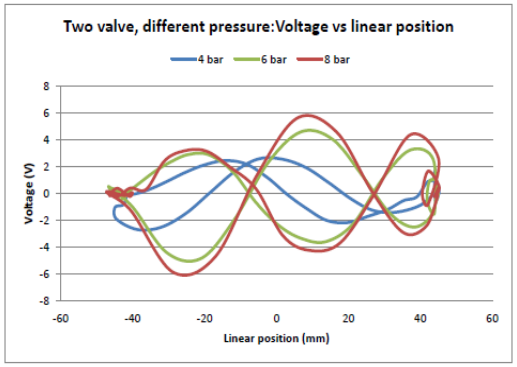


Fig. 10 : Voltage profile of two valve with different pressure

It was also observed in Figure 11 which is the graph of velocity and power output versus linear position. The highest velocity is gained at the peak of power generated. According to the equation of brushless motor, which is E=Kv x V, where E=electromagnetic force, emf (voltage), Kv = motor constant and V = Velocity; it is proved that higher velocity gives higher voltage.

The power output and efficiency is calculated from the formula in the Microsoft Excel. The calculated data is shown in Table 2 below. It was observed that the highest power generation is achieved from 8 bar pressure with two valve inlet. This means higher pressure gives higher power output. The hypothesis is not reliable for the efficiency part as the maximum efficiency of the FPLG is achieved at 4 bar of pressure with two inlet valve instead of 8 bar pressure with two valve inlets. This is because of the compatibility of air pressure inside the chamber. It is optimum desirable condition for 4 bar pressure with two valve inlet as the air inside the chamber is less compact and the pistons have to travel more to expand the air inside the chamber means the required work input is higher thus produced less work output while for 6 bar of pressure, as the air inside the chamber is more compact for the expanding of air, it gives higher required work input and deliver greater work output. But it is different for 8 bar of pressure as the air inside the chamber is too compact and this situation cause back-pressure that disrupts the system of expansion process and the required work input and work output is higher which yields lower efficiency.

From below graph (Figure 12), it can be seen that power output generated is directly proportional to the supply pressure while the efficiency is inversely proportional to supply pressure.

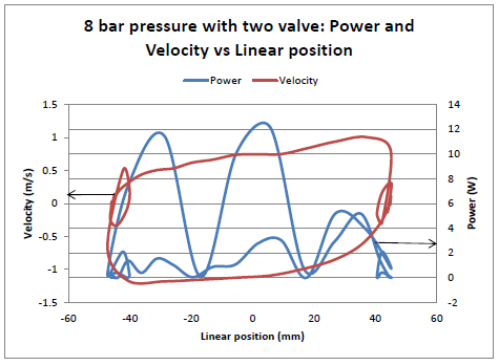


Fig. 11: Velocity and power output as function of linear position for 8 bar pressure with two valve

Table 2: Power output and efficiency calculated data

	One Valve		Two valves	
Press (bar)	Power Output (W)	Efficiency (%)	Power Output (W)	Efficiency (%)
4	34.7	1.21	41.0	1.29
6	50.7	1.02	59.5	1.23
8	58.9	0.83	79.7	1.10

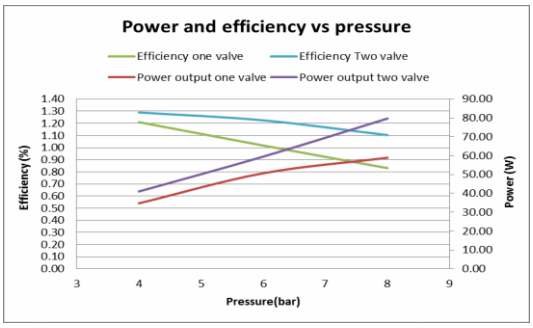


Fig.12: Efficiency and electrical power output as function of supply pressure

The engine was also test with transformer steel. A set of transformer steel is installed in the middle of the engine by replacing the use of Perspex as shown in Figure 4. This is done to improve the magnetic flux of the circuit. With this transformer steel, the loss of magnetic flux can be reduced by the permanent magnet as the magnetic flux is concentrate to the transformer steel. One experiment of 8 bar pressure with two valve is conducted to observe the results for the upgrade changes. The configuration of transformer steel is slotted as there are arranged with small and larger round of transformer steel. There was cogging effect determined for this experiment. The cogging effect is called cogging force which is produced due to the static interaction between the permanent magnet on the translator and the iron core of the stator. This cogging force applies in opposite direction to the translator motion (Ibrahim, 2012). This result in torque as well as speed ripple. It is prominent at lower speeds with the symptom of jerkiness but at high speed but at higher speed the motor moment of inertia filters out the effect of cogging torque. The magnitude of the magnetic cogging force is either assisting or opposing the motion of the piston depending on its position of the piston. This testing result in higher power output generated which is 782.5 W, higher than the project's experiment (previous results). From the P-V diagram constructed in Figure 13, it was observed that the pattern of the graph is same but the peak pressure is much higher. The position of graph constructed is not aligned with position as the findings of the linear generator assembly were not aligned with center of engine. There is same pattern for next few graphs constructed in this section.

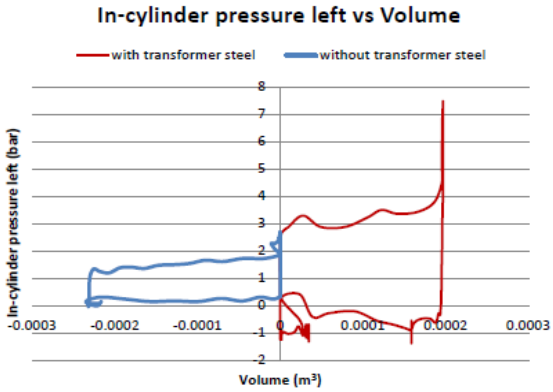


Fig. 13: P-V diagram for both experiments with and without transformer steel

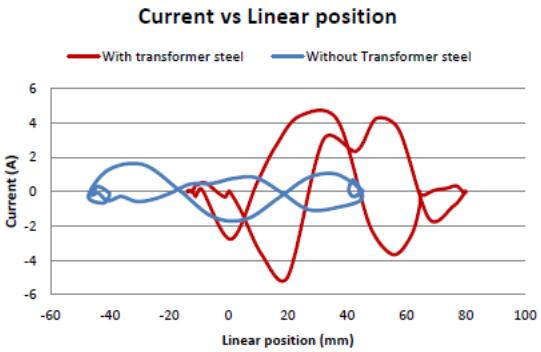


Fig. 14: Current profile for both experiments with and without transformer steel

It also contributes to the same results for the velocity and current profile. Higher peak velocity and higher peak current and power output were obtained compare to previous result without transformer steel as shown in Figure 14. This graph shows the power output and velocity versus linear position of the piston. From this graph, the relationship between power and velocity can be determined. The velocity increasing at the middle position of the motion of the piston as the cogging force enhances the motion of the piston.

Different position of piston has different magnitude of cogging force. As the velocity increase, the power increase. This can be relating to the equation of brushless motor. The use of the transformer steel helps in improving the motor constant value. It can be seen that with this upgraded changes, better performance of the engine is achieved. The efficiency for the testing was the highest among all of the experiments which is 5.43%.

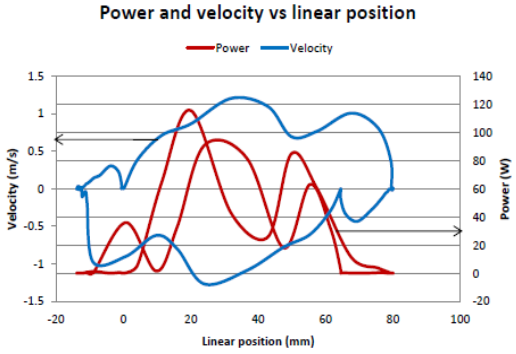


Fig. 15: Power output and velocity as function of linear position for experiment with transformer steel

4. Conclusion

This research is performed by optimizing the injection supply pressure and flowrate of compressed air to obtain optimum FPLG performance. It was observed that the highest power generation is achieved by employing 8 bar of pressure with two inlet valve. However, the maximum efficiency of the FPLG is achieved at 4 bar of pressure with two inlet valve. Further experimentation of the FPLG with the use of transformer steel might improve the performance of the engine.

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References

[1] A.K. Mohanty, A. Wibowo, M. Misra and L.T. Drzal, "Effect of process engineering on the performance of natural fiber reinforced cellulose acetate biocomposites," Composites Part A (35), 363-370 (2003).

[2] C. Baley, "Analysis of the flax fibres tensile behaviour and analysis of the tensile stiffness increase," Composites Part A (33), 939-948 (2002).

[3] B.V. Van Voorn, H.H.G. Smit, R.J. Sinke, B. de Klert. "Natural fibre reinforced sheet moulding compound". Composites: Part A (32), 1271-1279 (2001).

[4] K. Diharjo, "The Effect of Alkali Treatment on Tensile Properties of Random Kenaf Fiber Reinforced Polyester Composites," Part III of Doctorate Dissertation Research Result, Post Graduate Study, Indonesia (2005).

[5] T. Nishino, K. Hirao, M. Kotera, K. Nakamae and H. Inagaki. "Kenaf reinforced biodegradable composite," Composites Science and Technology (63), 1281-1286 (2003).

[6] L. Wang and Y. Han, "Compressive relaxation of the stress and resistance for carbon nanotube filled silicone rubber composite", Composites Part A (47), 63–71 (2013).

[7] J. N. Coleman, U. Khan, W. J. Blau, Y. K. Gun'ko, "Small but strong: a review of the mechanical properties of carbon nanotube–polymer composites", Carbon, (44), 1624 (2006).

[8] M. K. F. Md Radzi, A. B. Sulong, N. Muhamad, M. A. Mohd Latiff, & N. F. Ismail, "Effect of Filler Loading and NaOH Addition on Mechanical Properties of Moulded Kenaf/ Polypropylene," Tropical Agricultural Science, (38), 583–590 (2015).

[9] R. Muthuraj, M. Misra, F. Defersha, AK. Mohanty, "Influence of processing parameters on the impact strength of biocomposites: A statistical approach", Composites Part A (83) 120-129 (2016)

[10] H. Raghu, S. Bose and P.A. Mahanwar, "Effect of Particle Size of Filler on Coloration and Properties of High Density Polyethylene," Journal of Mineral and Materials characteristics and Engineering (5), 87-100 (2006).

[11] H. Ismail, A. Suryadiansyah, "Effects of Filler Loading on Properties of Polypropylene–Natural Rubber–Recycle Rubber Powder (PP-NR-RRP) Composites," Journal of Reinforced Plastics and Composites (23) 639-650 (2004).