

The Performance Characteristics of a Hydrogen Fuelled Free Piston Engine and Linear Generator System

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ABSTRACT: A power generation system which utilizes a hydrogen fuelled free piston engine and a linear generator is under development. Free piston engine gives power output more efficiently compared to conventional reciprocating piston engines, because it doesn't have a crank mechanism which brings out mechanical loss. In addition, if hydrogen fuel is used in a free piston engine, it would be possible to make exhaust emission level almost zero without sacrificing the efficiency. In this study, a prototype free piston engine, two-stroke twin cylinder engine, was developed and a linear generation system was incorporated in between the cylinders to get the electricity and the start of the engine, as well. It was possible to operate the engine at a velocity of 17Hz. The free piston engine was found to give different piston positions at TDC (Top dead center) and this irregular piston movement affected significantly both the compression process and the subsequent combustion of the other cylinder of the engine at the same time. Both CNG (Compressed natural gas) and hydrogen were supplied to the test engine and the results showed different combustion characteristics with the fuels used. Since the scavenging efficiency easily gets worse in such low speed operation of the two-stroke engines, hydrogen fuel has been found to give higher burn rate and resultantly to show improvements in power output and the emissions.

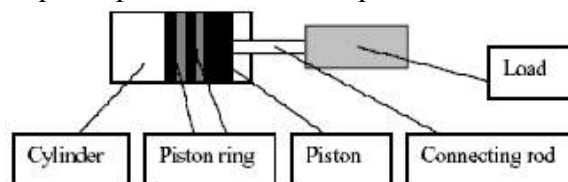
Keywords: Hydrogen, Free piston engine, Generator, Two-stroke engine, Scavenging efficiency

1. INTRODUCTION

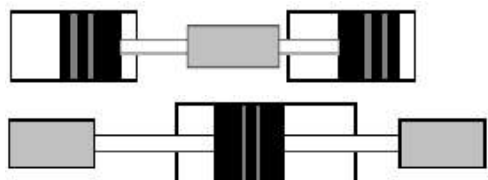
Free piston engines (FPEs) are combustion engines, which piston motion is not restricted by any mechanical linkages while conventional engines have slider-crank mechanism to produce shaft work. The FPEs can be divided into three categories according to number and location of the pistons as shown in Fig. 1[1].

The basic operation principle is similar i.e. the chemical energy of the fuel is transformed into mechanical energy by means of linearly moving piston assembly. The main design concept is to utilize minimum amount of energy transformations from fuel's energy into electric[2~7] or hydraulic[8~10] energy, which is used by linear generators or hydraulic actuators. A

two-stroke engine is usually used because it requires power stroke once per each stroke.



(a) Single piston



(b) Dual piston



(c) Opposed piston

Figure 1: Various free piston configurations [1]

There are some advantages over the conventional crankshaft engine which could be achieved by the free piston concept.

The power density of the FPE is higher than the crankshaft engine since it requires less weight and less space due to the structural simplicity. The friction losses are lower because of fewer parts and piston has no side forces, which are induced by crank mechanisms.

The free piston configuration allow the stroke length or compression ratio almost instantaneously, cycle-by-cycle variable and reliable compression ratio control enables the optimization of the compression ratio in different operation conditions, which is not possible with conventional crankshaft engines. Thus, a variety of alternative fuels can be applied to the engine without major hardware modifications[2, 7, 8].

In addition, the FPE offers some inherent efficiency and cold start emissions benefits during engine startup. Its small mechanical inertia and ability to achieve its target speed almost on the first piston stroke, against a

lower friction, make startup transients comparatively short and more efficient[8].

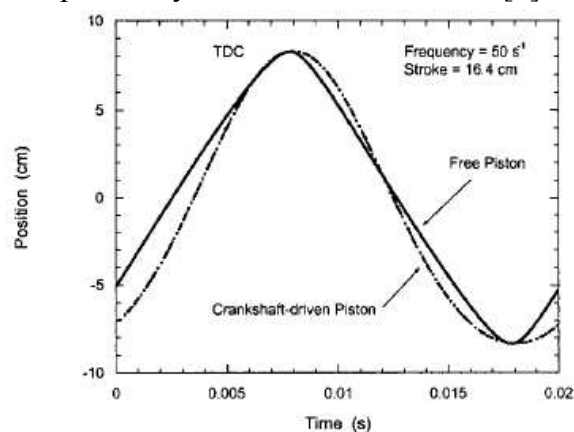


Figure 2: Piston position vs. time [2]

Goldsborough et al. indicated that with the same stroke and piston frequency, there are some differences between the piston motions from a free piston engine and a crankshaft driven engine. As shown in Fig. 2, the free piston spends less time at TDC (Top dead center) relative to the crankshaft-driven piston. This shorter residence time at TDC for the free piston could be attractive in terms of heat transfer losses and NO_x formation since shorter time at higher temperature is desirable[2].

The last but not least benefit is the price of the engine and the production costs are much lower in the FPE because of its simple design.

The lack of crank mechanism creates some disadvantages as well: the control system have to be more complicated than in the conventional engines. The compression ratio is indefinite and it depends on the energy balance of the piston in each stroke. The low emission level and efficient burning require controlled piston motion.

For a FPE generation system to be commercially available, it is strongly demanding to show high efficiency and stable operation apart from the low cost benefit. In this study, a prototype of a free piston engine and a linear generator were operated to evaluate the performance to get higher efficiency and lower emissions than the conventional generation systems.

2. EXPERIMENTAL SETUP

The test engine has dual pistons and consists of two opposite combustion cylinders with an integrated linear alternator in between (see Fig. 3). The pistons of each cylinder are connected by a mover shaft on which permanent magnets are mounted. A two-stroke cycle of combustion in alternating cylinders pushes the mover back and forth through the alternator coils, inducing electric current for power generation. The alternator is also used to control the shaft's motion and motor the engine for start-up.

The test engine is originally a two-stroke gasoline spark ignition engine and has almost 100 cc of displacement volume. The crank case was modified for the free piston operation and the engine was fuelled with both CNG (Compressed natural gas) and hydrogen, respectively. When CNG fuel was supplied to the engine, the piston stroke was elongated half of the original stroke in order to draw more useful work out from the generator.

The main specifications of the test engine are listed in Table I.

Table I: Specification of the test engine

Bore (mm)	50.6
Stroke (mm)	75 ¹⁾ / 50 ²⁾
Displacement (cc)	150.8 ¹⁾ / 100.5 ²⁾
Compression ratio	7.8
Intake port timing	-7.5 ~ -23.5
Exhaust port timing	2.5 ~ -18.5
Mass of mover (kg)	8.91

1) is for CNG and 2) is for Hydrogen application.

The engine speed is controlled mainly by the ignition timing on the fixed piston location, defined by an absolute position linear encoder attached to the mover magnet inside the linear alternator. The fuel injection was also synchronized with the piston encoder signal.

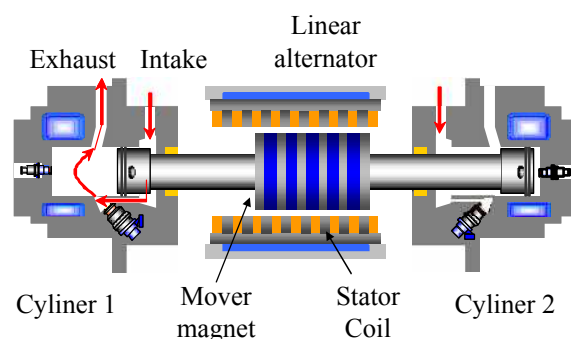


Figure 3: Schematic of the test engine

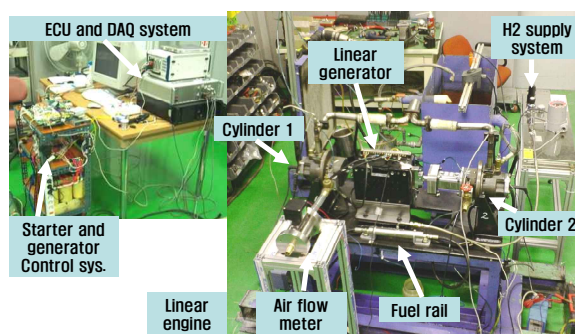


Figure 4: Photo of test engine setup

All through the tests, cylinder pressure was measured at every 0.1ms and used for the cycle analysis.

3. RESULTS AND DISCUSSIONS

3.1 Typical combustion characteristics

Since a free piston engine shows different piston positions at TDC, the compression ratio changes every cycle. This irregular piston movement affected significantly both the compression process and the subsequent combustion of the other cylinder of the engine at the same time.

Figure 5 shows an example of an abnormal combustion encountered during the test. The operational frequency changes every cycle due to the change of the piston stroke. A partial burn happened in cylinder 1 resulted in a decrease of frequency in the subsequent stroke from 13 to 8. In addition, a misfire happened in cylinder 2 eventually caused engine stop.

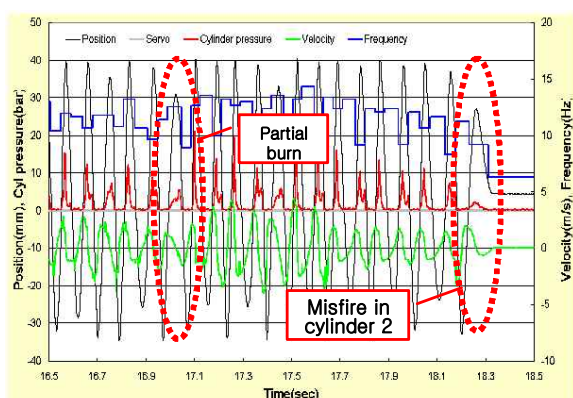


Figure 5: Abnormal combustion phenomena encountered during the test (injection timing: 64mm BTDC, ignition timing: 23mm BTDC)

A free piston engine does not have any mechanism to preserve inertial energy to continue the piston motion such as flywheel in a conventional rotational engine. Thus, a single misfire from one of the cylinders provides a critical cause of the loss of piston movement resulting in the engine stop. To avoid this happening, the control scheme should be involved for the precise mover position or ignition timing is carefully chosen.

3.2 CNG combustion

With the CNG fuel applied, the free piston engine and generator was operated continuously at about 13 Hz speed and it is turned off to save it from the possible undesirable damage after more than one hour operation.

Figure 6 shows measured cylinder pressure as a function of volume. The sharp edge near peak pressure point was observed all through the tests with different load condition. This is because of the shorter residence of piston near TDC compared with the conventional rotational engine, due to the indefinite piston in FPEs.

In the expansion stroke, the abrupt decrease in cylinder pressure shows the commencement of the scavenging process in the two-stroke engine. While there is no further useful work during the scavenging process, the mover continuously moved to

the other side and this helped to increase the electricity output.

The pressure and rate of heat release rate in Fig. 7 show that most of combustion heat is released after the peak pressure or near TDC and continued until the exhaust port opened. This is due to the high dilution rate caused by low efficiency of the loop scavenging of the test engine.

The elongated stroke is also considered to contribute to the low scavenging efficiency. Because the over-stroke downwards made the cylinder vacuum even more while the fresh charge in the intake chamber is limited, the burned gas from the exhaust port re-entered to the cylinder. Thus the stroke length was chosen to have the original value afterwards.

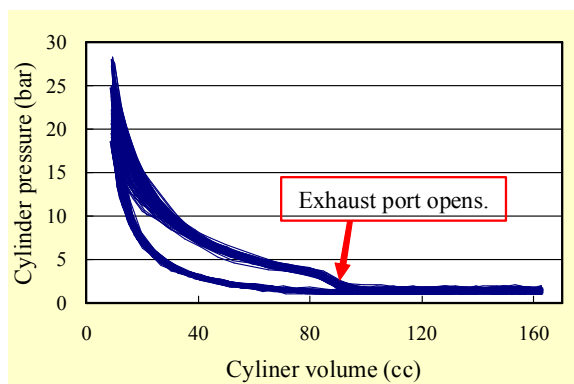


Figure 6: Cylinder pressure vs volume diagram (CNG case)

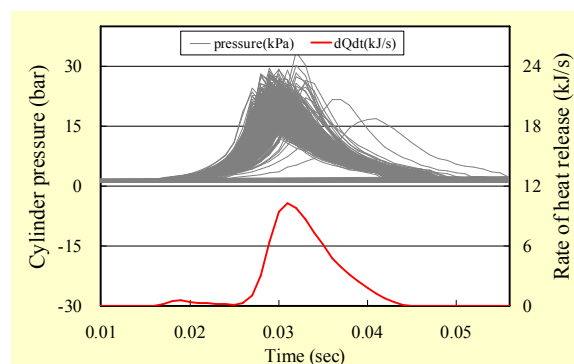


Figure 7: Cylinder pressure and heat release rate as a function of time (CNG case)

3.3 Hydrogen combustion

With the hydrogen fuel applied, the test engine was operated more than 20 minutes with 13 Hz speed. The cylinder pressures attained from the hydrogen combustion in the test engine is shown in Fig. 8. The pressure rise was much bigger than that in the CNG combustion due to the high combustion speed for the hydrogen. The rates of heat release of both CNG and hydrogen are shown in Fig. 9 and the combustion duration is shorter for the hydrogen than that for the CNG.

With increasing the load, the peak pressure was advanced even before TDC and this increased the compression work loss resulting in worse engine efficiency. As is noted in Fig. 9, all the combustion heat is released before the piston reaches TDC.

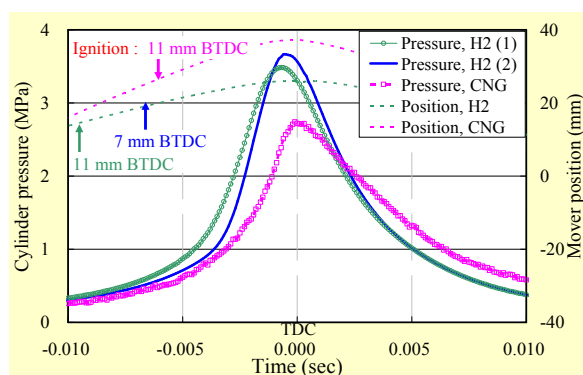


Figure 8: Comparison of the combustion pressures between CNG and hydrogen fuel

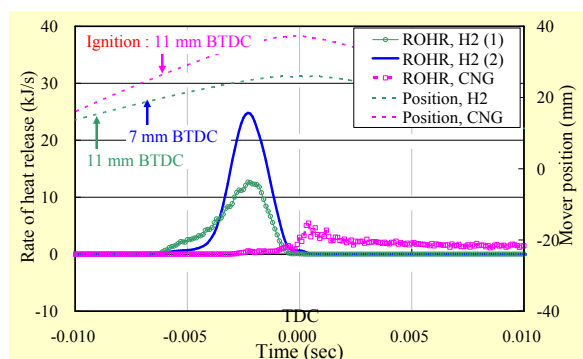


Figure 9: Comparison of the rates of heat release between CNG and hydrogen fuel

Thus it is highly required to retard the ignition timing to utilize more combustion heat into useful work to generate the electricity. During the test, the ignition was retarded more towards TDC and higher frequency from 15 to 17 Hz was attained with 3 to 5 mm delay. However, the cyclic variation increased and this made engine stop after a few minutes operation.

Further study is required to overcome this operational instability and to improve the scavenging efficiency. To this end, a modified free piston engine generation system was proposed as shown in Fig. 10. In order to improve the gas exchange process, the new engine was designed to utilize the generator vacancy as a supercharger to push the fresh charge into the cylinder. The bottom intake port and the top exhaust valve forms a uniflow scavenging. The ignition control system is also adjusted to have a time delay from a fixed piston location to avoid the case that the piston stroke is abruptly shortened leading to an engine stop with combustion instability.

4. CONCLUSION

In this study, a prototype of a free piston engine and a linear generator was operated with both CNG and hydrogen fuels, respectively. From the test results, major findings are as follows:

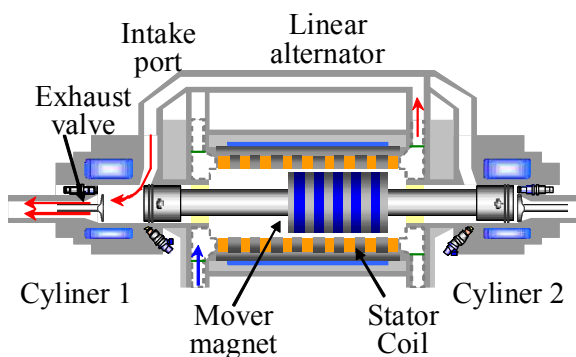


Figure 10: Schematic of the modified free piston engine generation system

A prototype of a two-stroke, twin cylinder free piston engine and a linear generator was operated successfully at the frequency of 13 Hz with CNG and hydrogen fuel.

Two-stroke linear free piston engine requires faster combustion to overcome high charge dilution due to the low scavenging efficiency. Hydrogen fuel has been found to give higher burn rate but require more precise ignition control.

In order to draw out the higher efficiency and lower emissions, a modified free piston engine generation system was proposed. It utilizes the generator as a supercharger and an exhaust valve to form a uniflow scavenging.

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