The performance characteristics of a hydrogen-fuelled free piston internal combustion engine and linear generator system

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Abstract

A power generation system that utilizes a hydrogen-fuelled free piston engine (FPICE) and a linear generator are under development. A FPICE gives power output more efficiently compared with conventional reciprocating piston engines, because it utilizes many benefits such as low friction loss and inherently variable compression ratio apart from the low emission of hazardous exhaust gases. In addition, if hydrogen fuel is used in an FPICE, it would be possible to make the exhaust emission level almost zero without sacrificing the efficiency. In this study, a prototype FPICE, 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 17 Hz. The FPICE was found to give different piston positions at top dead centre, 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 compressed natural gas and hydrogen were used to the test engine, and the results showed different combustion characteristics with the fuels used. Since the scavenging efficiency easily gets worse in such a 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

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1 INTRODUCTION

In a free piston engine (FPE), piston motion is not restricted by any mechanical linkages whereas conventional engines have slider-crank mechanism to convert piston linear motion into a rotary motion. The FPEs can be divided into three categories according to the number and location of the pistons as shown in Figure 1 [1].

The basic operation principle is similar to that of a conventional reciprocating engine 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 transformation of fuel's energy into electricity [2–7] or hydraulic energy [8–10], which is used by a linear generator or a hydraulic actuator, respectively. A two-stroke engine is usually used because it requires power stroke once per each stroke.

There are some advantages over the conventional crank-shaft engine, which could be achieved by the free piston concept since it utilizes many benefits such as low friction loss, inherently variable compression, efficient transient operation, short residence at TDC, and manufacturing cost savings.

The structural simplicity allows the FPE to have higher power density since it requires less weight and less space. Moreover, the friction losses are lower because fewer moving parts exist and piston has no side forces which are induced by the crank mechanism. Though the larger part of the friction losses are attributed to the piston assembly, the other parts of about 20 percent of the friction is still responsible for the crankshaft at 1500 rpm which is regarded as about 25 Hz in the FPE [11].

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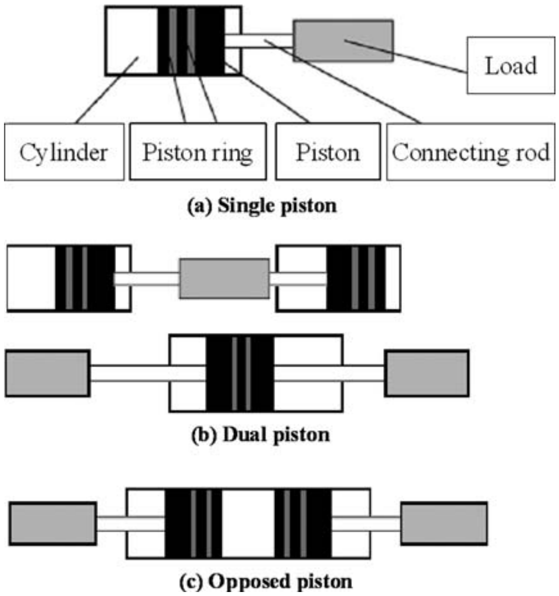

Figure 1. *Various free piston configurations [1].*

The free piston configuration allows the stroke length or compression ratio almost instantaneously, cycle-by-cycle variable and reliable compression ratio control enable the optimization of the compression ratio in different operation conditions, which is not possible with conventional crank-shaft 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 the startup transients comparatively short and more efficient [8].

Goldsborough *et al.* [2] indicated that with the same stroke and piston frequency, there are some differences between the piston motions from an FPE and a crank-shaft-driven engine. As shown in Figure 2, the free piston spends less time at top dead centre (TDC) relative to the crank-shaft-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 as shorter time at higher temperature is desirable [2].

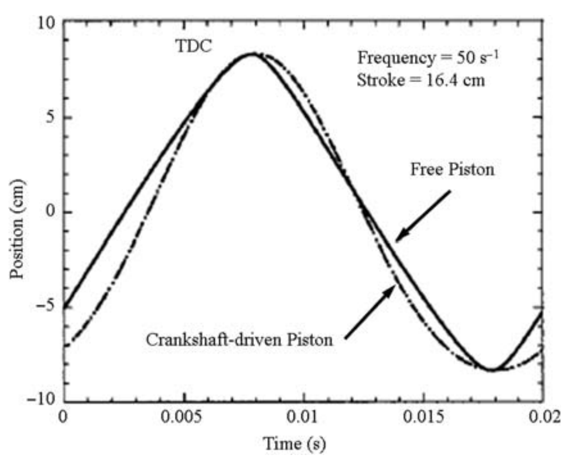

Figure 2. *Piston position vs. time [2].*

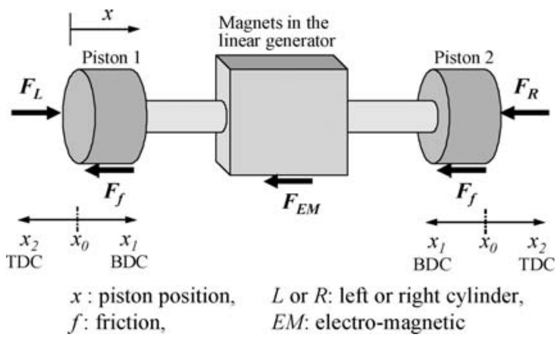

Figure 3. *Forces acting on the mover of the test engine.*

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

The lack of crank mechanism creates some disadvantages as well: the control system is more complicated than 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.

Though there has been suggested so many free piston configurations in the referred literature, many of them are only for the computational approaches prior to the demonstration or just for the introduction of their own prototypes which are far from the completion of stable operation. That is because there are still many technical difficulties remained and this makes the goal for the stable and more efficient free piston engine combustion hardly attainable. 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 an FPE and a linear generator were tested to evaluate the performance to obtain higher efficiency and lower emissions than the conventional generation systems.

2 THEORETICAL ANALYSIS

Since the test engine utilizes sequential combustion for each stroke in the two cylinders, they are assumed to have the same geometry and also deliver the same power to the pistons. When the left cylinder is under the expansion process as shown in Figure 3, the equation for the piston motion is given by

$$\sum F = F_L - F_{EM} - 2F_f - F_R = m\ddot{x} \qquad (1)$$

where F_L is the expansion force of the burned gas, F_{EM} is the electro-magnetic detent force, and F_f is the friction force of

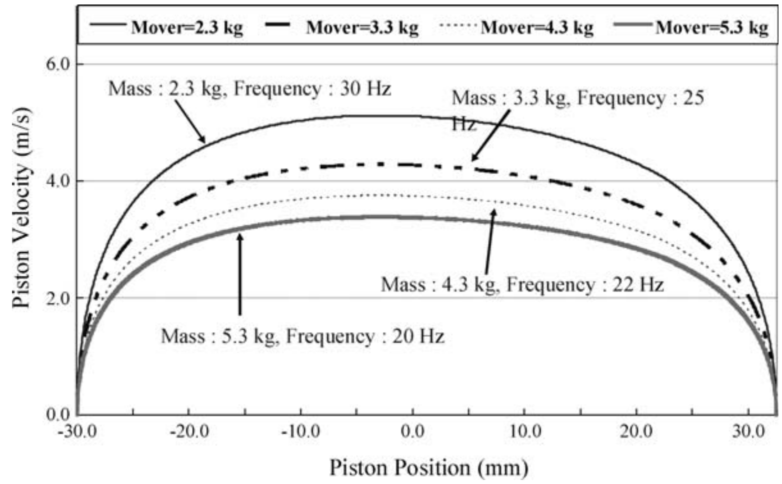

Figure 4. *Piston moving frequency with respect to the mover weight.*

each piston assembly and F_R is the compression force of the combustible mixture, respectively.

In order to get the value of F_L, F_R, an ideal gas cycle assumed which consist of polytropic compression and expansion process as well as constant volume heat addition. For the friction force, an empirical correlation of friction mean effective pressure proposed by Blair in his book [12] was applied. For the electro-magnetic detent force was assumed to have 400 N from the analysis of magnetic field density. From the calculation results shown in Figure 4, the target frequency of 30 Hz was attained with mover mass of 2.3 kg.

3 EXPERIMENTAL SETUP

The test engine has dual pistons and consists of two opposite combustion cylinders with an integrated linear alternator in between (Figures 5 and 6). 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 startup.

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 compressed natural gas (CNG) and hydrogen, respectively. When CNG fuel was used to the engine, the piston stroke was elongated half of the original stroke to draw more useful work out from the generator. The main specifications of the test engine are listed in Table 1 and a photo of the engine setup is shown in Fig. 6.

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

4 RESULTS AND DISCUSSIONS

4.1 Typical combustion characteristics

Since an FPE shows different piston positions at TDC, the compression ratio changes in 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 7 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 the engine to stop.

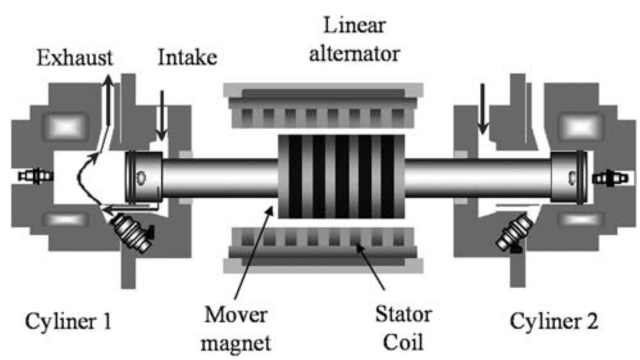

Figure 5. *Schematic of the test engine.*

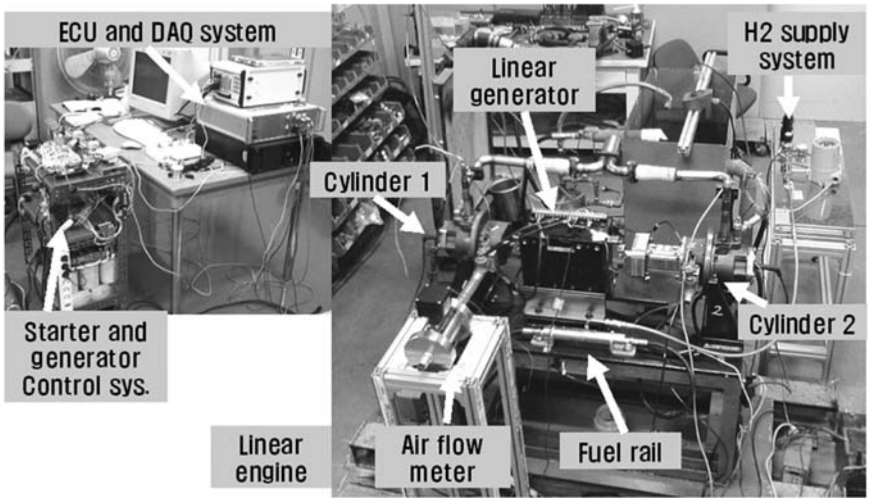

Figure 6. *Photo of test engine setup.*

Table 1 *Specification of the test engine.*

Bore (mm)	50.6
Stroke (mm)	75[a]/50[b]
Displacement (cc)	150.8[a]/100.5[b]
Compression ratio	7.8
Intake port timing	−7.5 to −23.5
Exhaust port timing	2.5 to −18.5
Mass of mover (kg)	8.91

[a]For CNG.
[b]For Hydrogen application.

An FPE 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 to stop. To avoid this happening, a control scheme should be used for the precise mover position or ignition timing is carefully chosen.

4.2 CNG combustion

With the use of CNG fuel, both the FPE and the generator were operated continuously at about 13 Hz speed, and after more than 1 h of operation, both were turned off to save them from the possible undesirable damage.

Figure 8 shows the 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.

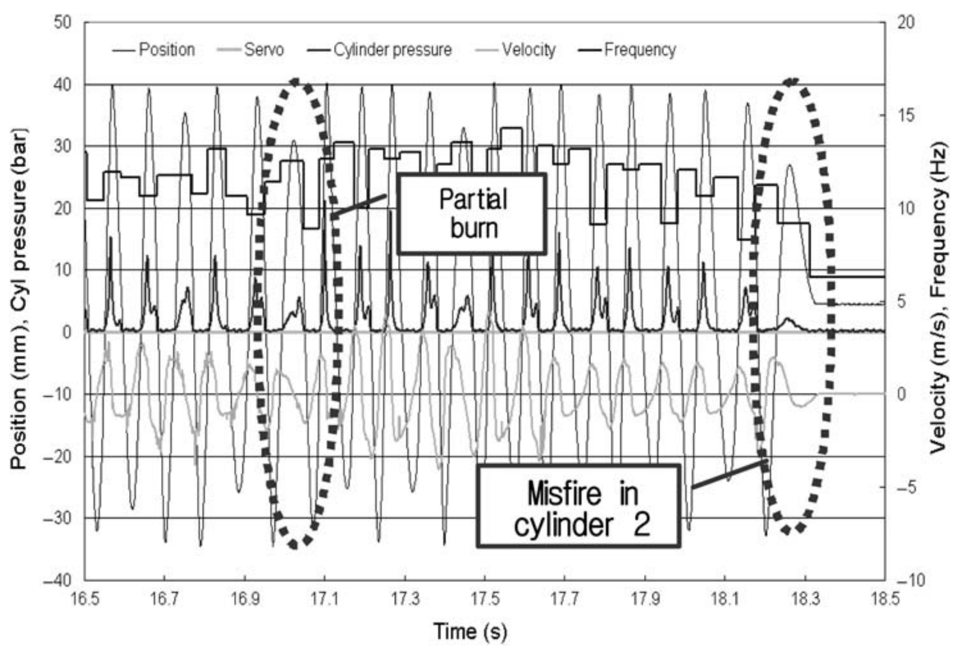

Figure 7. *Abnormal combustion phenomena encountered during the test (injection timing: 64 mm BTDC, ignition timing: 23 mm BTDC).*

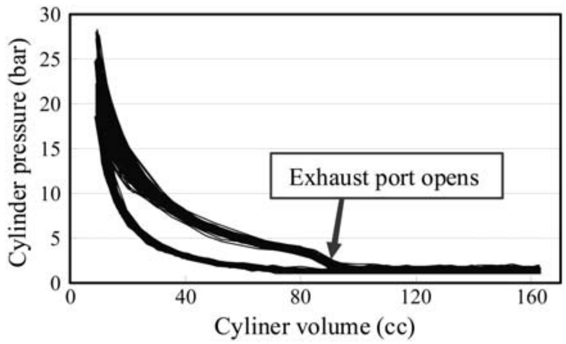

Figure 8. *Cylinder pressure vs. volume diagram (CNG case).*

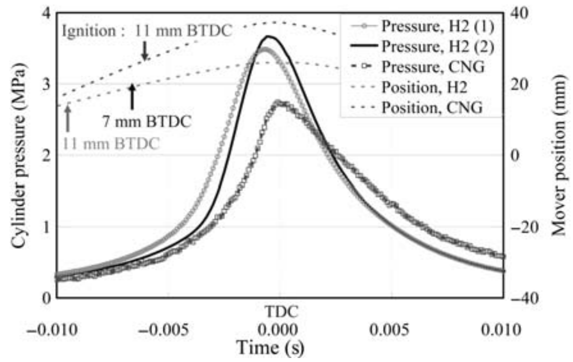

Figure 10. *Comparison of the combustion pressures between CNG and hydrogen fuel.*

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 shown in Figure 9 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 downward over-stroke 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.

4.3 Hydrogen combustion

With the use of hydrogen fuel, the test engine was operated more than 20 min with 13 Hz speed. The cylinder pressure attained due to the combustion of hydrogen in the test engine is shown in Figure 10. The increase in pressure was much higher in the hydrogen combustion than that in the CNG combustion due to the high combustion speed of hydrogen. Figure 11 shows the rates of heat release of both CNG and hydrogen, which shows that the combustion duration is shorter for hydrogen than that for the CNG.

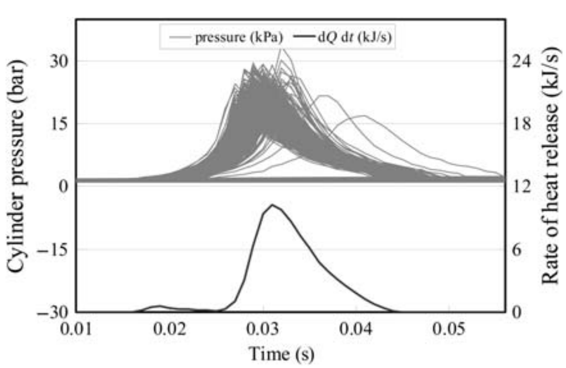

Figure 9. *Cylinder pressure and heat release rate as a function of time (CNG case).*

With increasing the load, the peak pressure was advanced even before TDC, which increases the compression work loss resulting in worse engine efficiency. As is noted in Figure 11, all the combustion heat is released before the piston reaches TDC.

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 3–5 mm delay. However, the cyclic variation increased and this made the engine to stop after a few minutes of operation.

Further study is required to overcome this operational instability and to improve the scavenging efficiency. To this end, a modified FPE generation system was proposed as shown in Figure 12. 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.

5 CONCLUSION

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

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

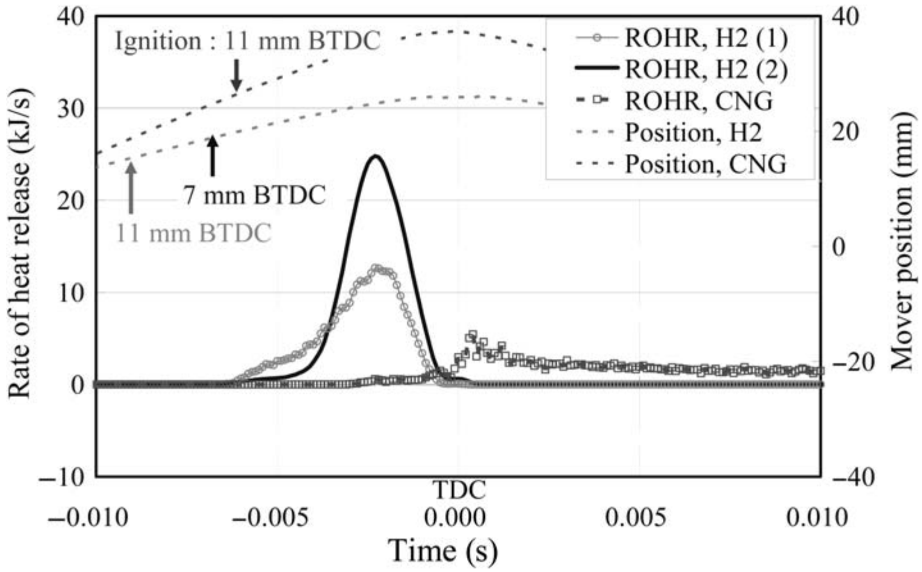

Figure 11. *Comparison of the rates of heat release between CNG and hydrogen fuel.*

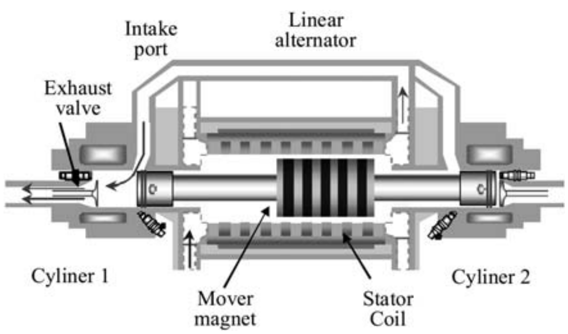

Figure 12. *Schematic of the modified free piston engine generation system.*

Two-stroke linear FPE 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 FPE generation system was proposed. It utilizes the generator as a supercharger and an exhaust valve to form a uniflow scavenging.

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REFERENCES

[1] Csaba Tóth-Nagy, Nigel N. Clark. The linear engine in 2004. SAE paper 2005-01-2140.

[2] Goldsborough SS, Van Blarigan P. A Numerical study of a free piston IC engine operating on homogeneous charge compression ignition combustion. SAE paper 1999-01-0619.

[3] Goldsborough SS, Van Blarigan P. Optimizing the scavenging system for a two-stroke cycle, free piston engine for high efficiency and low emissions: a computational approach. SAE paper 2003-01-0001.

[4] Carter D, Wechner E. The free piston power pack: sustainable power for hybrid electric vehicles. SAE paper 2003-01-3277.

[5] Shoukry E, Taylor S, Clark N, Famouri P. Numerical simulation for parametric study of a two-stroke direct injection linear engine. SAE paper 2002-01-1739.

[6] Clark NN, Nandkumar S, Famouri P. Fundamental analysis of a linear two-cylinder internal combustion engine. SAE paper 982692.

[7] Kleemann AP, Dabadie JC, Henriot S. Computational design studies for a high-efficiency and low-emissions free piston engine prototype. SAE paper 2004-01-2928.

[8] Brusstar M, Gray C Jr, Jaffri K *et al*. Design, development and testing of multi-cylinder hydraulic free-piston engines. SAE paper 2005-01-1167.

[9] Vael GEM, Achten PAJ, Fu Z. The innas hydraulic transformer the key to the hydrostatic common pressure rail. SAE paper 2000-01-2561.

[10] Kaario O. 'Comparison between single-step and two-step chemistry in a compression ignition free piston engine. SAE paper 2000-01-2937.

[11] John B. Heywood. Internal combustion engine fundamentals. McGraw-Hill, 1988.

[12] Gordon P. Blair. Design and Simulation of Two-Stroke Engines. SAE International, 1996.