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Effect of Injection Timing on the Operation of Hydrogen-Fuelled Free-Piston Linear Generator Engine during Starting

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ABSTRACT: A linear engine type with piston assembly that swings between two oppositely placed combustion chambers considered in this study. The study investigated the effect of injection timing on starting of the engine. The injection position varied at five different positions (17mm to 27mm) before the maximum switching limit of the engine reached. It was observed that advancing the injection position in free-piston engine slows down the compression stroke and increases the combustion duration. Furthermore, lower peak pressure and rate of heat release occurred at 17 mm, 20 mm, and 23 mm injection timing. Relatively stable operation of the engine was achieved at 25 mm.

KEY WORDS: heat engine, spark ignition engine, combustion analysis, free-piston engine, injection timing, linear generator, starting of the engine [A1]

1. Introduction

According to the International Energy Agency (IEA), world primary energy demand will increases 36% from 2008 to 2035 [(1)]. Transportation is one of the main sectors that consume the world's energy generated. It is indicated on IEO 2010 reference that the transportation sector consumes almost 30 percent of the total world's energy produced and accounts for the largest increment in total liquids demand, making up nearly 80 percent of the world liquids consumption increase by 2035 [(2)]. Hence, environmental policy makers enact laws that restrict and impose a limit on the level of emissions released by internal combustion engine. Thus, searching and developing new techniques and technologies for use in the current internal combustion engine is the most important aspect in addressing future energy and environmental crises.

As a result, more researches have been undertaken to improve the current internal combustion engine by speculating that the future development of the internal combustion engine mainly relies on improving the emission, mechanical and thermal efficiency in part load operation and fuel efficiency. Conversely, some researchers are claiming that the required improvement on the current engine can be achieved by using free-piston engine due to its structural simplicity, flexibility, higher mechanical and thermal efficiency [(3-7)]. These have fashioned universal aspiration among some researchers to scrutinize free-piston engine for having a potential of emission reduction by limiting the time that the combustion charges spend at the Top Dead Center (TDC) after the end of compression stroke [(8)]. For instance, Van Blarigan showed that the indicated thermal efficiency of free-piston engine is 56% with essentially zero NOx emissions as compared with 45% thermal efficiency of conventional engine. In conventional engine, the piston motion is constrained by crank mechanism that limits the range of the compression ratio of the engine. However, the freely moving piston of free-piston engine allows the stroke length or compression ratio to vary instantly that resolves the challenges of obtaining variable compression ratio. This feature of free piston engine enables it to operate with multi-fuel [(6, 9, 10)]. Besides, the engine would be more quiet and vibrationless during the operation. The current engine requires torque transmission and multiplication, such as drive shaft, gearboxes and differentials, before their power is utilized in vehicles [(11)]. In free-piston engine, however, the power generated can be transmitted either through wires to the motors or connected to the wheels with a hydraulic coupling to drive the vehicle.

Depending on the type of the load device used, a free-piston engine may produce various useful outputs, such as compressed air, hot gas, hydraulic energy and electrical energy. Thus, the engines are called a free-piston air compressor, free-piston gas generator, hydraulic free-piston engine and free-piston linear generator engine, respectively. In this study, a free-piston linear generator engine type is considered. Eventhough, this new technology is still under research stage, many researchers have explored and contemplated that the promising future applications of free piston engine linear generator include: to use as a power unit in hybrid electric vehicle [(12)] and micro power generation system for portable device [(3)].

1.1. Challenges of Free-Piston Linear Generator Engine

A thorough examination of published literature indicated that there have been far less rigorous researches on free-piston engine and the literature is not extensive. However, some of the few reported researchers on free-piston linear generator indicate that there are still technical issues that need to be addressed in order to drive the advantage from free-piston engine [6, 13]. The challenges are due to the absence of kinematic constraints in free-piston linear generator engine that allows the motion of the piston to be influenced by imbalance of forces acting on the piston, mainly by the gas pressure developed in the cylinder of the engine due to combustion process [3, 4]. As a result, the engine has challenges in controlling the motion of the piston and starting of the engine [6, 13]. The slight variation of pressure in one cylinder will adversely affect the other cylinder which eventually leads to unsustainable operation of the engine. The pressure can be indirectly influenced by the amount of fuel injected into the combustion chamber [14] and injection and ignition timing of the charge. Huang et al. [15] showed that fuel injection timing is an important parameter to control the combustion characteristics in natural gas direct injection combustion. The effect of injection timing on the combustion characteristics for hydrogen direct injection operation is due to the formation of different mixture distribution at early and late injection timing and it was reported that efficiency benefits of up to 4% can be gained when employing an optimized injection strategy [16]. Improper injection timing will disturb the stroke length of the engine that results in cycle-to-cycle variation and finally the piston will stop running after a few cycles.

1.2. Starting Mechanism of Free-Piston Linear Generator Engine

West Virginia University (WVU) researchers developed a two-stroke, spark ignited (SI) free-piston linear generator engine prototype for electrical power generation and two starter solenoid coils from a heavy duty engine were used to act directly on the connecting rod for starting the engine [17]. They reported that this mechanism was successful for proving motoring force for the engine, however, more space needed to locate the solenoids. After investigating the SI version of the engine thoroughly, they concluded that unthrottled operation of the engine is desirable for easy controlling the engine. Hence, WVU researchers developed diesel type of free-piston linear generator [18]. The starting mechanism for a compression ignition prototype version of the two stroke linear engine was designed to use alternator as a motoring device. It is reported that the second version of the engine could not motor due to some difficulties encountered in the starting process of the engine as a result of cranking circuit transistors burning out [18].

Further study on starting of free-piston linear generator engine was conducted by Arof et al. [19] and Zulkifli et al. [13]. Arof studied the methods for reducing the cogging force and starting the free-piston linear generator engine. The cogging force developed from the static interaction between the permanent magnet on the translator and the iron core of the stator. Since the cogging force applies in opposite direction to the translator's motion, it causes a problem for starting the engine. They proposed two methods for starting the linear generator. In the first method, an extra coil was attached to the starter where a direct current is injected into the main coils and the extra coil simultaneously with different polarities, where as in the second method the two main coils of the generator are split into four sub-coils. The later method provides easy means to control the injected currents and different current values or polarities in the coils.

In a similar study, Zulkifli et al. [13] studied the starting methods and its control strategy for free piston engine linear generator by energizing the alternator electrically using stored electrical energy based on open-loop and rectangular current commutation. The current is injected into the alternator's coil to drive the piston back and forth until it reaches sufficient compression so that combustion can be initiated. According to Zulkifli et al., if a sufficient large, fixed-magnitude force is constantly applied on the translator in the direction of motion, the system can be reciprocated and resonated to the full required amplitude. Since the motoring force is directly proportional to the amount of current injected into the coil, a higher constant force require a higher current supply from the source so as to have high frequency of the engine. For motoring the free-piston linear generator engine, a number of standard automotive batteries connected in series were used for energizing the coils. It was claimed that they could successfully motor the engine and control the piston motion. Even though firing could briefly occurred in the combustion chamber, it was reported that the engine could not run without motoring due to low frequency of the engine. Hence, this research aims to study the effect of injection timing on the operation of hydrogen-fuelled free-piston linear generator engine during starting.

1.3. Development of Free-Piston Linear Generator Engine at UTP

The work presented here is undertaken at Universiti Teknologi Petronas (UTP) on a new free-piston linear generator engine developed by group of UTP researchers in collaboration with other two universities (Universiti Malaya and Universiti Kebangsaan Malaysia) for being environmental friendly and for using as a power generation unit to charge power accumulators battery packs on-board for hybrid electric vehicle [20, 21]. After several generation of free-piston engine development, the researchers could produce a prototype that has two pistons connected by translator shaft at both end and placed between two opposing combustion chambers as shown in Fig. 1. Moreover, the prototype has linear generator that consists of stator coil and three phase tubular permanent magnet, mounted in the center of the integrated pistons. It acts like a generator when the linear motion of the translator assembly reciprocates between two combustion chambers to produce electricity and it acts also like a motor when the current is injected into the alternator's coil from the standard automotive battery bank for starting the engine. Since there is no energy storage device in free-piston engine, the power stroke is required for every cycle. This restricted the development of the engine to two-stroke cycle. The developed engine employs variable electronic ignition and direct injection system that can be fuelled by compressed natural gas (CNG) and hydrogen (H_2). The target was to generate 5-kW from the prototype meeting certain power density specifications. The developed prototype and the specification of the engine are depicted in Fig. 1 and Table 1 respectively.

Table. 1 General specifications of UTP free-piston linear generator engine prototype

No	Descriptions	Specification
1	Engine type	Two-stroke, Spark Ignition
2	Number of cylinders	2
3	Bore	76 mm
4	Design Stroke	69 mm
5	Engine Capacity	313cc/cylinder
6	Maximum Compression Ratio	1:14
7	Exhaust Port Start Opening	40 mm from the maximum end of the stroke
8	Exhaust Port length	28.5 mm
9	Intake Port Start Opening	56.5 mm from the maximum end of the stroke
10	Intake Port length	12 mm
11	Moving mass	6 kg

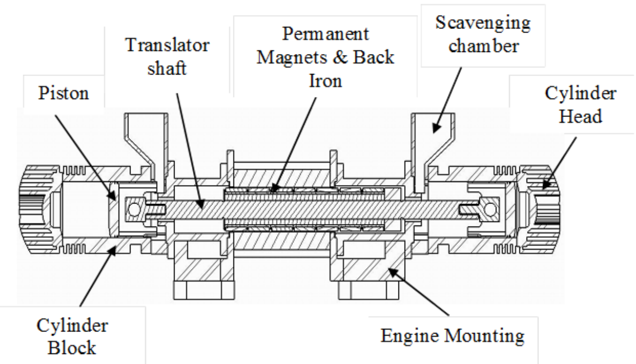

Fig. 1 UTP two-stroke, free-piston linear generator engine prototype.

The maximum compression ratio provided in Table 1 was determined based on the engine's geometry using the maximum cylinder volume and the minimum cylinder volume, in which the minimum cylinder volume consists of the clearance volume and crevice volume. In the design of the developed free-piston engine, around 2.2 mm additional clearance was provided between the cylinder head and cylinder block so as to have spring mass effect to prevent collision of the piston with the cylinder head in case of misfiring. The crevice volume of the engine was 14.33 cc. The location of the exhaust and intake port of the free-piston linear engine shown in detail in Fig. A.1 in Appendix section.

2. Research Methodology

The experiment was performed on a two-stroke, direct injection, UTP free-piston linear generator engine with two oppositely placed combustion chamber, which has a specification of 76mm bore, 34.5mm nominal stoke length and 313cc/cycle engine capacity (Table 1). Using data acquisition system, cylinder pressure, the amount of current flowing into the coil and the corresponding piston linear displacement data for the left and right cylinders was gathered. An electrical power was supplied from the standard 12-Volt automotive battery bank to the engine through the alternator's coils for motoring the engine. Two types of battery configuration (3-battery and 5-battery configurations) were chosen during the experiment due to the limitation imposed by the capacity of MOSFET (Metal–oxide–semiconductor field-effect transistor) driver used in the experiment. The 3-battery configuration experiment injects a current to the alternator's coil using a maximum of 36 V that is supplied from three standard automotive batteries (each 12 V) connected in a series, where as the 5-battery configuration supplies 60 V. Figure 2 and Figure 3 show an experimental set up of UTP free-piston engine and MOSFET driver for free-piston linear generator engine, respectively.

For direct injection system, a Synerject high pressure direct injector was mounted on the engine with 790 exit angle. The cylinder head design showing the arrangement of direct fuel injector, spark plug and pressure sensor for free-piston linear generator was shown in Appendix (see Fig. A.2). The hydrogen fuel was used in the experiment and injected into the combustion chamber after intake valve was closed. The cylinder pressure measurements were taken using a Kistler 6061B piezoelectric pressure transducer that was connected to Kistler charge amplifier type 5037B to convert charge to voltage. Unlike conventional engine, free-piston engine requires a linear displacement magnetic encoder (Baumer MLFK-08T7101) for measuring the linear displacement that was used as input to the controller for controlling the switching point of the power switches.

Free piston linear generator engine control parameter such as injection timing, ignition timing, amount of fuel delivery, amount of current injection for motoring the engine and the maximum switching end-point of the piston were executed by using PXI embedded controller and computer program that was implemented in LABVIEW software. Micro-motion mass flow meter (sensitivity of 0.0001 g/s) was used to measure the fuel flow rate to the engine. With the help of developed LABVIEW program, the data was logged at 0.125 mm linear displacement resolution. A maximum of 25 and 75 consecutive engine cycles could be recorded for different engine operating scenario for motoring the engine with combustion and without combustion, respectively [22].

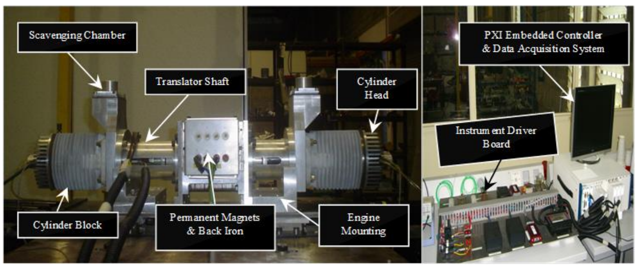

Fig. 2 Experimental setup of UTP free-piston linear generator engine and data acquisition system

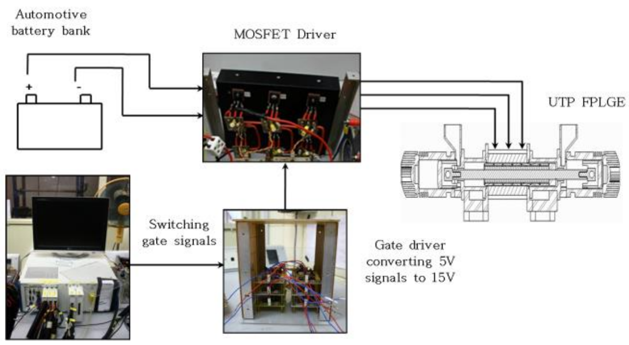

Fig. 3 Experimental setup of MOSFET driver for free-piston linear generator engine

Hydrogen fuel at pressure of 19 bar was injected directly into the combustion chamber. It was supplied by a gas tank and regulated using a double stage gas regulator to obtain accurate and constant pressure throughout the the cycle frequency range. Fuel mass per cycle was controlled by varying the duty cycle of the injector using Labview 7.0. Mass of the air that is entering the engine were measured and then the air fuel ratio was calculated. Spark timing was also controlled by using Labview 7.0 based on the input of the user. It was defined to be 27.5 mm (see Table 2).

The collected experimental data were post-processed by using MATLAB software. The heat release result shown in this study was calculated by using apparent heat release model. The result showed a sever ringing that occurred due to the pressure transducer that picks up the local pressure disturbance. In order to avoid high ringing on the heat release curve (Fig. 11) and instantaneous IMEP curve (Fig. 9), the disturbance was filtered out by using a continuous segment moving average method. A 15-point smoothing procedure was used to reduce sensitivity to noise spikes so as to modify the calculated rate of heat release curve and the instantaneous IMEP curve. The detail result of the experiment is presented in the subsequent sub-sections.

3. Results and Discussions

3.1. Motoring the Engine Without Combustion

The first experiment was carried out to investigate the operating behavior of the engine by motoring the engine without combustion using 3-battery and 5-battery configurations. Motoring the engine without combustion was used for warming up and starting the engine by injecting the current into the alternator's coil for moving the piston assembly back and forth. Fig. 4 depicts the averaged displacement versus time for running the engine with 3 and 5-battery configurations without combustion for a total of 75 cycles. The 3-battery configuration experiment injects a maximum of 36 V and the 5-battery configuration injects a maximum of 60 V. It is observed that the cycle-to-cycle variation is not prevalent for motoring the engine without combustion if the batteries are fully charged. Since higher current is obtained in 5-battery configuration, the engine runs at higher engine frequency (345 cpm) than in 3-battery configuration (240 cpm).

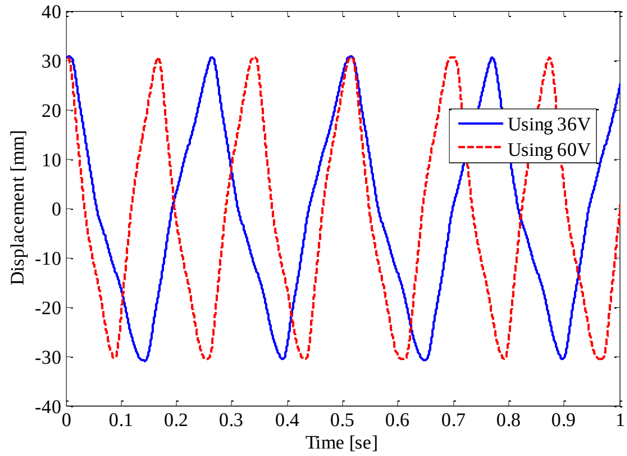

Fig. 4 Displacement versus time for the free-piston linear generator engine

Fig. 5 shows pressure versus displacement curve for the left and right cylinder of the engine by using 3-battery and 5-battery configuration without combustion. It shows that the pressures in the left and right cylinder are not equal in both configurations. This can be attributed to the fact that there is a leakage in the left cylinder. The maximum pressure is observed in the left and right cylinders for 5-battery configuration (4.949 and 5.566 bar respectively) than for 3-battery configuration (4.026 and 4.441 bar respectively) due to higher engine frequency in 5-battery configuration. Furthermore, it is investigated that the compression profile (curve A-B-C) is higher than the expansion profile (curve C-D-A). Hence, the region under the curve A-B-C-D-A is a negative work due to the work done by motoring force applied to the piston. This shows that the energy is supplied to the engine rather than extracting from it.

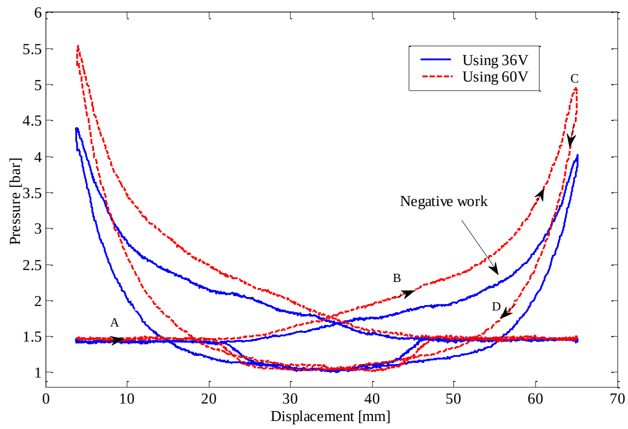

Fig. 5 Pressure versus displacement of free-piston linear engine for the left and right cylinder

3.2. Motoring the Engine With Combustion

The experiment test was extended to encompass the combustion of the engine assisted by motoring the engine that was achieved by injecting the current continuously via coil. After the combustion was established, it was repeatedly attempted to run the engine without motoring, however the trial was not successful due to less pressure developed in both cylinders in all experimental set up. Hence, the experiment was continued to be focused on the combustion of the engine with motoring to study the effect of start of fuel injection on the engine by sweeping from 17mm to 27mm before maximum switching point reach.

Fig. 6 depicts the in-cylinder pressure versus time profile for 17 mm, 20 mm, 23 mm, 25 mm and 27 mm injection timing, where as Table 2 shows the fuel pressure, fuel flow rate, the air fuel ratio and the spark position defined to carry out the exprement. In this study, cycle frequency were calculated based on the pressure profile of the combustion. All the pressure indicated in this study are in absolute pressure.

Table. 2 Experimental parameters for free-piston linear generator engine

Injection Position (mm)	Pressure (bar)	Fuel Flow (mg/cycle)	Air Fuel Ratio	Spark Position (mm)	Cycle Frequency (cpm)
17	19	5	31.2	27.5	610
20	19	5	31.2	27.5	716
23	19	5	31.2	27.5	601
25	19	5	31.2	27.5	812
27	19	5	31.2	27.5	809

The result shows a moderate cylinder pressure rise before the start of combustion, followed by a higher cylinder pressure rise during combustion for 25 mm and 27 mm injection timing as compared to the other injection timing setting.

Very fast combustion is observed at 27 mm injection timing than 25mm. However, higher peak cylinder pressure is obtained at 25mm injection timing. In all cases, the maximum cylinder pressure is occurred after the piston switches to the opposite direction (after the TDC). Another important observation of Figure 6 is that expansion stroke is faster than the compression stroke as indicated in Table 3. The compression and expansion time given in Table 3 are the time spend by piston to travel from the exhaust port opening postion (Fig. A.1) to TDC during compression process and the time spend by piston to travel from TDC to the exhaust port opening position during expansion process, respective. This feature of the free-piston engine can be attributed to the fact that the absence of flywheel or crankshaft allows the piston to accelerate rapidly away from the TDC that limits the time available for combustion. In free piston engine, it is observed that it is essential to inject the required amount of fuel at a right time when the piston is near the TDC depending on the operating condition of the engine (piston stroke, load, etc) to ensure that the pressure peak will occur near or after TDC. This is to prevent the piston from decelerating while moving towards TDC. By varying the injection timing, a relatively stable operation of the engine by motoring with combustion is achieved by injecting the hydrogen fuel at 25mm before the maximum switching point is reached.

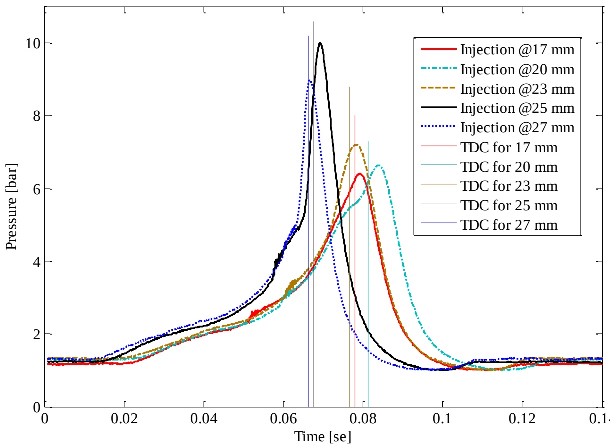

Fig. 6 Pressure versus time of free-piston linear generator engine for various injection timing

Table. 3 The time required for compression and expansion process

Injection Position (mm)	Compression time (ms)	Expansion time (ms)	TDC position (ms)
17	54.6	32.6	78.0
20	55.2	33.5	81.3
23	52.7	35.5	76.6
25	49.4	28.9	67.7
27	49.3	30.5	66.4

Further analysis of the measured pressure data indicates that the negative work region observed during motoring the engine without combustion (Fig. 5) partly develops a positive work region when running the engine with combustion (curve B-C-D-B) as revealed in Fig. 7. This positive work region is due to the combustion process occurred in the cylinder. It is observed that the higher the pressure developed in the cylinder due to combustion, the larger positive work and the smaller negative work region produced. For instance, small area is covered by negative work region for 25 mm injection timing compared to 17mm injection timing that produces lower pressure rise. A similar phenomenon based on varying the load was shown experimentally by Tóth-Nagy [23]. Indicated mean effective pressure (IMEP) for varies injection positions are calculated and the results are discussed below.

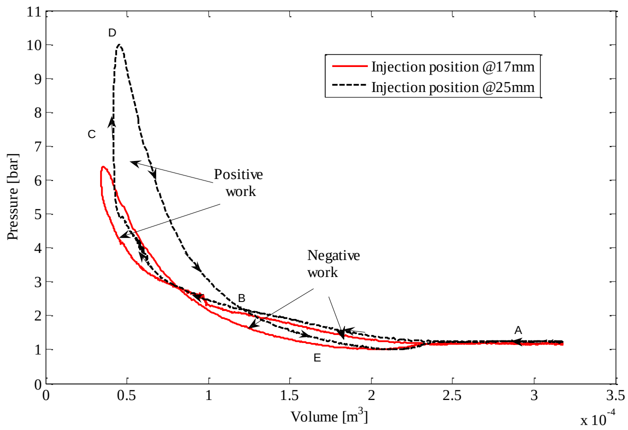

Fig. 7 Pressure versus volume of free-piston linear generator engine for various injection timing

The indicated mean effective pressure is determined by dividing the area under the P-V curve (Fig. 7) in a number of segments perpendiculars to the V-axis, the mean value of the height of the segments will give the IMEP for the operating condition. Hence, it is investigated that the IMEP for 17 mm, 20 mm and 23 mm injection timing are negative (-0.039, -0.098 and -0.048 bar, respectively) that reveals the work done by motoring force (negative work) is higher than the work done due to combustion process (positive work). This means that the engine cannot be run without motoring at this operating condition. Eventhough very fast and relatively higher pressure is obtained at 27 mm fuel injection timing, the IMEP for 27 mm injection timing is 0.036 bar which result in a smaller indicated power. However, a relatively higher IMEP (0.42 bar) and indicated power (11.77 J) are obtained for 25 mm injection timing.

The rate of heat release and cumulative heat release are determined to evaluate the pressure rise rate and combustion characteristics for different operating condition. Fig. 8 and Fig. 9 display the rate of heat release and the cumulative rate of heat release curve for free-piston linear engine by varying injection timing respectively. Lower rate of heat release and longer combustion duration (determined as the time difference between the start of ignition and end of combustion at the time when the heat release rate becomes less than or equal to 0) are observed for 17 mm, 20 mm, and 23 mm injection timing as compare to 25 mm and 27 mm injection timing (Fig. 8). The result clearly indicates that injecting hydrogen fuel at 27 mm and 25 mm speeds up the combustion. The combustion starts earlier for both injection timing with higher rate of heat release. One can observe that faster and earlier combustion occurs with slightly lower maximum rate of heat release for 27 mm injection timing compared to 25 mm injection timing. However, relatively stable operation of the engine could be achieved by injecting hydrogen fuel at 25 mm. The combustion duration is shorter at 27 mm injection timing (6.6 ms) than at 25mm injection timing (7.7 ms), which both show rapid pressure rise rate after the start of combustion and a higher rate of heat release greater than 20 kJ/se. Furthermore, it is observed that the maximum total cumulative heat release, 356 kW, is obtained at 25mm injection timing.

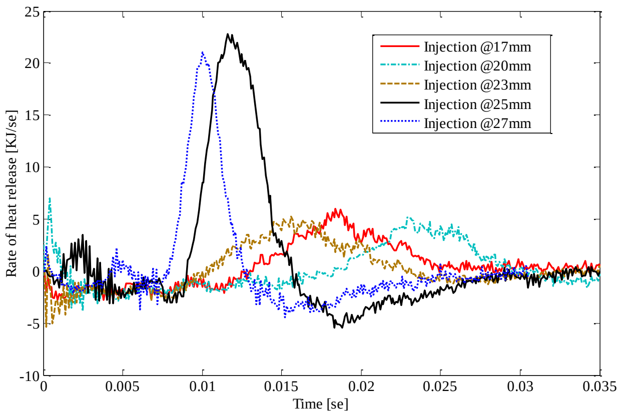

Fig. 8 Rate of heat release versus time of free piston engine for various injection timing

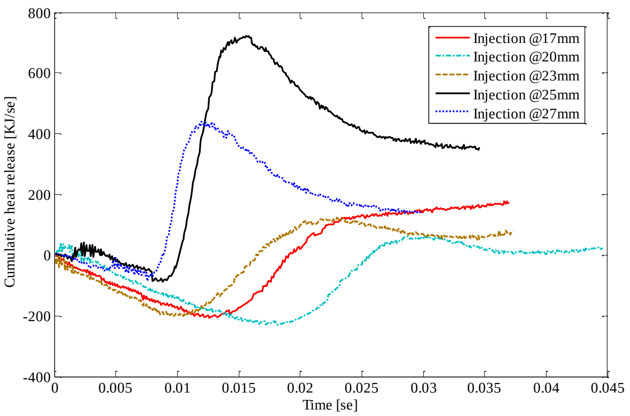

Fig. 9 Cumulative heat release versus time of free-piston linear engine for various injection timing

It is clear that advancing injection timing allows the combustion to occur earlier in the cycle that develops early pressure in the cylinder before the piston reaches TDC. The developed pressure pushes the piston to the opposite direction against the motoring force that still pushes the piston to the desired TDC. This slows down the motion of the piston while travelling towards the TDC. Thus, advancing injection timing in free piston engine extends the compression stroke by increasing the combustion duration. Moreover, it reduces the overall peak pressure and rate of heat release as it was observed in 17 mm, 20 mm and 23 mm injection position. On the other hand, if the combustion occurs near TDC by retarding the injection timing, higher peak pressure develops near TDC and the piston reverses its direction and accelerates rapidly away from TDC. Hence, higher rate of heat release and lower combustion duration will occur.

4. Conclusions

The experimental work has been performed on free-piston linear generator engine to investigate the behavior of the engine by motoring the engine without combustion. The experimental result shows that the free-piston linear generator engine runs at higher engine frequency when higher amount of current is injected into the coil and develops higher pressure inside the combustion chamber. Moreover, the experiment has been carried out by motoring the engine with combustion by injecting hydrogen fuel into the combustion cylinder. The effect of injection timing on starting of free-piston engine has been studied by varying the injection timing from 17 mm to 27 mm before TDC. It has been investigated that higher cylinder pressure is required to increase the positive work region so as to have a significant net work to start and run the engine without assisted by motoring. The comparison between different operating conditions of the engine has shown that the injection timing has an effect on the starting of the engine. In free piston engine, it is observed that it is essential to inject the required amount of fuel at a right time when the piston is near the TDC depending on the operating condition of the engine to ensure that the pressure peak will occur near or after TDC. For the current engine setup, the maximum cylinder pressure, rate of heat release, cumulative rate of heat release and IMEP are produced at 25 mm injection timing.

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Appendix

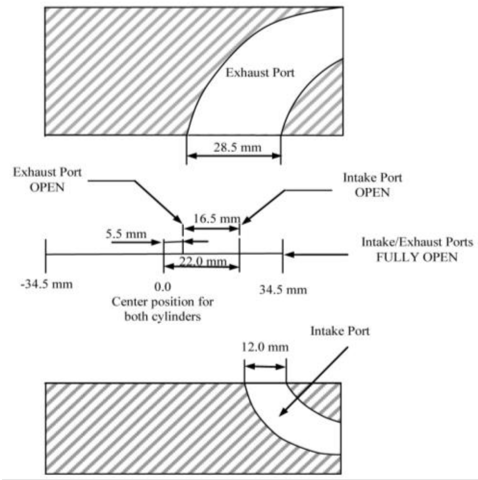

Fig. A.1 The location of the exhaust and intake port of the free-piston linear engine

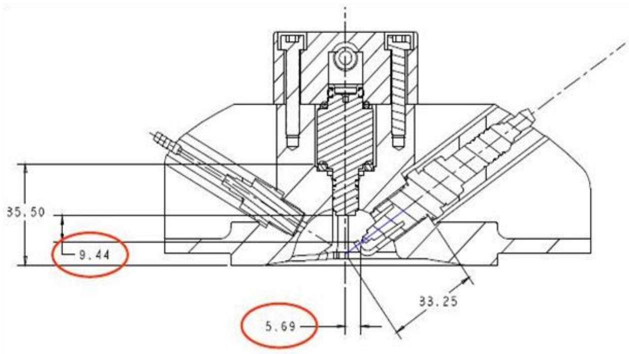

Fig. A.2 The cylinder head design showing the arrangement of direct fuel injector, spark plug and pressure sensor for free-piston linear generator