A Calculation Model of Free-Piston Internal Combustion Engine

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Abstract: *Vehicle contributes greatly to the rapid and strong economic development and other aspects of society. Besides, the operation of the transport impact on health and the environment seriously. Therefore, the study of solutions to improve fuel efficiency and environmental protection is one of the most pressing issues today. The main objective of this study is to calculate and identify important parameters to choose the appropriate design model of the free-piston internal-combustion engine (FPE). That can be used for generating electricity. The contribution of the research has proposed a selection for high-efficiency internal combustion engine (ICE), free-piston engine linear generator. That was not entirely dependent on traditional internal combustion engines, using fossil fuels. This engine will be going to take advantage of excess biogas from remote rural areas to operate and generate electricity for production activities and daily life. The research has completed the initial intentions: a theoretical investigation, calculation, and determination of the engine model. Preliminary results have confirmed the feasibility of proposing the FPE model.*

Keywords: *Free-piston engine, linear generator, hybrid electric vehicle, Internal Combustion Engine*

1. INTRODUCTION

In recent years, along with the increase in population and the growth of economies, there has been a rapid increase in the number of private vehicles. When working, internal combustion engines emit many components that pollute the environment such as carbon dioxide (CO2), carbon monoxide (CO), nitric oxides (NO and NO2), sulfur dioxide (SO_2), hydrocarbons and this substance in high concentrations will directly affect human health, the environment, and the atmosphere. This is one of the great challenges for the fields of internal combustion engine, energy, and environment.

Improvements in the fuel system, intake system to reduce pollution emissions have conducted. However, in recent years, the overall solutions on internal combustion engines while moving from traditional engines to other generation engines to increase efficiency are also of great concern to scientists. In this study, we present a solution that takes advantage of internal combustion engines and electric vehicles while minimizing the limitations of each type. This type of engine knows as a free-piston engine (FPE). That provides a promising alternative to conventional engines in applications such as hybrid electric vehicles or electricity generation [1,2]. As an electrical power generator, the free-piston engine has several potential advantages over conventional crankshaft engines: It is mechanically simple and has a compact design due to the integrated generator and single moving component. On the other hand, the crankshaft generators have crankshaft mechanisms, flywheels, and mechanical couplings. The absence of a crankshaft will reduce the frictional losses significantly since there is no piston slapping resulting from the rotary to linear motion conversion and by reducing the number of moving components, which means less contact friction in the system [3]. Moreover, this 'crank-less' operation produces a faster expansion stroke, which reduces the in-cylinder heat transfer loss [4].

Free-piston engines have been done by many research groups around the world, for example; Chalmers University of Technology simulated a dual cylinder linear engine to investigate the multi-fuel capabilities of this device [5]. In addition, Pempek System (Australia) developed the free-piston 3 (FP3)concept which represents a package of three piston engines [6]. In France, a research done by IFP showedan efficiency within the range of 50 % using high compression ratios and EGR [7]. The German AerospaceCenter (DLR) developed an 8 kW prototype that includes a mechanical springs with an operating frequency of 20 Hz [8]. Toyota announced about a 10 kW single cylinder linear engine, this engine will be used in hybrid vehicles as a system assistance device [9, 10]. By this time, a Korean group investigated the free piston engine using a dual cylinder, spark ignited propane fueled prototype. They explored the feasibilities of the system control and the possibility of transiting from spark to HCCI ignition approach [11].

Based on the aims of the study,the linear generator combined with free-piston engine is one of the generations of IC engine, the power conversion device will be studied extensively due to its potential advantages high efficiency, low emissions, and multi-fuel capability compared to traditional internal combustion engines. The calculation and selection of appropriate design options for FPE adapt to Vietnamese technology conditions play a very important role.This kind of engine will be going to take advantage of excess biogas from remote rural areas to operate and generate electricity for production activities and daily life.The results of this study will be the premise for improvements of the internal combustion engine in general and a feasible solution of free-piston engine to graduallyreplace the traditional internal combustion engine.

2. CALCULATION MODELS OF FREE PISTON INTERNAL COMBUSTION ENGINE

Engine working modes are specialized by the basic values such as power, torque, velocity, etc. Those values can be stabilized or changed in a wide range based on the uses of the engine.

The mode that is used to calculate is called the "Calculation mode". This mode has to be the mode that has great influences on the durability, lifespan of parts with each specific engine, and Idling mode.With a high-speed engine, the calculation mode is the mode with the maximum power, due to the massive air force and momentum. The calculation modes have to be done with full idling mode, with the maximum fuel provided because at that state can the engine achieve the highest temperature and mechanical idling strain.Other calculation modes like local load, when changing the mixture, the ignition time, or fuel injection, etc. are only needed when doing an individual evaluation. The value of maximum pressure and mean pressure can be a difference from 5% to 10%.This is due to many conditions: air condition of the intake process, the fluctuation in the fuel injection process, and air-fuel ratio.

Each of the engine strokeiscomputed basing on the specification in Table 1 end other parameters such as temperature, pressure, volume of each substances at the beginning and the end of the process. Based on the theory of thermodynamics, chemical thermodynamic, theory of ICE, determines the value of the above figures.

Table 1: Internal combustion engine specifications

Specifications	***Parameters***
Number of cylinder	1
Type of engine	2 stroke
Bore	33 mm
Stroke	28 mm
Moving mass	0.580 kg
Nominal compression ratio	7.5/1
Fuel	gasoline

2.1. *Thermodynamic calculations*

In two-stroke engines having no valvemechanism, recharging of the fresh air into the cylinderand discharging of the exhaust gases out of the cylinderis accomplished by ports taking part on the cylinderwall. The opening and closing of the ports areperformed by the piston motion

Clearance volume: $V_c = 3.63\ (cm^3)$ (1)

Total volume:

$V_a = V_h + V_c = 25.4 + 3.63 = 29.03\ (cm^3)$ (2)

Trapped volume: $V_{trapped} = 22.9\ (cm^3)$ (3)

The compression and expansion stroke can be determined:

Compression: $$p_{xn} = p_r\left(\frac{V_{trapped}}{V_{xn}}\right)^{n_1} \quad (4)$$

Expansion: $$p_{xp} = p_z\left(\frac{V_c}{V_{xp}}\right)^{n_2} \quad (5)$$

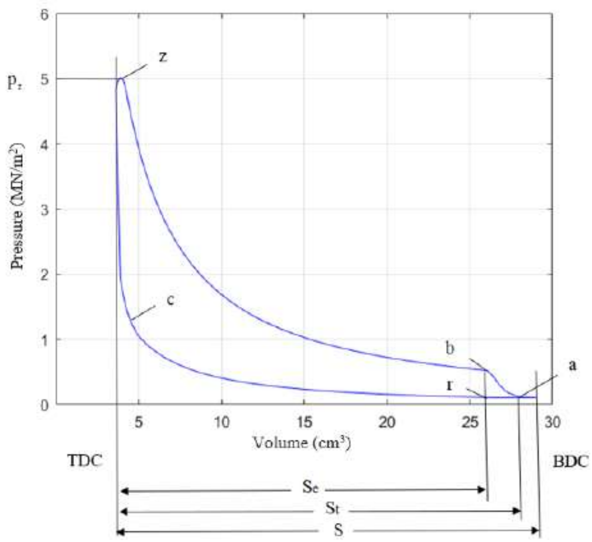

Fig-1: Cylinder -pessure versus cylinder-volume trace for actual cycle

After the exhaust ports open at b point, the cylinder pressure falls rapidly as burned gases flow out of the cylinder into the exhaust system, in a blowdown process as shown in Fig.1, from p_k = 0.112 (MPa) decreases to p_a = 0.106 (MPa) at BDC. The scavenging or transfer ports then open, and once the cylinder pressure falls below the scavenging pressure, fresh charge flows into the cylinder. Burned gases, displaced by this fresh charge, continue to flow out of the exhaust port (along with some of the fresh charge). Once the ports close as the piston starts the compression stroke, compression, fuel-injection and fuel-air mixing in direct-injection engines, combustion, and expansion processes proceed. Fresh charge is fuel vapor and air in engines where fuel and air are "premixed" before entry into the cylinder. Considering the changeof pressurein intake strokeis

$$p_r \approx p_a = 0.106\ (MPa)$$

In compression stroke, cylinder pressure increases to $p_c$at point c and after spark plug ignites, an explosion takes place, pressure increases suddenly top_z = 5.83 (MPa).

But in real model,maximum pressure

$P_z \approx 0.85 p_z = 4.955\ (MPa)$

Maximum pressure has been reached at the$p_z$pointto lacate at10 ÷ 15°after TDC.

We have thoroughly documented and findings a design and operation of the combustion engine and analysis of the combined system in Fig. 2[12]. The calculation results is reported to have achieved 316 W power output at 23.1 Hz, with 33 mm bore and 28 mm maximum stroke.

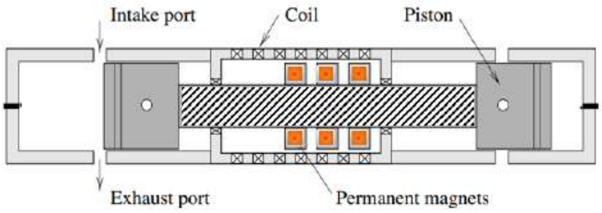

Fig-2: Illustration of the free-piston engine generator

2.2. Dynamic calculations

When crankshaft mechanism is removed for FPEG system, the movement of piston and connecting rod and magnetic coil just be affected by the forces that apply over the pistons, like in the Fig. 3:

Balanced forces acting onFPEG as following :

- Air force inside cylinder from 2 cylinders (F_1,F_r) is pressure inside cylinder after expansion process and compression force in parallel piston.

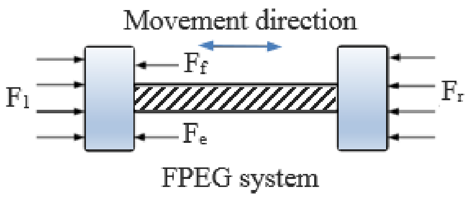

Fig-3: Forces applied over piston-connecting rod mechanism

- Resistance force from linear alternator (F_e) is electromagnetic force from linear alternator.
- Mechanical friction force (F_f)is total friction force from mechanical operation, depend on the structure.
- Inertia force of moving body(F_{qt})is resultant force of the forces on piston - connecting rod mechanism movement.

Dynamic conservation equation affecting on piston - connecting rod has been formulated:

$$\overrightarrow{F_1} + \overrightarrow{F_r} + \overrightarrow{F_e} + \overrightarrow{F_f} = m.\frac{d^2x}{dt^2} = m.\vec{a} \quad (6)$$

If consider the dimension like Fig. 3 weobtain the equation:

$$F_1 - F_r - F_e - F_f = m.\frac{d^2x}{dt^2} = m.a \quad (7)$$

To calculate the resultant force apply on piston-connecting rod mechanism to determine ingredient force in that formula [13], especially connecting rod since it is small and long so easy to deform.

Friction force $F_f$consists of 2 ingredient forces are static friction force and viscous friction force by formula:

$$F_f = F_s + f.\frac{dx}{dt} \quad (N) \quad (8)$$

Where$F_s$is static friction force (N), f is viscous friction coefficient (N.m.s^{-1}) depends on temperature and working speed of FPEG. In working process, velocity of piston and cylinder temperature is low so viscous friction force is negligible.

The electromagnetic force is final ingredient force need to calculate so we can use force balance equation applied on piston - connecting rod, we can determine electromagnetic force F_e:

$$F_e = F_1 - F_r - F_f - F_{qt} \quad (9)$$

3. RESULTS AND DISCUSSION

Based on the calculation studies, the piston dynamics of the free piston engine is shown in Fig. 4. The displacementmeasures how far the piston is from a reference position (x = 0 m) which is at the centerof the combustion chamber. Fig. 5 also compares the FPE piston dynamics with aconventional ICE of the same specifications operating at the same compression ratio andfrequency. A much higher acceleration is found around TDC and BDC of the FPE. Thehigh acceleration is desirable because it provides shorter combustion duration, bettermixing of in-cylinder gas and less time for heat transfer loss.

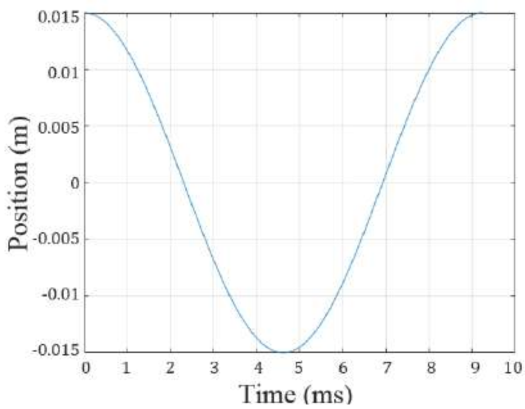

Fig-4: Conventional ICE piston dynamics

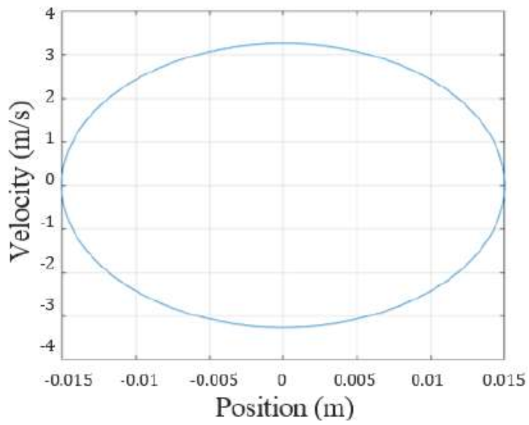

Fig-5: FPE piston dynamics

4. CONCLUSIONS

The research focuses on the modeling and dynamic analysis of the free-piston engine system to understand the characteristic of the engine operation. The objective of the proposed research is to calculate and identify important parameters to choose the appropriate design model of the free-piston internal-combustion engine (FPE). The advantage of the model lies in its simple design with few moving parts, giving a compact engine with low maintenance costs, reduced frictional losses, and better fuel economy by eliminating the crankshaft. FPE as an alternative of the conventional internal combustion engines (ICE) offers the ultimate flexibility for variable compression ratio.

ACKNOWLEDGEMENT

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