Investigation of performance of free-piston engine generator with variable-scavenging-timing technology under unsteady operation condition

Abstract

A substantial number of free-piston engine generators still use cross scavenging, which limits scavenging quality and performance under unsteady condition. Variable-scavenging-timing technology is a novel method to change the fixed scavenging process so that the scavenging process is coordinated with piston movement. This paper investigated effects of the variable-scavenging-timing technology implemented on the free-piston engine generator. In designed case that the free-piston engine generator has different compression ratios, cyclic variation and frequency, the variable-scavenging-timing technology improved the scavenging quality and performance. The delivery ratio of the free-piston engine generators applied with the variable-scavenging-timing technology decreased about 0.3 at different compression ratios, 0.18 at different cyclic variations and 0.2 at different frequencies on average. The trapping efficiency of FPEG rose over 70 % and the scavenging efficiency was maintained at least 85 %. As for different compression ratios, the power increased by an average of 0.18 kW. While the power was improved 0.2 kW on average under the other condition. The increase of indicated efficiency had an increase varying from 1 % to 2 % compared with before. The changes of the performance about free-piston engine generators under different unsteady condition also were discussed.

Key words: free-piston engine generators; scavenging efficiency and performance; variable-scavenging-timing technology; compression ratio; frequency; cyclic variation

1 Introduction

1.1 Background

In order to cope with climate warming and excessive energy exploitation, people are more inclined to seek new environmentally friendly power plants with better performance. Since the technology of four-stroke internal combustion has encountered

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kinds of bottlenecks, two-stroke internal combustion became one of the research objectives for its potential indicated performance and efficiency, and thus attracted more and more attention. However, it is not as precise and sophisticated as four-stroke combustion engine. In order to overcome the inherent shortcomings of two-stroke internal combustion engine, the free-piston engine generator (FPEG) thus emerged [1].

FPEG consists of two free-piston engines and a linear alternator, with variable compression ratio, compact structure and other characteristics [2]. Compared with traditional two-stroke combustion, it requires less mechanical compartments and is driven by linear piston force, which helps reduce overall complexity and facilitates the use of algorithmic control, resulting in better device maneuverability and less mechanical loss. Variable compression ratios help improve efficiency and realize the potential to meet a wide range of power requirements [3]. In addition, FPEG has potential applications as a range extender for hybrid electric vehicles, which gives it the ability to convert electrical energy and kinetic energy.

Due to the characteristics of the FPEG, it is believed that FPEG should be popularized to ensure its stable operation [4]. Combustion is a dynamic response. For example, if its compression changes, its piston motion must become inconsistent. Optimal ignition timing and other factors need to be adjusted. On the basis of maintaining the continuous operation of FPEG, it is proposed to transform the internal structure and external combination of new technology[5]. For the sake of internal integrity, one attempt is to optimize intrinsic scavenging using new methods. It is suggested that scavenging is matched with piston displacement to create a suitable environment for the generation and scavenging of internal combustion engine. In this paper, it is identified as variable-scavenging-timing technology. The variable-scavenging-timing technology is to provide appropriate scavenging mode for different operating modes of free-piston, which means scavenging serves good performance and is not limited to structure. In recent years, many researchers studying the FPEG seem to be focused on improving efficiency and performance. They built different simulation models and ran some experiments on their prototypes around the world. However, problems about scavenging are rarely focused as a key issue, and there is a phenomenon that study on new scavenging technology to be shelved after failing to the extent of the exploration. There are inadequate cases about the free-piston engine generator with new scavenging method.

Nomenclature table	
BMEP	Brake mean effective power
ATDC	after top dead center
BTDC	before top dead center
ε	compression ratio
CA	crank angle
Var	variation (mm)

VST	Variable-scavenging-timing
m	mass of the left piston(kg)
F_l	the in-cylinder gas force from the left cylinder (N)
F_r	the in-cylinder gas force from the right cylinder (N)
F_f	the frictional force the assembly of the piston (N)
F_g	the resistance force from linear electric motor (N)
C_f	the viscosity friction coefficient (N/(m·s^{-1}))
K_v	the coefficient of electromagnetic resistance (N/(m·s^{-1}))
v	the velocity of the piston (m/s)
η_s	the scavenging efficiency
η_t	the delivery ratio
η_{te}	the trapping efficiency
$\dot{m}$	the instantaneous air flow (kg/s)
m_0	the mass of fresh air trapped in the cylinder(kg)
m_r	the mass of the exhaust gas trapped in the cylinder (kg)
m_t	the mass of the intake air (kg)
m_{sv}	The mass required to fill the swept volume (kg)
ρ	gas density at the inlet manifold (kg/m^3)
v_m	the total average flow velocity at the port (m/s)
n	the engine speed of the FPEG (rpm)
ϕ	The angle of the air port (CA°)
A_f	the instantaneous cross section area of air flow (m^2)
x_b	the mass fraction burned
t_0	the beginning of the combustion (CA°)
Δt	the duration of the combustion (CA°)
a	Vibe coefficients
m	Vibe coefficients
h_c	heat transfer coefficient
B	the characteristic length of the bore (m)
p_c	the cylinder pressure (Pa)
T_c	The cylinder temperature (K)
C	empirical parameters
η	empirical parameters
ω	the gas velocity (m/s)
η_i	the indicated efficiency
b_i	the fuel consumption per hour (g/(kW·h))
H_u	the low heating value of the fuel (MJ/Kg)

P_b	brake power of the free-piston engine (kW)
L	the piston stroke (m)
A	the area of the piston head (m^2)
V_s	the sweeping volume (m^3)
$\bar{p}_b$	the brake mean effective pressure (MPa)

1.2 Literature review

In the 1920s, the study of free-piston engine began to appear, and Pescara put forward the numerical free-piston internal combustion engine model [6]. Since 1930, different types of free-piston engine have emerged. However, due to the slow development and many technical bottlenecks in the early stage, it was difficult for formal industrial products to appear before the public. At that time, free-piston engines were used as air compressors and gas generators to complement conventional internal combustion engines and gas turbines [7]. It can be classified as symmetric and asymmetric. In addition to diesel, it can also be used as fuels such as heavy oil, crude oil and natural gas.

Researchers from West Virginia University have proposed a spark-ignited free-piston linear engine that reports achieving a cylinder diameter of 36.5 mm and a maximum stroke of 50 mm in continuous operation [8-10]. They also simulated the motion characteristics and other performance parameters of the piston by combining experimental data with basic theory. However, in the absence of an active control method for the electromagnetic force and piston motion to regulate its operating conditions, the FPLE ultimately produced a power output of 316 W and energy efficiency of 11 % in converting fuel to electricity.

Mikalsen and Roskilly studied a numerical model of a single-cylinder FPLA generated by spark ignition [11, 12]. They developed a series of theories about the effects of piston motion, compression ratio, scavenging system and approaches of ignition functioning on the combustion [13, 14]. Jia et al. proposed a new approach of using cascade control to help the machine maintain stable operation [15-17]. Based on the accumulated experience, Ugochukwu Ngwaka et al. analyzed the parameters of a semi-closed-loop linear joule engine generator using argon and oxy-hydrogen combustion [18]. They found that extending the exhaust time of the expander could improve system efficiency and power output. It is suggested that free-piston engines should pay attention to scavenging.

Bergman and Fredriksson et al. presented a CFD of two-stroke free-piston converter with single-flow scavenging [19]. They studied the performance of the single-flow scavenging under the conventional and HCCI (Homogeneous Charge Compression Ignition) modes [20]. In order to avoid complicated calculation, the piston motion is fixed. This method was further used in the subsequent simulations or experiments, in which ignition timing was changed to achieve different results. The results showed that under the traditional mode, low compression ratio led to low emission. And Blarigan et al. from Sandia National Laboratories developed an optimized scavenging system using Kiva-3V computational fluid dynamics (CFD) code and a zero-dimensional piston dynamics model to improve power, economy, and emission performance[21]. In addition to the scavenging performance, the design schemes of circulation, various charge delivery options and single flow scavenging were also discussed. The results showed that the single-flow scavenging system had a constant and low value of thermal charging environment.

Sofianopoulos et al., at Stony Brook University conducted experiments on the scavenging process and found that in the early stages of the scavenging process, fresh charge with low momentum ran into the exhaust passage, reducing trapping efficiency [22]. The fresh charge with high momentum brought into the combustion chamber and exhaust gas produced in the final stage of scavenging affected the cycle loss. The residual combustion waste in scavenging port would reduce scavenging efficiency. Although the boosting pressure might improve the scavenging efficiency, the initial cycle loss was bound to increase, leading to a decrease in the trapping efficiency. Therefore, Lu et al. from Beijing Institute of Technology focused on the scavenging ports width to scavenging process based on the opposed-piston two-stroke engine and explore the limit of scavenging limit by adjusting the structure [23]. Their results indicated that the width of exhaust ports had a greater impact on the scavenging efficiency and that when load and speed increased, the timing of free exhaust would decrease while that of the scavenging process would increase.

In order to surge the diversity of researches on scavenging of free-piston, Yuan et al. used a coupling model to explore the difference between free-piston linear engine and conventional two-stroke engine [24, 25]. Compared with the conventional two-stroke engine, it a has shorter scavenging period and greater movement speed [26]. Therefore, the higher the speed, the more residual combustion wastes it would produce. The faster piston motion results in the loss of scavenging efficiency, with more residual gas coming from the cylinder. In addition, he also claimed that late ignition and long combustion duration are conducive to improve scavenging efficiency to the 96.82% at the highest and a little in-cylinder fresh charge [27]. Dong et al. studied the characteristics of gas consumption, which is scavenging flow through the valve per unit time in the reference. [28]. They believe that tail gas back pressure has a great influence on gas consumption, showing a trend of intersection between tail gas consumption curve representing high gas consumption and curve representing low gas consumption. In order to obtain the same mass flow, when the mass flow is lower than the crossing point, the lower the exhaust back pressure is, the lower the inlet compression ratio which means the ratio of scavenging pressure to exhaust pressure is. Above the crossing point, the lower the exhaust back pressure, the smaller the required intake compression ratio.

In addition, Mao and Feng et al. used a multi-dimensional CFD model to conduct a global study on the loop scavenging piston linear engine ignited by spark [29]. The simulation results showed that proper scavenging efficiency and trapping efficiency required higher effective stroke to bore ratio, a larger disc overlapping angle and a low supercharge. Gibbes and Hong proposed a free-piston engine alternator with piston-mounted passive inlet poppet valve and its relative two-dimensional axis-symmetric CFD scavenging model [30]. Wang et al. from Tianjin University used a three-dimensional CFD model based on piston displacement to analyze the single-flow scavenging of opposed-piston and opposed-cylinder hydraulic free-piston engines [31]. The simulation results showed that the radial angle of the inlet had an important effect on the scavenging performance, and that the effect of piston movement on the ventilation performance was also worth further study. Zhaoping Xu et al. proposed a prototype of a novel internal combustion linear generator integrated power system [32]. It is found that variable intake stroke length can be used to achieve different power output, and thermal efficiency can be improved by increasing expansion stroke length when the compression ratio is fixed.

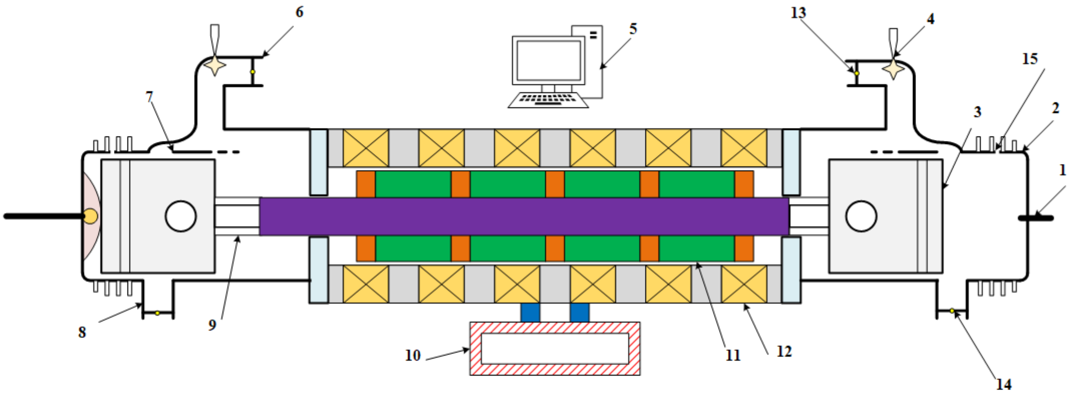
Ensuring the relative stability of the gas exchange process is very important to maintain the stability of the air-fuel ratio and has a fundamental impact on combustion. As far as the existing simulation and experiment are concerned, most of the literatures reflect the results and laws of fixed scavenging process and steady working condition. Due to the movement characteristics of the FPEG, unsteady working conditions will be encountered in the experiment. In recent years, scavenging under the unsteady operation conditions such as different compression ratios or cyclic variations have been paid attention in the research about FPEG. The way to improve the performance and scavenging efficiency of the FPEG by solving the problem of unstable working environment has not been widely studied at present. The fixed scavenging hardly meets the demand in this aspect and the new technology should be introduced.

In this paper, a series of numerical simulations are carried out by using the control variable method, which responds to unsteady conditions by changing the scavenging process. By comparing the effect of conventional cross scavenging and variable-scavenging-timing technology on the performance and scavenging efficiency of the FPEG, some suggestions for improving the scavenging method are proposed. Specific results and discussion are described in the further section.

2 System configuration and problem description

2.1 FPEG configuration

The FPEG (schematic diagram is shown in Fig.1, with the corresponding prototype designed in the authors' group) is designed as a dual-cylinder, dual-piston engine with two-stroke thermodynamic cycle that it uses spark ignition instead of compression ignition [33]. Two opposing free-piston engines are combined with a linear motor located between the two cylinders. In addition, FPEG has the characteristics of compact structure and high power to weight ratio. The important moving parts of the system are the two pistons connected with the engine of the linear generator. The control system is adopted to ensure the stable operation of FPEG. Compared with an internal combustion engine using a conventional crankshaft linkage mechanism, FPEG has fewer components, which makes it easier to assemble and significantly more mechanically efficient.



1. Spark plug 2. Cylinder 3. Piston 4. Fuel injector 5. Control system 6. Air-intake tube 7. Scavenging port 8. Exhaust port 9. The connecting rod 10. External load 11. Mover 12. Stator 13.Intake valve 14.Exhaust valve 15.lubrication oil hole

Fig. 1 Prototype schematic figure

Fig. 2 Prototype figure

For the air port scavenging type, the opening/closing of the air port is determined by the movement of the piston, and the timing is determined by the displacement of the piston. The FPEG prototype designed by the author’s group adopts cross-scavenging type, that is, the inlet and exhaust ports are not on the same side. This scavenging method mainly uses the pressure difference to sweep up the exhaust gas and take in, which means that excessive air is needed. Fig.1 shows that the power stroke occurs in the left cylinder and the scavenging process occurs in the right cylinder. The prototype specifications and the values of the input parameters are listed in Table 1. Some parameter settings refer to related literature [34]. TDC and BDC are the abbreviation for top dead center and bottom dead center.

Table 1

The geometric parameters of FPEG.

Parameters	Value (Unit)

Bore	52.5 (mm)
Maximum stroke	54.0 (mm)
Maximum effective intake flow area	1000 (mm^2)
Maximum effective exhaust flow area	500 (mm^2)
Intake port opening angle	108 (CA°,ATDC)
Intake port closing angle	108 (CA°,BTDC)
Exhaust port opening angle	80 (CA°,ATDC)
Exhaust port closing angle	80 (CA°,BTDC)

2.2 Description of scavenging problem

For conventional two-stroke combustion engine, the scavenging efficiency of the cross-scavenging type is limited due to its relatively shorter gas changing time and scavenging loss. Therefore, its thermal efficiency is considered to be worse than that of the four-stroke combustion with independent intake/exhaust process. For a free-piston engine, it can be seen as an unstable two-stroke internal combustion engine with variable compression ratio that seems more difficult to control than a conventional crankshaft two-stroke engine.

Since free-piston engines often operate under different conditions, it is obvious that the engine stroke and corresponding compression ratio are variable. For traditional cross-scavenging where the opening and closing angles of the valve is fixed, it cannot always match with the working condition of the free-piston engine to achieve better scavenging performance. Therefore, free piston engines cannot burn well organized air-fuel mixture. If the air-fuel mixture falls outside the normal ignition range, it may result in inadequate combustion or even a misfire. In addition, due to the elimination of mechanical systems, the cyclic change of free-piston engine can make their scavenging performance worse.

In order to develop free-piston engine, a more efficient system was designed to ensure higher scavenging efficiency and to accommodate erratic operation. Variable-scavenging-timing technology is considered to be a strategy for improving performance. It is advised that the intake/exhaust valves are installed in the intake/exhaust ports, which can achieve the stepless adjustment of the intake/exhaust flow area. In this way, the degree of valve opening can be controlled to change the effective area of intake/exhaust ports. The effective area of intake/exhaust ports is depended on the operation rather than the piston motion. Similarly, the openning and closing of intake/exhaust can be decided by the operation on the intake/exhaust valve. And their time about the openning and closing also can be controlled to change the scavenging progress.

However, due to the lack of research on the actual scavenging process of FPEG, researchers may set too high scavenging parameters in the simulation, and it is often difficult to achieve the expected value in the experiment. In order to verify the improvement of FPEG performance by variable-scavenging-timing technology, the numerical simulation and simulation are emphatically carried out in this paper.

According to the characteristics of FPEG, three instabilities are considered in this study, and the detailed results will be given in the next chapter:

a) The operation in different frequencies with fixed ignition time and stroke;

b) Different compression ratios with fixed stroke and frequency;

c) The cyclic variation at the same frequency and compression ratio.

3 Numerical modelling and simulation method

3.1 Numerical modelling

3.1.1 The FPEG dynamic equations

During the operation of the FPEG system, the forces acting on the pistons with the mover are generally composed of four parts, *i.e.* the in-cylinder gas forces from each cylinder, the electromagnetic force of the linear electric machine, the frictional force from the mechanical parts, and the inertial force of the moving parts. According to Newton's second law, the dynamic equations of the piston can be expressed as:

$$\mathrm{m}\frac{d^2x}{dt^2} = F_l - F_r - F_f - F_g \tag{1}$$

where m (kg) is the mass of the left piston, x (m) is the displacement of the piston, F_l (N) is the in-cylinder gas force from the left cylinder, F_r (N) is the in-cylinder gas force from the right cylinder, F_f (N) is the frictional force the assembly of the piston needs to be overcome during the operation, F_g (N) is the resistance force from the linear electric motor when it acts as a generator.

The frictional force implemented on the piston and the connecting rod is usually dominated by viscosity friction of lubricating oil, which can be described as:

$$F_f = C_f \frac{dx}{dt} \tag{2}$$

where C_f (N/m·s^{-1}) denotes the viscosity friction coefficient.

In the process of stable operation, the linear electric machine is used as a generator to provide resistance force. Based on the electromagnetic theories, the resistance force F_g (N) can be expressed as:

$$F_g = K_v \cdot v \tag{3}$$

where K_v (N/(m·s^{-1})) represents the coefficient of electromagnetic resistance, v (m/s) is the velocity of the piston.

3.1.2 Definition of scavenging performance

The amount of fresh air or air/fuel mixture entering the cylinder in each cycle is an important indicator to evaluate the quality of the engine's gas exchange process, and there are three parameters for evaluation, *i.e.* scavenging efficiency, delivery ratio the mass of intake gas flow and trapping efficiency.

The scavenging efficiency reveals the quality of scavenging, which is defined as:

$$\eta_s = \frac{m_0}{m_0+m_r} \tag{4}$$

where η_s is the scavenging efficiency, which is usually between 0.7 and 0.9. m_0 (kg) is the mass of fresh air trapped in the cylinder and m_r (kg) is the mass of the exhaust gas that is trapped in the cylinder.

The delivery ratio is applied to describe the ability of absorbing fresh air, and can be given as:

$$\eta_{dr} = \frac{m_t}{m_{sv}} \tag{5}$$

where η_{dr} is the delivery ratio, which is normally in the range of 1.0 to 1.5 without the crankcase (when there is a crankcase, it is then supposed to be from 0.5 to 0.9). m_t (kg) is the mass of the intake air. m_{sv} (kg) is the mass required to fill the swept volume.

The intake air mass is expressed by the equation. Ignoring the effect of temperature difference, the mass of intake air can be expressed as:

$$\dot{m} = \frac{60\rho v_m}{n}\int_{\phi_2}^{\phi_1} A_f \tag{6}$$

where $\dot{m}$ (kg/s) is the instantaneous air flow. ρ (kg/m^3) is gas density at the inlet manifold. v_m (m/s) is the total average flow velocity at the port. n (rpm) is the engine speed of FPEG. ϕ (CA°) is the angle of the intake-air port and A_f (m^2) is the instantaneous cross section area of air flow when the intake port is open.

The trapping efficiency is defined by the equation:

$$\eta_{te} = \frac{m_0}{m_t} \tag{7}$$

where η_{te} is the trapping efficiency, which is usually less than 0.9.

3.1.3 Thermodynamic model

To estimate the completion of FPEG combustion, a single-zone Wiebe function is employed for depicting the proportion of burned fuel and is expressed as:

$$x_b = 1 - exp\left[-a\left(\frac{t-t_0}{\Delta t}\right)^{m+1}\right] \tag{8}$$

where x_b is the mass fraction burned, t_0 (CA°) is the beginning of the combustion, Δt (CA°) is the duration of the combustion which stems from the magnanimous experimental data and m is the parameter to fit the actual mass fraction burned curve, which is usually taken as 2. a is also a constant that can be changed to meet the computational needs, and is typically defined as 5 in the two-stroke combustion.

With regard to heat transfer coefficient h_c, Woschni's correlation is used to calculate the heat transfer loss, which is written as

$$h_c = CB^{\eta-1}{p_c}^{\eta}\omega^{\eta}{T_c}^{0.75-1.62\eta} \tag{9}$$

where the bore length B (m) determined for the characteristic length, p_c (Pa) and T_c (K) are the cylinder pressure and temperature respectively, C and η are empirical parameters, and the gas velocity ω (m/s) is used for a two-stroke engine without swirl.

3.1.4 Main evaluation indexes of the performance

For the overall engine performance of the FPEG, it occurs in brake power and its indicated efficiency. They are expressed as

$$P_b = \frac{\bar{p}_b V_s n}{30} \tag{10}$$

$$\eta_i = \frac{3.6\times10^3}{H_u b_i} \tag{11}$$

$$V_s = LA \tag{12}$$

where η_i is the indicated efficiency, b_i (g/(kW·h)) is the fuel consumption per hour and H_u (MJ/Kg) is the low heating value of the fuel. P_b (Kw) is the brake power of the free-piston engine, L (m) is the piston stroke, A (m^2) is the area of the piston, V_s (m^3) is the volume at which the engine sweeps and $\bar{p}_b$ (MPa) is the mean effective pressure of the brake.

3.2 Simulation method

Matlab/Simulink and AVL Boost are used for coupling simulation of the system model. As mentioned earlier, the force acting on the piston can be divided into three main types: the gas force generated by the left and right cylinders, the electromagnetic force generated by the linear generator, and the friction force acting in the opposite direction of the piston motion. According to the dynamics formula in Section 3.1.1, the piston displacement profile was obtained through the Matlab/Simulink model. Fig.3 represents four sub-models in the simulation model. The in-cylinder gas force sub-model takes compression/expansion, gas ignition, scavenging and heat transfer into account. The friction sub-model is generally used to calculate the friction force arising from the piston rings and the cylinder wall during the operation. Friction is the resistance opposite to the direction of the piston velocity. The force sub-model of linear motor mainly describes the force that FPEG drive component receives due to electromagnetic shock during operation. The results of Matlab/Simulink model are imported into AVL BOOST to simulate the characteristics of FPEG. Detailed model description and validation results of the Matlab/Simulink model can be found the authors' previous publications [35].

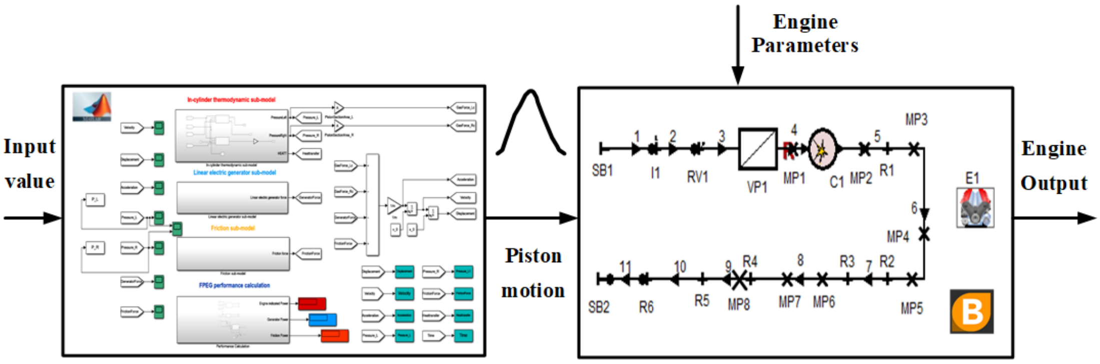


Fig. 3 Matlab & AVL Boost combined simulation illustration

The traditional two-stroke structure is used for modeling, and the pumping loss and most of the combustion loss are not considered when simplified. In the AVL BOOST model, some initialization settings are required such as inlet and outlet environment, initial temperature in cylinder and some thermal parameters, and the key features are indicated in Table 2. Some of the combustion-related settings refer to some literature and previous experiments [36].

Table 1

The primary initial parameters

Parameters	**Value (Unit)**
System operating frequency	30 (Hz)
Inlet temperature	293 (K)
Inlet pressure	1.181 (bar)
Outlet temperature	500 (K)
Outlet pressure	0.981 (bar)
Air-to-fuel ratio	12.5
Geometrical crankcase compression ratio	1.2
Initial combustion duration	40 (CA°)
Initial start of combustion	15 (CA°,BTDC)

Considering that the cylinder head is scavenged by orifice, it is suggested to introduce the curve of effective flow area in the cylinder modular. Fig.4 is the section of the effective flow area measured from the cylinder used in the design prototype. Due to the limitation of the actual size of the intake and exhaust ports, the effective flow area has a certain range. Different effective flow area distributions are used at the intake and exhaust ports to facilitate the scavenging process. Under flexible operating conditions, these scavenging angles could be changed by piston movement. For example, it is assumed that the opening Angle of the intake timing can be adjusted to ensure that there is sufficient fresh air to remove residual heat in the cylinder. The effective flow area profile of the piston motion based on the geometry of the prototype combined with the design will be implemented in the AVL BOOST model

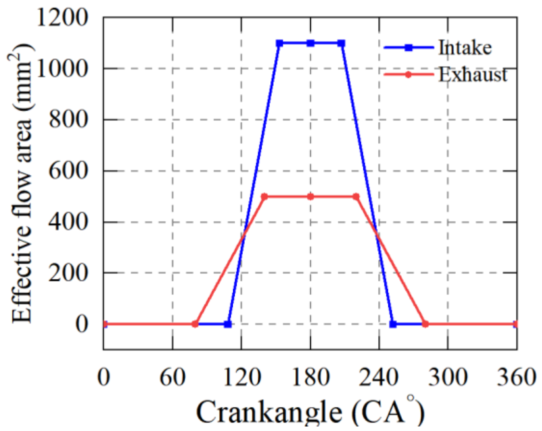


Fig. 4 Effective flow area illustration

In academic articles, two simple models for scavenging, namely perfect displacement model and complete mixing model, are introduced as the boundary of scavenging performance. The former model assumes that the intake gas and the combustion gas do not mix, while the latter assumes that the intake gas and the combustion gas mix completely and instantaneously. The former model implies the upper bound of the scavenging efficiency, while the latter one implies the lower bound. Most of the scavenging efficiency curves designed by users are obtained by these models, which are in line with the actual data and expected indicators. Although the shapes of different simulation curves are different, scavenging efficiency generally tends to be positively correlated with delivery ratio. In AVL Boost's simulation, it is used by the user to define the purge model. In this article, the curve is plotted in Fig.5, which is based on some reference[37].

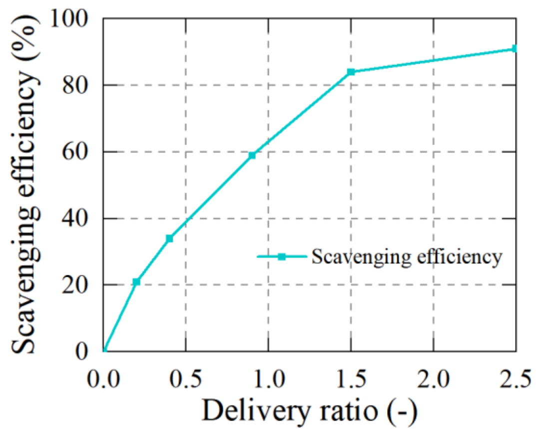


Fig. 5 User-defined scavenging efficiency

During the operating of the FPEG, the engine compression ratio and stroke could be flexibly changed according to different working conditions while the engine design parameters remain unchanged throughout the simulation. Five simulation cases of different working conditions are selected to further discuss the influence of different working conditions on the scavenging characteristics and engine performance of FPEG, as shown in Table 3. ε represents the compression ratio and Var refers to the cyclic variation near the TDC. The different combustion durations at the different compression ratios are 45 CA°(ε=7), 44 CA°(ε=8), 43 CA°(ε=9), 42 CA°(ε=10) and 41 CA°(ε=11). The starts of combustion are before bottom dead center 15 CA°(ε=7), 14 CA°(ε=8), 13 CA°(ε=9), 12 CA°(ε=10) and 11 CA°(ε=11). As for the other cases, they are maintain the original setup.

Table 3

Simulation cases with different working conditions

Parameters (Unit)	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**
ε (-) (Var=0, frequency=30 Hz)	7	8	9	10	11
	Case 6	**Case 7**	**Case 8**	**Case 9**	**Case 10**
Var (mm) (**ε**=7, frequency=30 Hz)	-2	-1	0	1	2
	Case 11	**Case 12**	**Case 13**	**Case 14**	**Case 15**
Frequency (Hz) (**ε**=7, Var=0)	28	29	30	31	32

In addition, cyclic variations should be taken into account. The variable-scavenging-timing technology also focuses on the partial optimization of scavenging. In order to highlight the advantages of variable-scavenging-timing technology, the displacement generated by Matlab is applied to the operation of the AVL BOOST model, which has different changes in each cycle. According to the displacements, the curves of effect flow area fluctuate within an appropriate range. Its function is to keep the FPEG proper air intake and scavenging smoothly.

4 Results and discussion

4.1 Influences with different compression ratios

The prototype usually works at a compression ratio of 10 and a stroke of 54 mm. However, due to the lack of stability, different compression ratios are produced in operation. As shown in Fig.6, displacement also shows diversity. Each compression ratio corresponds to its own stroke, TDC and BDC. Under the condition of constant stroke, the increase of compression ratio is closely related to the contraction of piston displacement and the backward shift of TDC and BDC. Different compression ratio would destroy the dynamic balance of piston motion, so that the piston deviates from the ideal operating range. At this time, the existing working conditions often conflict with the piston movement displacement. Scavenging, combustion and other processes are more or less affected. Obviously, the performance of FPEG is far from satisfactory.

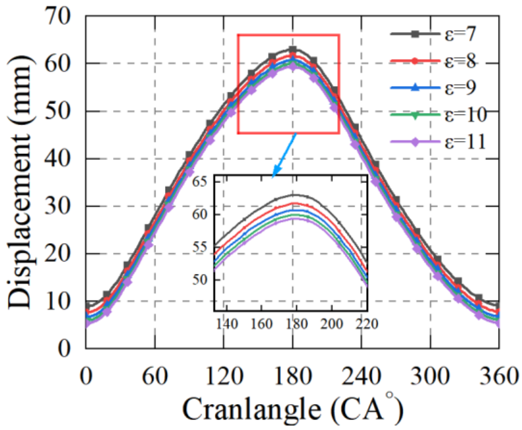


Fig. 6 Displacement with different compression ratios

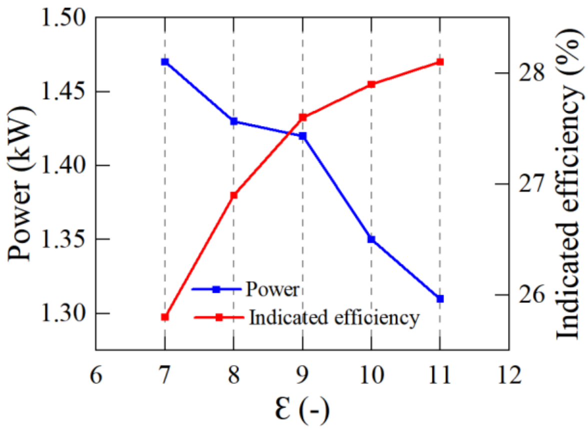


Fig. 7 Performance with different compression ratios

The amplitude of the power and indicated efficiency are shown in Fig.7. The results show that the highest indicating efficiency is about 28.1 % and the lowest indicating efficiency is about 25.8 %. The maximum power and minimum power of cross scavenging are 1.47 kW and 1.31 kW. In these cases, it can be learned that the indicated efficiency increased with the increase of compression ratio. In other words, the amplification of the indicated efficiency does not seem to have reached its limits, implying that there is still room for optimization. On the contrary, power has a tendency not to rise at higher levels. It is pointed out that this piston motion may be suitable for medium compression ratio.

The indicated efficiency is positively correlated with the compression ratio from many angles, but the power does not always behave well on this PFEG. In fact, this piston motion of FPEG is different from traditional two-stroke combustion and may not match past experience and is reflected in practice. Irregular piston movement displacement, which means the piston motion of FPEG is unlike traditional two-stroke internal combustion engine and usually asymmetry is more sensitive to slight changes representing the instability in compression ratio, movement frequency and the variation which could lead to the different performance and scavenging quality, which might lead to abnormal phenomena presented as fluctuation in performance or the other evaluation index. Therefore, different compression ratios directly affect pressure transformation. As can be seen from Fig.8, the scavenging time is too long and the inlet and exhaust angles overlap greatly, which might lead to the difficulty in effective operation of some strokes because the pressure at this time is close to the intake pressure. The higher the compression ratio, the more serious the situation. As can be seen from Fig.8, the equivalent is relatively low, and the maximum pressure is inconsistent with the demand at high power, which also explains the reason why the power is not high enough in the design and simulation.

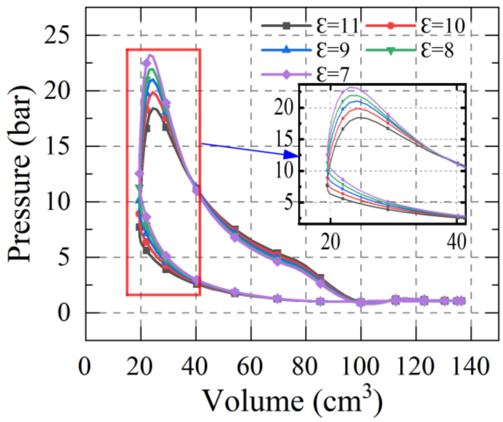


Fig. 8 P-V with different compression ratios

In addition, continuous improvement in indication efficiency is noted. For one thing, in this case, the speed is almost constant, and the settings are the same except for the compression ratio. Therefore, according to the above discussion, fuel loss, friction loss and other losses should not differ much. For another thing, the heat transfer loss accounts for a large proportion of the total energy consumption. There is an obvious change in heat transfer loss in Fig.9. As the compression ratio increases, the heat transfer loss decreases. Because in this case, the higher the compression ratio is, the lower the maximum temperature is. Temperature difference is related to heat transfer loss. Although power might be limited by high compression ratios for various reasons, the percentage of power in the effective power increases as losses decrease. From this perspective, it is understandable why the high compression ratio in this paper leads to high indicating efficiency. Therefore, as the compression ratio increases, the FPEG has higher indicating efficiency, but more energy is consumed in the other part of the braking power output, indicating that the model is suitable for medium compression ratio when piston movement and other conditions are similar to the simulation settings.

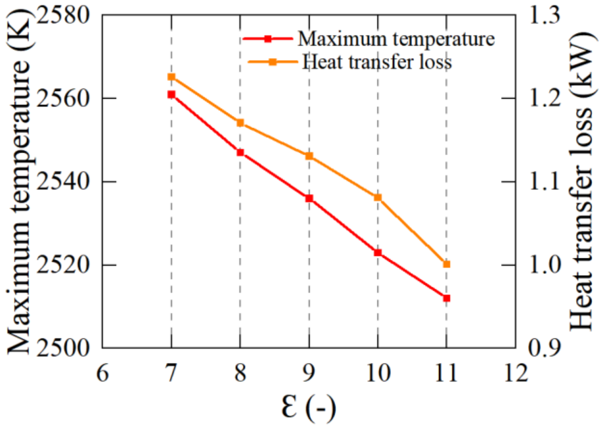


Fig. 9 Maximum temperature and heat transfer loss with different compression ratios

Compression ratio not only affects mechanical properties, but also changes scavenging rate. The scavenging process is managed by piston movement due to the use of scavenging with vents. Fig.10 and Fig.11 shows the different effective flow area of intake/exhaust for different compression ratios. With the influence of compression ratio on piston movement and displacement, scavenging capacity also change. As can be seen from Fig.12, scavenging efficiency between different compression ratios tend to have a small gap. The highest scavenging efficiency is 86.7 % and the lowest is 85.1 %. The delivery curve fluctuates gently. It can climb as high as 1.671 or as low as 1.66. The scavenging efficiency curve is wavy, indicating the existence of compression ratio, which makes the FPEG work inefficiently. As a result of the use of user-defined models, as mentioned in Section 3.1.2, the delivery ratio largely determines the scavenging efficiency. The delivery ratio has a great influence on scavenging efficiency, and the similar delivery ratio leads to the similar scavenging efficiency.

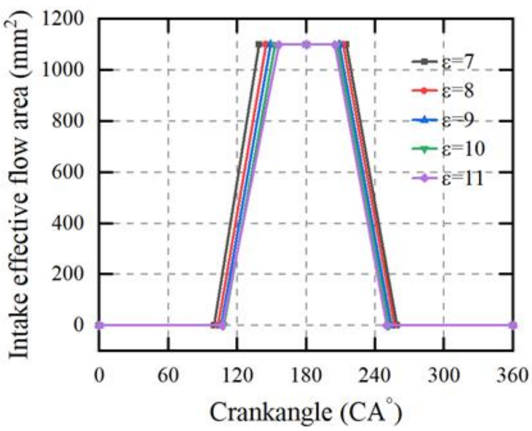


Fig. 10 Intake effective flow area with different compression ratios

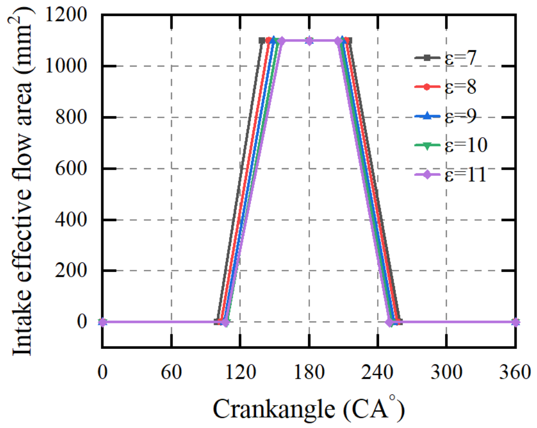


Fig. 11 Exhaust effective flow area with different compression ratios

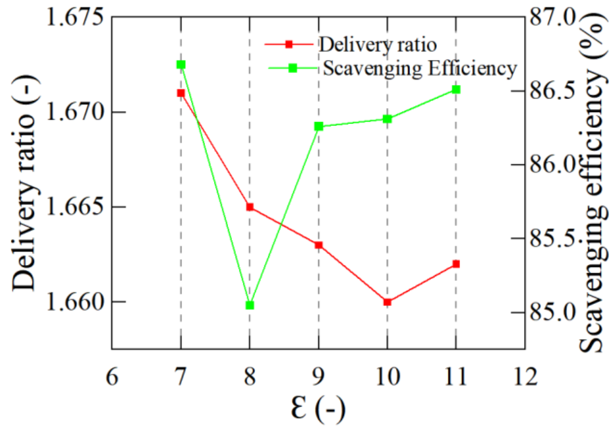


Fig. 12 Delivery ratio and scavenging ratio with different compression ratios

Due to the constant opening and closing time of traditional cross-flow scavenging, the FPEG cannot show its advantages over traditional two-stroke engine in this scavenging mode. FPEG can benefit from variable-scavenging-timing technology when ignition time, fuel injection volume, and other setting conditions that affect performance remain constant. According to the results of previous studies, it is suggested that the overlap of scavenging angle should be reduced to reduce unnecessary scavenging loss. The results indicate that the opening angle of intake is adjusted from 108 CA° to 120 CA° and the closing angle of intake is changed from 252 CA° to 240 CA°. At these compression ratios at which FPEG works, the machine integrated with variable-scavenging-timing technology tends to perform better. In terms of power, the FPEG with this technology is obviously more ideal. After several iterative calculations, the power in Fig.14 remains above 1.45 kW. As can be seen from Fig.13, the FPEG using variable-scavenging-timing technology (VST) works at an indicated efficiency of no less than 27 %, which is more efficient and more stable than the cross-scavenging FPEG. There are obvious differences between the two descriptions for the delivery ratio generated by different scavenging modes.

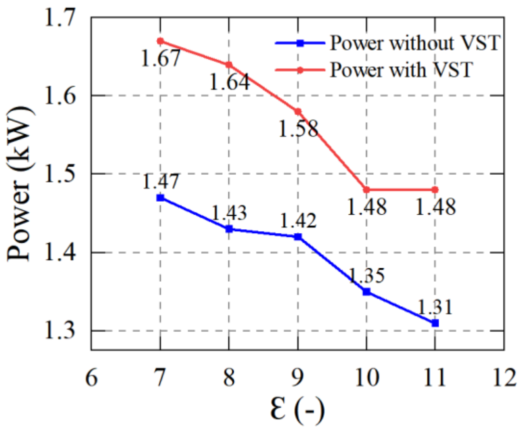


Fig. 13 Comparison of the power

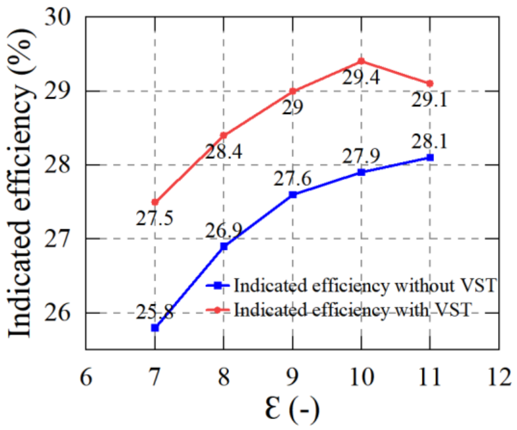


Fig. 14 Comparison of indicated efficiency

There are many reasons for the above phenomenon, and the main consideration is the possibility related to scavenging. The variable-scavenging-timing technology enables scavenging process to adapt to different compression ratio, reduces unnecessary gas loss, and makes scavenging more effective. Due to the control of fuel injection ratio, FPEG has a similar combustion environment, resulting in the same trend of power variation under such conditions. In other words, the variable-scavenging-timing technology may be beneficial to improving electricity and maintaining its regular pattern, since there is sufficient gas mixture to burn. This functionality is beyond the scope of cross scavenging.

In terms of indicated efficiency, the FPEG using variable-scavenging-timing technology is superior to that using cross scavenging. On the one hand, it is clear that variable-scavenging-timing technology offers more appropriate magnitude of fresh air for the mixture of air and fuel. The correct air-fuel ratio means that the combustion has reached one of the best initial conditions, requiring no additional air or fuel to produce the same amount of power. On the other hand, this new technology also has better performance to capture gas in cylinders. As it can be seen from Fig.15, this new technology has enhanced absorbability of fresh air at the specified compression ratio. The new trapping efficiency has been improved 13 % or so higher on average. Trapping efficiency in FPEG operations can make a remarkable difference in performance. It is reasonable to speculate that the variable-scavenging-timing technology is beneficial to reduce the possibility of over-scavenging and air leakage, and to improve the economy of the machine.

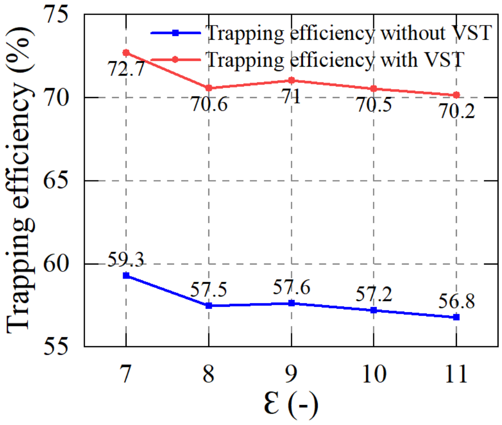


Fig. 15 Comparison of trapping efficiency

For scavenging efficiency under different compression ratios, it can be seen that the synergistic effect of variable-scavenging-timing technology and piston motion significantly determines scavenging process and volumetric efficiency, meaning that the vast majority of fresh air is used to clean up residues and air-fuel mixtures. Too long scavenging process would take in excessive cold air, which might cool mixed gas, and too short scavenging time would result in insufficient air to burn. Although the three-dimensional structure of scavenging parts is not considered, scavenging loss may be slightly reduced in the zero-dimensional simulation due to the coordinated operation mode of scavenging parts. In addition, the custom scavenging model defined in Section 3.3.2 has the greatest impact on the calculation of scavenging efficiency. It can be predicted that the variable-scavenging-timing helps to maintain a stable delivery ratio. It could be inferred that the delivery ratio without variable-scavenging-timing technology is about 1.66, for which the corresponding scavenging efficiency is remained about 0.86 according to the curve of relationship about scavenging efficiency and delivery ratio. In Fig.16, delivery ratio decreases by an average of about 0.3. Based on previous research, with constant power, a lower delivery ratio might help reduce the amount of fresh air available for combustion, thus reducing fuel costs. Meanwhile, the volumetric efficiency gets improved indirectly. They promote more mixture gas to staying in the cylinder. Finally, it also gives a positive feedback in performance.

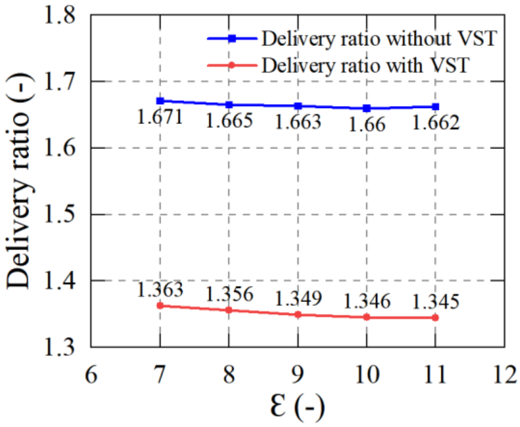


Fig. 16 Comparison of the delivery ratio

4.2 Discussion on cyclic variations

Given the instability of piston motion, there are many other forms besides different compression ratios. For example, the effect of cyclic change on purification efficiency and other evaluation criteria is worth discussing. In fact, cyclic variation can take many forms, such as early or late arrival at the TDC, sudden acceleration or deceleration in motion, etc. Fig.17 shows several classical displacements with different cyclic variations, and the compression ratio is approximately regarded as 7, and the simulation ignores the fluctuation of working frequency.

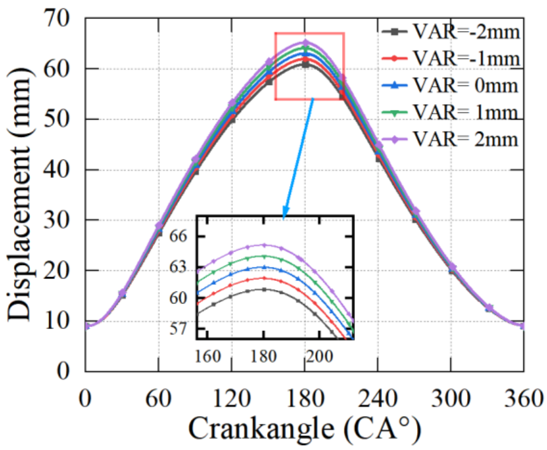


Fig. 17 Displacement with different variations

When the traditional cross-scavenging method is used, the cyclic variation of two-stroke combustion will affect the scavenging process. It can be seen from Fig.18 that the cyclic variation in the figure leads to the irregular drift of the transport ratio, and there is a gap between the normal curve and other curves in the figure without the variable-scavenging-timing technology. The results show that the lowest fuel supply ratio is 1.529, the highest is 1.563, and its fluctuation corresponds to the curve of piston displacement with cyclic variation. In addition, the cyclic variation causes the piston to do extra work, which results in a small additional energy consumption in terms of frictional power or heat transfer loss (as mentioned in Section 3.2, other parts of the energy loss may be ignored). The friction power consumption is larger when the three-dimensional structure is considered.

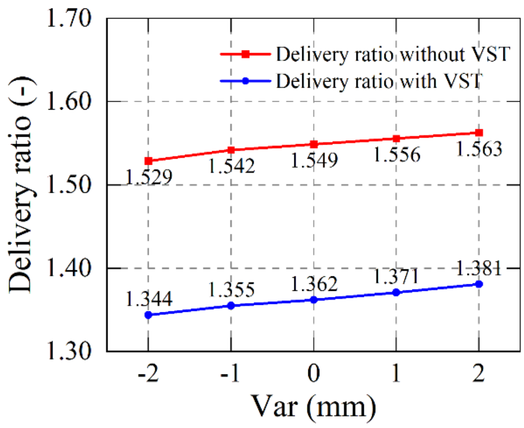


Fig. 18 Comparison of the delivery ratio

The impact of scavenging, which is rooted in the cyclic variation, ultimately affects performance. In the Fig.19, the attenuation of FPEG power with a change of less than 0 is represented. According to the fixed setting, note that the initiation of combustion occurs simultaneously with insertion rather than with the corresponding cyclic variation, which means that the mixture of air and fuel is improperly affected by the cyclic change or the ignition combustion time is not ideal. In fact, cyclic variation requires many parameters to accommodate multivariate displacement in order to transform a good thermodynamic environment. In addition, cyclic variation may also produce some force asymmetries, leading to dysfunction.

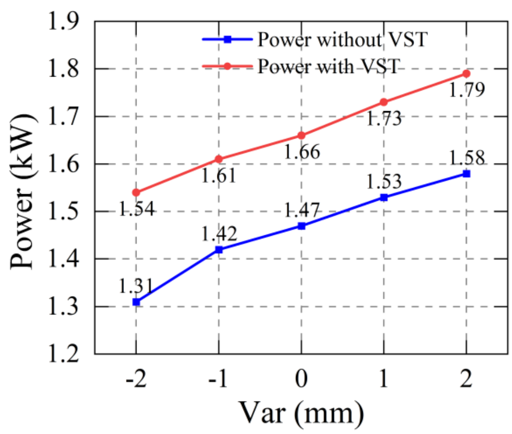


Fig. 19 Comparison of the power

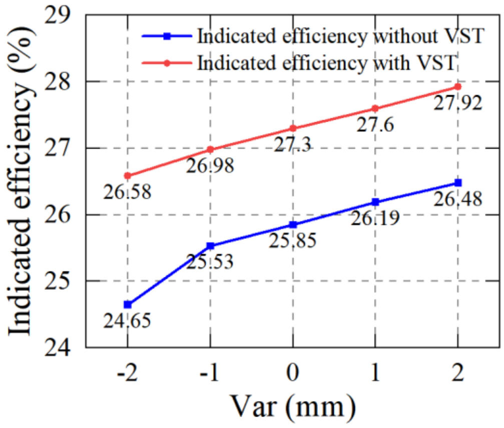


Fig. 20 Comparison of the power

This bad performance is reversed when variable sweep speed regulation technology is adopted. In contrast to the cross-scavenging method, Fig.18 shows that the variable-scavenging-timing technology helps reduce fresh air consumption with the cyclic variation. The Fig.19 and Fig.20 show the variable-scavenging-timing technology improves the performance. The results show that the power and indicating efficiency are improved to some extent. Compared with cross scavenging, the delivery ratio is 1.381, much lower than before. Power and indicating efficiency are kept in a better state than before. Although the variable-scavenging-timing technology cannot completely suppress the effect of cyclic variation, when it is greater than 0, it seems that the variable-scavenging-timing technology could hardly make its performance equal to the variation of 0, which indicates that cyclic variation is important to deal with. Otherwise, the more variations occur, the worse performance would be.

4.3 Consequences about variable frequency

Despite cyclic variation and the change about frequency occur simultaneously in practice, for simultaneous analysis, it is divided into two parts. Section 4.2 discusses the displacement of cyclic variation. Here, it is mainly about the difference of frequency without considering the change of displacement frequency. The range of frequency variation lists in Table.3 is small. Otherwise, the operation environment is not stable or the apparatus is not running well.

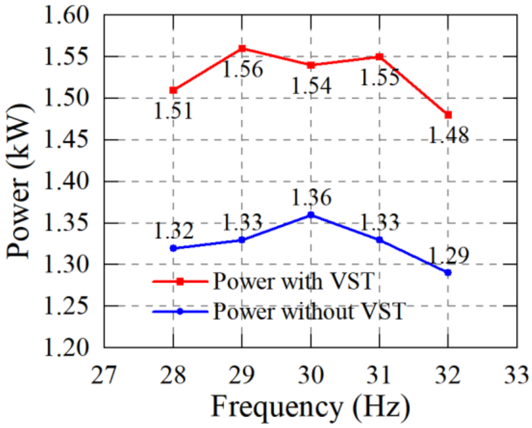


Fig. 21 Comparison of power

Predictably, a change in frequency makes the difference. According to Fig.21, the maximum power is 1.36 kW and the minimum power is 1.29 kW. Meanwhile, the variable frequency has little influence on the power, which results from the fixed working-volume. There seems to be a spike in this trend, which means that 30 Hz may be the best operating frequency in this range. As can be seen from Fig.22, the increase in frequency promotes the indicated efficiency, while the increase in frequency promotes the mixing of fresh air and fuel. The highest indicating efficiency is 25.76 %, the lowest is 24.62 %, so there is a lot of room for improvement. As for the delivery ratio, it is clear that the frequency is inversely correlated with the transport ratio. When the frequency reaches the lowest value, the delivery ratio is 1.62. Conversely, the highest frequency corresponds to the lowest delivery ratio of 1.43, because the increasing frequency is equivalent to the decreasing scavenging time. In the case that the scavenging environment remains unchanged, the intake mass usually declines, while the retention mass remains at a stable state. Therefore, according to the theory in Section 3.1.2, the delivery ratio becomes smaller.

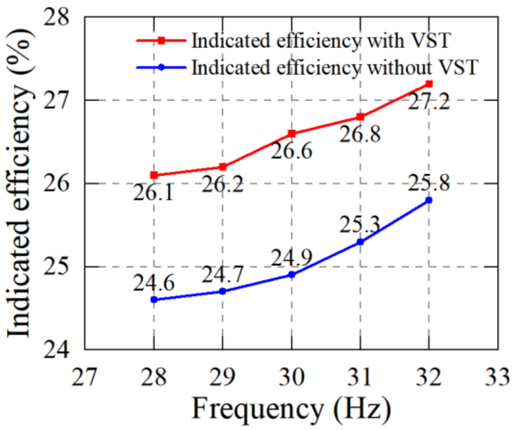


Fig. 22 Comparison of indicated efficiency

Through the optimization with the variable-scavenging-timing technology, it can be seen from the Fig.21 and Fig.22 that part of the performance deteriorated by frequency conversion is improved. With the application of the variable-scavenging-timing technology, the performance of the FPEG in this interval is improved by a notch. The new maximum power is 1.56 kW and the new minimum power is 1.48 kW. The new highest indicated efficiency is 27.2 % and the lowest is 26.1 %. Although the value is increased, the curve has a similar trend. From the preliminary analysis, the variable-scavenging-timing technology still keeps the FPEG staying in the normal working condition. That is why the curves of the performance have a similar shape. Similar to the performance results, the delivery ratio with VST is improved, and the shape of the delivery ratio curve is not different from that without VST. In the Fig.23, the new maximum and minimum delivery ratio is 1.43 and 1.23. In the absence of VST, they are all less than the minimum output ratio. It can be inferred that this technology can effectively reduce the quality of incoming fresh air or escaping gas. Most of the gas is burned, rather than exhausting the cylinder, and most of the intake forms a mixture of gases, rather than being scavenged to the outside. Finally, within the same scavenging efficiency range, the scavenging efficiency is between 85 % and 87 %, because in this simulation, the curve of scavenging efficiency is defined by the user. When the delivery ratio is more than 1.5, the scavenging efficiency increases slowly macroscopically.

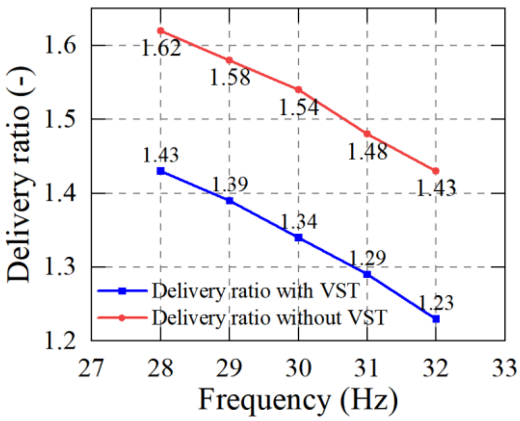


Fig. 23 Comparison of delivery ratio

Since the change of the operating frequency would cause the change of the piston speed, the friction loss would also change. Therefore, the energy balance of FPEG should also be considered in this unstable situation. In the Fig.24, it is known that the energy balance varies with the operating frequency. High operating frequency has a better indication of thermal efficiency while heat transfer loss is smaller. The combustion loss is supposed to be assumed in the simulation, thus the combustion loss is set to 15 % according to the many experiments and references. And "the other loss" is the sum of all losses that are not listed separately, including pumping loss and exhaust loss. It can be known from Fig.24 that additional friction loss would occur if some high-frequency operating condition occurs during the movement of the piston. And there would be more "the other loss" under low-frequency operating condition. After the application of VST, it is obvious that the indicated efficiency and "the other loss" has been optimized. It is clear that "the other loss" which has the proportion from 38 % to 35.4 % in the entire energy comes to a level of 33.1 % to 35.1 %. Although the heat transfer loss has also increased by about 1 % to 2 %, the corresponding output power has also increased according to Fig.21. It should be noted that the proportion of "the other loss" in the entire energy loss is always large, and there is still a lot of space of optimization for this problem in the future.

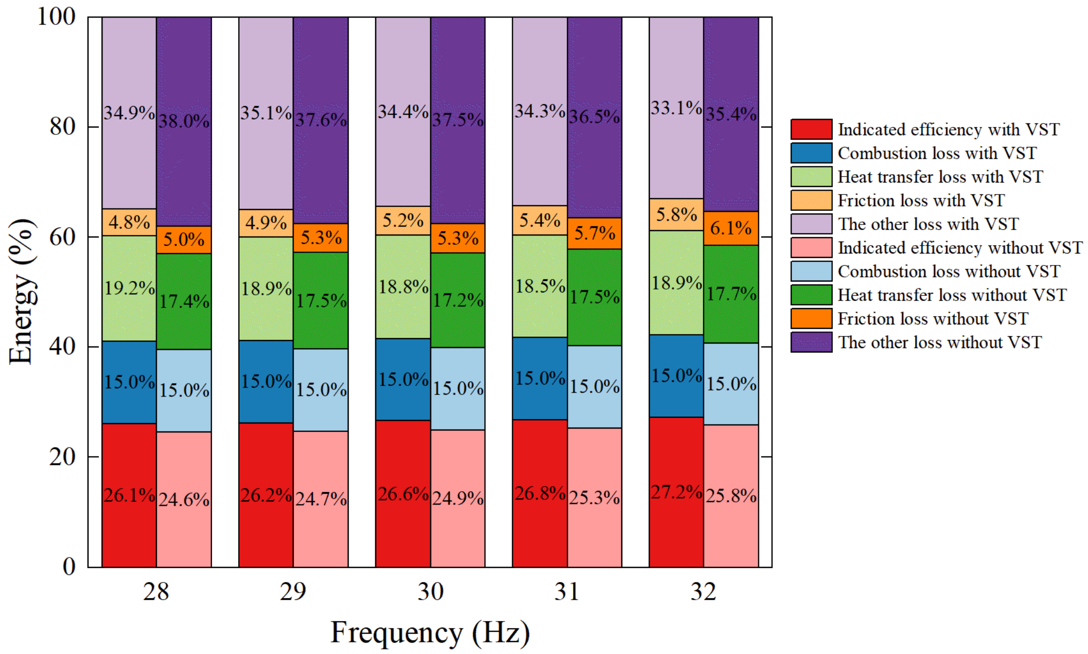


Fig. 24 Energy balance at different frequencies

5 Conclusion

Improving scavenging efficiency and performance is a crucial challenge for research on FPEG because it is not just about intake mass flow. It is often associated with combustion, heat transfer, exhaust gas recycling and other important aspects of performance. In this paper, the effects of two cross scavenging and variable-scavenging-timing technology on FPEG are studied under different compression ratios, cyclic variations and frequencies. By controlling variables, a series of cases are run in AVL BOOST to obtain necessary results. And their effects on the scavenging efficiency and other performances of FPEG are discussed. The results on the FPEG are demonstrated by figures.

The results show that different compression ratio, cyclic variation and variable frequency have some adverse effects on scavenging efficiency and other performance. The change of compression ratios has a more negative impact on FPEG, especially on power when the compression ratio is relatively high. The lower frequency and situation that the piston cannot reach the design TDC both decrease performance and scavenging quality of the FPEG. It is difficult to exactly predict or control the tendency of the piston motion in the actual experiment. The proportion of energy loss at different frequencies also shows that the technology has a lot of space for technological improvement and application prospects, especially in terms of some losses such as pumping loss and exhaust loss. Therefore, the variable-scavenging-timing technology is worth developing in the research of FPEG.

Once the variable-scavenging-timing technology is adopted, FPEG is very likely to have better performance under unsteady operation conditions. According to the simulation results, the delivery ratio of the FPEG applied with the variable-scavenging-timing technology is reduced by about 0.3 at different compression ratios, 0.18 at different cyclic variations and 0.2 at different frequencies on average. Especially under different compression ratios, the trapping efficiency of FPEG using VST has reached at least 70 %, which has been improved significantly compared to before. At the same time, in most cases, the scavenging efficiency is maintained at least 85% %. Under different compression ratios, the power increases by an average of 0.18 kW. While the power increases 0.2 kW on average under the other condition. The increase of indicated efficiency is in a varying range from 1 % to 2 % under unsteady conditions.

The variable-scavenging-timing technology can reduce the scavenging quality, which implies that the air-fuel ratio and combustion are in the appropriate stage. As a result, FPEG performance is unlikely to degrade. In addition, the variable-scavenging-timing technology pursues that the scavenging process gets along with the displacement of the piston. Trapping efficiency and the stability of scavenging are improved, which might be of great significance to the economy and reliability of FPEG. The variable-scavenging-timing technology can be driven in many ways, such as hydraulic drive, mechanical drive or electromagnetic drive, which implies many existing valve drive technologies may be integrated with it. Future work will focus on exploring the application scope of this technology and developing simple and effective actuators.

Declaration of Competing Interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled.

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