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수소 2행정 프리피스톤엔진의 SI-HCCI 변화에 관한 수치해석적 연구

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Simulation of SI-HCCI Transition in a Two-Stroke Free Piston Engine Fuelled with Hydrogen

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Abstract >> A free piston linear engine could be operated under HCCI combustion due to its variable compression ratios. To obtain HCCI combustion, the free piston linear engine needs a high compression ratio to achieve auto-ignition of the fuel/air mixture. In this study, an idea for obtaining a high compression ratio using the transition from SI combustion to HCCI combustion was proposed. The fuel used in this study is hydrogen, which is considered to be an environmentally friendly fuel. Besides, the effects of key parameters such as equivalence ratio (ϕ), load resistance (R_L) and intake temperature (T_{in}) on the SI-HCCI transition were numerically investigated. The simulation results show that the SI-HCCI transition is successful without any significant reduction of in-cylinder pressure as the intake temperature is increased from T_{in}=300K (SI mode) to T_{in}=450K (HCCI mode), while the load resistance and equivalence ratio are retained respectively at R_L=120Ω and ϕ=0.6 in both SI mode and HCCI mode.

Key words : Linear engine, Linear alternator, Equivalence ratio, Load resistance, Intake temperature

Nomenclature

A_B : area of piston crown
P_{in} : intake pressure
P_l : pressure in left cylinder
P_r : pressure in right cylinder
F_f : friction force
F_e : electric force
F_{sl} : spring force in the left
F_{sr} : spring force in the right
m : mass
x : displacement of translator
x_0 : initial coordinate of translator
a : acceleration of translator
t : time
x_m : the maximum stroke of piston
p : instantaneous pressure in cylinder
γ : specific heat ratio
V : instantaneous volume in cylinder

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Q_c : combustion heat
Q_{in} : heat input
Q_{ht} : heat transfer
χ : mass fraction burned
t_0 : start of combustion
Δt : duration combustion
h : heat transfer coefficient
A_t : heat transfer area
T : instantaneous temperature in cylinder
T_w : wall temperature
M_F : mean magneto motive force
τ : pole pitch
τ_p : width of permanent magnet
x_m : coordinate of survey point in translator axis
x_s : coordinate of survey point in stator axis
μ_0 : permeability
g : air gap length
B : magnetic induction density
Φ : flux contained in the coil
N_{coil} : number of turn in the coil
λ : total flux contained in the coil
H : length of coil cutting magnetic line
i : current in the equivalent circuit
ε : voltage generating operation
R_I : internal resistance of coil
R_L : load resistance
L : induction
W : average cylinder gas velocity
V_d : displaced volume
V_r : volume at reference state
P_r : pressure at reference state
T_r : temperature at reference state
P_m : motored cylinder pressure

Subscripts

l : left
r : right
f : friction
e : electric
0 : initial
w : wall

1. Introduction

A free piston linear engine (FPLE) is considered to be a crankless internal combustion engine with free motion of a piston in a cylinder. Unlike the conventional engines with crankshaft mechanism, the FPLE can optimize the combustion process through the variable compression ratios[1-3]. Besides, the variation of compression ratio in FPLE also allows the engine to operate with various kinds of fuels[4]. Goldsborough[5] presented a numerical study of a free piston linear engine with dual piston type. The simulation results indicated that the operating compression ratio of engine was variable, and it particularly depended on the operating conditions of the engine such as equivalence ratio, scavenging efficiency, intake temperature, etc. In addition, the authors showed that the NO_x emission levels of the engine were significantly reduced over conventional internal combustion engine since very low equivalence ratio homogeneous-charge combustion was possible. Li[6] submitted a simulation study of a two-stroke free piston engine for electrical power generation. Therein, the authors also investigated the performance of a free piston linear engine under HCCI combustion, and compared it with conventional engine. The simulation results showed that the piston acceleration in the free piston engine was better than that of traditional engine with a crankshaft mechanism. Particularly, the authors indicated that by changing external loads, the tops dead center of the engine could be changed easily. Besides, using a lean mixture to acquire a higher compression ratio could improve the indicated thermal efficiency effectively in the

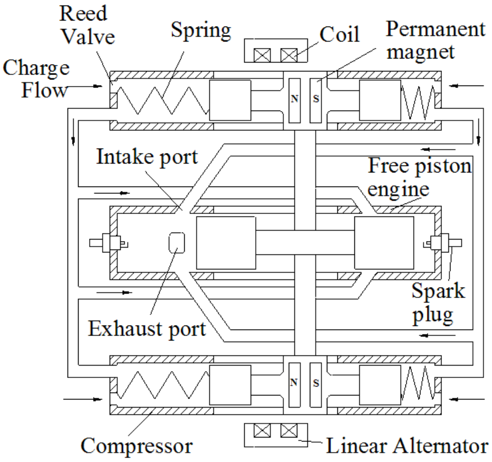

Fig. 1 Operating model of FPLE

engine.

A FPLE needs a high compression ratio to achieve auto-ignition of the fuel/air mixture as well as HCCI combustion. Therefore, an idea for obtaining a high compression ratio using the transition from SI to HCCI combustion is proposed. Further, the parameters such as equivalence ratio, load resistance, and intake temperature have a significant influence on the auto-ignition of fuel/air mixture as well as HCCI combustion. Therefore, it is reasonable that these parameters have an effect on the transition from SI combustion to HCCI combustion. In this paper, the effects of the above parameters on the SI-HCCI transition using hydrogen fuel are investigated.

2. Operation of the FPLE

The FPLE is a combination of two main components including a free piston engine and a linear alternator, as shown in Fig. 1. To start engine, the linear alternator will operate as a beginning device to drive the free piston engine through a connecting rod system. After certain frequencies, spark plugs are activated, and the compression process will occur alternatively at each cylinder, forcing the connecting rod to move back and forth. The movement of connecting rod will generate the current in the windings due to the magnetic flux linked with winding in stator is changed.

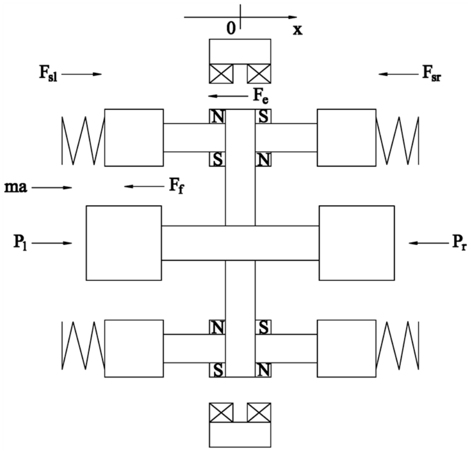

Fig. 2 Free body diagram of FPLE

3. Simulation Model

3.1 Dynamic model

The forces applied on the linear engine are expressed through a free body diagram as Fig. 2.

The dynamic model is described by equation that obeys Newton's second law:

$$P_l A_B - P_r A_B - F_f - F_e + F_{sl} - F_{sr} = m\frac{d^2x}{dt^2} = ma \qquad (1)$$

3.2 Linear alternator model

The model of a single phase linear alternator with permanent magnet is built as shown in Fig. 3. Therein, the permanent magnet creates a magneto motive force (MMF) in the air gap length.

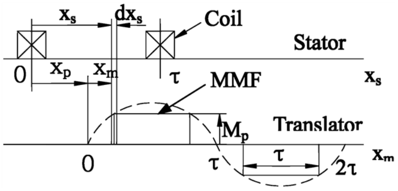

Fig. 3 Model of the linear alternator

The flux density in the air gap is calculated by equation:

$$B(x_m) = \frac{\mu_0}{g} M_F(x_m) = B_m \sin\left(\frac{\pi x_m}{\tau}\right) \tag{2}$$

Where

$$B_m = \frac{\mu_0}{g}\frac{4}{\pi} M_p \sin\left(\frac{\pi \tau_p}{2\tau}\right) \tag{3}$$

The flux contained in the differential element dx$_s$ is calculated by equation:

$$d\phi = B(x_s)dA = B(x_s).H.dx_s \tag{4}$$

Combine the equation (2) with the Fig. 3, the equation (4) is rewritten as follow:

$$d\phi = B_m.H.\sin\left(\frac{\pi(x_s - x_p)}{\tau}\right).dx_s \tag{5}$$

Because the permanent magnet linear alternator operates on the same basic physical principles as conventional rotary alternators, so the voltage generating operation of the alternator is Faraday's Law expressed as:

$$\varepsilon = -\frac{d\lambda}{dt} = -N_{coil}\frac{d\phi}{dt} \tag{6}$$

Combine the equation (5) and the equation (6), the total flux contained in the coil can be derived:

$$\begin{aligned} \lambda &= N_{coil}\int_0^{\tau} B_m.H.\sin\left(\frac{\pi(x_s - x_p)}{\tau}\right)dx_s \\ &= \tau.H.N_{coil}.B_m.\frac{2}{\pi}.\cos\left(\frac{\pi x_p}{\tau}\right) \end{aligned} \tag{7}$$

The voltage generating operation is also calculated by the equivalent circuit of the linear alternator as follow:

$$\varepsilon = (R_I + R_L).i + L\frac{di}{dt} \tag{8}$$

From the equation (8), the induced current can be easily found:

$$i = \frac{\varepsilon}{R_I + R_L}\left(1 - e^{-\frac{R_I + R_L}{L}t}\right) \tag{9}$$

The electromagnetic force which contained in equation (1) is determined by equation:

$$F_e = i\frac{\partial \lambda}{\partial x_p} \tag{10}$$

Combine the equations (6), (7), (8) and (9), the electromagnetic force can be derived:

$$F_e = \frac{1}{R_I + R_L}\left(1 - e^{-\frac{R_I + R_L}{L}t}\right)H^2.N_{coil}^2.4.B_m^2.\sin^2\left(\frac{\pi x_p}{\tau}\right).\frac{dx_p}{dt} \tag{11}$$

3.3 Thermodynamic model

The compression and expansion process are assumed to obey an isentropic process[7)].

The combustion process in SI mode is assumed to occur immediately after the spark occurs, which means that the ignition delay is ignored. On the other hand, in HCCI mode, auto-ignition occurs when the cylinder charge is hightly compressed after closing the exhaust port. In this study, the HCCI auto-ignition delay model is described by an Arrhenius equation[4)]

The pressure in the combustion process is calculated as follow:

$$\frac{dp}{dt} = -\gamma \frac{p}{V}\frac{dV}{dt} + \frac{\gamma - 1}{V}\left(\frac{dQ_c}{dt}\right) \tag{12}$$

$$\frac{dQ_c}{dt} = \frac{dQ_{in}}{dt} - \frac{dQ_{ht}}{dt} \tag{13}$$

The heat release rate dQ_{in}/dt is calculated when the mass fraction burned is known. The mass fraction burned can be found through the Wiebe function. The Wiebe function is usually used to calculate the mass fraction burned versus crank angle for crankshaft engine. Because the FPLE has no crankshaft, the mass fraction burned is calculated as a function of time

$$\chi = 1 - \exp\left[-a\left(\frac{t - t_0}{\Delta t}\right)^{m+1}\right] \tag{14}$$

Where, a and m are adjustable parameter (according to Heywood[7)], a=5, m=2), t0 is the start of combustion, Δt is the total combustion duration.

By differential two sides of the equation (14), the mass fraction burned rate is given

$$\frac{d\chi}{dt} = a\frac{m+1}{\Delta t}\left(\frac{t - t_0}{\Delta t}\right)^m \exp\left[-a\left(\frac{t - t_0}{\Delta t}\right)^{m+1}\right] \tag{15}$$

From equation (15), the heat release rate can be calculated as follow:

$$\frac{dQ_{in}}{dt} = a\frac{m+1}{\Delta t}\left(\frac{t - t_0}{\Delta t}\right)^m \exp\left[-a\left(\frac{t - t_0}{\Delta t}\right)^{m+1}\right].Q_{in} \tag{16}$$

The heat transfer rate is calculated by:

$$\frac{dQ_{ht}}{dt} = h.A_t.(T - T_w) \tag{17}$$

In the equation (16), the heat transfer coefficient is calculated by[7)]:

$$h = 3.26.B^{-0.2}.P^{0.8}.T^{-0.55}.W^{0.8} \tag{18}$$

Where

$$W = \left[C_1\bar{S}_p + C_2\frac{V_d T_r}{P_r V_r}(P - P_m)\right] \tag{19}$$

4. Results and discussion

The simulation parameters are shown in Table 1, which was selected based on the operating conditions and specifications of a real FPLE. The transition from SI combustion to HCCI combustion is investigated under the variation of key parameters, as shown in Tables 2, 3 and 4, corresponding to case 1, case 2 and case 3.

In the first case (Table 2), the FPLE is directly adjusted from SI mode (spark=1) to HCCI mode (spark=0) without any change of the key parameters. Namely, the intake temperature, equivalence ratio, and load resistance are retained at T_{in}=300K, ϕ=0.6, and R_L=30Ω respectively. The results of the first case

Table 1 Simulation parameters

Parameters	Value
Effective stroke length	18mm
Bore	30mm
Reciprocating mass	0.8kg
Intake temperature	300K
Intake pressure	1.1bar
Equivalence ratio	0.6
Width of magnet	10mm
Number of turns	240
Load resistance	30Ω
The natural spring length	50mm
Spring stiffness	2.9N/mm
LHV of Hydrogen	120MJ/kg

Table 2 Case 1

Parameters	SI mode	HCCI mode
ϕ	0.6	0.6
T_{in}	300K	300K
R_L	30Ω	30Ω

Table 3 Case 2

Parameters	SI mode	HCCI mode
ϕ	0.6	0.6
T_{in}	300K	450K
R_L	120Ω	120Ω

Table 4 Case 3

Parameters	SI mode	HCCI mode
ϕ	0.6	0.55
T_{in}	300K	650K
R_L	120Ω	150Ω

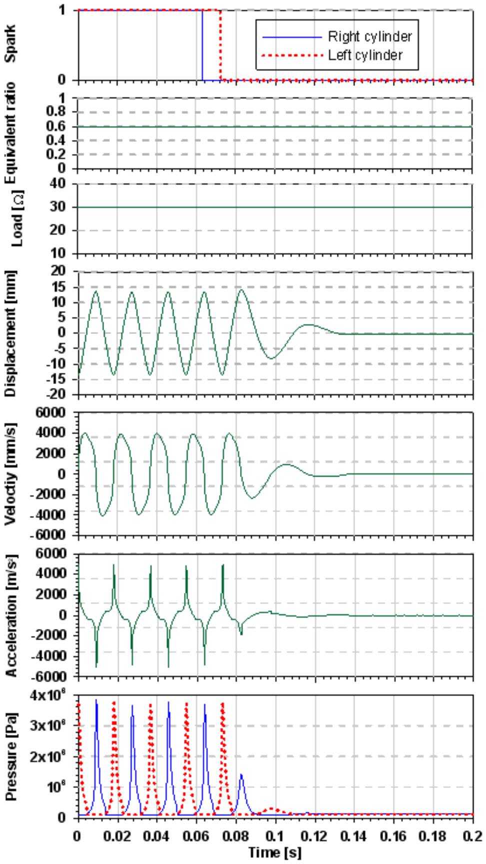

Fig. 4 Motion profiles of the piston and in-cylinder pressure in the transition from SI combustion to HCCI combustion (Case 1). SI mode (Spark=1), HCCI mode (Spark=0)

are shown in Fig. 4. It can be seen that the pressure in the right cylinder is dropped immediately after HCCI mode is activated. The decreased right cylinder pressure results in an extremely low left cylinder pressure, as can be seen in Fig. 4. The high imbalance in pressure between the left and right cylinders leads to decreased piston displacement, velocity, and acceleration. To solve this problem, some parameters are adjusted as shown in Table 3 (the second case). Therein, equivalence ratio is still retained at ϕ=0.6 in both SI mode and HCCI mode to ensure that the FPLE can be operated with a lean air/fuel mixture, while load resistance is adjusted to R_L=120Ω in both two modes to increase piston stroke and the intake temperature is increased from T_{in}=300K (SI mode) to T_{in}=450K (HCCI mode) to provide a suitable auto-ignition timing of the air/fuel mixture in HCCI mode. The results of these changes are shown in Fig. 5. It can be seen that the transition from SI mode to HCCI mode is successful.

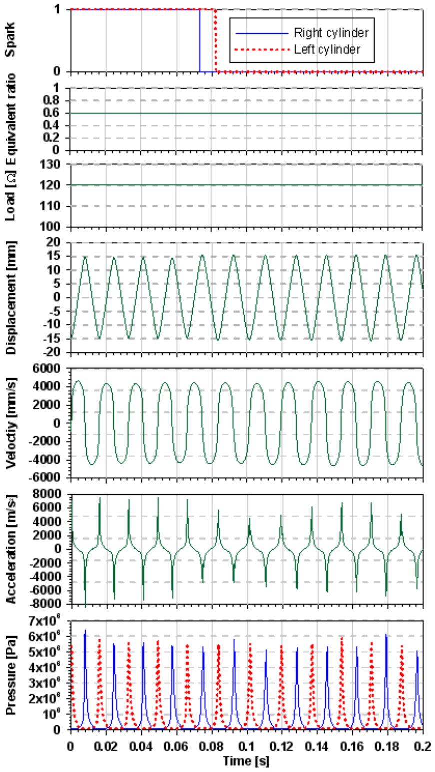

Fig. 5 Motion profiles of the piston and in-cylinder pressure in the transition from SI combustion to HCCI combustion (Case 2). SI mode (Spark=1), HCCI mode (Spark=0)

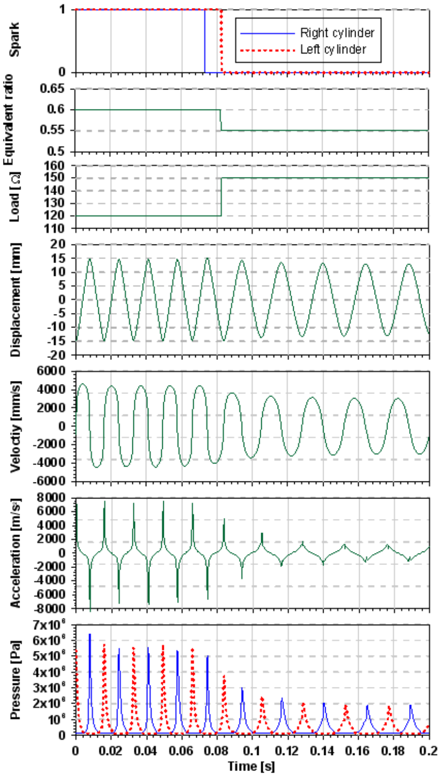

Fig. 6 Motion profiles of the piston and in-cylinder pressure in the transition from SI combustion to HCCI combustion (Case 3). SI mode (Spark=1), HCCI mode (Spark=0)

As can be seen in Fig. 5, the transition from SI mode to HCCI mode takes place successfully as the FPLE is operated with an equivalence ratio ϕ=0.6 and the other parameters as shown in Table 3. In order to examine the operating behavior of the FPLE at a smaller equivalence ratio in HCCI mode, the engine is operated by changing the key parameters as shown in Table 4 (the third case).

In the third case, equivalence ratio is adjusted from ϕ=0.6 (SI mode) to ϕ=0.55 (HCCI mode). The smaller equivalence ratio in HCCI mode results in reduced pressure in the left and right cylinders as well as reduced piston stroke. Therefore, to ensure that the piston stroke is not so much reduced, the load resistance should be increased to a suitable value. Here, the load resistance is adjusted from R_L=120Ω (SI mode) to R_L=150Ω (HCCI mode). Besides, the intake temperature is increased from T_{in}=300K (SI mode) to T_{in}=650K (HCCI mode) for controlling the appropriate auto-ignition timing of the air/fuel mixture in HCCI mode. The results of these change are shown in Fig. 6.

As can be seen in Fig. 6, the transition from SI mode to HCCI mode is successful. However, the peak pressure in the left and right cylinders is much reduced in HCCI mode, compared with SI mode. This is because the air density is reduced as the intake temperature is increased, as shown in Table 4. As a result, the piston acceleration and velocity are decreased.

5. Conclusion

A two-stroke free piston engine has been modeled and simulated based on a combination of three mathematical models. Besides, the effects of the key parameters such as equivalence ratio, intake temperature, and load resistance on the transition from SI combustion to HCCI combustion has been investigated. The simulation results indicated that the SI-HCCI transition was successful if the key parameters were adjusted appropriately. In order to ensure that the FPLE could be operated in the successful transition without any significant decrease of the in-cylinder pressure, the engine should be operated using the second case.

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