COMBUSTION MODELING OF GASOLINE TWO-STROKE LINEAR ENGINE BY THE MODIFIED WEIBE FUNCTION

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Abstract

This paper presents the mathematical modeling of combustion in a two-stroke linear combustion engine incorporating combustion and kickback chambers. A thermodynamics simulation is performed using a Weibe function that applied to linear engine. The computer program is developed to compute the instantaneous velocity and temperature in the combustion chamber. The fuel is gasoline and the cylinder bore sizes to be considered are of 50mm and 76mm. From the computation, the results show that the peak temperatures are 870 K and 995 K, the mean velocities during expansion are 3.8m/s and 5m/s, the mean velocities during compression 2.9m/s and 4.4m/s, respectively.

Keywords: mathematical modeling, combustion, linear engine

1. Introduction

Linear internal combustion engines may find application in the generation of electrical power using linear motion. The operation of this engine is distinct from that of a conventional slider-crank mechanism engine, insofar as the motion of the two horizontally opposed pistons is not externally constrained [10]. This technology is advantageous because it is mechanically simpler and allows for a great deal more freedom in defining a piston motion profile, enabling the use of novel combustion regimes [11].

The most important process taking place in an engine is the combustion process. In addition to its obvious importance in the generation of power, it provides a key driving input to the heat transfer that originates in the in-cylinder gasses. Thus, modeling of combustion is an important part of engine simulation codes in order to understand the mechanism of the quick and complete combustion in an internal combustion engine [8].

Temperature measurements in the thermodynamics analysis are important for the determination of the parameters that characterize internal combustion engine. A finite heat release model can determine the temperature during combustion process in the internal combustion engine [4]. Through the pressure measurements, the principal approaches are the calculation of mass fraction burned in the engine using crankshaft for the determination of the characteristic crank angles in the combustion stroke, and the heat release analysis [9].

The mean piston speed is an indicator of how well an engine handles load such as friction, inertia, and gas flow resistance. In a free piston configuration, the relationship between engine speed, operating conditions, and design parameters is much more complicated [1]. On the other hand, the engine speed is one of important parameter to compute the instantaneous heat transfer [4]. The purpose of this paper is to determine the mathematical modeling of heat transfer in the combustion chamber of a linear combustion engine incorporating a combustion chamber and a kickback chamber. The result is important in determining the temperature distribution in whole engine.

2. Thermodynamic model

In this paper, it is considered a two-stroke incorporates combustion and kickback chamber model is depicted in Figure 1. The thermodynamic model of such engine has been performed by the authors in [12]. The piston traverses horizontally with the stroke of 50mm.

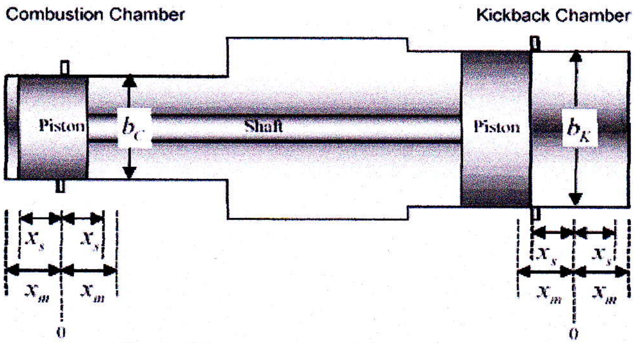


Fig. 1 *Schematic view of the linear engine*

The force balance for the left-to-right (expansion) stroke can be written as equation (1) with x positive in the left-to-right direction.

$$P_C(x)A_C - P_K(x)A_K - F_f(x) = m_s \frac{d^2x}{dt^2} \tag{1}$$

where P_C and P_K are the instantaneous pressure in the combustion and kickback cylinder, A_C and A_K are the areas of the piston in combustion and kickback chamber, respectively, F_f is the frictional force, and m_s is the mass of translator. On the other hand, the force balance for the right-to-left can be expressed by exchanging the sign of equation (1) by the first and second terms.

According to the combustion heat addition, Q_{in}, during the compression stroke and the ideal gas law, and using adiabatic Otto cycle process, the force balance can be described as the Equations (2) and (3) for the compression and the expansion stroke, respectively.

$$P_{1C}\left(\frac{x_m + x_s}{x_m + x}\right)^n\left(\frac{\pi b_C^2}{4}\right) - P_{1K}\left(\frac{x_m + x_s}{x_m - x}\right)^n\left(\frac{\pi b_K^2}{4}\right) + Q_{in}(n-1)\frac{(x_m - x_s)^{n-1}}{(x_m + x)^n} - F_f(x) = m_s\frac{d^2x}{dt^2} \tag{2}$$

$$P_{1K}\left(\frac{x_m + x_s}{x_m - x}\right)^n\frac{\pi b_K^2}{4} - P_{1C}\left(\frac{x_m + x_s}{x_m + x}\right)^n\frac{\pi b_C^2}{4} - F_f(x) = m_s\frac{d^2x}{dt^2} \tag{3}$$

Using the force balance for the whole strokes, the displacement, x, and the velocity, v, as a function of time, t, have been computed to analyze the instantaneous temperature.

3. Weibe function

In the conventional engines the Weibe function is defined as follows.

$$x_b(\theta) = 1 - \exp\left[-a\left(\frac{\theta - \theta_s}{\theta_d}\right)^n\right] \tag{4}$$

where θ is crank angle, θ_s is start of heat release, θ_d is duration of heat release, n is Weibe form factor, and a is Weibe efficiency factor. In the linear engine cases, the Weibe function must be expressed as a function of time, t, as follows [3]

$$x_b(t) = 1 - \exp\left[-a\left(\frac{t - t_s}{Cd}\right)^{b+1}\right] \tag{5}$$

where Cd is the combustion duration, t_s is the start of the combustion, a and b are functional shape parameters and are adjustable. According to Heywood [5], the actual mass fraction burned curves are well fitted with $a = 5$ and $b = 2$, while varying a and b changes the shape of the curve significantly. For the Weibe function using in the conventional engine, the piston positions have a relationship with the crankshaft angle. Comparing with the Weibe function using in the conventional engine, the Weibe function using in the linear engine considers start times of combustion at any fix piston positions in each cycle.

Minimizing the combustion duration in an engine requires a high turbulence intensity, a flame area that increases with distance from the spark plug, and a centrally located plug to minimize flame travel. As one expects, minimizing the combustion duration maximizes the work done, since the combustion approaches constant volume, and it also lowers the octane required.

4. Heat generated by combustion

Consider a closed system differential energy equation in the combustion chamber,

$$\delta Q - PdV = mc_v dT \tag{6}$$

where m is the mass of gas in the cylinder, and c_v is the constant volume specific heat. Per unit time, the energy equation can be written as:

$$\frac{dQ}{dt} = P\frac{dV}{dt} + mc_v\frac{dT}{dt} \tag{7}$$

The rate of heat release for usual engine is obtained by differentiating the cumulative heat release Weibe function [4], and for the linear engine can be formulated as

$$\frac{dQ}{dt} = Q_{in}\frac{dx_b}{dt} \tag{8}$$

The mass fraction burned rate is the derivative of the Equation (5) and has the following form

$$\frac{dx_b}{dt} = a\frac{b+1}{Cd}\left(\frac{t-t_s}{Cd}\right)^b \exp\left[-a\left(\frac{t-t_s}{Cd}\right)^{b+1}\right] \tag{9}$$

The heat release rate can be written as a function of time as

$$\frac{dQ}{dt} = a\frac{b+1}{Cd}\left(\frac{t-t_s}{Cd}\right)^b \exp\left[-a\left(\frac{t-t_s}{Cd}\right)^{b+1}\right]\cdot Q_{in} \tag{10}$$

Using the chain rule to the Equation (7) and substituting the result to the Equation (6), it will be obtained the following equation

$$Q_{in}\frac{dx_b}{dt} = P\frac{dV}{dt} + mc_v\frac{dT}{dt} \tag{11}$$

The finite heat release model can be modified to include the differential heat transfer dQ_w to the cylinder walls, if the instantaneous average cylinder heat transfer coefficient $h_g(t)$ and engine speed N are known. The finite heat release equation, Equation (11), with the addition of wall heat transfer is

$$Q_{in}\frac{dx_b}{dt} - \frac{dQ_w}{dt} = P\frac{dV}{dt} + mc_v\frac{dT}{dt} \tag{12}$$

The heat addition in the engine cycle is calculated with the lower heating value of the fuel based on per mass of air [6]. Based on the fuel air ratio, the heat addition can be calculated using the following formula

$$Q_{in} = (F/A)m(LHV) \tag{13}$$

where (F/A) is the fuel air ratio, m is the mass of the mixture of air and fuel, and LHV is the lower heating value.

5. Heat transfer in the combustion chamber

The heat transfer rate at any time unit to the exposed cylinder wall at an engine speed N is determined with a Newtonian convection equation

$$\frac{dQ_w}{dt} = h_g(t)A_w(t)\left(T_g(t) - T_w\right)/N \tag{14}$$

The cylinder wall temperature T_w in the above equation is the area-weighted mean of temperatures of the exposed cylinder wall, the head, and the piston crown. The heat transfer coefficient $h_g(t)$ is the instantaneous area averaged heat transfer coefficient. The exposed cylinder area $A_w(t)$ is the sum of the cylinder bore area, the cylinder head area, and the piston crown area.

The characteristic gas velocity in the Woschni correlation is proportional to the mean piston speed during intake, compression, and exhaust. During combustion and expansion, it is assumed that the gas velocities are increased by the pressure rise resulting from combustion, so characteristic gas velocity has both piston speed and cylinder pressure rise terms.

$$U = 2.28\overline{U}_p + 0.00324T_0\frac{V_d}{V_0}\frac{\Delta P_c}{P_0} \tag{15}$$

where $\overline{U}_p$ is the mean piston speed (m/s), T_0 is the temperature at intake closing (K), V_0 is the cylinder volume at intake closing (m^3), V_d is the displacement volume (m^3), ΔP_c is the instantaneous pressure rise due to combustion (kPa), P_0 is pressure at intake closing (kPa).

The instantaneous pressure due to combustion in the Equation (15) is determined as the pressure difference between the motoring pressure, p_{motor} and the pressure calculated from the ideal gas law, p, [7], as follows

$$\Delta P_c = (p - p_{motor}) \tag{16}$$

where

$$p_{motor} = \left(\frac{rV_d}{(r-1)V}\right)^{\gamma} P_0 \tag{17}$$

The Woschni correlation is

$$h_g = 3.26P^{0.8}U^{0.8}b^{-0.2}T^{-0.55} \tag{18}$$

where the units of h_g, P, U, b and T are in W/m^2K, kPa, m/s, m and K, respectively.

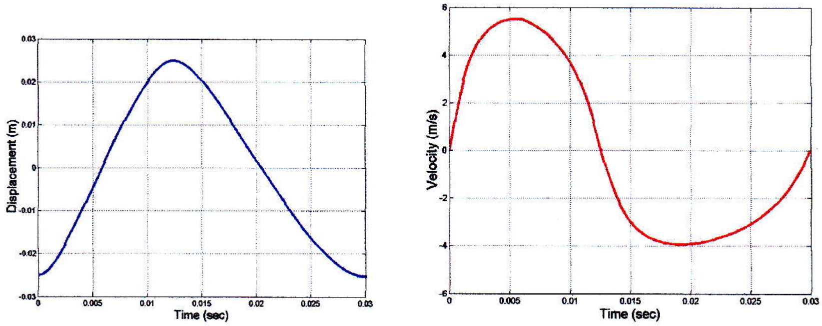
6. Results and Discussion

A numerical computation has been performed using the following values of parameters:

(i) combustion chamber bore 50mm, kickback chamber bore 74mm, stroke 50mm,

(ii) combustion chamber bore 76mm, kickback chamber bore 101mm, stroke 76mm

The bore sizes of kickback chambers are calculated using an algorithm by author in [2]. Pressure at the beginning of compression stroke is 100kPa, compression ratio is 10, and specific heat ratio is 1.3. Using these values of parameters applied to Equations (2) and (3), the graphic of the displacement and velocity versus time for the type of parameter (i) are depicted in the Figure 2. Figure 2 (a) shows that the piston need 0.03 seconds for one cycle moving. By using this result, the engine speed is around 2000 cycles per minute (cpm). Figure 2 (b) shows that the maximum piston velocity in the expansion stroke is 5.5 m/s and in the compression is 4 m/s. The mean velocity during expansion is 3.8m/s and during compression is 2.9m/s. The piston needs more time to get one stroke for compression then for expansion.



(a) Piston displacement (b) Velocity

Fig. 2 *Piston displacement and velocity vs. time, cylinder bore 50mm*

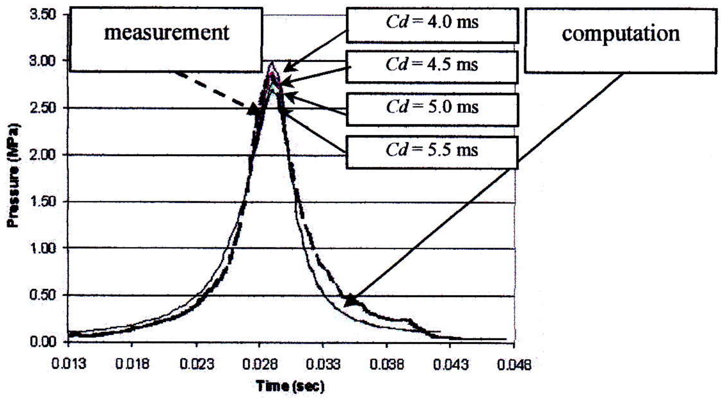
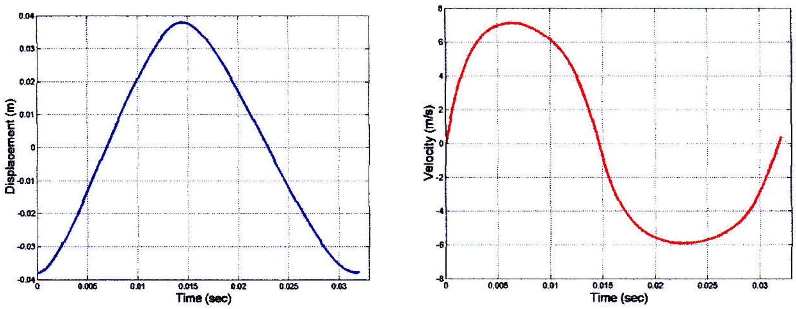


Fig. 3 *The pressure vs. time for variation in combustion duration comparing with measurement*

Figure 3 shows the in-cylinder pressure versus time for the variation in the combustion duration and the comparison with the mean pressure of the measurement. The mean peak pressure from measurement is 2.83 MPa. This peak pressure is appropriate with the pressure resulting from the combustion duration of 4.5 ms.

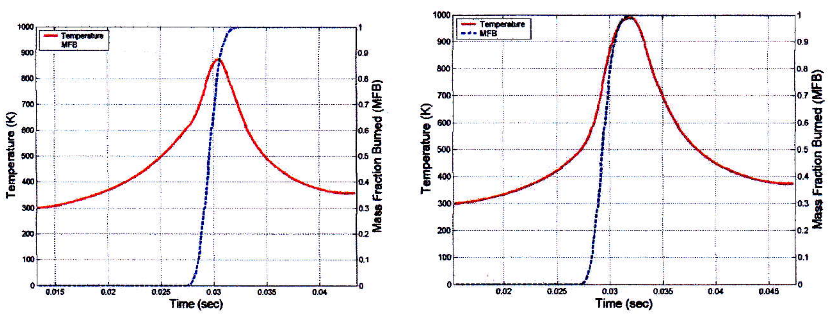
Figure 4 presents the piston displacement and velocity versus time for the linear engine with cylinder bore of 76mm. Figure 4 (a) shows that the engine need 0.034 seconds time to get one cycle. Figure 4 (b) shows that the maximum velocity, 7.2 m/s, occurs in expansion stroke. The mean velocity during expansion is 5m/s and during compression 4.4m/s.



(a) Piston displacement (b) Velocity

Fig. 4 *Piston displacement and velocity vs. time, cylinder bore 76mm*

The following values of parameters are required to calculate the instantaneous temperature in the combustion chamber. The temperature at the beginning of compression is 298K, and the wall temperature is set 373K. In the next computation, the combustion duration of 4.5 ms is applied. Figure 5 presents the curve of mass fraction burned and the temperature versus time. Figure 5 (a) shows that for the engine with cylinder bore of 50mm, the peak temperature in the combustion chamber is 870 K. After one cycle, the temperature at the next start of compression is 360 K. Figure 5 (b) shows that for the engine with cylinder bore of 76mm, the peak temperature is 995 K. After one cycle, the temperature at the next start of compression is 375 K.



(a) cylinder bore 50mm (b) cylinder bore 76mm

Fig. 5 *The mass fraction burned and temperature vs. time*

7. Concluding Remarks

The combustion in a linear combustion engine can be modeled to analyze piston movement and the instantaneous temperature in a cycle. A numerical algorithm for the calculation of the instantaneous temperature problem has been developed. For the linear engine cases, the Weibe function can be derived by time variable. By using a number of parameter values, it is obtained the instantaneous temperature in the combustion chamber of a linear engine. The peak temperature and the position of piston that obtained above are very important to evaluate the heat transfer problem in the whole engine.

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