Asian Journal of Scientific Research

ISSN 1992-1454

science alert
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Asian Journal of Scientific Research 6 (2): 388-394, 2013
ISSN 1992-1454 / DOI: 10.3923/ajsr.2013.388.394

Double Stage Wiebe: An Approach to Single Zone Modeling of Dual Fuel HCCI Combustion

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ABSTRACT

Homogeneous Charge Compression Ignition (HCCI) engines have become potential power units to satisfy the stricter emission regulations and obtain higher thermal efficiency values. The HCCI operating principle has been widely investigated in order to improve the ability to control the HCCI combustion phasing. The zero dimensional model, Wiebe function, is known to be able to simulate the general behavior of engine combustion. However, the standard Wiebe cannot represent dual fuel HCCI combustion and a two-stage Wiebe is suggest here as a solution for this problem. This study describes this work and concludes that a double-stage Wiebe is viable of predicting the dual fuel HCCI combustion more accurately than the standard Wiebe. The work also showed that, in the dual fuel environment, each fuel acted as a single fuel according to its own properties especially if the gaps between the injections of the two fuels are wide.

Key words: HCCI engine, double-fuel, Wiebe function, HCCI combustion

INTRODUCTION

The internal combustion engine has become the heart of the transportation sector for decades. There are two types of internal combustion engines: Spark Ignition (SI) and Compression Ignition (CI). For the last decades, rapid improvements in the efficiency have been achieved for both types of IC engine. However, due to stringent regulation on emissions and increasing concerns over the environmental effect of combustion engines, further improvements to both types of engine need to be achieved. The Homogeneous Charge Compression Ignition (HCCI) engine promises to achieve both high thermal efficiency and lower emission. HCCI essentially involves the autoignition of a premixed mixture that leads to a very rapid combustion process.

The HCCI concept was originally introduced by Onishi *et al.* (1979) to improve the combustion stability of two stroke gasoline engines. They found that there were significant improvements in the fuel economy and exhaust emissions. Noguchi *et al.* (1979) performed optical investigations on this system and found that there is no discernable flame front during the combustion process. Earlier works on HCCI combustion has opened new possibilities of a different combustion system. However, there are still some drawbacks of HCCI method implementation on the real engine. Among the drawback, the limited operating range has become the main focus for the next development of HCCI combustion systems. In the search for a way to control the HCCI combustion, recent investigations showed that dual fuel offers a significant way of controlling HCCI combustion. The most common combination is a fuel with Lower Octane Number (LON) combined with a higher octane fuel (HON).

The introduction of dual fuel to the HCCI combustion system and its effect to the performance and combustion has been investigated. Al-Khairi *et al.* (2011) had investigated the dual fuel HCCI combustion in compared with Compressed Natural Gas Direct Injection engine (CNGDI). They found that the dual fuel HCCI combustion characteristic is in compared with CNGDI combustion and there are some significant effects on the emission such as hydrocarbon, carbon monoxide and nitrogen oxide.

In exploring the HCCI combustion phenomena and understanding factors influencing it, models were used, with varying degrees of detail, to understand how the mixture preparation and in-cylinder thermodynamic conditions affect the chemical kinetics of the autoignition. These efforts ranged from a very sophisticated three dimensional model that predicted the thermodynamics state of every single engine condition by solving the equation for mass, momentum, energy and species conservation to the much simpler zero-dimensional models that assume an average state throughout the gas. Other paper by author had investigated the combustion behavior of dual fuel HCCI using the SHELL model which is focusing on the interaction between the fuels regardless the engine. While this paper is focusing on the zero-dimensional models and their modification in order to describe the dual fuel HCCI combustion in the engine operation.

Zero-dimensional models are the most commonly used tools for parametric studies associated with HCCI engine development. The governing equations are ordinary differential equations since there is only one independent variable. However, Zero-dimensional dual fuel HCCI models have to contain multiple zones due to the property variations of the fuels which lead to a different combustion behavior. However, as systematic spatial trends often have little influence, the simplest approach is for a single zone model spatially undifferentiated the LON and the HON.

Within this type of zero-dimensional model, combustion progress can be described by a Wiebe function fitted as far as possible to the accumulated heat release derived from the measured cylinder pressure as mentioned by Klein and Eriksson (2004). The Wiebe method can describe the engine operating conditions for which it has been tuned and is often accurate enough to be used for semi-predictive modeling if care is taken when analyzing the results (Elmqvist *et al.*, 2003).

However, there are two problems with using the standard Wiebe function for dual fuel application. Firstly, the parameters that appear in the function vary with the operating conditions. Secondly a standard Wiebe function can only be made to adopt a limited range of combustion progress shapes and if there are large differences between the burn rates due to the fuel properties variation at different times it can be difficult to obtain an accurate match between any Wiebe shape and the real combustion progress variable through all stages of combustion. In dual fuel HCCI, here are often large differences in effective burn rates between the main combustion of HON and LON. These differences arise due to the large differences in the combustion behavior between the HON and LON fuel such as the flame speed and autoignition temperature.

Yasar *et al.* (2008) used a double Wiebe function to represent the temperature variation inside the combustion chamber for a single fuel (gasoline) HCCI system. It was shown that double Wiebe able to simulate the variation in the combustion speed due to the temperature variation in the combustion chamber. On the other hand, Double Wiebe had also been used to discriminate the contribution of spark ignition and HCCI combustion for every individual cycle and predict the cyclic variability in the spark assisted HCCI combustion (Glewen *et al.*, 2009).

Double Wiebe is also shown to be able to simulate the dual fuel combustion in spark ignition engine. Yeliana *et al.* (2011) compared double Wiebe with other approximations method and shows that double Wiebe has the best fits to the experimental data of the combustion of ethanol-gasoline blends in SI engine over variable compression ratio and Exhaust Gas Recirculation (EGR) rates.

In this study, the benefits of adding the second Wiebe function to represent the combustion behavior of both fuels thus creating a "double-Wiebe function" model. Double-Wiebe has become a reliable approach in zero dimensional model for HCCI combustion.

Model: The Wiebe function can be expressed as follow:

$$x_b = 1 - \exp\left(-a\left(\frac{\theta - \theta_0}{\Delta\theta}\right)^{m+1}\right) \quad (1)$$

where, x_b is the mass fraction burned, θ is the crank angle, θ_0 is the crank angle at the starts of combustion, a and $\Delta\theta$ are adjustable constants that determine the combustion duration and m is an adjustable parameter that fixes the shape of the combustion progress curve.

However, this study will be using time constant rather than the crank angle parameter for the duration and time as the experiments for the dual fuel combustion were done in a constant volume chamber. The time based Wiebe function can be expressed as:

$$x_b = 1 - \exp\left(-a\left(\frac{t - t_0}{\Delta t}\right)^{m+1}\right) \quad (2)$$

where, x_b is the mass fraction burned, t is current time, t_0 is the time at the starts of combustion, a and Δt are adjustable constants that determine the combustion duration and m is an adjustable parameter that fixes the shape of the combustion progress curve.

In this single Wiebe function, the dual fuel parameter has not been included. Fuels with different combustion speed and behavior are commonly represented by the variation of the variables m and Δt that cannot be implemented in the standard Wiebe function. As a solution, modification and combination of two standard Wiebe (single stage) to double-stage Wiebe is used to simulate the characteristics of the combustion process of dual fuel. The double-stage Wiebe function can be expressed as:

$$x_b = f_1\left(1 - \exp\left(-a_1\left(\frac{t - t_0}{\Delta t_1}\right)^{m_1+1}\right)\right) + f_2\left(1 - \exp\left(-a_2\left(\frac{t - t_0}{\Delta t_2}\right)^{m_2+1}\right)\right) \quad (3)$$

where, the a_1, Δt_1 and m_1 are the combustion duration constant, the mass ratio of the LON and HON at the high temperature area and shape parameters of the combustion of the first fuel (LON), respectively and a_2, Δt_2 and m_2 are the combustion duration constant, the total combustion durations and shape parameters for the combustion of the second fuel (HON). While the f_1 and f_2 are the mass fractions of the first fuel (LON) and the second fuel (HON), respectively.

MATERIALS AND METHODS

The experiments were carried out in a cylindrical Constant Volume Chamber (CVC) as shown in Fig. 1. The CVC has cylindrical dimensions with a diameter of 100 mm and is 100 mm in length. This CVC was equipped with a direct access for the fuel injectors, pressure transducer and visualization windows.

The pressure vs time data is recorded by a Kistler pressure sensor using the trigger point on which the pressure starts to increase to a certain level as an indicator of the start of combustion.

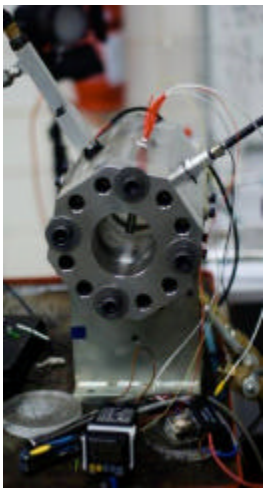

Fig. 1: Constant volume chamber

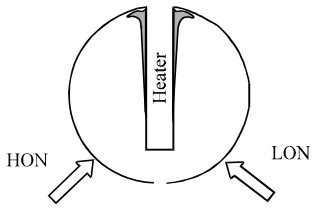

Fig. 2: Fuel injectors and heater arrangement in the CVC, HON: High octane number, LON: Low octane number

Table 1: Fuel injections properties

Fuels	Injection pressure (bar)	Injection duration (msec)
Gasoline	1.5	50
CNG	18.0	10

A probe heater is used to condition the temperature inside the combustion chamber to 800°C in order to achieve auto ignition of the mixture. Fuel injectors and heater arrangement in the CVC are presented in Fig. 2.

The fuels used in this experiment were commercial Gasoline as the LON and commercial CNG as the HON. The injection conditions for both fuels are given in Table 1.

Eight injection time gaps between the LON and HON fuels were investigated in order to observe the effect of mixing time between the two fuels on the combustion process. The injection time gaps were 0, 50, 100, 150, 200, 250, 300 and 350 msec.

RESULTS AND DISCUSSION

Figure 3 show the experiment results of the dual duel combustion. It shows that the 0 msec injection gap has the fastest early combustion rate and the slowest rate for the later combustion process while the opposite behavior was shown by the 350 msec injection gap where a slow rate was observed for the early stages and a faster rate for the later stages of the combustion. The double stage Wiebe parameters were inputted and fitted to the experimental data (Fig. 4a-h). It can be

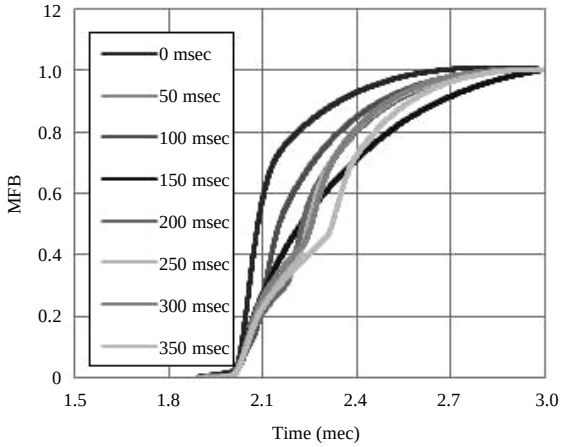

Fig. 3: Pressure trace of the autoignition process in constant volume chamber with dual fuel, MFB: Mass fraction burned

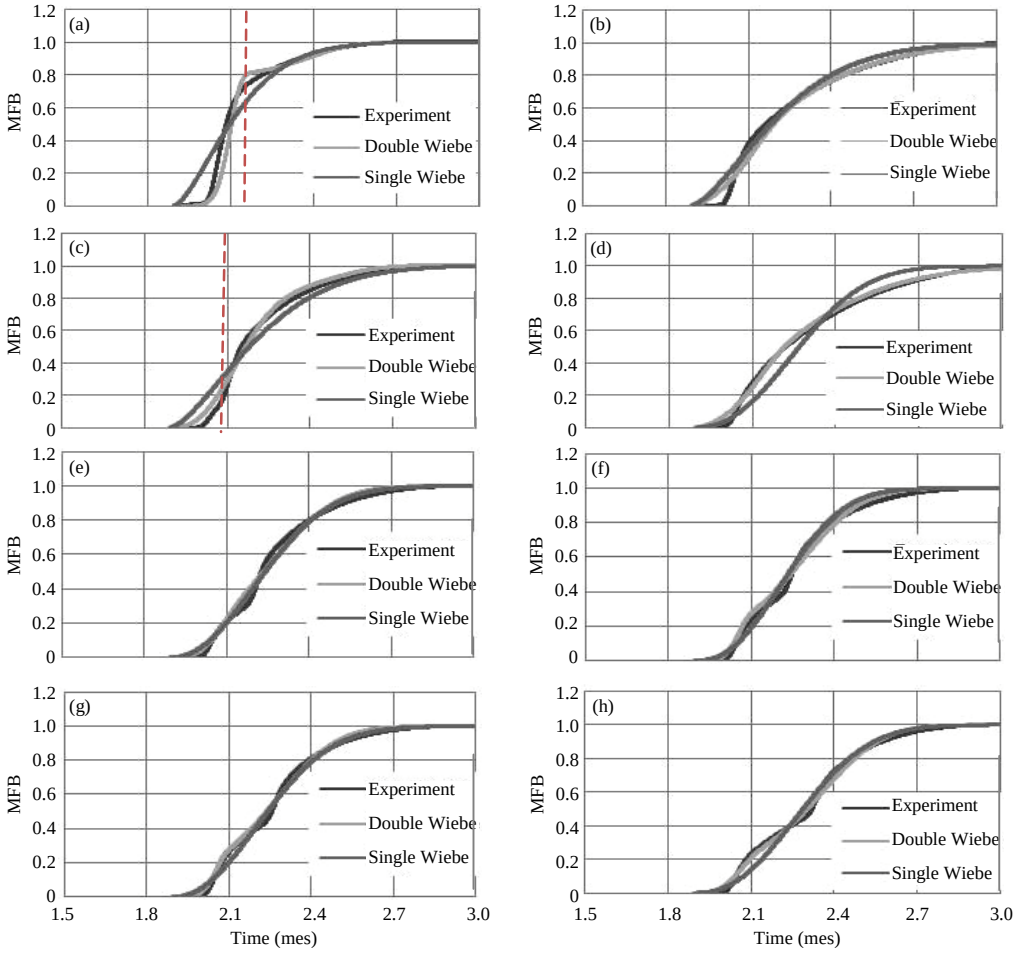

Fig. 4(a-h): Mass fraction burned (MFB) for gasoline-CNG fuel mixture with (a) 0 msec, (b) 50 msec, (c) 100 msec, (d) 150 msec, (e) 200 msec, (f) 250 msec, (g) 300 msec and (h) 350 msec time gap between the injections

seen from Fig. 4a-h that 0 to 150 msec injection gaps MFB profile are different that the MFB for 200-350 msec injection gap. The MFB curve for the 0-150 msec injection gap are similar to single fuel combustion profile stated in Heywood (1988) with unnoticeable transition between the HON and LON combustion process while the 200-350 msec injection gap MFB curves clearly shows the transition between the LON and HON combustion.

These results also show that the combustion process of the LON fuel for 200-350 msec injection gap had entered its later stage of the combustion process at the time the HON was injected and combust. This may describe the combustion process of HCCI combustion method that used LON as the pilot ignition in order to control HCCI combustion. Furthermore, the combustion for the 0-150 msec injection gap shows the effect of the HON to the combustion of LON. It is seen in Fig. 4 that the slow combustion rate occur earlier as the injection gap increases. This may occur due to the suppression effect of the HON to the LON combustion that suppresses the combustion propagation as the increased stratification level of HON at the start of combustion.

Figure 4 also demonstrate the double-stage Wiebe capabilities in representing the dual fuel combustion. It can be seen that the double-stage Wiebe is in good agreement with the experimental results compared to the standard Wiebe. These results show that each single fuel was still acting accordingly to its properties in the dual fuel combustion environment especially for the injection gap above 200 msec.

Table 2 shows the parameters used in both standard and double-stage Wiebe. It can be seen from the Δt_1 parameter at the double stage Wiebe for various injection gap that the values of Δt_1 tend to decreased as the injection gap increased.

From the double stage Wiebe equation, Δt_1 is representing the mass ratio of the LON over HON fuels at the high temperature area. The decreasing result of the Δt_1 values shows that the amount

Table 2: Standard Wiebe and double-stage Wiebe parameters for various injection gap

		Dual-stage Wiebe			
No.	Parameters	0	50	100	150
1	a1	10.000	10.0	10.0	10.00
2	m1	3.000	2.5	2.8	2.50
3	dt1	0.925	0.5	1.1	0.50
4	a2	4.500	4.5	4.5	4.50
5	m2	1.900	0.5	1.6	0.65
6	dt2	1.250	1.7	1.6	1.70
7	f1	0.200	0.2	0.2	0.20
8	f2	0.800	0.8	0.8	0.80
		Dual-stage Wiebe			
No.	Parameters	200	250	300	350
1	a1	10.00	10.000	10.000	10.00
2	m1	2.40	4.500	4.500	2.40
3	dt1	0.40	0.250	0.250	0.35
4	a2	4.50	4.500	4.500	4.50
5	m2	1.65	1.800	1.775	2.10
6	dt2	1.20	1.025	1.025	1.20
7	f1	0.20	0.200	0.200	0.20
8	f2	0.80	0.800	0.800	0.80

of the LON fuel at the high temperature area is less at longer injection gap at the start of combustion. This may be due to the evaporation of the LON fuels to the surrounding area during the injection gap. As a result, at the time of HON injection, the LON concentration at the high temperature area was reduced. Furthermore, it can be extracted from the data that around 60% of the mass of LON was evaporated during the 350 msec gap time.

CONCLUSIONS

An experimental and modeling study was carried out to compare the performance of the standard Wiebe function with a double-Wiebe function that allows us to define a proportion of dual fuel combustion for HCCI engine modeling. The standard and double stage-Wiebe functions were used to simulate the dual fuel HCCI combustion in a constant volume vessel.

The study showed that by describing dual fuel combustion by double stage Wiebe, it was possible to achieve a better match to the experimental data than with a standard Wiebe. It can be argued that results closer to the multi-zone models can be achieved by using the double stage-Wiebe function in a single zone HCCI of a dual fuel HCCI combustion process.

ACKNOWLEDGMENT

Author acknowledges Universiti Teknologi PETRONAS (UTP) for the support in this research work.

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