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A SIMPLIFIED METHOD FOR THE COMPUTATION OF THE PREMIXED MODE HEAT RELEASE IN DI DIESEL ENGINES

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Abstract. *Diesel engines have a wide spread of mobility applications and a solid reputation of high efficiency, low fuel consumption and reliability. The most challenging demand for its further development are the simultaneous reductions on fossil fuel consumption and pollutant emissions induced by an ever strict legislation scenario. High precision digitally controlled fuel injection systems and real time engine control strategies based on in-cylinder pressure control could contribute for the achievement of the low emissions goal. One aspect with particular interest regarding the engine control is to limit the premixed phase diesel combustion. Near stoichiometric fuel-air mixture is rapidly burned at high temperatures in the premixed mode, causing engine vibration, noise and nitrogen oxides emissions. In the current work, a methodology is developed for the rapid determination of the premixed mode combustion total heat release. It is based in the direct interpolation of the gross heat release curve by a single Wiebe function, which after some manipulation demands the solution of two trivial equations for the premixed combustion angle and total heat released in premixed mode, besides a nonlinear equation for determining the premixed mode form factor. In order to establish a precision benchmark, a detailed program using quasi-Newton minimization and finite-difference gradient was also employed to approximate the experimental heat release data by two Wiebe functions, according to Miyamoto's model. The proposed methodology and the baseline detailed interpolation routine were applied to approximate experimental data from a turbocharged DI diesel engine operating in three distinct engine operational conditions; low, mid and full load. According to the obtained results, the simplified method proposed here has shown to be around* 20 *times faster than the benchmark detailed program, with a precision loss of only up to* 1% *for all tested regimes.*

Keywords: *Wiebe Function Fitting, Heat Release Analysis, Premixed Mode Combustion, Diesel Engine.*

1. INTRODUCTION

An important aspect in the combustion process in compression ignition engines is the time for each combustion phase; ignition delay, premixed, mixing-controlled and late combustion. They impact efficiency, emissions, and overall engine performance (Yeliana *et al.*, 2011). Figure 1 illustrates a typical heat-release-rate (HRR) diagram for diesel combustion engine (Heywood, 1988).

In this type of diagram, the combustion is characterized by four phases. The first phase characterizes the ignition delay, which corresponds to the period between when the fuel injection starts and the first fuel burn signal. The last stage, late combustion phase, has a low combustion rate that decreases until the phase is completed. Through the diagram, the two phases where the greatest amount of heat release occurs are the premixed combustion phase and mixing-controlled combustion phase.

In the premixed combustion phase, shortly after starting the ignition, the fuel burning occurs rapidly, causing a sharp increase in the rate of heat release, as seen in Fig. 1. At this phase the reaction rate is controlled by the kinetics of the chain reactions, which depends on the ignition delay and the homogeneity of the mixture of reagents occurring in the first phase. The velocity of the reactions in the second phase will define the behavior of the cylinder pressure, where the value of the maximum pressure in this phase represents the maximum pressure of the cycle. This can be used as a design

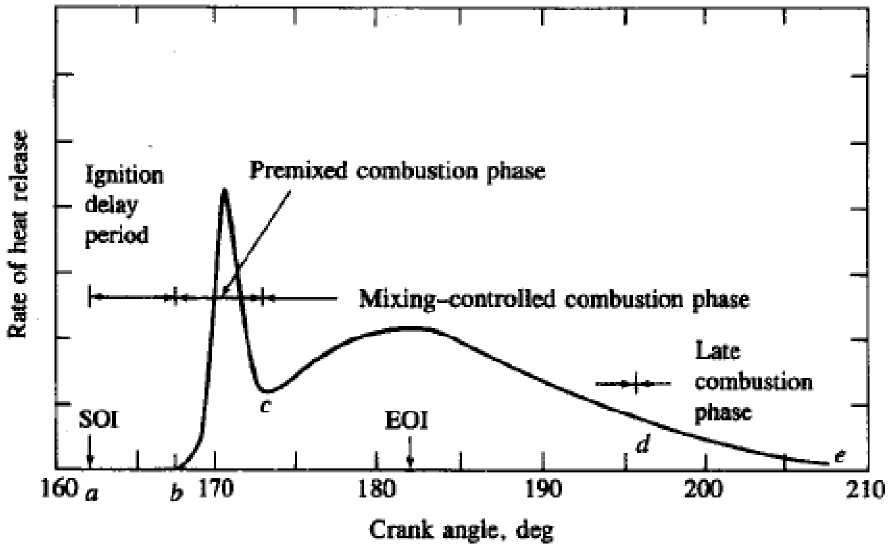

Figure 1. Typical heat-release-rate diagram diesel combustion phases.

parameter (Heywood, 1988).

In mixing-controlled combustion phase, also called diffusive combustion, any injected fuel reacts instantaneously with the oxygen of the mixture due to the high values of pressure and temperature inside the cylinder. In this phase, the subsequent increase in pressure is controlled by the injection rate and the process of mixing the reactants, which is the diffusion of the vaporized fuel mixing with the remaining air. These can also be used as design parameters (Heywood, 1988).

According to Miyamoto *et al.* (1985), a lot of research has been done to understand the combustion processes in diesel engines, thus enabling improvements in design, performance and emissions. Ghojel (2010) reports in his review that the tool most commonly used to estimate the behavior and performance of combustion in engines is the Wiebe function.

The Wiebe function describes the burnt mass fraction of a combustion process. It is common to use a double Wiebe function for diesel engines, in which one accounts for the premixed combustion and the second for diffusive combustion (Merker *et al.*, 2006). Ghojel (2010) presents several applications on engines using double Wiebe function.

According to Oh *et al.* (2015), the control of closed-loop combustion has been the subject of much research, both aimed at improving engine performance and emissions control. In his work, Fang *et al.* (2017) affirms that combustion variables, e.g. indicated mean effective pressure (IMEP), mass fraction burned (MFB), etc., are capable of being monitored and controlled in real time. Dowell *et al.* (2017) presents some models and requirements for real-time combustion control using one-parameter heat release.

One of the common pitfalls associated to the real time control of diesel engines is the achievement of real world combustion related control parameters. Current real time engine control studies use to focus on engine performance and fuel consumption aspects. Strict pollutant emissions limits suggest that, besides performance, the combustion characteristics also need to be controlled in order to obtain clean burning and thus engine operating conditions. If one takes into account the classical phase division of the diesel engine combustion, it is easy to attribute to the premixed combustion phase the preeminence in generating some undesired combustion characteristics. Near stoichiometric fuel-air mixture is rapidly burned at high temperatures in this mode, causing engine vibration, noise and high nitrogen oxides emissions. Modern engines apply a pre-injection event in order to sustain the levels of premixed burning under control, however the angle and the amount of pre-injected fuel are determined in the engine calibration and remain unaltered through the product's life. Changes in operational conditions such as altitude, air temperature and fuel cetane number can lead to important impacts in the ignition process of the pre-injected fuel, thus causing the amount of fuel burned in the premixed combustion mode to drift from the original limits established in project. Thus, to monitor and even actively control the amount of fuel burned in premixed mode appears to be a relevant aspect to engine control from both points of view: performance and emissions. In the current work, a methodology is developed for the rapid determination of the premixed mode combustion total heat release, with perspective of future application in an on-board combustion control system. The proposed method is tested against experimental data and its computational cost and precision are compared to the ones achieved with a baseline program, which uses quasi-Newton minimization and finite-difference gradient to approximate the combustion heat release by two Wiebe functions.

2. METHODOLOGY

The experimental HRR data used by the proposed method and the benchmark program were acquired and treated by the Laboratory of Internal Combustion Engines from the Federal University of Ceara (UFC). The tests were taken in a turbocharger diesel engine MWM TD-229-6. The data was collected at speed of $1800rpm$ for three different load regimes; 33%, 66% and 100% of the maximum load. The values of the root-mean-square (RMS) deviation with relation to the experimental heat release data were used to evaluate the accuracy of both methods.

2.1 Simplified Premixed Heat Release Interpolation - Single Wiebe

The procedure proposed here to calculate the total premixed mode heat release uses the derivative of a single Wiebe function to approximate the premixed combustion HRR as a function of the crank angle θ:

$$\frac{dQ}{d\theta} = Q_p \cdot 6,908(m+1)\frac{(\theta-\theta_0)^m}{\Delta\theta^{m+1}} \exp\left[-6.908\left(\frac{\theta-\theta_0}{\Delta\theta}\right)^{m+1}\right] \tag{1}$$

where, Q_p is the total energy released by the premixed combustion, θ_0 is start of combustion, $\Delta\theta$ is the duration of the premixed combustion and m is called form factor. Equation (1) presents a single peak, meaning that $\left(d^2Q/d\theta^2\right)_{max} = 0$. This leads to Eq. (2). The total energy released can also be estimated by the maximum HRR value, Eq. (3). Both equations are function of m and θ_0.

$$\Delta\theta = (\theta_{max} - \theta_0)\left[\frac{6.908(m+1)}{m}\right]^{1/(m+1)} \tag{2}$$

$$Q_p = \frac{\left(\frac{dQ}{d\theta}\right)_{max}}{\frac{6.908(m+1)}{\theta_{max}-\theta_0}\left(\frac{6.908(m+1)}{m}\right)^{(m-1)/(m+1)} \cdot \exp\left[-6.908^2\frac{(m+1)}{m}\right]} \tag{3}$$

After the injection, the fuel absorbs energy from the chamber before the combustion starts. This process causes a negative energy released rate and it is better reflected on the derivative of pressure. Therefore, the start of combustion θ_0 was estimated as the first minimum point located right before the global peak on the derivative pressure diagram, Fig. 2.

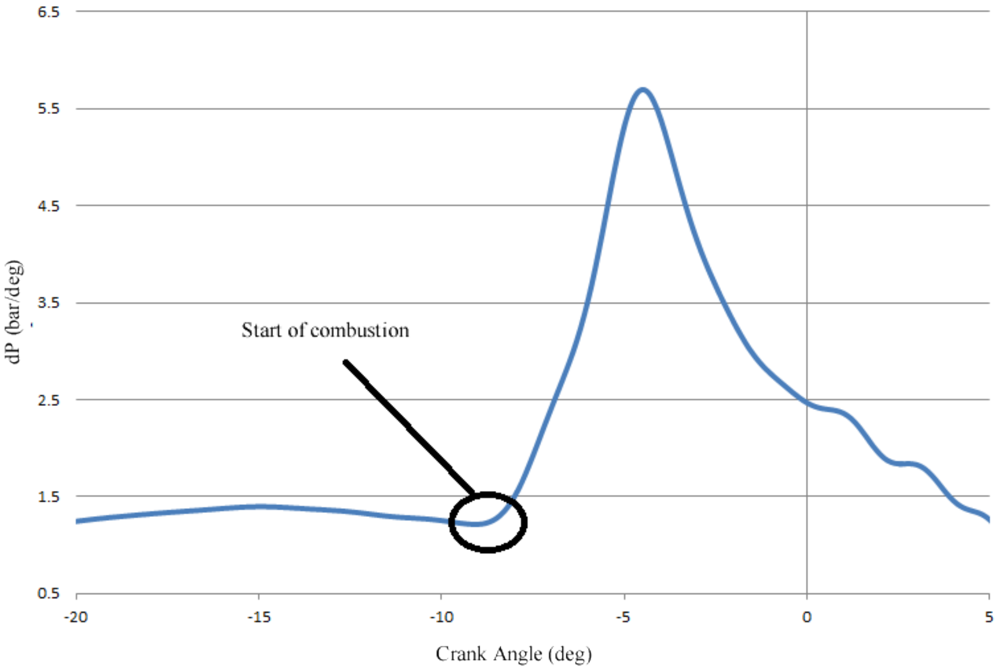

Figure 2. Typical derivative pressure diagram.

The form factor was calculated using the HRR value at θ_{mid} where $\theta_{mid} = (\theta_{max} - \theta_0)/2$. Substituting Eq. (2) and (3), Eq. (1) becomes a non-linear function of m only, therefore requiring numerical solution. The bisection method was initially used to guarantee convergence and the secant method was applied after to increase the pace.

Knowing the form factor, the combustion time and total energy released in the premixed combustion can be estimated from Eq. (3) and Eq. (2), respectively.

2.2 Standard Fitting of Two Wiebe Functions - Fitting Wiebe

In order to test the precision and the computational cost of the simplified model proposed here, a detailed program that employs Quasi-Newton minimization and finite-difference gradient Developers (2007) was also used to approximate the experimental heat release by two Wiebe functions, according to the combustion model proposed by Miyamoto et al. (Miyamoto *et al.*, 1985), Eq. (4). The values of m, $\Delta\theta$ and Q_p and the execution times provided by this standard Wiebe fitting program were used as benchmarks for both precision and computational costs within the tests conduced with the simplified model proposed here.

$$\begin{aligned}\frac{dQ}{d\theta} = 6.9\frac{Q_p}{\Delta\theta_p}(m_p+1)\left(\frac{\theta}{\Delta\theta_p}\right)^{m_p}\exp\left[-6.9\left(\frac{\theta}{\Delta\theta_p}\right)^{m_p+1}\right] \\ + 6.9\frac{Q_d}{\Delta\theta_d}(m_d+1)\left(\frac{\theta}{\Delta\theta_d}\right)^{m_d}\exp\left[-6.9\left(\frac{\theta}{\Delta\theta_d}\right)^{m_d+1}\right]\end{aligned} \tag{4}$$

An offset on the start of the diffusive combustion was added in order to separate more precisely the influence of both phases, since the start of diffusive combustion of modern diesel engines is delayed by a few crank degrees. The parameters calculated by the simplified method were used as input for the standard program in order to reduce computing time.

3. RESULTS

Figures 3, 4 and 5 illustrate the estimated HRR values using the proposed method and the benchmark approach for loads of 33%, 66% and 100%, respectively. The estimated premixed combustion time in crank degrees by the simplified method were; $\Delta\theta_{33\%} = 8.30$ $\Delta\theta_{66\%} = 9.0$ and $\Delta\theta_{100\%} = 8.60$.

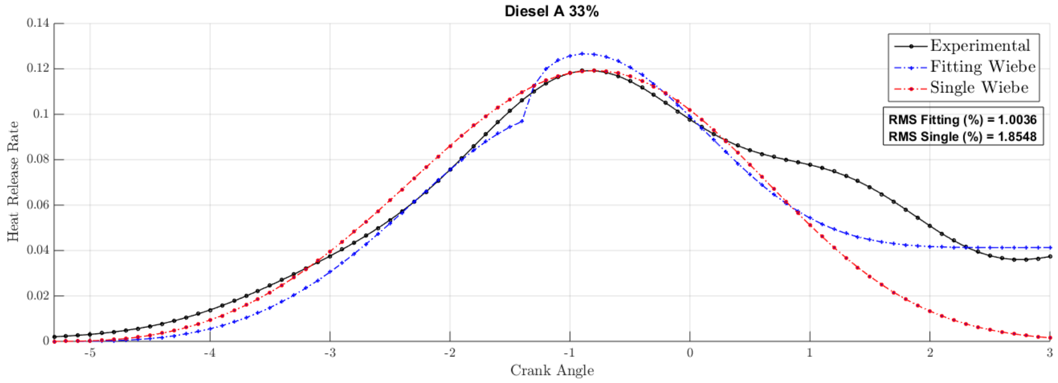

Figure 3. Heat Release Ratio for premixed combustion at 33% load

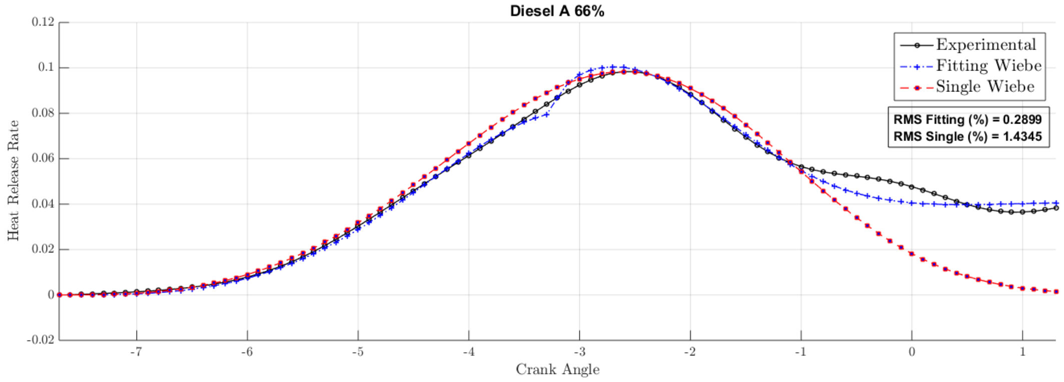

Figure 4. Heat Release Ratio for premixed combustion at 66% load

The simplified single Wiebe analysis presented similar precision for all load regimes, below 2%. However, the standard approach has shown to be 1.0% more accurate overall. At low load conditions (33% load) the large ignition delay interval

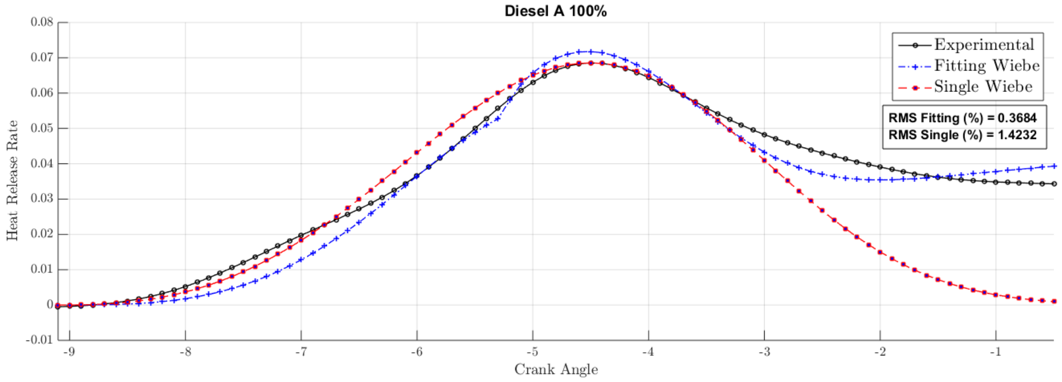

Figure 5. Heat Release Ratio for premixed combustion at 100% load

hinders the determination of the ignition event and both methods presented its lower precision levels. Overall, the Fitting Wiebe method has a gain of about 1.0% in accuracy over the Single Wiebe. About one degree of crank angle after the peak the Single Wiebe function starts to deviate from the experimental data while the standard method maintains fairly similar. This occurs due to the increasing in relevance of the diffusive combustion with time (Heywood, 1988). Since the Fitting approach uses a double Wiebe function model, it is able to estimate the effects of both combustion phases.

A comparison of computing time between the Single Wiebe and Fitting Wiebe approach is shown in Tab. 1. The average of 30 measured computing time has been taken. The data has been normalized by the fastest procedure in order to demonstrate the order of magnitude. The Fitting Wiebe is around 20 times more expensive for all the load regimes. The computing time estimated for the Single Wiebe ranged from 14 to 22 milliseconds for all load regimes. The 66% regime has the highest $\Delta\theta$ hence reflecting its computing time above the others for the Single Wiebe. Even though the 100% load has greater $\Delta\theta$ than the 33%, it has shown to be faster due to its quicker convergence while estimating the factor form. Therefore, a more precise initial value for m can accelerate the process around 10%.

Table 1. Comparison of computing times

	Single Wiebe	**Fitting Wiebe**
33%	1.10	20.28
66%	1.17	19.44
100%	1.00	20.80

4. CONCLUSIONS

The Single Wiebe method has shown to be about 20 times faster than the Fitting technique and it presented a loss on RMS values of only around 1%. Therefore, the Single Wiebe approach is a better option than the Fitting Wiebe for real-time investigations of the premixed combustion in diesel engines, such as combustion time and total energy released.

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