



Combined mean value engine model and crank angle resolved in-cylinder modeling with NOx emissions model for real-time Diesel engine simulations at high engine speed



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ABSTRACT

This study is an extension of a previous MVEM (Mean Value Engine Models) and in-cylinder single zone model dedicated for HIL (Hardware In the Loop) applications. The in-cylinder single zone model has been modified into a two zone model for the combustion phase. Thus a Zeldovich extended mechanism has been used to simulate engine out NOx level. The entire model works as a combination of an MVEM approach for the engine periphery, of a single zone in-cylinder model for the intake-compression-exhaust strokes and of a two zone model for the combustion process. The combustion process is modeled through a double Wiebe equations developed previously. The proposed two zone and NOx models have been first coded using Matlab/Simulink software before its implementation on a HIL test bench. The in-cylinder extended model has required a quad Core RTPC to reach the step time of real time simulations where one core has been dedicated to the combustion process. The comparison of measured and calculated in-cylinder pressure and NOx emissions has shown a good accuracy. The mean relative error between the calculated and the measured indicated mean effective pressure is for example lower than 2%.

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1. Introduction

In order to reach stricter environment regulations, HIL (Hardware In the Loop) test bench is a powerful tool to reduce the number of time consuming and expensive vehicle tests. In addition, HIL test system is used to optimize and to validate the ECU (Engine Control Unit) [1]. The introduction of innovative solutions, as for example in-cylinder pressure sensing, has increased the number of involved variables, calling for improvements in modeling approaches dedicated to HIL system. HIL requires models able to run in real time simulations, to catch the engine behavior in terms of performances, pollutant emissions reduction and fuel consumption.

MVEM (Mean Value Engine Models) are able to run in real time and are appropriate for HIL test systems. MVEM can generate consistent sensor values like engine speed and torque, air mass flow, pressure, etc, according to the actual actuator controls, like injection, EGR (Exhaust Gas Recirculation) rate, boost pressure, etc.

All sensor values are mean values over one engine cycle corresponding to 720 CAD (Crank Angle Degree). MVEM approach is based on highly reduced mass and energy balances for each engine component and a parameterization process is required for each HIL project. Generally, test bench measurements are done and used as calibration data. Besides, the calibration phase required by MVEM approach leads to many look-up-tables. As an example in published papers dealing with MVEM approach, the same process is used: Schulten et al. [2] have used MVEM to model the gas exchange of a four-stroke Diesel engine. In Refs. [3,4] MVEM approach has been applied to a large turbocharged two-stroke Diesel engine [3] and to a turbocharged SI engine [4].

Similarly to published papers, in our previous study [5,6] a complete MVEM model for a standard HIL test bench dedicated to the complete Diesel powered vehicle, able to run in static and dynamic modes, has been developed, using experimental data from an OEM (Original Equipment Manufacturer) engine and vehicle project. Available experimental data from the engine test bench (injected fuel mass, air mass flow, temperature, pressure, air fuel ratio, etc) and the engine geometrical data (plenum and chamber volumes, stroke, bore, etc) have been used as calibration data and as

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model parameters. In this previous study where the details can be found in Refs. [5], our effort has been focused on the air path including: turbocharger, intake manifold, exhaust manifold, etc. A mean value combustion model has been developed to calculate the enthalpy and mass flow rates of the OEM engine. This model has been tuned to include lookup tables for volumetric and combustion efficiencies. These maps have been established from experimental data including normal and late injections. The complete MVEM model implemented on HIL test bench has been used to test some specific driving conditions: cold start, winter and summer constraints, high altitude.

In order to further improve fuel economy and emissions while maintaining higher power, future ECU for Diesel engines will also be equipped with in-cylinder pressure sensors. This in-cylinder pressure signal will be used for engine control to minimize fuel consumption and to reduce soot and NOx emissions significantly. Consequently, crank angle in-cylinder pressure models instead of MVEM models are required for upcoming HIL test bench. The fuel injection pattern affects directly the progress of Diesel combustion and thereby the in-cylinder pressure. Hence, mean value modeling is unsuitable to validate ECUs including future closed-loop control strategies. Therefore, real time crank angle in-cylinder pressure modeling in accordance with the injection mode is needed. In addition, models of engine-out emissions (and particularly NOx emissions) are useful in many applications. Exhaust aftertreatment systems represent usual components of the complete engine system. The engine cannot be separated from the aftertreatment system when it comes to optimization.

In-cylinder crank angle models without engine-out emissions modeling are mainly based on in-cylinder single zone model for real time application. The combustion sub-model is modeled through a single Wiebe function [7] or a double Wiebe function to describe the behavior of conventional Diesel engine [8,9], of the HCCI (Homogeneous Charge Compression Ignition) combustion process [10] and of the spark ignition engine combustion over variable operating conditions [11]. Single zone models require short computational time, and give good accuracy in term of in-cylinder profiles compared to experimental data. Note that this accuracy is strongly linked to the ignition delay time and Wiebe equations parameters identification. In another investigation [9] by the same authors, a single zone thermodynamic model has been developed to simulate the in-cylinder pressure. The combustion sub-model has been modeled through a double Wiebe function [12] to describe the premixed and diffusive burning process. The aim of this previous study was to analyze the effects of ignition delay time (modeled through an Arrhenius correlation and an algebraic simple correlation), on the accuracy of the model in predicting the in-cylinder pressure at high engine speed (from 4000 rpm up to 4750 rpm). Note that at these engine speeds the engine operates with single injection mode and without EGR. The comparison of the two developed correlations has shown that the simple correlation has a greater potential in simulating the ignition delay time and the in-cylinder pressure profiles, keeping short computational times.

Note that the final goal of our project is to build a crank angle resolved in cylinder model for real time simulation excluding lookup tables. The complete model must be able to predict in-cylinder pressure and NOx emissions at varying engine conditions (BMEP (Brake Mean Effective Pressure), engine speed, etc) with the required accuracy level. Additionally, during the real time simulation the model needs to be executed within the time period associated with one crank angle degree. Consequently, in the first stage of this project, we have focused our effort on high engine speed, mainly because the computational time window is very short at these engine speeds. For example when the engine speed is

equal to 4750 rpm one crank angle degree corresponds to 35 micro seconds. In the present study, the NOx model has been added to an extended in-cylinder model with the constraints of short computational time required by real time simulations.

As far as simulation of engine-out emissions (especially NOx emissions) are concerned, the published studies in the literature can be classified into two main categories: single zone models and two zone (or multi-zone) spray models. When NOx mechanism is used in single zone approach, the burnt gas temperature required by NOx reactions is estimated with a correlation function of adiabatic flame temperature [13,14]. In this case, look-up-tables are used, similarly to MVEM approach. Two zone spray models (or multi-zone spray models) dealing with real time applications available in the literature focus on the spray modeling to calculate the burned zone gas temperature. The published multi-zone spray models [15,16] describe in details the fuel spray. This later is modeled through several zones independent from each other. This approach is accurate to predict the pollutant formation via the combustion progress, when the number of spray zones is relatively high, which leads to an increased CPU time unfit for real time applications. Barba et al. [17] have published a two zone spray model, each zone dedicated to the premixed combustion process and to the diffused combustion process respectively. Their approach presents a shorter CPU time in comparison to the multi-zone spray approach. In Refs. [18] and [19], the authors adopt the same model as in Refs. [17]; a mixing model based on the turbulent kinetic energy generated by the spray is added to calculate the burned gas temperature. This approach introduces a characteristic mixing time calculated by a simple correlation in Ref. [18] and directly related to the turbulent kinetic energy and its dissipation in Ref. [19]. However, in a view of real time simulations, multi-zone spray models require high computational time window inappropriate for real time specifications, and especially when the entire vehicle has to be modeled. In Refs. [20], the authors have developed a highly reduced NOx model based on a single global reaction where the combustion and emissions are treated as quasi-static processes. The model is dedicated to be embedded in an MVEM model and requires a map and 10 scalar parameters and has a very short computational time.

We have opted in this study for an in-cylinder two zone model to calculate the burned gas temperature required by the NOx mechanism, in order to avoid the recourse either to lookup tables used with the adiabatic flame temperature approach [13,14,20,21] or to spray modeling approach [15–19] inducing a higher CPU time. In-cylinder two zone (burned zone and unburned zone) model is usually used for SI engines [21,22] where the air-fuel mixture is assumed perfectly homogenous. For Diesel combustion the mixture is not homogenous, and the most appropriate approach for this combustion process is the multi-zone spray model with an emission model. However, as stated above this kind of models present their own limitation for real time application. The motivation for developing this two zone in-cylinder model for Diesel combustion has been guided by the fact that the combustion progress parameters (ignition delay time, Wiebe parameters) have been calibrated from experimental heat release rate, therefore taking into account the heterogeneities of the air-fuel mixture. Furthermore, the premixed and diffusive combustion phases modeled by Wiebe correlations have been expressed as function of the overall equivalence ratio.

In the present study the content of the combustion chamber is then divided into two zones, the burned and unburned zones; the temperature of the burned zone is quite different from that of the unburned zone and is more appropriate for NOx formation for Diesel engine. As in Ref. [16,19] NOx emissions have been modeled by a well known extended Zeldovich mechanism. This mechanism can only account for NOx formation at relatively high temperatures.

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