Energy Conversion and Management 151 (2017) 481–495

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Development and validation of a marine sequential turbocharging diesel engine combustion model based on double Wiebe function and partial least squares method

Yongrui Sun, Hechun Wang*, Chuanlei Yang, Yinyan Wang

College of Power and Energy Engineering, Harbin Engineering University, Harbin 150001, China

ARTICLE INFO

Keywords:
Marine diesel engine
Sequential turbocharging
Combustion model
Wiebe function
Partial least squares

ABSTRACT

Developing an accurate combustion model for a Sequential Turbocharging diesel engine is an efficient way to reduce the time consumption and the expensive experiment costs in the process of determining the control strategy of a Sequential Turbocharging system. In this paper, 142 operations of a marine diesel engine with two Sequential Turbocharging systems are used for this research. A novel method is proposed to calculate the initial values and limit bounds of the Wiebe parameters, and the use of this method could effectively avoid the occurrence of impossible solutions or multiple solutions caused by only using nonlinear least square fitting. The calculated Wiebe parameters could achieve a high level of accuracy that the mean value of the determination coefficient between the simulated and experimental heat release rate profiles is 0.98 for all the operations, and they are accurate enough for developing the combustion model. The partial least square regression is first imposed to relate the Wiebe parameters to the operating conditions. For the ability to solve the multiple correlations among the operating conditions, the prediction performance of the combustion model developed by partial least square regression is much higher than that by least square regression. The mean absolute percentage errors of the brake specific fuel consumption and maximum in-cylinder pressure simulated by the model are 0.284% and 1.39%, respectively. The model could accurately predict the engine performance and is sufficient to make the reasonable control strategies for the different Sequential Turbocharging systems.

1. Introduction

Ninety-eight percent of marine propulsion are provided by the diesel engine. Based on the request for the high brake mean effective pressure and efficiency, the high compression-rate turbocharger (TC) is widely adopted in this field. However, the turbo nozzle area is always too large for the exhaust flow at the partial load condition, which leads to the lack of intake air flow to the fuel injection mass. So the brake specific fuel consumption and the particulate matter emissions significantly increase. Characterized by the large space in the main engine room of the marine, the Sequential Turbocharging (STC) system is an effective way to solve this problem by changing the number of TCs at work [1]. This means that only one TC works at the low load operation, while two or more TCs are used for the high load operations. For an STC system, the key point is to work out a reasonable STC control strategy for projecting the range of operations with different phases of the STC system. Ref. [2] carries on an experiment to developed the STC control strategy by the rule of the minimum fuel consumption, at the partial load the brake specific fuel consumption (*BSFC*) and the temperature before the turbo are reduced by 7.1% and 12.6%, respectively. Meanwhile, Ref. [3] finds that the maximum decrease of the emission of Nitrogen Oxide (NO_x) and Particulate Matter (PM) are 64% and 76% by using one TC at the partial load. The conventional approach for the control strategy is by experiment. However, only testing all the operating points in the different phases of the STC system requires a great quantity of work, let alone coordinating with the variables in other systems like the injection parameters, the EGR rate, the valve timing, etc. Considering that the power of the marine engine is almost greater than 100 kW, developing a theoretical model is a powerful way to reduce the very high fuel consumption and pollutant emissions during the experiments. In addition, the theoretical model could predict the engine performance in a limiting external environment, which is sometimes an incapable task on a test-bed, and provide the crucial data for the STC control strategy without harming the engine.

The precision of the theoretical model strongly depends on the simulation accuracy of the combustion process. In the published literatures, the combustion models can be divided into four parts: full CFD model, zero–dimensional model, Mean Value Engine Model (MVEM)

---

* Corresponding author.
E-mail address: wanghechun@hrbeu.edu.cn (H. Wang).

http://dx.doi.org/10.1016/j.enconman.2017.08.085
Received 8 June 2017; Received in revised form 27 August 2017; Accepted 28 August 2017

and difference-pressure model. The CFD model is used for the structure optimization [4] and performance prediction [5] in diesel engine design. The CFD model requires a high simulation time and a lot of work in calibration processes, and it's very difficult to predict the performance of the engine coupling with different turbochargers. The MVEM is able to run in real time by generating a consistent mean value over one engine cycle to reflect the combustion process [6]. The difference-pressure model is a real-time estimation algorithm of the indicated mean effective pressure [7]. However, the MVEM and difference-pressure model could not provide the maximum in-cylinder pressure which is the one of the important constraint parameters to evaluate the turbocharging systems. Based on the assumptions of the zero–dimensional model, the combustion can be solved in a rapid way and provide the in-cylinder pressure. The zero-dimensional multi-zone model could take into account the spatial and temporal variation of temperature and concentration by separating the fuel spray into a large number of zones [8]. But the multi-zone model still requires a high computational time window for the real time applications, and especially when the entire vehicle has to be modeled [9]. The mixture controlled combustion (MCC) model and Wiebe function solve the combustion with less zones or even single zone, which could significantly increase the calculation speed. For considering the effect of the fuel injection on the turbulent kinetic energy, the fuel evaporation and the distribution of the fuel and oxygen in the MCC model, the heat release rate could be directly simulated by using the injection rate and calibrating a set of constants [10]. However, the structure and fuel property of a marine engine could significantly change for the differences of the applications and design concepts, such as the structure of the piston bowl, with/without a pre-chamber, different fuel systems, gas fuel and biodiesel, etc. The extensive applicability of the Wiebe function has been verified. Ref. [11] studies the feedback mechanisms affecting the SI-HCCI mode transition by Wiebe function. Ref. [12] carries on a comprehensive uncertainty analysis of Wiebe combustion model for a pilot-ignited natural gas engine. Ref. [13] calculates the double-Wiebe function parameters by using least square method for the combustion process of ethanol-gasoline blending in a spark-ignition engine. Ref. [14] develops a multi-Wiebe combustion model to predict the engine performance using different kinds of biodiesel from wastes. Ref. [15] developes a double-Wiebe combustion model of gas engines with pre-chamber to consider the effect of the actual air humidity on the combustion. Ref. [16] predicts the heat release rate in the multi-injection mode combustion processes by multi-Wiebe function, and the feasibility of the Wiebe function for hardware in the loop applications is verified in this study. Meanwhile, the NO_x can be accurately calculated by the Zeldovich extended mechanism coupling with a Wiebe function combustion model [9]. Because of the simplicity and extensive applicability, the Wiebe function is suitable for the further research on this subject. In order to accurately simulate the combustion processes by the Wiebe function, two issues need to be determined: (1) getting the exact and unique solutions of the Wiebe parameters; (2) finding a reasonable method to calibrate the Wiebe parameters.

There are mainly two methods in tuning the Wiebe parameters to the experimental data. The first one is calculating the Wiebe parameters from the experiment data based on their physical significances [17], the other is the nonlinear least square fitting (NLSF). The former one is usually used for determining the parameters of the single Wiebe function, and the simulation accuracy is prone to a low frequency noise signal in the combustion process. NLSF is a common method to achieve the parameters of the single Wiebe, double Wiebe [11,18,19] and Multi-Wiebe function [14,20]. However, Ref. [11] finds a set of Wiebe parameters calculated by NLSF may exist that fits the heat release rate quite well but are impossible solutions or multiple solutions, and properly selecting initial values and bounds will minimize the occurrence of these situations. This insufficiency of NLSF would increase the uncertainty between the Wiebe parameters and engine operating conditions, and influence the precision of the combustion model. But only a few of the literatures using Wiebe function introduce their calculation methods of the initial values. Ref. [21] carries on a sensitivity analysis of the burnt fraction and proposes a new method to estimate the start of combustion, but only determining this parameter is not enough. Ref. [20] estimates the premixed combustion's proportion by the mass injection during the ignition delay period and proposes a function between the premixed combustion duration and the form factor. Because the start of combustion is not a fixed event, the ignition delay period can't be easily determined [22]. So the calculation process of the mass injection during the ignition delay period is very complex. Determining the initial values and limit bounds artificially by analyzing the Wiebe parameters of each operating point is undesirable, especially for a large number of operating points. Thus, it is essential to develop a new simple and physically based approach to automatically calculate the Wiebe parameters.

The Wiebe parameters need to be identified and calibrated because of their significant variation for a wide range of engine conditions [19]. The artificial neural network [20] and least square regression (LS-R) analysis [14–16,19] are the common methods to relate the Wiebe parameters to the engine operating conditions. The combustion model is preferred to a series of algebraic expressions developed by the latter method, which can clearly express the effect of the variables on the Wiebe parameters and be used to investigate the correctness of the developed model based on the physical significance of the variables. However, the premise of the effective application of the LS-R is that the variable set should satisfy the hypothesis of Gauss-markov, and one of the hypothesis is that there are no significant correlations among the variable set. Therefore, it is a quite complex way to establish an accurate model by LS-R for the high dimensionality and relevancy [23], which is prevalent among the operating parameters of the diesel engine. And only pursuing the accuracy of the LS-R model in the calibrating process, the predictability can't be guaranteed duo to the concept of overfitting, especially for the higher term in the expression. Thus, it's difficult to identify the significant independent variables for the LS-R model. In Ref. [15], each Wiebe parameter is related to all the potential variables without identification. This may lead to some redundant variables in the expressions and destroy the statistical tendency. In Ref. [16], the number of variables are reduced by a sensitivity analysis from a wide range of the experimental data, but the process of analysis isn't introduced in detail. The partial least squares regression (PLS-R) is an effective method to solve the multiple correlations by projecting the original parameter data into low-dimensional orthogonal latent variables [24]. The cross validation can be used to avoid the occurrence of overfitting, and with help of this method the significant variables can be easily identified. The PLS-R is widely used in the estimation of the biodiesel cetane number [24], the analysis of a common-rail fuel injection system [25] and establishing a prediction model of the nitrogen oxide (NO_x) [26]. But calibrating a combustion model by the PLS-R has not been published.

In fact, this complete project wants to establish a kind of marine STC diesel engine combustion and pollutant model for all the operating conditions. The final goal of the model wants to predict the maximum in-cylinder pressure, NOx, PM and *BSFC* for different STC systems, which are the crucial parameters for developing an STC control system. In this paper, the modeling approach of the combustion process is widely discussed, and original materials and technique for the current study is introduced as the follows. The combination of double Wiebe function and PLS-R is first imposed to develop a combustion model of a marine STC diesel engine with 142 operation points, 105 operation points covering the overall range of the operating conditions are used for calibration, 37 operation points with two kinds of STC systems are obtained for validating the prediction ability of the developed model with different turbochargers. A novel method to automatically compute the initial values of Wiebe parameters according to the heat release rate at each operation is proposed to avoid the inherent weakness of NLSF. Due to the characteristic of the large valve overlap and the intake-