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A real-time capable mixing controlled combustion model for highly diluted conditions

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ABSTRACT

A new real-time capable heat release rate model is presented that captures the high dilution effects of exhaust gas recirculation (EGR). The model is a Mixing Controlled Combustion type with enhancements to account for wall impingements, pilot injections, charge dilution caused by EGR at part load. The model was parameterised in two steps using a small set of measured data: the majority of model parameters were identified without EGR before identifying additional EGR related constants. The model performance was assessed based on key metrics: start of combustion; peak heat release and point of peak heat release and cylinder pressure. The model was evaluated over the full engine speed, load and EGR operating envelope and cylinder pressure metrics were predicted with R^2 values above 0.94. With EGR, the model was able to predict qualitatively and quantitatively the performance whilst being parameterised by only by a small dataset. The model can be used to enable the engineering of robust new control algorithms and controller hardware for future engines using offline processes.

1. Introduction

Diesel engines are used in a significant proportion of automotive applications due to their inherent high efficiency compared to Gasoline engines However, Diesel engine suffer from higher emissions of nitrous oxides (NOx) and particulate matter due to the nature of the combustion processes. To address this problem, Diesel manufacturers are having to resort to an increasing number of active emissions control technologies such as air management and exhaust gas recirculation (EGR), Lean NOx traps (LNT) and selective catalytic reduction (SCR) [1]. These systems all require careful design and management if the high efficiency of the Diesel engine is to be maintained. Virtual development of the complete system is a promising way of being able to design and optimise the engine system before development hardware is available. The virtual development can consist of many system models or of models working in parallel to real hardware, such as hardware-in-the-loop approach (HiL). Accurate and real-time capable mathematical models are a pre-requisite for this approach [2].

Combustion is the key process for any engine as it affects all other engine subsystems. Therefore, real-time capable combustion models are an essential tool to enable virtual development and HiL methodology. For example, the real-time model replaces real engine hardware and allows the engine controller to be trialled can be tested at very early stages of the design process, and much more intensely than could be achieved though real experiments. The model emulates each of the engine's sensors and actuators however, the method is underpinned by the accuracy of the mathematical model and the ability to parameterise the model based in a way that is predicts engine performance well in extrapolated regions.

The recirculation of exhaust gases (EGR) to control NOx emissions in Diesel engines poses specific challenges through thermal, chemical and dilution effects that need to be accounted for within the combustion model. EGR critically affects the combustion process by delaying ignition and reducing the reactivity of the cylinder charge [3]. These effects need to be captured in a model that can easily be parameterised using only small amounts of experimental data.

The aim of this paper is to create a crank angle resolved, real-time capable, Diesel combustion model that captures the effects of EGR. The empirical model parameters must be generally applicable and determined using only a small number of engine operating points such that they could be established from an early prototype build or from a higher order modelling environment [4,5]. The model must be able to predict combustion with EGR rates

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of up to 40–60% (equivalent to up to 5% CO2 by volume in the cylinder charge). This is relevant for small, high speed Diesel engines in passenger car and light duty truck applications for the foreseeable future.

2. Background

2.1. Reduced order combustion model types

As most combustion, related control strategies could be developed using cycle average quantities such as the peak heat release, maximum cylinder pressure and IMEP [6], the first reduced order models for real-time applications were Mean Value Engine Models (MVEM). This approach essentially used look-up tables for the cycle averaged values as a function of engine operating points (e.g. engine speed, fuelling quantity, injection timing, EGR rate …) [2,7–9]. As these models run on a cycle-by-cycle basis, they can easily be made to run many times faster than real time [10–14]. More recently, thermodynamic based MVEMs have been proposed based on ideal thermodynamic cycles thus including a description of the physical processes and reducing the amount of empirical data required to obtain an accurate model [15]. Whilst these MVEMs do not simulate the full combustion process, they do allow key quantities such as peak pressure and temperature to be estimated.

As the computing power of HiL simulation machines increased, real-time crank-angle resolved models have been proposed that calculate the evolution of in-cylinder pressure during the engine cycle. This type of model provides a breakdown of the time related variations in cylinder conditions throughout the engine cycle. These models have the advantage of being able to estimate the average state of the charge and have been linked to emissions that capture specific mechanisms of formation of NOx [16–20] and soot [21].

These models typically comprise:

- A combustion model to predict the heat released from combustion.
- A cylinder model to calculate the gas properties and thermodynamic state of the charge.

The crank angle resolved models can be split into 2 categories: "single zone" models or quasi dimensional models.

The term single zone is expressed in italics as it refers to models that consider the heat released from combustion to influence a homogeneous pressure and temperature throughout the combustion chamber. The properties of this single zone may be calculated from the different compositions of fresh air, burnt gas and unburned fuel. One of the major challenges of these single zone models is in defining a set of model coefficients that are not specific to each operating point of the engine [22].

Quasi-dimensional models break down the combustion chamber into small packets and therefore provide a spatial decomposition of the combustion process [23–25]. Most are built on the work of Hiroyasu [26,27]. They are still built on empirical equations and their superiority over simple models is not yet proven [22]. Recent publications presenting these types of models can run with a calculation time of less than 1s per engine cycle, but these are still too slow for real time applications [28]. Gao et al. [29] simplified a quasi-dimensional model [20] to increase the run time. They limited the number of zones to 2, thus increasing the calculation time by a factor of over 100 to nearly real-time. An alternative approach was presented by Bittle et al. [30] who used the multi-zone approach for calculating local gas compositions whilst maintaining a single zone model for the heat release to reduce the model calculation time.

2.2. Real-time phenomenological combustion modelling

Crank-angle resolved Combustion models for real time simulation models typically treat the engine cylinder as a small number of control volumes, composed of gasses of various species representing the fresh air, unburnt fuel and burnt products. In a single zone more, the combustion chamber is represented by variable size control volume (Fig. 1). The control volume exchanges mass through the fuel injector, the intake and exhaust valves and via blow-by flows seeping through the piston ring pack. Energy is exchanged with the control volume through the combustion of fuel, heat transfer to the combustion chamber walls and through work transfer to the piston. Performing an energy balance on the control volume yields Equation (1) [31].

$$dU = dQ_C - dQ_{HT} - dW + dH_{inl} - dH_{exh} - dH_{bb} \quad (1)$$

This work is focussed exclusively on the calculation of the combustion heat release term (dQ_c/dt) for a Diesel engine with EGR. The combustion models found in the literature typically fall into two categories:

- **Shape Functions**: the most common is the Wiebe model [32,33] although other shape functions or Neural Networks are also used [9,34]. These models aim to replicate previously measured behaviour. Sometimes the model parameters are loosely linked to physical parameters [35] but empirical correlations are almost always required [36,37].
- **Physics Based:** these models are based fuel availability and an assumption of combustion process and the most common is the

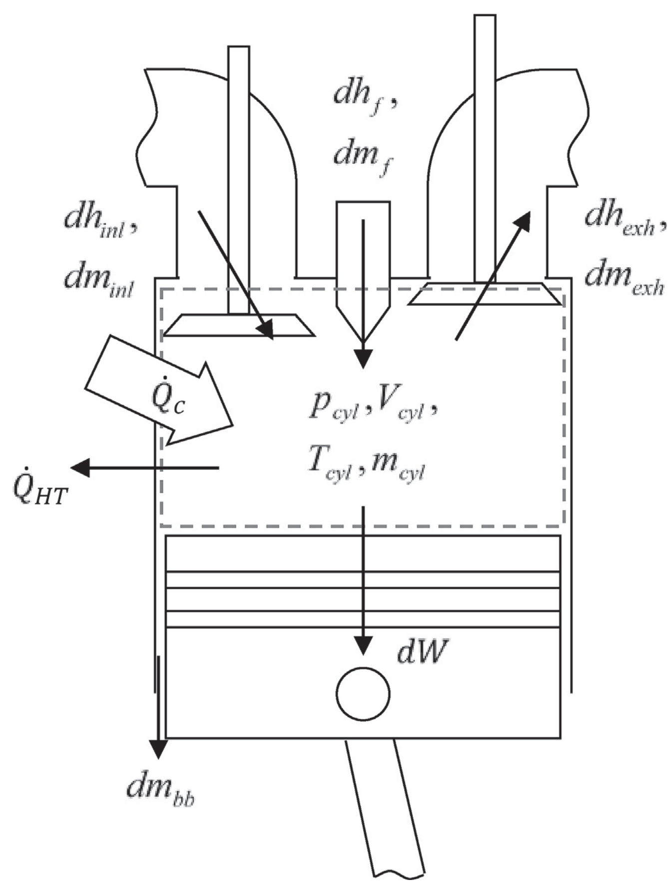

Fig. 1. Combustion chamber control volume with mass and energy transfer for a single zone model.