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A new methodology for uncertainties characterization in combustion diagnosis and thermodynamic modelling

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HIGHLIGHTS

- An adjustment methodology to determine combustion diagnosis and thermodynamic modelling uncertainties is proposed.
- The methodology is based on a sensitivity study of the effect of each uncertainty on RoHR and simulated pressure.
- The methodology considers several uncertainties at the same time and takes into account their cross effect.
- The adjustment is carried out using motoring test and validated in combustion conditions.

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ABSTRACT

Combustion diagnosis based on in-cylinder pressure signals as well as 0D thermodynamic modelling, are widely used to study and optimize the combustion in reciprocating engines. Both approaches share some uncertainties regarding the sub-models and the experimental installation that, for the sake of accuracy, must be reduced as much as possible in order to obtain reliable results. A methodology, based on the sensitivity effect of such uncertainties on heat release and simulated pressure, is proposed to adjust their values. The methodology is capable of identifying the separate influence of each parameter and to provide a set of values thanks to the Multi-Variable linear regression (MLR) in motoring conditions. The method is flexible enough to deal with different number of uncertainties and can be applied to different engines and thermodynamic models. The final results of the adjustment are validated in combustion conditions, showing an improvement of the apparent combustion efficiency of about 7% with respect to the reference values.

1. Introduction

To fulfil the more and more stringent regulations of ICE, a well understanding of combustion process is essential, thus some researchers efforts have been aimed at improving both combustion diagnosis and predictive modelling.

Although there are many methods for combustion diagnosis based on different experimental variables such as exhaust pressure [1] or block vibration [2], in-cylinder pressure is the most reliable variable for combustion diagnosis, through the determination of the rate of heat released (RoHR) [3]. It has been widely used in recent works for different applications such as analysing the effect of fuel blends or catalyst [4–9], developing NOx models based on RoHR aimed to control [10],or assessing the effect of different injection strategies on the engine performance, emissions and noise reduction [11].

On the other hand, thermodynamic predictive models are useful to obtain pressure and temperature evolution in the combustion chamber, allowing to estimate engine operation features in different applications such as engine design, control and performance prediction [12–16]. Moreover, they provide the boundary conditions for detailed combustion or emission models [17–19] with a high computational efficiency.

Combustion diagnosis and thermodynamic modelling can be seen as “opposite” methods [20]: in the first case, starting from pressure, the RoHR is obtained thus providing information of combustion development [21,22]; in the second case, if accurate RoHR is available (using a physical [17–19] or empirical [12,23]

Abbreviations: ACE, apparent combustion efficiency; BBDC, before bottom dead centre; BTDC, before top dead centre; CI, compression ignition; ICE, internal combustion engine; MLR, multi-variable linear regression; SI, spark ignition; SOI, start of injection; TDC, top dead centre.

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Nomenclature

CR	compression ratio [−]
C_{W1}	heat transfer coefficient 1 [−]
C_{W2}	heat transfer coefficient 2 [−]
D	cylinder bore [m]
EVO	exhaust valve opening [°]
h	heat transfer coefficient [W/m^2 K]
$h_{\mathrm{f,inj}}$	specific enthalpy of the injected fuel [J/kg]
HR	heat released [J]
imep	indicated mean effective pressure [bar]
IVC	intake valve closing [°]
k_{def}	deformation coefficient [−]
m	mass [kg], [mg]
$\dot{m}$	mass flow rate [g/s]
n	engine speed [rpm]
p	in-cylinder pressure [bar]
$p_{\max}$	maximum in-cylinder pressure [bar]
p_{ref}	reference pressure [bar]
Q	heat transferred to the combustion chamber walls [J]
R	specific gas constant of the charge [J/kg K]
RoHR	rate of heat released [J/∘]
r_W	relation between C_{W1} and C_{W2} [−]
S	piston stroke [m]
T	temperature [K], [°C]
$u_{\mathrm{f,g}}$	internal energy of the evaporated fuel [J/kg K]
V	volume [m^3]
α	crank angle [∘]
$\Delta\alpha$	TDC position [∘]

combustion model), they provide an estimation of the pressure and temperature evolution in a determined operating condition. They have in common the thermodynamic processes in the chamber and the sub-models required for their determination. Different approaches range from simple models such as net heat release calculation [3] or pressure simulation based on isentropic pV^n evolution, to detailed analysis including blow-by, fuel injection, gas properties depending on temperature and composition, accurate heat transfer model, etc. [12,24–27].

The results of the thermodynamic analysis are affected by some uncertainties due to the sub-models imperfections and the inaccuracy of their fitting constants determination. On the other hand, some engine parameters, such as compression ratio may require to be determined. Several works dealing with the effect of such uncertainties and proposals to determine them can be found in the literature. A brief description includes:

- Pressure pegging: the different methods for its determination [28,29] can be grouped in two categories: experimental methods based on the estimation of the reference pressure on the basis of an experimental measurement [29], or using thermodynamic methods such as the simulation of the polytropic evolution of the gas during the compression stroke in combustion tests or the compression and expansion stroke in motoring test [20].
- Compression ratio: it is the main geometric uncertainty and affects the instantaneous volume calculation and thus the gas properties [30]. Klein [31] evaluated four methods for the CR determination by comparing the real compression process with polytropic evolutions. Striker [32] proposed a methodology in which available sensors of production engines, a high gain observer and a volumetric efficiency model were combined. Lapuerta [33] used characteristic geometrical points to adjust CR with a symmetry criterion.
- Engine deformations: the piston and connecting rod are slightly deformed due to the gas pressure in the chamber and the inertial forces. In general, its effect on engine performance or RoHR calculation uses to be smaller than the CR effect [30]. In previous works [12,30] the authors used a simple model to determine the clearance variations taking into account the pressure and the inertial effects. Aronsson [34] used a similar model in an optical engine, and measured the variation of the piston position by means of an optical window in the liner.
- Heat transfer model fitting: a large amount of works dealing with the heat transfer in reciprocating engines can be found in the literature, being most of them focused on the heat transfer to the walls due to convection. Some of the most widespread proposals for heat transfer coefficient are based on the well-known Woschni [35], Annand [36] or Hohenberg [26] formulations. Nowadays, each author carries out a tuning process for a specific engine, based on experimental measurements or thermodynamic assumptions [37–41], in order to adapt the models to one specific engine.
- TDC position: it can be obtained by means of experimental techniques [42] or thermodynamic methods. The last ones allow determining the angular interval ($\Delta\alpha$) between the TDC and the trigger, on the basis of the effect of $\Delta\alpha$ on some variables such as heat release [25], simulated pressure [31] or entropy [43]. In this work, the TDC is determined based on the Hohenberg proposal [26].

The stated uncertainties have a different effect on the results but in general they are all relevant for the thermodynamic analysis in the chamber. Although different approaches for the determination of one uncertainty have been presented, there are very few works dealing with the adjustment of several of them at the same time while taking into account the cross effects. This work is aimed at describing a global methodology for adjusting different uncertainties at the same time, separating their specific effects. The proposal is based on the thermodynamic analysis in motoring conditions, thus the effect of the uncertainties in the compression and expansion strokes can be assessed using the apparent RoHR and the experimental and simulated pressure comparison. The methodology is based on the minimization of the errors in the RoHR calculation and in the pressure simulation. Although it has been developed using some specific sub-models, it is flexible enough to be used with different models and different engines.

The method has been developed for a multi-cylinder CI engine in motoring conditions and then the suitability of it application in combustion tests is assessed. As it will be shown, the available information is limited in these conditions, thus affecting the performance of the method. The validation of the adjustment is carried out through the combustion analysis at several operation conditions.

2. Methodology

The estimation of one parameter can be affected by the incorrect value of other uncertainties that are simultaneously adjusted. Moreover, a combination of parameters can provide a low residual, according to one criteria, but not so good with other one. For example, the effect of an incorrect pressure pegging and CR have