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Combustion study of a spark-ignition engine from pressure cycles

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This work presents investigations on combustion analysis of an experimental spark-ignition engine fueled specially by a mixture of 15% in volume of hydrogen and 85% in volume of methane with an equivalence ratio of 0.67 at 100% load, corresponding to optimum conditions for SI engine, using two models, zero dimensional model based on Rassweiller & Withrow theory and first law-single zone either at constant or variable specific heat ratio of gases requiring experimental data of engine cylinder pressures. The results show the happening in the combustion chamber to the burning of real fuel with respect to time since the mass burned fractions and the heat release rate are evaluated. It can be seen that the two models have not the same rate of mass combustion during combustion process since it happens at different crank angles. The dependence of $\gamma(T)$ is visible for high pressure since the variation of temperature exists and is not negligible. A comparison was attained between the results that used $\gamma(T)$ with that used constant specific heat. A program in Fortran 77 has been developed for the complete simulations of SI engine combustion. The results are consistent with those found in the literature.

1. Introduction

The energy crisis and environmental pollution created an incentive to study and evaluate alternative fuels in spark ignition engines. Natural gas vehicles are a potential alternative in the short term. They are less polluting and the fuel is available. The use of hydrogen blended with natural gas or methane in conventional combustion engines has generally shown decreased pollutant emissions [1–9] primarily due to the lean burn characteristic of hydrogen and reduction of carbon atoms in the fuel [10,11]. Hydrogen gas is characterized by a rapid combustion speed wide combustible limit and low minimum ignition energy [4,12–14]. Hydrogen/methane mixture was chosen in this study with the cited composition since a previous work was realized on experimental investigations on combustion characteristics and emissions in the same SI engine [23]. SI (Spark ignition) engine cycles consist of four consecutive processes; intake, compression; combustion including expansion and exhaust. Of these processes, the combustion process is the most important one because the chemical energy of the fuel is converted into sensible internal energy of the charge during this process. The details of combustion, its characteristics influence the efficiency of energy conversion and engine performance as well as the pollutant formation [15]. Because of the cited reasons, a significant part of the research studies conducted on spark ignition engines has been devoted to simulate the combustion process [16–18]. In the combustion modeling studies, the main purpose is to specify the mass burned fraction of gases at any time during the combustion process. The simplest type is that of thermodynamic model which is termed zero-dimensional model and it is ideal for general parametric studies since it does not necessitate the combustion details. Hence, modeling of combustion in this manner is more practical but it gives less reliable or less sensitive results on SI engine combustion. Zero-dimensional models have been used in a large number of studies in order to study different engine parameters [6], numerical model to predict the performance and emissions of an internal combustion fueled by natural gas blending with hydrogen was developed by scientists [19]. The results showed that the poor combustion at lean conditions can be improved by the addition of hydrogen. A comparison of performance and combustion characteristics of an engine fueled with both hydrogen and compressed natural gas was evaluated by such researchers [20]. They found that brake thermal efficiency improved with hydrogen operation compared with CNG. Experimental results of a natural gas fueled internal combustion engine claiming that hydrogen as additive to NG can strongly improve the performance of such engines in efficiency power and emissions at lean conditions [21]. Investigation on heat release using the first law single zone model with $\gamma(T)$ was

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performed [22]. Calculations on heat release and noise level using cylinder pressure measurement for different spark timing are realized and authors used times series of heat release to calculate the correlation coarse-gained entropy. The results showed that for large ignition timing, the system was more deterministic. A quasi-dimensional model for the simulation of the combustion process was developed in SI engines fueled with hydrogen-methane by such researchers using the flame front development [23]. It subdivides the in–cylinder into two distinct zones: burned and unburned. In some recent papers, optical diagnostic strongly benefits from technological innovation, macroscopic and microscopic analysis, gives the possibility to collect significant information on the combustion process [24,25]. Infrared measurements were performed in order to study the behavior of biofuels combustion [26]. Some other researchers [7], optical measurements were performed to analyze the combustion process with high spatial and temporal resolution. In particular, the optical techniques based on 2D-digital imaging were used to follow the flame propagation in the combustion chamber. UV–visible spectroscopy allows the detection of chemical markers of the combustion process.

The aims of the present work are using the measured cylinder pressure of spark ignition engine to establish investigations on combustion analysis of an SI engine fueled with methane blending with 15% hydrogen in volume at 100% load using two models such as zero dimensional model based either on Rasswweller & Withrow theory or first law of thermodynamic single zone either at constant or variable specific heat ratio. Hydrogen/methane mixture was chosen with the cited composition in this study since a previous work was realized with the same fuel on experimental investigation on combustion characteristics and emissions on the same SI engine [23]. The main gain of this work is to evaluate the gas temperature dependence and specific heat ration γ(T) on combustion process knowing that the heat transfer rate through cylinder walls is estimated from Woshni model: an accurate mass burned fraction with respect to time corresponding to appropriate heat release rate were obtained compared to those attained with constant gamma or implicit temperature parameter. Characteristics of the combustion such as the start of combustion, end of combustion and the corresponding maximum temperature or pressure with respect to time are given.

2. Experimental set up

This study was carried out on a six-cylinder, four-stroke indirect spark-ignition engine. The experimental SI engine details are given in Table 1. All experiments were realised in INSA laboratories of Rouen (France). For this combustible, the flammability limits were calculated to allow the flame propagation inside the engine. The upper and lower flammability limits characterize the extreme limits of flammable mixture composition [27]. Piezoelectric pressure transducer (GU13 Z-24) related to spark plug adapter ZF42 (0–200 atm) is used for measuring cylinder pressures. The pressure sensitivity is about 15.55 PC/atm and, a specified linearity is smaller than ± 0.3%. The temperature range is 400 °C and its frequency is about 130 kHz. A charge amplifier model, so called piezo amplifier 03 is used to convert the signal from pressure transducer to a data acquisition card (model PCI–MOI-16E). The data acquisition covered 200 completed cycles. The average value of these cycles indicates the mean pressure data employed for calculating the combustion parameters.

Table 1
Engine specifications.

Bore (mm)	128
Stroke (mm)	155
Displacement volume(L)	1.9945
Total volume(L)	11.9670
Clearance volume(L)	0.1734
Compression ratio	12.5:1
Connecting-rod/crankshaft	4
Speed (rpm)	1500
Cooling	water
Cylinder number	6 in line
Thermal power	160 kW
Torque at 1500 rpm	880 N m
Firing order	1-5-3-6-2-4
spark ignition timing (°)	12° BTDC

A program in Fortran language was developed for the complete simulations of SI engine combustion. It consists of main program including the models cited above and subroutines corresponding to sub-models such as the instantaneous volume of the cylinder, specific heat ratio, the instantaneous heat transfer coefficient, the velocity of burning gas, and convective heat transfer during the four phases of the engine cycle.

3. Combustion analysis

The present study is based on combustion analysis using either zero dimensional model, Rassweiller & Withrow theory, or first law thermodynamic single zone model with constant or variable specific heat ratio which is built around certain assumptions as outlined as follows:

- The cylinder charge during combustion is assumed to be in a single zone: The burned products.
- The contents of the cylinder are fully mixed and spatially homogeneous in terms of composition and properties during intake, compression, expansion, and exhaust processes.
- The cylinder walls temperature is assumed to be uniform and constant. The temperature's variations of inner cylinder surface during the thermodynamic cycle are weak compared to the temperature's variations of the combustion gases.
- All crevice effects are ignored, and the blow-by is assumed to be zero.
- The engine is in steady state such that the thermodynamic state at the beginning of each thermodynamic cycle (two crankshaft revolutions) is the same as the end state of the cycle.

3.1. Zero-model: mass burned fraction

Despite the several limitations of the Rassweiler and Withrow model for computing the fraction of mass burned (mbf) which includes among others, its inability to account for crevice volumes, its sensitivity to selection of appropriate polytropic index during compression and combustion process, its inability to predict accurately the EOC (end of combustion), and its poor accountability of heat transfer effects, studies by researchers clearly points to the fact that it is still a preferred model for its simplicity and for its computationally undemanding requirements, while being almost as accurate as more complex models. In the present work therefore, this equation has been used for estimation of mass fraction burnt during combustion. It gives an indirect way to estimate SOC and EOC parameters of combustion (start and end of combustion). It was evaluated from the indicated mean pressure cycle described in experimental setup section. The following equation is applied.

$$\mathrm{mbf} = \left(\mathrm{PV}^{\gamma} - \mathrm{P_i}\,\mathrm{V_i^{\gamma}}\right) \Big/ \left(\mathrm{P_f V_f^{\gamma}} - \mathrm{P_i V_i^{\gamma}}\right) \quad (1)$$

The beginning of the combustion is considered at 348° CA. The final combustion process is estimated from Fortran sub-program at