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Exploring the performance limits of a stratified torch ignition engine using numerical simulation and detailed experimental approaches

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ABSTRACT

In a torch ignition engine system, the combustion starts in a pre-combustion chamber, where the pressure increase pushes the combustion jet flames through calibrated nozzles to be precisely targeted into the main combustion chamber. This paper presents the layout of the prototype engine and the developed fuel injection system. It continues with a detailed description of the performance of the torch ignition engine running on a gasoline/ethanol blend for different mixture stratification levels as well as engine speeds and loads. Also detailed analyses of specific fuel consumption, thermal and combustion efficiency, specific emissions of CO_2 and the main combustion parameters are carried out. A numerical model based on thermodynamic and kinetic analyses has been established in order to explore the performance limit of a stratified torch ignition engine. The paper concludes presenting the main numerical results obtained in this work, which show a significant increase in the torch ignition engine performance as compared with the commercial baseline engine.

1. Introduction

Emissions legislation continues getting stricter for pollutant emission limits, while at the same time having to comply with the need for the reduction of carbon dioxide emissions. This generally contrary trend makes a compromise very difficult with current technology. Thus, new or alternative solutions and approaches need to be used. To reduce CO_2 emissions and prevent an increase in pollution levels, many countries have introduced government promotions for the use of bio-fuels [1]. In 2003, vehicles that were designed for the use of blends of gasoline and ethanol (flex-fuel) technology were introduced into the Brazilian market; these vehicles are capable of operating on gasohol (gasoline blended with 18–27% volume anhydrous ethanol) or 100% hydrous ethanol (4.0–4.9% volume of water) or any blend of these fuels [2]. As a result of governmental promotions, the volume of flex-fuel vehicles rapidly increased to a market share of more than 88% in 2014 [3,4]. Based on the information published by the National Metrology, Quality and Technology Institute (Instituto *Nacional de Metrologia*, *Qualidade e Tecnologia – INMETRO*), the estimated increase in fuel consumption due to the widespread use of flex-fuel technology in Brazil is, on average, approximately 6% [3]. Experience gained with mass-produced vehicles by Honda [4] in the 1970s showed that an implemented torch ignition system with a pre-combustion chamber could generate many flame fronts containing high thermal and kinetic energy inside the main combustion chamber. Such a system could therefore initiate a faster and more complete combustion and thereby reduce the risk of knock phenomena, which enables the use of higher volumetric compression ratios. Furthermore, the high ignition potential generated by the system enables the use of lean mixture preparation in the main chamber, which reduces the CO_2 level as well as specific fuel consumption and NO_x emissions [5]. Therefore, it is believed that the torch ignition system can be employed to improve the engine's thermal efficiency, specific fuel consumption and emission levels.

2. Objective of the study

This paper presents a detailed description and analysis of the performance of a stratified torch ignition (STI) engine in the fields of thermal efficiency and engine out-emissions. Numerical simulation is carried out to predict the performance limit of the STI engine in regard to thermal efficiency and specific engine

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Table 1
Baseline engine main data.

Displacement volume	1596 cm^3
Number of cylinders	4
Combustion chamber arrangement	Pent roof-shaped
Top piston geometry	Dish top piston crown
Camshaft	2 – DOHC without VVT
Connecting-rod length	137 mm
Bore x stroke	79.0 × 81.4 mm
Geometric compression ratio	11.0:1
Intake valve opening (B-TDC)	10° (1 mm Ref.)
Intake valve closure (A-BDC)	20° (1 mm Ref.)
Intake valve diameter × lift	30 × 7.95 mm
Exhaust valve closure (B-BDC)	30° (1 mm Ref.)
Exhaust valve closure (A-TDC)	0° (1 mm Ref.)
Exhaust valve diameter × lift	24 × 7.00 mm
Firing order	1-3-4-2
Vehicle application class	Super mini

out-emissions. It is important to point out that numerical results obtained will support the definition of future torch ignition engine layout and the next steps to be taken in future experiments.

2.1. Baseline engine layout

A commercial 4-cylinder, 1.6-l, 16-valve SI-engine was used as a basis for the prototype engine layout. The mixture preparation system implemented for this engine was a direct injection high-pressure system. The main engine data is presented in Table 1.

3. Details of the STI pre-combustion chamber layout

The entire cylinder head of the baseline engine was replaced by a specially designed new head, which enabled implementation of the torch ignition-system specific enhancements. Fig. 1 shows the layout of the new cylinder head.

Fig. 2 shows the details of the pre-combustion chamber adaptor. In Fig. 2, the locations of the spark plug (2) and the direct fuel injector (3) can be identified. The pre-combustion chamber (1) is where the primary fuel-air mixture takes place and is subsequently ignited. Due to the pressure rise in the pre-combustion chamber the burning charge is expelled through the transfer bore (4) towards the main combustion chamber. At the end of the transfer bore a single hole diffuser was inserted, which spreads the burning gases to provide a large surface arrival in the main chamber.

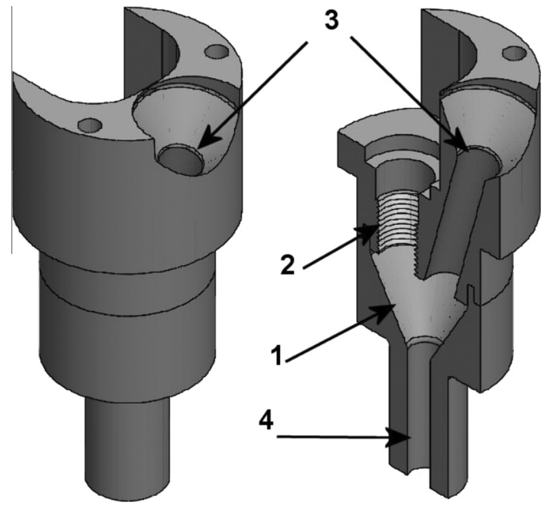

Fig. 2. Pre-chamber adaptor [3–5].

The pre-combustion chamber main data is presented in Table 2. The performance of an STI system is conditioned by the volume of the pre-combustion chamber and its internal geometry, the location of the spark plug and the fuel injector layout.

Furthermore, the dimensions, number and configuration of the diffuser plate holes are located on the bottom side of the transfer tube (4 on Fig. 2). In the present study the number of diffuser plate holes was varied from 1 to 5. Fig. 3 shows the differently designed diffuser plate layouts used to determine numerically the optimal mixture and flame distribution in the main chamber. The numerical simulation tool used is a dynamic 3-D CFD, thermodynamic and chemical tool, which can be applied to the entire engine structure contained within the boundaries of the inlet throttle body and the exhaust pipe. This model is called a Virtual Engine Model (VEM).

Only a few comments will be made about the usage and the reliability of the VEM approach used. Whenever a totally predictive research work is made, such as the analysis of new combustion chamber geometry or the impact on the dynamic mixture preparation of a new fuel injector atomizer, it is very important that the user/researcher knows the validity and limits of all the assumptions related to the models and sub-models involved in the computations. As all this knowledge is only available in very few commercial computation codes, the VEM software basis used for

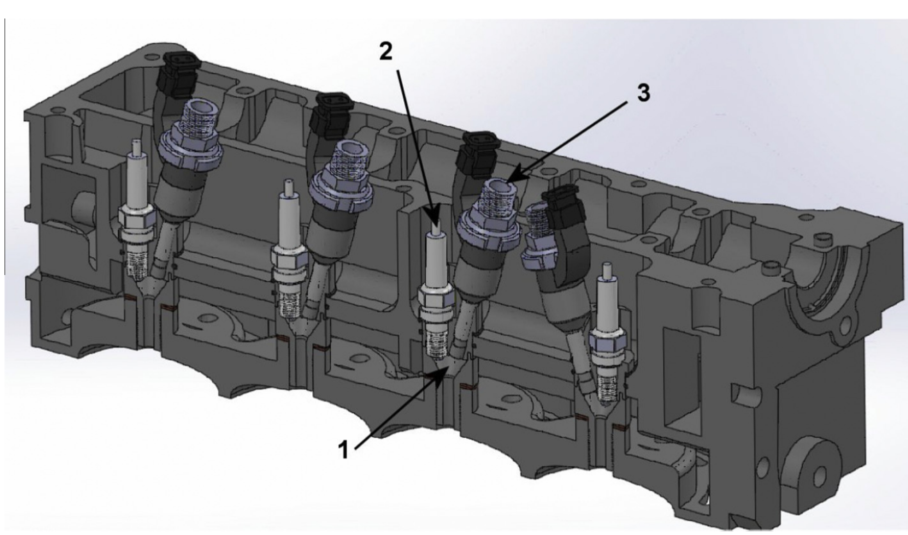

Fig. 1. New cylinder head layout.