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A review of prechamber ignition systems as lean combustion technology for SI engines

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HIGHLIGHTS

- Concepts about homogeneous and stratified prechamber ignition systems are presented.
- Summary is provided for the main works concerning the prechamber ignition systems.
- Influence on combustion and emissions characteristics are discussed.
- Key advantages and challenges in prechamber ignition technology application are identified.

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ABSTRACT

Use of lean or ultra-lean air-fuel ratios is an efficient and proven strategy to reduce fuel consumption and pollutant emissions. Previous works indicate that lean burn mixtures improves engine thermal efficiency by improving combustion quality, reducing heat transfer losses and increasing the possibility of apply higher compression ratios. However, lower fuel concentration in cylinder hinders mixture ignition, requiring greater energy to start combustion. To favor the ignition process, several high energy providers methods have been studied. Between them, prechamber ignition system presents potential reductions in emission levels and fuel consumption, operating with lean burn mixtures and expressive combustion stability. In this paper, a literature review has been made about prechamber ignition systems as lean combustion technology, focusing in the several investigations regarding combustion and emissions characteristics and presenting the key advantages and challenges in prechamber ignition technology application. From this review can be observed that the pre-chamber ignition system is an important way to increase thermal efficiency, reduce fuel consumption and emissions in spark ignition engines.

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Abbreviations: ACIS, Advanced Corona Ignition System; APIR, Self-Ignition Triggered By Radical Injection; BMEP, Brake Mean Effective Pressure; BPI, Bowl-Prechamber-Ignition; BSFC, Brake Specific Fuel Consumption; BTDC, Before Top Dead Center; CA, Crank Angle; CFD, Computational Fluid Dynamics; CFR, Cooperative Fuel Research; CNG, Compressed Natural Gas; CO, Carbon Monoxide; COV, Coefficient of Variation; CVCC, Compound Vortex Controlled Combustion; DI, Direct Injection; EGR, Exhaust Gas Recirculation; GHG, Greenhouse Gases; H_2, hydrogen; HAJI, Hydrogen Assisted Jet Ignition; HC, Unburned Hydrocarbon; HCCI, Homogeneous Charge Compression Ignition; ICE, Internal Combustion Engines; IMEP, Indicated Mean Effective Pressure; $IMEP_n$, Net Indicated Mean Effective Pressure; IPCC, Intergovernmental Panel on Climate Change; JISCE, Jet Ignition Stratified Charge Engines; LAG, Ignition by Avalanche Activation; LPG, Liquefied Petroleum Gas; MAP, Manifold Absolute Pressures; MBT, Maximum Brake Torque; MC, Main Chamber; MFB, Mass Fraction Burned; NO_x, Nitrogen Oxide; PC, Prechamber; PCI, Prechamber Injection System; PFI, Port Fuel Injection; PJI, Plasma Jet Ignition; PSIE, Prechamber Spark Ignition Engines; RCM, Rapid Compression Machine; RF, Radio Frequency; SI, Spark Ignition; SKS, Stable Kernel of Combustion; TCCS, Texaco Controlled Combustion System; TGP, Turbulence Generating Pot; TJI, Turbulent Jet Ignition; VVT, Variable Valve Timing; VW, Volkswagen.

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1. Introduction

Climate and other atmospheric changes have prompted studies to minimize environmental impacts. According to IPCC (Intergovernmental Panel on Climate Change), the average global temperature could reach an increase of 6.4 °C by the century end [1]. To prevent impacts like this, changes in climate policies has been adopted, forcing engine manufacturers to reduce pollutant emissions levels. Transport sector is one of the largest greenhouse gases (GHG) emitters, and has motivated extensive researches and developments. With current policies, it is estimated that in 2030 the transport sector will be responsible for 75% of GHG emissions [2]. Therefore, studies have been developed to use renewable fuels and more efficient and "cleaner" engines. According to Kleeman et al. [3], vehicular use of biofuels, electrical energy and hybridization are part of the current market for low fuel consumption. Besides that, it is possible to operate with lean mixtures, up to a limit, without geometric changes in engines. It can be the path to reduce specific fuel consumption and exhaust emissions, allying benefits of better efficiencies through lower pumping losses in comparison to stoichiometric mixtures [4], mainly at medium loads. Despite the benefits of lean combustion, high cyclic variability resulted from lower burn velocity represents a major challenge which must be overcome, requiring a greater source of energy to ignite the mixture [5]. For this, lean burn ignition systems have been widely studied [6–12]. Among these systems, stand out the plasma igniters [8,9,13–16], laser-induced ignition [17,18], corona spark plug system [13,19] and prechamber ignition systems [19,20].

Several technologies form plasma to initiate combustion instead of a spark plug discharge, as Plasma Jet Ignition (PJI) [15,16,18], Railplug [12,21], Microwave-assisted Plasma Ignition [22–24] and Radio Frequency (RF) Plasma Ignition [25–27]. Compared to conventional spark plug, the plasma igniters have proved to be more rapid and allow the lean limit to be extended [14,27]. However, NO_x levels increased considerably [14,27], the igniters tend to suffer from erosion problems due to temperature rise [28] and the systems can cause interferences either in measurements and electronic control unit [24,27]. Laser-Induced Ignition provides faster combustion, higher engine power and lower specific fuel consumption if compared to the conventional ignition system [17,29]. On the other hand, higher levels of NO_x were observed, which is explained by higher flame temperature generated by the rapid combustion [18]. Advanced Corona Ignition System (ACIS) presents another method of high energy ignition for burning lean mixtures [14]. Comparing to the conventional ignition system, ACIS improves ignition efficiency, extends lean limit, improves cyclic variations and reduces HC emissions for low loads and idle conditions. However, it had no effect on other exhaust gases, and, at higher loads, the benefits of ignition system decreases, presenting no advantages if compared to conventional system.

Stratified charge ignition is an effective method to achieve the lean combustion, which had been proved by many researchers, with studies mainly focused on tumble flows [30], direct injection [31,32] and prechamber uses [19,33]. Though, prechamber ignition systems has demonstrated a reduction in combustion duration and an extension of the lean limit [33,34], and, unlike the other systems, NO_x emissions in this case are drastically reduced, due to lower peaks of temperature, reaching levels close to zero (<10 ppm) [35]. Whereas the emission reduction capacity of this technology and its effectiveness in burning lean mixtures, this paper aims to present a technical review about Prechamber Spark Ignition Engines (PSIE) concepts, summarizing the latest developments of this system, highlighting its influences on combustion and emissions, identifying advantages and challenges in prechamber ignition technology application.

2. Fundamentals of prechamber spark ignition

An effective concept to lean burn combustion can be a prechamber combustion system. Adams [36] investigated the use of prechambers to generate combustion turbulence and reduce burn time of lean mixtures, through the high energy flame jets from prechamber. According to Jamrozik [19], the use of prechamber systems usually consists in a very lean mixture, with λ factor above 2.0, entering the engine intake port and being aspirated to the cylinder, while a nearly stoichiometric mixture is added to the prechamber. When the prechamber mixture is ignited, large amounts of CO and HC are produced. With the pressure rise, the

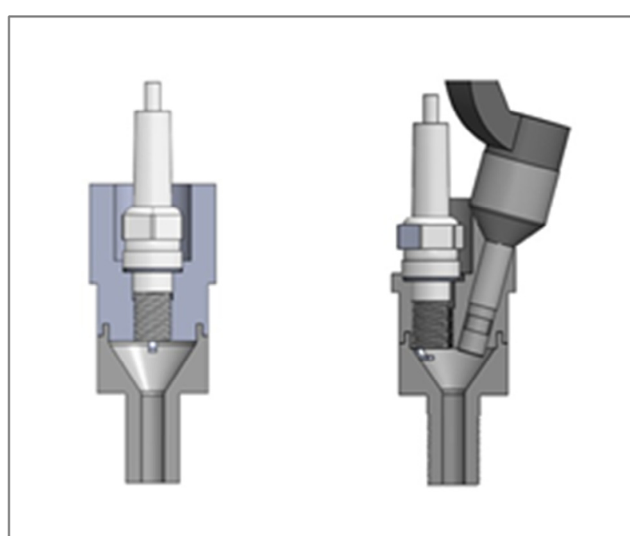

Fig. 1. Homogeneous charge prechamber system (left) and stratified charge prechamber system (right). Source: Author.

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