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Evaluation of Homogeneous Charge Compression Ignition (HCCI) autoignition development through chemiluminescence imaging and Proper Orthogonal Decomposition

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HIGHLIGHTS

- The spatio-temporal preferences of autoignition are evaluated in a HCCI engine.
- Chemiluminescence images of the flame are analyzed through POD analysis.
- Multiple locations of single autoignition sites are identified in the POD modes.
- Secondary sites of autoignition are observed in the early stages of combustion.
- Open valve injection timing or iEGR lead to multiple autoignition sites.

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ABSTRACT

Homogeneous Charge Compression Ignition (HCCI) engines deliver high thermal efficiency and, therefore, low CO_2 emissions, combined with low NO_X and particulate emissions. However, HCCI operation is not possible at all conditions due to the inability to control the autoignition process and new understanding is required. A high-swirl low-compression-ratio, optically accessed engine that can produce overall fuel lean, axially stratified charge (richer fuel mixture close to the cylinder head was achieved using port injection against open valve and homogeneous mixture during injection against closed valve timing) was operated in HCCI mode without and with spark-assist mixture ignition. The present study investigates the differences in the HCCI autoignition process and the propagation of the autoignition front with homogeneous mixture or fuel charge stratification, internal Exhaust Gas Recirculation (iEGR) (introduced by utilizing different camshafts) and spark-assisted iEGR lean combustion. In order to visualize the HCCI process, chemiluminescence flame images, phase-locked to a specific crank angle, were acquired. In addition, time-resolved images of the developing autoignition flame front were captured. Proper Orthogonal Decomposition (POD) was applied to the acquired images to investigate the temporal and spatial repeatability of the autoignition front and compare these characteristics to the considered scenarios. The eigenvalues of the POD modes provided quantitative measure of the probability of the corresponding flame structures. The first POD mode showed higher probability of single autoignition sites originating from a particular location (depending on the scenario). However, the contribution from other modes cannot be neglected, which signified multiple locations of the single autoignition and also, multiple sites of self-ignition of the fuel-air mixture. It was found that increasing iEGR resulted in random combustion (multiple autoignition sites and fronts), which, however, became significantly non-random due to addition of spark-assisted ignition. It was identified in the POD analysis of the time-resolved flame images that the presence of inhomogeneity either in the temperature or the mixture fraction distribution increases the probability of random combustion during the very early stages of flame development. Thus, the fluctuations of heat release is higher during this period.

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1. Introduction

With stricter regulations on both heavy and light-duty vehicle emissions, it is not surprising that the automotive and oil industry are continuously looking for new fuels and new ways of improving the efficiency of Internal Combustion (IC) engines. Homogeneous Charge Compression Ignition (HCCI) – also referred to as Active Thermo-Atmosphere Combustion (ATAC), Premixed Charge Compression Ignition (PCCI), Homogeneous Charge Diesel Combustion (HCDC), PREmixed lean DIesel Combustion (PREDIC) and Compression-Ignited Homogeneous Charge (CIHC) – is one of the most promising alternatives to conventional Spark Ignition (SI) combustion and Compression Ignition (CI) combustion. HCCI combustion gained significant attention over the last 15 years [1,2].

In IC engines the HCCI combustion can be achieved by premixing the air-fuel mixture (either in the manifold or by early Direct Injection (DI) – like in a SI engine) and compressing it until the temperature is high enough for autoignition to occur (like in a CI engine). Since under HCCI combustion the fuel/air mixture to be ignited does not rely on the use of a spark plug or direct injection near the Top Dead Centre (TDC), overall lean mixtures can be used resulting to high fuel economy. Thus, the combustion temperature remains low and therefore nitrogen oxide, NO_x, emissions decrease significantly compared to SI and CI operation [3,4]. Furthermore, since a homogeneous fuel/air mixture can be prepared in the manifold with low equivalence ratios, low soot can be achieved [5]. Under optimum operating conditions, HCCI combustion can lead to carbon monoxide (CO) and hydrocarbon (HC) emissions comparable to SI and CI combustion. However, under very lean conditions the low combustion temperature is low (approximately below 1500 K), thus, incomplete combustion can occur in the bulk regions leading to partial oxidation of the fuel, low combustion efficiency and increase in CO and HC emissions [6]. On the other hand, HCCI combustion with richer fuel/air mixtures leads to knocking. HCCI combustion in a production engine is therefore limited by two main regimes [7–9], viz. (i) lean fuel to air ratio limit – leading to incomplete combustion, which results in low power and high HC and CO emissions, and (ii) rich fuel to air ratio limit – leading to knocking if the rate of pressure rise is too high, which may damage the engine or results in high NO_x emissions due to high combustion temperatures. Several operational issues with the HCCI engines and the possible strategies for their solution have been reviewed earlier (for instance, see [10]).

In order to extend the operating limits of the HCCI combustion to a wider load engine speed region, control on the ignition timing and the combustion rate is highly desirable [2]. However, ignition control is still challenging. The HCCI combustion can be described by the oxidation of the fuel driven solely by chemical reactions governed by chain-branching mechanisms [11,12]. Various strategies have been adopted based on adjusting the engine operating parameters, such as the valve timing, Exhaust Gas Recirculation (EGR) rate or inlet temperature, in order to control the chemical kinetics of the charge [13–15]. However, it is necessary to improve the understanding on the autoignition and combustion process under low temperature conditions in order to control the heat release rate to ensure optimal performance of the engine and high combustion efficiency [16].

Regardless of the chemical reactions associated with autoignition, the spatial initiation and the development or "propagation" of the autoignition sites are of interest. Chemiluminescence and Planar Laser Induced Fluorescence (PLIF) imaging of the autoignition phenomenon have shown that autoignition starts at various locations throughout the combustion chamber [17,18] probably due to local inhomogeneities. Due to the heat released from the burn regions, the temperature and pressure in the cylinder increase, and, therefore, more autoignition sites appear until the whole fuel-air mixture is ignited. It has also been shown using both chemiluminescence and formaldehyde PLIF imaging [19] in a highly stratified engine (hot Exhaust Gas Recirculation (EGR) gases on one side and cold fresh fuel/air mixture on the other) that these autoignition sites initiated neither at the location of the maximum temperature nor the location of the maximum fuel concentration, but at the boundary of these two regions. Once the first autoignition sites appeared, the double-exposure PLIF and chemiluminescence imaging showed that these sites grow in size at different speeds – they can appear to be propagating "*flame fronts*" in the absence of any other information (i.e. A/F ratio, in-cylinder temperature, "*flame front*" speed, double-exposure timing).

In order to better understand the spatial evolution of the autoignition process during HCCI operation and the effect of fuel and temperature inhomogeneities on the early stages of HCCI combustion, various computational models have been developed. The Partially Stirred Plug Flow Reactor-Interaction by Exchange with the Mean Mixing (PaSPFR-IEM) simulation model was used for the investigation of combustion of natural gas and it was shown that, with decreasing turbulence mixing time scale, the ignition delay was retarded and a steeper pressure rise was calculated. On the contrary, with increasing the turbulence mixing time scale, an earlier ignition timing and a moderate temporal pressure rise were calculated since the hot areas in the engine did not have time to mix with the colder ones [20]. The influence of thermal inhomogeneities on the advancing combustion wave of hydrogen was also studied using Direct Numerical Simulation (DNS) [21,22] and it was found that, in the 1-D case, ignition started at the location of highest temperature and propagated towards the colder end-gas. An enthalpy-based flamelet technique has also been applied to a Rapid Compression Machine (RCM) operated under HCCI conditions [22]. It was found that ignition started at the location of highest enthalpy and that the model predicted well the timing of the combustion, peak pressure and rate of pressure rise. It was calculated that the increase in temperature is dominated by the chemical reactions at the location of the ignition front, by the diffusion term in the unburned gases ahead of the ignition front and by the pressure term in the regions far from the ignition front. It was, therefore, concluded that diffusion in enthalpy-space affected the HCCI combustion process.

Based on the findings in the literature, it is expected that the differences in the temperature distribution and/or the charge stratification in a combustion chamber can lead to the differences in the HCCI combustion process. However, detail investigation on the propagation of the "autoignition front" is essential to address the consequence on the thermal efficiency and the pollutant emission. From our previous work [23,24], we have shown that altering the injection timing and introducing internal Exhaust Gas Recirculation (iEGR) and/or spark discharge lead to the differences in the HCCI combustion, for instance, both ensemble-averaged autoignition sites and propagation of the autoignition front were found to be different. The aim of the present paper is to apply Proper Orthogonal Decomposition (POD) technique [25,26] to investigate the temporal and the spatial repeatability of autoignition for various scenarios of HCCI combustion (with and without iEGR, and without and with spark assisted combustion). In addition, the time-dependent behaviour of the autoignition flame front(s) for different scenarios was also studied. POD has been used in internal combustion engines, especially to study the in-cylinder flow field measured by either Hot Wire Anemometry [27] or mostly by the application of Particle Image Velocimetry (PIV) (for example, see [28,29]). In the above studies, the spatio-temporal flow field was decomposed into sets of spatial modes and corresponding coefficients, which provide a lower order description of the flow structures and the related dynamics. Such decomposition allowed temporal reconstruction of the modal coefficients to provide continuous space-time description of the flow [30] or to decompose the flow field into mean, coherent and incoherent parts [31] such that cyclic variability of the flow field could be studied in detail. However, as pointed out by Bizon et al. [32], the application of POD for analysing light emission images during the combustion process, which can also provide the information on cyclic variation phenomena, is rare. These authors applied POD to the light emission images of the combustion process in both SI and multi-injection CI engines [32]. They