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Flow and thermal field effects on cycle-to-cycle variation of combustion: scale-resolving simulation in a spark ignited simplified engine configuration

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HIGHLIGHTS

- Cycle-to-cycle variation is investigated in a spark-ignited lean gas engine.
- Flow field was shown to have a higher relative contribution to the cyclic variations.
- Early variations near spark region are the major origins of the cyclic variations.
- Burning rate and convection velocity ahead of flame described the flame asymmetry.
- Increasing the spark size significantly reduced the cyclic variations.

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ABSTRACT

Premixed, spark ignited combustion of lean methane at fuel to air equivalence ratio of 0.58 is numerically investigated in a piston-cylinder assembly. The simplified numerical configuration is tailored to emulate the intake, compression and spark ignition processes in engines. Large-eddy simulation is employed in the core flow along with a zonal hybrid wall treatment in near-wall regions. The G-equation level-set method is used to simulate flame propagation with a detailed chemistry based laminar flame speed correlation developed herein. The main numerical findings of this paper are as follows: (1) Despite the geometrical simplicity, the present set-up is shown to exhibit relatively large cycle-to-cycle variation for the three investigated cycles. (2) The local thermodynamics and fluid dynamic conditions around the spark close to the ignition location initiate the first discrepancies between the cycles. (3) These early variations are then amplified due to the subsequent differences in the early growth of flame area. (4) The cycle-to-cycle variation in the present set-up is shown to be largely a consequence of the local flow fluctuations close to the spark position and timing, while the results indicated a less dominating role of thermal stratification on cycle-to-cycle variation. (5) The asymmetric combustion behavior was explained to be a combined effect of burning rate and convection velocity, while convection velocity proved to be the major contributor. (6) Finally, a numerical test in the present model setup indicated large spark kernels being less prone to cycle-to-cycle variations than small kernels.

1. Introduction

Cycle-to-cycle variation (CCV) in internal combustion (IC) engines refers to the non-repeatability between different combustion cycles. During the past decades, numerous research efforts have been made to better understand and explain the phenomenological origin of CCVs. CCVs are known to lead to various undesirable effects such as reduced efficiency [1] and increased emissions [2]. Various engine combustion concepts including homogeneous charge compression ignition (HCCI) [3], reactivity controlled compression ignition (RCCI) [4], spark ignition (SI) lean premixed combustion [5], stratified combustion [6], and engine downsizing [7] have been proposed to provide cleaner and more efficient combustion process [8]. However, the operational range of such concepts may be significantly limited by CCVs [9].

Although CCVs are present in both compression ignition and SI engines, they are more commonly associated with SI concepts [10]. Particularly, in lean burn SI engines, large cyclic variability has been shown to lead to considerably increased levels of emissions [10], increased fuel consumption of as high as 6% and decreased power output of even 10% [11]. Yet, when compared to stoichiometric burn SI

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combustion, lean burn SI combustion has been noted to have various benefits such as increased thermal efficiency [12] and decreased NOx emissions [13]. However, the operational range of lean combustion is strictly limited by CCVs [14,15] as the concept is known to be relatively sensitive to CCVs. An improved and detailed understanding of CCV sources would be a crucial step towards better understanding and, eventually reducing CCVs.

Experimental studies have provided invaluable insights into the CCV problem. For example, previous experimental studies have shown the connection of CCVs with exhaust gas recirculation [16], global fuel-air ratio [17], in-cylinder turbulence level [12], engine speed [18], inlet air temperature [19], spark timing [20,21] and knock tendency [22]. However, experimental engines are often prone to uncertainties in terms of exact boundary and operating conditions. In fact, as enabled by optical engine measurement, it is nowadays possible to measure various details of the in-cylinder flow field including planar images of flow field, temperature and mixture stratification [23]. Attempts have also been made to optically access the full three-dimensional (3D) fields in a spark-ignition engine using temporally resolved multi-planar laser diagnostics [24]. However, there are limitations regarding optical access in certain set-ups which restrict diagnostic possibilities and gaining full access to the 3D flow quantities within the turbulent combustion process.

Limitations in studying CCV sources are present in computational fluid dynamics (CFD) approaches as well. In the Reynolds Averaged Navier-Stokes (RANS) approach, all turbulent scales are modeled and consequently RANS approaches provide only information about a typical, average cycle. Hence, detailed phenomena such as flame-turbulence interaction cannot be studied in detail with the RANS approach. Such details are expected to be important when studying the unsteady characteristics and formation of CCVs [25,26].

On the other hand, large-eddy simulation (LES) has been shown to be able to quantitatively reproduce CCV through various studies e.g. [27–29]. Most of the reacting LES CCV studies mainly concentrate on reproducing CCV levels in various conditions in order to establish the predictive capability of the numerical approach e.g. [30–34]. Thickened [30] and coherent [31] flame models have been employed with LES, successfully reproducing CCV in single-cylinder engine configurations. Curto-Risso et al. [32] investigated the effect of fuel-air ratio on CCV while reproducing heat release rate data from experiments. Later, Granet et al. [33] performed both LES and experiments of CCV in stable and unstable operating points of an SI engine. LES reproduced the flame behavior in both cases in terms of combustion progression and flame shape. In fact, quantitative prediction of CCV amplitude was demonstrated as well. In a more recent work, Ameen et al. [34] provided a parallel perturbation model to dissociate the long time-scale CCV problem into several shorter time-scale problems. The provided model was shown to be capable of predicting quantitative trends of CCV. We note that the studies above demonstrated how LES produces CCVs in certain engine configurations. Yet, the studies provided only limited insight to the interactive physical and chemical processes behind CCVs. Such phenomena are further investigated in the present paper in a more simple engine configuration.

Some of the reacting LES studies concentrated on the causes of CCVs in SI engines [27–29,35–37]. Vermorel et al. [27] used LES in SI four-valve single cylinder engine fueled with a homogeneous propane–air mixture. It was suggested that variation in the coherent tumble motion, produced during the intake stroke, was the major triggering factor for CCVs. In the studied case, the effects of local or overall mixture variations were reported to be insignificant. Enaux et al. [28] carried out an LES study of CCVs in a propane-fueled SI engine. It was suggested that CCVs are essentially due to velocity fluctuations around the spark plug, which induce variations of the early flame kernel growth and of the overall combustion duration. A similar observation regarding the significance of the convection flow effect on the spark was recently reported by Truffin et al. [36]. It was suggested that causes of CCV depend on the type of engine and its operation conditions. In a more recent work, Kodavasal et al. [29] used machine learning techniques to understand CCV causes. They suggested that machine learning techniques can implicitly learn complex relationships between different parameters defining the eventual outcome of each cycle.

Furthermore, Fontanesi et al. [35] performed a multi-cycle LES of a V-8 engine. They reported that inhomogeneity and variation in fuel distribution, turbulent energy, and velocity magnitude in the spark gap from cycle to cycle were major contributors to CCV. Koch et al. [37] performed an LES of multi-cycle SI engine using the G-equation, and Damköhler turbulent flame speed (s_t) closure. They reported that the cyclic variations are mainly related to the fluctuations in the sub-grid scale (SGS) kinetic energy rather than the thermodynamics conditions. However, it is noted that in such closure terms, the s_t is usually tuned to represent the experimentally observed burning rate. Thereby, we note that any inaccuracy in the modeling of laminar flame speed may be compensated by tuning the s_t for matching experimentally observed global combustion trends. A similar observation was recently reported by Burke et al. [38] who carried out a comparative study on different s_t correlations. With relevance to s_t correlation modeling, commonly used laminar flame speed (s_L) correlations, such as Gulder [39] and Metghalchi correlation [40], are known to be inaccurate at high pressure and temperature conditions. Thus, as part of this study, a detailed chemistry based model is developed for more accurate description of chemistry in such conditions.

Although lean combustion is known as a useful concept to reduce fuel consumption and emissions in SI engines, it has been noted to be prone to CCVs because the reduced flame speed in lean mixtures may not ensure a robust flame propagation [41,42]. Such aspects make lean combustion an important topic of study especially in the CCV context. However, reactive LES studies only rarely concentrate on understanding the sources of CCVs in lean SI engines. Additionally, the impact of temperature on flame speed diminishes when the mixture is close to stoichiometric condition [43]. This potentially contributes to the relatively low sensitivity of combustion to temperature stratification reported previously in the literature e.g. [37,28].

As a summary of the literature survey, we identify the following main research gaps on SI lean burn combustion. First, the role of turbulence and thermal field on local and global flame front propagation is presently not fully understood in lean conditions. Second, the role of initial spark kernel development and its connection to CCVs is presently unclear. In the present study a simple, spark-plug free configuration is investigated in order to assess the role of turbulence and thermal stratification on flame propagation. Third, it seems that much focus should be put on laminar flame speed modeling in high temperature and pressure conditions. This is important to better capture the effect of thermodynamical conditions on flame speed, especially for lean mixtures. Fourth, with relevance to thermal stratification, accurate wall heat transfer modeling has not been demonstrated previously in the context of CCV modeling.

The current numerical study concentrates on the effect of thermal and flow fields on CCV in a SI IC engine-like configuration with particular consideration of lean combustion conditions. The present computational setup can be considered to be an extension of a widely studied engine-like set-up [44,45] extended to a simple intake-compression configuration [46–48] with the expansion phase additionally included in the present work. The main objectives of the present study are the following: (1) Present an improved laminar flame speed correlation for lean mixtures based on detailed chemistry simulations for high temperature/pressure conditions, (2) Validate the present set-up in a non-reacting flow configuration with respect to (a) phase-averaged velocity and RMS velocity profiles gathered from 17 cycles during intake processes, and (b) net wall heat transfer and thermal stratification during compression, (3) Numerically investigate the occurrence of combustion CCV in the studied set-up, (4) Identify the sources of CCV in the present configuration and quantification of the