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On the ignition and flame development in a spray-guided direct-injection spark-ignition engine

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ABSTRACT

High-speed fuel, flow, and flame imaging are combined with spark discharge measurements to investigate the causes of rare misfires and partial burns in a spray-guided spark-ignited direct-injection (SG-SIDI) engine over a range of nitrogen dilution levels (0–26% by volume). Planar laser induced fluorescence (PLIF) of biacetyl is combined with planar particle image velocimetry (PIV) to provide quantitative measurements of equivalence ratio and flow velocity within the tumble plane of an optical engine. Mie scattering images used for PIV are also used to identify the enflamed region to resolve the flame development. Engine parameters were selected to mimic low-load idle operating conditions with stratified fuel injection, which provided stable engine performance with the occurrence of rare misfire and partial burn cycles. Nitrogen dilution was introduced into the intake air, thereby displacing the oxygen, which destabilized combustion and increased the occurrence of poor burning cycles. Spark measurements revealed that all cycles exhibited sufficient spark energy and duration for successful ignition. High-speed PLIF, PIV, and Mie scattering images were utilized to analyze the spatial and temporal evolution of the fuel distribution and flow velocity on flame kernel development to better understand the nature of poor burning cycles at each dilution level. The images revealed that all cycles exhibited a flammable mixture near the spark plug at spark timing and a flame kernel was present for all cycles, but the flame failed to develop for misfire and partial burn cycles. Improper flame development was caused by slow flame propagation which prevented the flame from consuming the bulk of the fuel mixture within the piston bowl, which was a crucial step to achieve further combustion. The mechanisms identified in this work that caused slower flame development are: (1) lean mixtures, (2) external dilution, and (3) convection velocities that impede transport of the flame into the fuel mixture.

1. Introduction

The spray-guided spark-ignition direct-injection (SG-SIDI) engine offers the potential to improve fuel economy in gasoline engines. Fuel savings are greatest at low-to-moderate loads, where direct-injection allows the engine to operate with unthrottled load control, thereby reducing pumping losses and improving engine efficiency [1]. Here, fuel is injected late during the compression stroke to create a locally-flammable stratified-charge, which allows flame propagation with an over-all lean fuel–air ratio. However, late injection stratified-charge operation is prone to combustion instabilities, which prevent its widespread application within the automotive industry.

For spray-guided systems, the fuel spray is targeted at the spark plug with the edge of the spray plume typically impinging on the spark plug electrodes [2]. For late-injection gasoline operation, optimum spark timing (ST) is typically limited to a narrow crank-angle regime occurring directly after the end-of-injection (EOI) [2,3]. The injection event exposes the spark discharge and initial flame kernel to high velocity magnitudes, large velocity gradients, and a highly stratified fuel–air mixture, which can vary in magnitude from cycle-to-cycle [4,5]. In the extreme case, fuel and flow conditions imposed by the injection can adversely affect ignition or flame development. This can lead to rare and random cycles that either misfire (little detectable heat release) or only partially burn [2,5,6–16]. Misfire (MF) and partial burn (PB) cycles must be eliminated in order to improve fuel economy and reduce emissions for successful implementation of the SG-SIDI engine as a cleaner and more economic powertrain component.

There has been a strong effort within the automotive and combustion research community to identify potential causes of rare and random MF cycles. Laser induced fluorescence (LIF) imaging of fuel [6–8], spark emission spectroscopy techniques [9,10], and computational efforts [11] have revealed that overly lean mixtures near the spark plug at the time of ignition are strongly correlated

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with the occurrence of MF cycles. In other studies, abnormal electrical discharge phenomena such as spark plasma extinguishment, short spark durations, multiple spark restrikes, surface sparks, and lower spark energy imparted on the mixture have been identified as causes of MF cycles [7,8,12,13]. In other observations, Smith and Sick identified MF cycles that had ample fuel distributions near the spark plug and exhibited normal discharge characteristics, but a flame kernel was never formed [8]. It was speculated that such MF cycles were possibly related to the local flow field in the vicinity of the spark plug which rendered an abnormally stationary spark discharge. In this regard, Fansler et al. utilized Mie scattering imaging to reveal that local flow velocity fluctuations can cause unfavorable spark motion, which leads a MF [14]. Unfavorable spark motion relocates the ignition site, which has further been shown to be a dominating source of initiating MF cycles [15].

The aforementioned studies clearly demonstrate that there is not one universal cause of misfire events within spark-ignited (SI) engines. In an attempt to diagnose the simultaneous influence of multiple parameters on ignition instability, Peterson et al. utilized high-speed PLIF, particle image velocimetry (PIV), Mie scattering, and spark discharge measurements to obtain measurements of fuel concentration, flow field, spark energy, and spark duration at every crank-angle degree (CA°) for well-burning (WB) and poor burning cycles [16]. Spark discharge measurements revealed similar spark energies and spark durations for WB and poor burning cycles, which determined that abnormal spark discharge was not an inherent cause of poor burning cycles. The spatial and temporal evolution of the flow field and fuel distribution during early flame development revealed distinct differences between WB and poor burning cycles. Misfiring cycles revealed a flame kernel that remained in the vicinity of the spark plug which quickly became fuel-lean as the fuel mixture traveled into the piston bowl. The fuel-lean mixtures surrounding the flame kernel were insufficient to develop the flame at a sufficient rate and the flame extinguished shortly after the end of spark. Partial burn cycles, exhibited a flame kernel that propagated, but lagged behind the flammable mixture as it traveled into the piston bowl. As a result, the flame kernel developed into the flammable mixture as the mixture became leaner with time and the flame did not fully consume the mixture before the mixture dispersed.

Stratified charge operation produces locally high temperatures, which leads to unacceptable engine-out NO_X. Consequently, exhaust gas recirculation (EGR) is often employed to reduce combustion temperatures for NO_X reduction [1,17], but this can also cause combustion instability [7,8,17,18]. Ignition instability findings from [16] were restricted to SG-SIDI operation without EGR dilution. Thus, the effect of EGR dilution on MF and PB cycles is investigated here using the experimental and analysis methods employed in [16]. Real EGR contains nitrogen, oxygen and product gases, the latter of which affects the heat capacity ratio of the mixture during compression [19]. In this study, nitrogen is used to simulate EGR and, thus, lowers the oxygen concentration.

The focus of this study is to investigate combustion instability in a SG-SIDI engine operating with nitrogen dilution levels of 0–26% by volume. As in [16], high-speed imaging of equivalence ratio (PLIF), flow field (PIV), flame propagation (Mie scattering) and spark discharge measurements are simultaneously utilized to diagnose the causes of the misfires. Additional tests are conducted at 0% dilution to demonstrate the test repeatability and increase the sample size of the poor burning cycles. High-speed imaging of fuel concentration, flow field, and flame development are utilized to carefully describe the spray, spark, and flame development within the SG-SIDI engine. Finally, the images are used to describe the distinctive differences of early flame growth for WB, PB, and MF cycles at each dilution level investigated (0%, 10%, 18%, and 26% by volume). The combined imaging techniques provided quantitative measurements that revealed specific mechanisms that impede flame development and rendered a PB or MF cycle.

For completeness we note that the results here are relevant to gasoline SG-SIDI sprays (or isooctane as a surrogate), which need be ignited in the wake of the liquid (i.e., near EOI) [2–7]. Recent studies [20,21] revealed SG-SIDI operation with E85 (85% ethanol and 15% gasoline) requires spark timing at the leading edge of the liquid spray. The partial burn and misfire behavior between different gasoline and ethanol mixtures is the subject of continuing studies.

2. Experimental

2.1. Optical engine and hardware

Experiments were conducted in a single-cylinder SG-SIDI engine (Fig. 1a). This engine features a twin-cam, overhead-valve, pentroof cylinder head, a full quartz-glass cylinder, and a quartz-glass Bowditch piston (Fig. 1b). Quartz windows are installed in the cylinder head and the piston bowl and provide optical access into the fire deck and piston bowl, respectively. The engine operated with a geometric compression ratio of 9:1, with an 86 mm bore and stroke. The engine was equipped with a 90° symmetric 8-hole fuel injector that was targeted to impinge one of the eight spray plumes upon the spark plug electrodes (1.3 mm electrode gap spacing). Fig. 1c shows a sketch of the engine combustion chamber, direction of the spray plume, and the region next to the

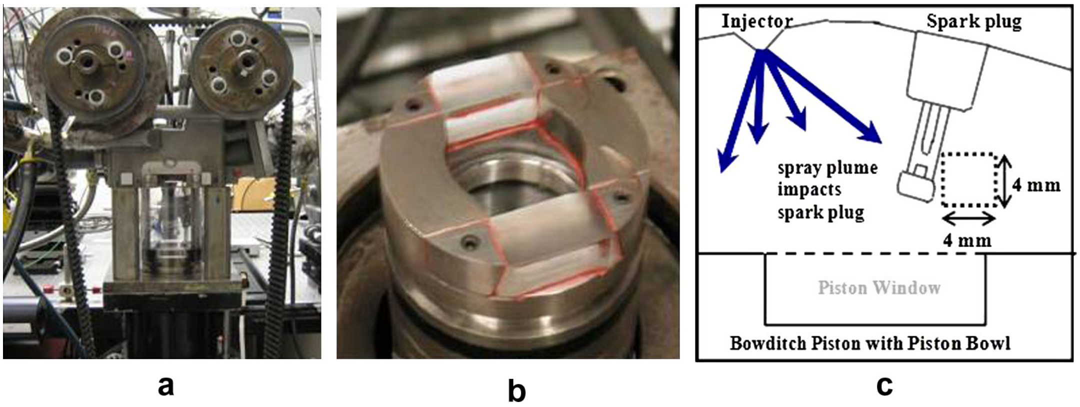

Fig. 1. (a) single-cylinder optical engine, (b) quartz-glass bottom piston with bowl configuration, and (c) field-of-view highlighting main features of combustion chamber and a 4×4 mm^2 region where values of fuel concentration and velocity were extracted.