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Combined effects of flow/spray interactions and EGR on combustion variability for a stratified DISI engine

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Abstract

This study investigates combustion variability of a stratified-charge direct-injection spark ignited (DISI) engine, operated with near-TDC injection of E70 fuel and a spark timing that occurs during the early part of the fuel injection. Using EGR, low engine-out NO_x can be achieved, but at the expense of increased combustion variability at higher engine speeds. Initial motored tests at different speeds reveal that the in-cylinder gas flow becomes sufficiently strong at 2000 rpm to cause significant cycle-to-cycle variations of the spray penetration. Hence, the fired tests focus on operation at 2000 rpm with N_2 dilution ($[O_2] = 19\%$ and 21%) to simulate EGR. In-cylinder flow, spray, and early-flame measurements are correlated to reveal their effect on the combustion variability.

Results reveal two types of flow/spray-interactions that predict the likelihood of a partial burn. (1) Proper flow direction before injection with a more collapsed spray leads to high kinetic energy of the flow during injection, thus generating a rapid early burn, which ensures complete combustion, regardless of the EGR level. (2) Improper flow direction and less collapsed spray generate low flow energy during the early phase of combustion. For this second type of flow/spray-interaction, application of EGR results in a partial-burn frequency of 30%, whereas without EGR, early combustion is shown to be insensitive to flow variations. Flame-probability maps illustrate that the partial-burn cycles for operation with EGR have a weak flame development in that the flame does not develop uniformly and reliably from the spark plug. Without EGR, the flame development is more repeatable regardless of the type of flow/spray-interaction, at the expense of higher NO_x emissions.

Keywords: Stratified DISI engine; Combustion variability; Flow/spray interactions; EGR; Optical diagnostics

1. Introduction

High efficiency can be achieved in spark-ignited automotive engines using un-throttled stratified-charge combustion for load control. However, practical implementation is inhibited by the need

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for lean-NO_x and particulate aftertreatment [1,2]. Recent studies by the authors have demonstrated that legislated levels of engine-out NO_x and soot abatement can be achieved using EGR combined with ethanol-gasoline blends, which enable later injection and spray-head ignition compared to pure gasoline. However, the in-cylinder emission control is limited to a small speed and load range due to cyclic variability [3,4]. Further research has been undertaken to identify the causes of the combustion variability with the goal of expanding the operating range. Testing at 1000 and 2000 rpm led to two hypotheses; (a) The spray-guided stratified-charge combustion rate is primarily controlled by the mixing rates and turbulence level associated with fuel injection, but (b) the in-cylinder flow field, generated by the intake and compression strokes, stochastically disturbs the mixing and flow associated with the fuel jets, thereby causing cycle-to-cycle variations of the combustion [5]. Particle image velocimetry (PIV), flame and liquid-spray measurements of non-fired operation support these hypotheses [6]. In this study, these in-cylinder optical diagnostics are instead applied to fired operation for correlation with the combustion variability. Here, tests are performed at 2000 rpm with and without N_2 dilution, and distinct differences in flow and combustion variability are observed.

The PIV measurement focused on the tumble plane right in between the injector tip and the spark plug gap. The 2D plane chosen allows simultaneous characterizations of the tumble flow and spray structures in the piston bowl. With 2D tumble plane measurement, investigations [7,8] on interactions of in-cylinder charge motion and sprays from multiple injections have revealed that the first injection significantly perturbed the tumble flow and fluctuations of the resulting flow structures correlated with the spray shape of the second injection. In this study, a single injection strategy is implemented. Statistical analysis is used to correlate the flow and spray structures with both the flow energy during injection and with the appearance of partial-burn cycles. The results provide unique insights of the physics responsible for the impact of flow/spray interaction on combustion variability of highly stratified DISI engine operation.

2. Experimental setup and methodology

2.1. Single cylinder engine

Testing was performed in a single-cylinder four-valve pent-roof DISI engine, operated with late injection for stratified-charge combustion. In a spray-guided configuration, an eight-hole injector was located near the cylinder axis and oriented with two of the eight jets straddling the ground

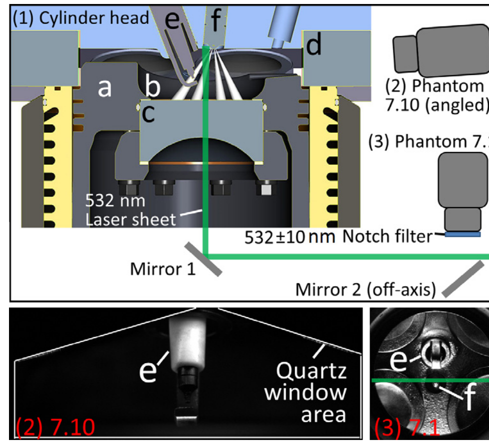

Fig. 1. (1) Single-cylinder optical engine with (a)-piston, (b)-piston bowl, (c)-piston-bowl window, (d)-pent-roof window, (e)-spark plug, and (f)-fuel injector, (2) camera view for PIV, (3) camera view for flame imaging.

electrode of the spark plug. The engine was operated in an all-metal configuration for continuously fired performance testing or in a geometrically-identical optical configuration as shown in Fig. 1. For optical access the Bowditch piston was equipped with a plano-concave ($R =$ 25 mm) quartz window to create a flat-bottom piston bowl with a large viewing angle. Also, a flat quartz window was located in the end of the pent-roof section closest to the injector to enable observation along the axis of the pent-roof. E70 fuel was prepared by blending pure ethanol and research-grade gasoline with $(R + M)/2 = 87$ in 70/30% proportions by volume [5]. All tests in this study were conducted with one intake valve deactivated to increase in-cylinder swirl and tumble levels, which generally provide more robust stratified operation. For fired engine operation, N_2 dilution was used to lower the intake mole fraction of oxygen $[O_2]$ to simulate EGR. In-cylinder pressure was acquired with 0.1° crank-angle (CA) resolution for 500 consecutively fired cycles during all-metal engine operations. The apparent heat-release rate (AHRR) was computed from the in-cylinder pressure using a constant ratio of specific heats (γ) following Ref. [9]. NO emissions were measured using a Horiba MEXA-584L emission analyzer. Engine specifications and operating conditions are given in Table 1. A complete description of the hardware and analysis is provided in Ref. [5].

2.2. Optical diagnostics

High-speed planar PIV and flame natural emission were acquired for Tests 4 and 5 (Table 1) to measure the in-cylinder gas flow, fuel injection, and combustion processes. A 25% duty cycle

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