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Spray-induced temperature stratification dynamics in a gasoline direct-injection engine

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Abstract

Simultaneous applications of high-speed toluene-LIF thermometry and PIV at kHz rates were utilized to investigate the evolution of gas temperature stratification imposed from direct-injection of liquid fuel within a motored SIDI engine. Temperature imaging was based on the two-color detection method that measures the LIF signal ratio from two separated wavelength ranges to enable LIF temperature imaging within inhomogeneously mixed systems. It was observed that cold gases associated with evaporative cooling exist within the regions of dense liquid fuel droplet clouds. As droplets disperse, the cold-gas regions expand and relative temperatures as low as −50 K exist. Average temperature gradients between cold- and bulk-gases are up to 30 K/mm and gradients persist but drop in magnitude throughout compression as cold- and bulk-gases mix. Temperature stratification is greatest as the fuel disperses within the field-of-view producing large areas of cold-gases with relative temperatures as low as −50 K. Individual temperature images and 2D PDFs of identified cold-gas regions reveal that local regions of cold-gas imposed from evaporative cooling can last up to 30 CAD after fuel injection for the given operating conditions. The time-resolved imaging study show the mechanics of localized evaporative cooling and bulk-flow motion-driven mixing that over time reduces temperature gradients but does not completely homogenize the temperature fields.
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Keywords: High-speed LIF; High-speed PIV; Direct-injection engine; Temperature imaging; Evaporative cooling

1. Introduction

Direct-injection (DI) as a load-control strategy, previously exclusive to compression-ignition (CI) engines, is now-a-days realizable within spark-ignition (SI) engines to further improve engine efficiency and performance. Direct-injection leads to temperature stratification that has large implications on ignition timing, combustion, and pollutant emission in both CI and SI engines [1–3]. Evaporative cooling lowers gas temperatures and thus delays the onset of autoignition, which can control combustion phasing in CI

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engines and reduce end-gas knock tendencies within turbocharged SI engines. New CI strategies (e.g. low temperature combustion (LTC) and homogeneous charged compression ignition (HCCI)) require precise control of the in-cylinder mixture and temperature distribution to optimize combustion phasing for maximal power output [3]. Inhomogeneous temperature distributions further determine local evaporation rates and ensuing mixture formation responsible for providing ignitable mixtures at spark-timing and controlling engine-out emissions within SI engines. There is a clear need to resolve the local temperature distribution resulting from DI within internal combustion (IC) engines.

Laser induced fluorescence (LIF) thermometry is a valuable diagnostic for spatially resolving temperature distributions and temperature gradients within spray and engine environments [4–17]. For sprays, Trost et al. [5] utilized LIF thermometry within a pressurized cell to evaluate local temperature distributions for ethanol and isooctane based fuels doped with 3-pentanone. LIF images resolved larger evaporative cooling for ethanol sprays due to higher heat of vaporization. Within engines, temperature distributions were measured during motored [6–14] and fired operation [8,15]. Such measurements have demonstrated the ability for LIF thermometry to resolve thermal gradients formed in IC engines under forced thermal stratification [13,16], natural thermal stratification [6–11], and spray evaporation [17]. LIF images have shown that natural thermal stratification is strongly correlated with locations of initial reaction zones in HCCI engines [8]. For DI engine operation, Zeger et al. [17] demonstrated the use of LIF to investigate evaporative cooling around a dense spray plume, but results were negatively affected by residual fluorescence of the base fuel. Gas-phase temperature measurements in a vaporized spray plume were better quantified using coherent anti-Stokes Raman (CARS) measurements [18]. These point-wise measurements quantified the distribution of evaporative cooled temperatures at a fixed timing from start-of-injection (SOI).

Further understanding of temperature stratification imposed from DI requires improved temporal and multi-parameter imaging capabilities. This work utilizes high-speed toluene-LIF thermometry simultaneously with particle image velocimetry (PIV) at a repetition rate of 6 kHz to investigate the temporal evolution of temperature stratification imposed from DI of isooctane during the compression stroke of a SIDI engine. PIV measurements and Mie scattering imaging provide relevance to understand spray-induced flow motion, fuel droplet distribution, evaporation, and thermal mixing after injection. Simultaneous measurements quantify the 2D temperature and velocity distribution in a 25 × 30 mm^2 region offset from the cylinder axis, near the cylinder head. The temperature, velocity, and Mie scattering images reveal the spray-induced temperature stratification and flow motion dynamics that quantify the magnitude of thermal stratification and mixing, which leads to prolonged existence of isolated cold-gas regions during compression.

2. Experimental

2.1. Engine

High-speed toluene-LIF and PIV measurements were performed in a 4-stroke, single-cylinder SIDI optical engine [18]. The engine is equipped with a 4-valve pentroof cylinder head, side mounted injector, centrally mounted spark plug, quartz-glass cylinder, and flat quartz-glass piston. For these experiments the spark plug was removed and replaced with a threaded plug. Non-fluorescing isooctane (Uvasol®, 12 mg/cycle) was injected during the compression stroke (crank-angle degree (CAD) 294–301, CAD 360 refers to top-dead-center (TDC) compression) through a seven-hole side mounted injector with 100 bar injection pressure and 20° spray angle. The injector is targeted so the fuel impinges upon the piston top (Fig. 1b) and is deflected towards the 25 × 30 mm^2 viewing plane. It is recognized that a side mounted injector for wall-guided systems and a flat piston is not optimal for fuel–air mixing or combustion within IC engines. The focus of the measurements however, is to resolve the local temperature stratification as the liquid fuel enters and disperses into a region of the combustion chamber away from the fuel injector. The side-mounted injector and flat piston surface are suitable for this scope. Fuel-injection parameters mimic low-load, idle operating conditions for stratified combustion in SIDI engines ($\Phi_{global} = 0.2$).

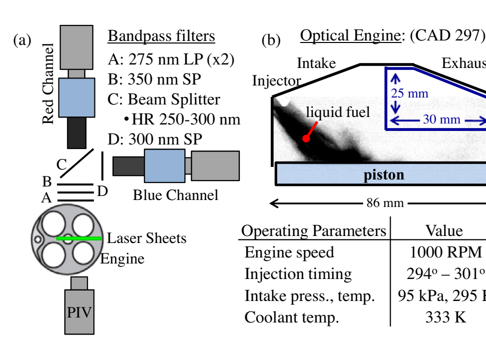

Fig. 1. (a) optical setup (b) fuel spray (Shadowgraphy) in optical engine at CAD 297 in relation to 25 × 30 mm^2 field-of-view. Important operating parameters are shown.