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Optical study of spray-wall impingement impact on early-injection gasoline partially premixed combustion at low engine load

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HIGHLIGHTS

- Spray-wall impingement of gasoline PPC was studied by multiple optical diagnostics.
- Fuel-trapping effect was verified when spray-wall impingement happened.
- The combustion chamber was filled with formaldehyde when misfire happened.
- Flame front propagation and sequential auto-ignition coexisted in gasoline PPC.
- The flame expansion speed of PPC-60 case was much higher than that in SI/SACI.

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ABSTRACT

Spray-wall impingement caused by early fuel injection for gasoline partially premixed combustion (PPC) can lead to low combustion efficiency and a significant rise of UHC emissions. But the influence of spray-wall impingement on the in-cylinder combustion process is not well understood. In this study, multiple optical diagnostics were applied to investigate the ignition, flame development and UHC formation of gasoline PPC with early single fuel-injection in a light-duty optical engine under low engine load. Natural combustion luminosity images and emission spectra were obtained. Planar laser-induced fluorescence (PLIF) of the fuel-tracer and formaldehyde were used to explore the fuel/air mixing and UHC formation in PPC, respectively. The results indicated that there was a fuel-injection time window (about −30° to −60° ATDC in the present study), during which the spray-impingement led to a decrease in combustion efficiency. The fuel-trapping effect in the squish region and piston crevice was shown to be the main reason because it prevented the fuel/air mixture from entering the combustion chamber. Two typical fuel injection timings of −35° (PPC-35) and −60° (PPC-60) were chosen for further study. For both cases, ignition sites first emerged in the fuel-rich regions and then the flames developed to the fuel-lean regions. The formaldehyde PLIF images revealed distinct flame front in the flame development process. For the PPC-35 case, residual formaldehyde persisted in the fuel-lean regions late during the power stroke and might become a source of UHC emissions. When misfire happened, the combustion chamber was filled with formaldehyde. For the PPC-60 case, the flame development was composed of initial flame front propagation and following sequential auto-ignition, and the flame expansion speed of the initial flame front propagation was much higher than that in SI (spark ignition) or SACI (spark assisted compression ignition) combustion. When the injection timing was further advanced (earlier than −60°), the impact of spray-wall impingement on PPC was reduced because of more time being available for fuel premixing.

1. Introduction

Homogenous charge compression ignition (HCCI) has the potential to achieve low NOx and soot emissions, which are major problems for conventional diesel engines. But HCCI is limited to low engine load due to the excessive pressure-rise rate (PRR), and the control of combustion phasing is a great challenge, since HCCI is governed by chemical kinetics [1,2]. As an intermediate process between HCCI and conventional mixing-controlled diesel combustion, partially premixed combustion (PPC) adopts later fuel injection timing than HCCI to control the combustion phasing and

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lower the PRR [3,4]. Generally, the fuel injection timing of PPC is earlier than for conventional diesel combustion so that the fuel has more time for mixing. Consequently, there are less locally fuel-rich regions that give rise to soot and the reduced combustion temperature cuts down NOx emissions [5].

Using diesel fuel with high fuel reactivity, a considerable portion of exhaust gas recirculation (EGR) is required to get a longer ignition delay. Although Diesel PPC is feasible at medium and low load with low soot and NOx emissions, when it comes to high engine load, the introduction of too much EGR results in a reduction of combustion efficiency and a large increase in unburned hydrocarbon (UHC) and CO [2,6–8]. To extend the operation range of PPC to higher engine loads and to reduce the demand for EGR, the fuel with a lower reactivity was favored [9]. Kalghatgi et al. [10,11] proposed a gasoline PPC strategy in which gasoline was used as fuel in a compression ignition engine. The high resistance to ignition of gasoline was utilized to gain a longer ignition delay. Manente et al. [12,13] indicated that gasoline PPC could be run as high as 25 bar gross indicated mean effective pressure (IMEP) with low emissions of soot and NOx, and the gross indicated engine efficiency reached more than 50% with acceptable maximum PRR and moderate EGR. Fig. 1 shows the energy flow of conventional diesel combustion, diesel PPC and gasoline PPC adapted from test engine results in University of Wisconsin-Madison [14,15]. It indicates that the gasoline PPC engine's efficiency is higher than that of conventional diesel combustion and diesel PPC due to the lower heat transfer and exhaust losses. The lower heat transfer and exhaust losses are achieved by more sufficient fuel/air premixing and lower local combustion temperatures.

An early injection strategy is often employed in diesel or gasoline PPC to increase the fuel premixing time. Under early-injection situations fuel sprays have longer liquid penetration length and may impinge on the piston or cylinder walls. The "spray-wall impingement" in this paper concerns impingement between the fuel spray and piston top, or spray and cylinder wall, like case 2 and case 3 in Fig. 2, respectively. In these two cases, fuel is injected onto the piston top or directly on the cylinder wall before ignition initiation. This spray-wall impingement has a great influence on the PPC at low engine loads because the lower piston or cylinder wall temperature can result in wall-wetting and hinder fuel/air

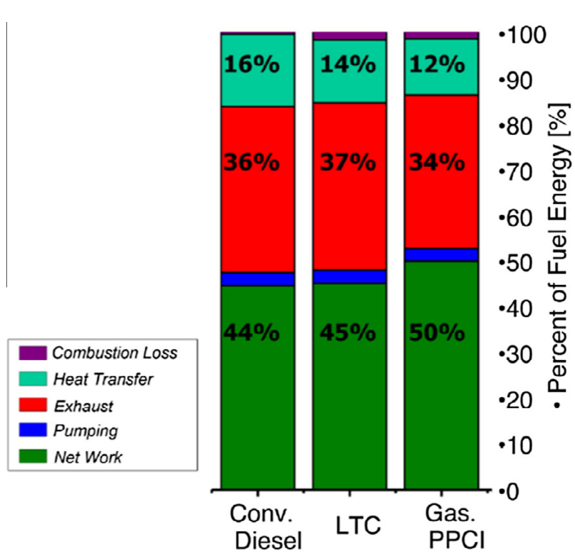

Fig. 1. Energy flow for conventional diesel combustion, diesel PPC (also called LTC) and gasoline PPC (also called gasoline PPCI). All three cases were taken using the same test engine at loads in the range of 9–11.5 bar net IMEP and similar engine speeds. Adapted from [14,15].

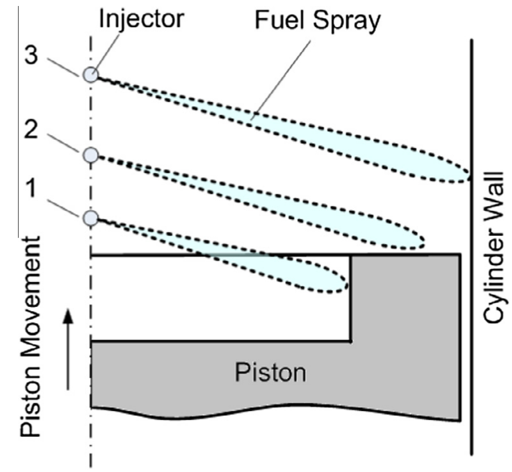

Fig. 2. Different cases of spray-wall impingement (Case 1: combustion chamber piston wall impingement, Case 2: piston top wall impingement, Case 3: cylinder wall impingement. The present study focuses on the latter two cases.).

mixing. Pickett et al. [16] found that the injection pressure had no effect on the maximum liquid penetration of a fuel spray, but the liquid penetration of the fuel spray got longer at earlier in-cylinder fuel injection timing due to lower ambient temperature and density. Hotta et al. [17] showed that, using a traditional wide included angle injector, fuel adhesion to cylinder wall caused by fuel impingement was observed when the fuel injection timing was kept at −40°. In a study on spray impingement of diesel PPC at low load (4 bar IMEP), Boot et al. [18,19] concluded that the high UHC emissions with early fuel injection timings, using conventional direct injection nozzles, was mainly due to liquid spray impingement against the cylinder liner wall. Kim et al. [20] asserted that fuel deposited on the cylinder wall with early diesel fuel injection timing led to decreasing IMEP and rising UHC emissions. By using a fuel injector with a narrow included angle the UHC emissions were reduced because of less fuel deposited on the cylinder walls. However, Fang et al. [21] and Marin et al. [22] demonstrated that "pool fires" caused by fuel-film deposition on the combustion chamber walls using a narrow included angle injector could result in increasing soot and NOx emissions. Thus, the spray included angle of the injector should be carefully optimized to balance between UHC/CO and soot/NOx. In a work combining spray visualization experiments and spray-wall impingement simulation, Kim et al. [23] observed that when the fuel spray impinged on the cylinder wall under early diesel fuel injection timings, a rich mixture was formed near the wall and a lean mixture was seen in the center of combustion chamber, but when the sprays impinged on the piston top and the border of the piston bowl, the mixture distribution was more uniform. Lee et al. [24] discovered that soot and CO production were minimized when the spray was targeted at the edge of the piston bowl near the squish region. They believed that the targeting position enhanced the premixing of fuel and air with the help of the air flow in squish region, which was supported by the simulation results of Kim et al. [23].

Although gasoline PPC has higher engine efficiency at middle to high engine loads, the great challenge comes from combustion stability at low load because gasoline has higher resistance to auto-ignition [25,26]. Compared to diesel PPC, spray-wall impingement could have larger impact on gasoline PPC due to the lower fuel reactivity. However, few works have concentrated on this issue. In particular, the detailed ignition, flame development and UHC formation of gasoline PPC under the spray-wall impingement conditions at low load still needs further investigation. Laser-based