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Effect of jet–jet interactions on soot formation in a small-bore diesel engine

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Abstract

This study presents planar laser-induced fluorescence of fuel and hydroxyl (fuel- and OH-PLIF) and incandescence of soot (soot-PLII) together with morphology and nanostructure information of soot particles sampled via thermophoresis to clarify the in-cylinder soot processes under the influence of jet to jet interactions. The experiments were carried out in a single-cylinder, small-bore optical diesel engine fuelled by a low-sooting methyl decanoate fuel for diagnostic purposes. Two different nozzle configurations of one hole and two holes were used to simulate isolated single-jet and double-jet conditions, respectively. Results show that fuel-rich mixture formed in the jet–jet interaction region causes the faster initial growth of soot that persists for a longer period of time, compared to the soot formed in the wall-impingement region of the single jet. These soot particles impacted by the jet–jet interaction have larger aggregates composed of larger primaries, and the nanoscale internal structures show higher carbon fringe-to-fringe separations, both of which indicate higher particle reactivity and the formation stage of soot.

Keywords: Jet–jet interaction; PLII; Soot particles; TEM; Diesel engine

1. Introduction

Soot formation in diesel engines is strongly influenced by jet-wall interactions [1] as demonstrated by the formation of high-sooting, fuel-rich regions in the wall-impingement region of the diesel jet [2,3]. In addition to this direct impact, the jet also travels along the curved bowl-wall and interacts with a neighbouring jet to form another fuel-rich region with very high soot formation [4,5]. Previous studies report that the presence of a neighbouring jet alone, regardless of the inter-jet spacing, does not impact the total mass of entrained air and thus fuel–air mixing significantly [6]; however, it is the head of the wall-interacting jet merging with another wall-jet head (i.e. jet–jet interactions) to create limited mixing regions for high soot formation [7,8]. Moreover, the jet head redirected back towards the centre of the combustion chamber due to the jet-wall and jet–jet interactions could cause the re-entrainment of the combustion gases, leading to the decreased distance between the

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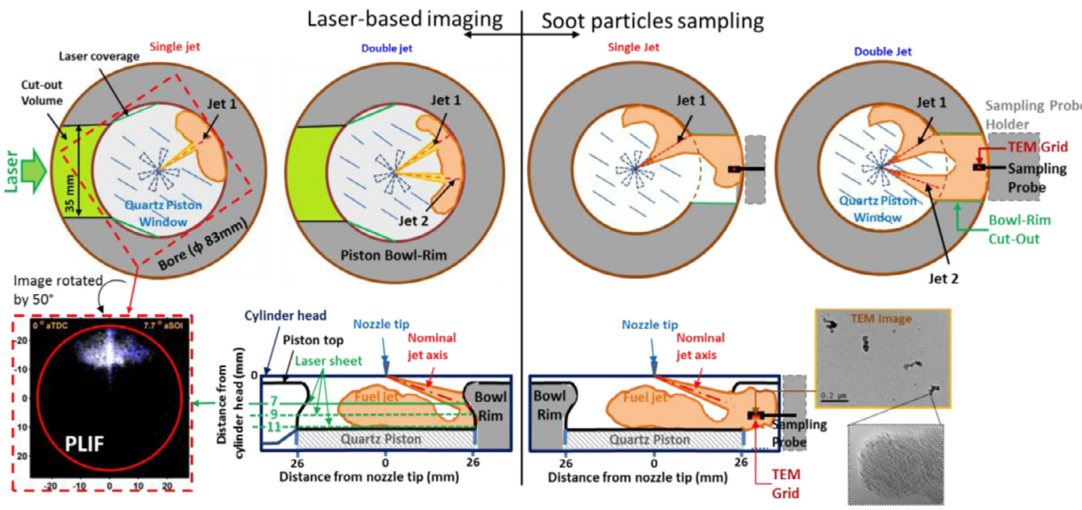

Fig. 1. Illustration of the engine combustion chamber and diagnostics setup for laser-based imaging diagnostics (left) and soot particles sampling (right). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

nozzle and the flame base and thereby increasing the downstream soot formation [3,9,10]. Due to recent downsizing trends, particularly in the automotive market, the wall is now closer to the injector [2,5], leading to an increased importance of jet–jet interactions, which is the focus of this study.

One of widely used methods to develop the aforementioned understanding of the effect of jet-wall and jet–jet interactions on soot formation is planar imaging of laser-induced incandescence (soot-PLII) as it is relatively easy to setup and useful to obtain spatial distributions of soot within the flame [2,7,11,12]. The soot-PLII, however, does not provide quantitative data unless it is calibrated against other measurements (e.g. light extinction [13]) requiring the questionable assumptions on soot optical properties [14]. Recently, thermophoretic soot particles sampling in diesel engine environments has received considerable research attention [13,15–17] because particle structures of both aggregates and primaries [18] as well as nanoscale internal patterns [19] can be visualised through transmission electron microscope (TEM) imaging. Detailed soot size and structural information can help understand the stage of soot formation and oxidation [19] and the status of particle reactivity within the diesel flame [20]. The soot sampling technique, however, is intrusive and is limited to a point measurement.

This study performs these complementary diagnostics of soot-PLII and particles sampling in an optically accessible, single-cylinder, small-bore diesel engine with an emphasis on the effect of jet–jet interactions on the spatial distribution as well as detailed structural information of in-flame soot. To our best knowledge, these elements have never been combined in a working diesel engine. The same diagnostics were repeated for an isolated single-hole injector and two-hole injector for a direct comparison between the soot in the wall-interacting jet and in the jet–jet interaction regions. Planar laser-induced fluorescence of fuel and hydroxyl (fuel- and/or OH-PLIF) were also performed to provide additional information about the mixture conditions and high-temperature reaction zones surrounding the soot pockets.

2. Experimental setup and diagnostics

2.1. Engine setup and operating conditions

Figure 1 illustrates the combustion chamber of the used optical diesel engine and diagnostics setup of the present study. Table 1 summarises the specification of this single-cylinder small-bore diesel engine and selected operating conditions for the laser-based imaging and soot sampling diagnostics. Details about this engine and operating conditions are found in our previous work [2,5,20–22] and thus only a brief summary is provided here. For the access of excitation laser sheets when the piston is at top dead centre, a 35-mm-wide portion of the piston-bowl rim was removed (Fig. 1 left). For the soot sampling experiments (Fig. 1 right), the piston was rotated by 180° so that the bowl-rim cut-out can be used to accommodate the sampling probe without causing possible collisions with the fast-moving piston and valves [20,22]. Previous full-cycle modelling work on the same engine [23] proved that this cut-out does not significantly affect the in-cylinder swirl flow. However, the different orientation of the bowl-rim cut-out means different jet dynamics for the laser-imaging