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The soot particle formation process inside the piston bowl of a small-bore diesel engine

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ABSTRACT

The present study unveils the soot formation processes occurring inside the piston-bowl of a small-bore diesel engine by conducting the thermophoresis-based soot sampling experiments at various locations along the flame development path. Based on planar laser-induced incandescence (PLII) and planar laser-induced florescence of hydroxyl (OH-PLIF) imaging performed in the same optical engine previously, it was understood that the sooting flame impinges on and then flows along the bowl wall, suggesting a soot growth and persistence near the fuel-rich wall region. In the present study, a soot sampling probe is placed in five different locations including the flame–wall impingement point and four further downstream regions: two 60° and two 120° from the jet axis with two different distances from the bowl wall in each angle. Methyl decanoate is selected as a surrogate fuel due to its low-sooting propensity and thus reduced laser attenuation in the reference PLII images; however, the fuel produces high enough number of soot particles for the in-flame sampling and their statistical analysis. The transmission electron microscope (TEM) images of the sampled soot particle aggregates and their statistical analysis of sizes and fractal dimensions as well as nanoscale internal pattern of the soot primary particles show that precursor-like, small soot particles with amorphous internal carbon layer structures form in the flame–wall impingement region, which grow in size and become large soot aggregates as travelling along the bowl wall. The detailed analysis clearly indicates that the soot precursors underwent the surface growth, aggregation and coagulation to produce large, long-stretched soot aggregates during which the amorphous soot carbon layers transformed into a typical core–shell structure. At further downstream locations, the continued surface growth increases the size of soot primary particles in the core region of the soot aggregates while the oxidation of the soot primary particles located in the outer region tends to reduce the aggregate size, resulting in more compact structures. In the outer region of the flame, the intensive soot oxidation induced by the hydroxyl attack further reduces the size of large soot aggregates and at the same time, eliminates the small soot aggregates. Throughout these soot formation/oxidation processes, the soot carbon layer gaps continue to decrease, indicating more mature soot primary particles.

1. Introduction

Soot formation process has long been of high interest to combustion scientists, which has been addressed in part through the soot sampling at various formation stages and the microscopic imaging of particle structure. Previous studies conducted in open flame burners showed a multi-step development in soot morphology through the nucleation, surface growth, and aggregation processes [1–8]. For instance, the thermophoresis-based sampling conducted in soot precursor regions showed small liquid-like particles with faint appearance in transmission electron microscope (TEM) images [1–5]. When the sampling location was varied along the laminar premixed or diffusion flames, it was shown that small nuclei grow further to become soot primary particles in high temperature conditions [2,4,5]. During this initial soot formation process, the carbonisation occurs as the precursors transform into the solid phase [4–6]. The subsequent surface growth increases the size of the soot primary particles, while the aggregation causes the production of large soot aggregates with complex fractal structures and various degrees of compactness [5]. Some soot aggregates

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show a long stretched chain-like structure (i.e. low fractal dimension) while other soot aggregates display highly agglomerated and compact structure (i.e. high fractal dimension) [5]. In the later stage of combustion, the soot aggregates showed a decreasing size due to the oxidation causing the breakdown of aggregates and the shrinkage of primary particles [4,5,7,8]. From the nanoscale structure analysis using high-resolution TEMs, it was also reported that the carbon layers within the soot primary particles present a transition from amorphous graphene segments to extended and ordered graphitic layers with decreasing interlayer spacing, namely, the graphitisation [7–11].

The soot formation processes have also been investigated for more complex lifted jet flames involving turbulent flows and high-pressure ambient gas conditions. In a constant-volume combustion chamber simulating diesel-engine-like ambient gas conditions, for instance, the thermophoresis-based soot particles sampling was conducted directly from a diesel jet flame [12–18], which reported fractal aggregate structures with varying numbers of soot primary particles forming long stretched or compact agglomerates. The findings made from these studies are consistent with the previous investigations conducted for fundamental flames. For example, when the sampling location was varied along the jet axis, small transparent particles were first found right downstream of the flame base indicating the soot precursors. At the peak soot volume fraction location further downstream of the flame base, the complex fractal soot aggregates were found [12–18], suggesting the surface growth and agglomeration. During this soot growth process, the nanoscale internal pattern analysis also showed a typical graphitisation process evidenced by reduced carbon interlayer spacing [17,18]. Then in the jet head region where decreased soot volume fraction is measured, the soot aggregates become smaller due to the oxidation [12–16].

Considering significant geometry and flow effects as well as transient ambient gas conditions [19–23], recent studies have focused on soot formation processes in a running engine. For instance, the crank angle-resolved bulk-gas sampling experiment reported that soot primary particles increase in size during the soot formation dominant phase of diesel combustion and then decrease in size during the oxidation dominant phase while the graphitisation continues to occur within the soot primary particles [24–26]. The same studies also showed that the soot aggregate fractal dimension decreases during the soot formation-intensive period, which however increases as the soot aggregates are oxidised and become more compact. The direct soot sampling in a running engine was also conducted using a TEM grid holder installed on the cylinder liner wall [27–35], which enabled the variation of the soot sampling location with respect to the diesel flame. Our previous study using this technique showed that the flame–wall impingement causes decreased size in the soot aggregates and the reduced fractal dimension, suggesting the fragmentation of soot aggregates [31]. The same study also showed that the highly concentrated portion of the large soot aggregates survive the soot oxidation leaving predominantly the substructure of the soot aggregates in the exhaust stream.

The previous studies conducted in a running engine successfully showed the fate of soot aggregates once the formation of the soot aggregates is complete [24–26,31]. On the other hand, the sampling work performed in a quasi-steady jet flame [12–18] revealed more details about the soot formation process, which however did not fully reflect the realistic engine conditions. The present study aims to bridge this gap by performing the soot particle sampling within the piston bowl in which the soot particles are anticipated to incept and grow while the flame develops along the bowl wall. To the best of our knowledge, the soot particle sampling from the piston-bowl region has never been attempted. This is realised by installing the soot TEM grid holder on the piston-bowl wall

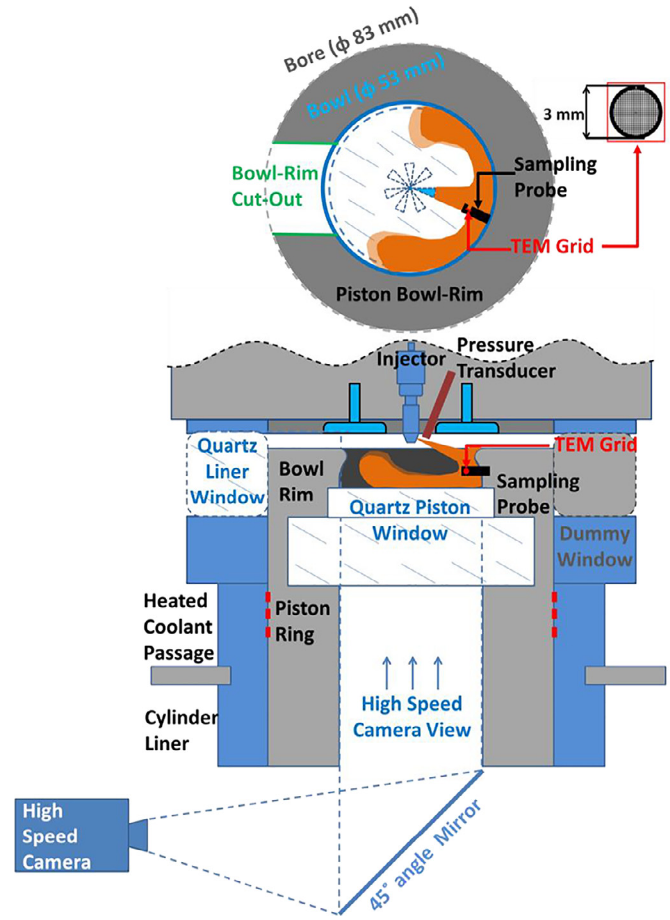

Fig. 1. Illustration of the optical diesel engine and soot sampling system in the bottom-view (top) and side-view (bottom) access. The high-speed soot luminosity imaging setup is also shown.

and varying the sampling locations with respect to the flame. In the present study, methyl decanoate was selected as a diagnostics fuel, which was successfully used to perform planar laser-induced incandescence (soot-PLII) and fluorescence of hydroxyl (OH-PLIF) imaging with no beam attenuation issue [36] and therefore served an excellent reference to determine the soot sampling locations. The thermophoretic sampling was conducted in five different in-bowl locations by varying the length and angle of the TEM grid holder. For each sampling location, a carbon-layer-coated mesh TEM grid and a lacy TEM grid were placed for the analysis of soot primary particles and aggregates as well as nanoscale internal pattern of the soot primary particles. The statistical analysis of the soot primary particle size, the aggregate radius of gyration, and the fractal dimension was conducted using an in-house-developed, automated processing code [37]. The carbon layers displayed as the fringes with various lengths and shapes in the high-resolution TEM images were also processed to obtain the fringe length, tortuosity, and fringe-to-fringe gap, similar to our previous study [30].

2. Experiments

2.1. Engine specifications and operating conditions

The in-bowl soot sampling experiments were conducted in a single-cylinder automotive-size diesel engine with optical access, as illustrated in Fig. 1. The specifications and operating conditions of the engine are summarised in Table 1. The engine has a displacement volume of 498 cm^3 with 83-mm bore and 92-mm