

Size Distribution and Structure of Wall-Deposited Soot Particles in an Automotive-Size Diesel Engine

Renlin Zhang, Kevin Szeto, and Sanghoon Kook
The University of New South Wales

ABSTRACT

Wall-deposition of soot particles occurs during the cylinder liner wall/flame interaction, which can potentially deteriorate engine oil quality and alter the heat loss rate in a diesel engine. These issues motivate a detailed study on structure and size of the wall-deposited soot particles. A morphological difference between the wall-deposited soot and in-flame soot particles is another focus of this study. We performed thermophoretic soot sampling in the cylinder liner wall using an in-liner-type sampler. Obtained soot particles were imaged by a transmission electron microscope and post-processed to acquire the number of particles, projection area on the sampling grid, and size distribution. The same set of data was also obtained for soot particles within the diesel flame using a probe-type sampler. The results show that the amount of soot particles deposited on the wall is about 2.7% (by means of number of particles and projection area on the grid) of those collected inside the flame. Close examination of soot particles structure suggests that the wall-deposited soot particles are largely different to the in-flame soot particles. It is observed that very small particles (radius of gyration < 10 nm) that are popular within the diesel flame disappear in the images of wall-deposited soot. Also, large particles (radius of gyration > 100 nm) with long stretched structure that are easily found within the flame do not present in the wall-deposited soot but smaller particles with cluster-like agglomerated shape. As a result, the mean radius of gyration of the wall-deposited soot and in-flame soot particles show nearly identical value of 38 nm at the tested conditions of this study, despite significant structural differences. It is suggested that the soot particles with highly concentrated core region are likely deposited on the cylinder liner wall during the flame/wall interaction.

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INTRODUCTION

Soot deposition on combustion chamber walls is commonly observed in diesel engines. For example, [figure 1](#) shows photos of a new piston and the same piston after a month of operations at various load conditions. The engine was a single-cylinder version of a small-bore diesel engine which equipped with a common-rail injection system using a second-generation Bosch pump and a seven-hole injector. It can be clearly seen that a layer of soot particles covers the piston surface leaving footprints of seven sooting diesel jets. Although previous studies suggest that only a small portion of soot particles presented within the diesel flame is deposited on in-cylinder surfaces (*e.g.* [1]), there are potential problems of engine oil contamination and increased wear of piston rings, liner wall and valve train [2, 3]. In addition, soot deposition affects the rate of heat transfer in the near-wall region and overall heat loss of the engine, which impacts the

engine efficiency [4, 5]. To resolve these durability and efficiency-related issues, detailed understandings of the soot wall-deposition mechanism are needed.

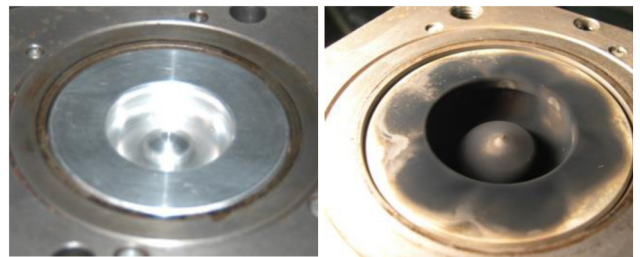


Figure 1. Photos showing a new piston installed in a performance-test engine sharing the same base engine of the optical diesel engine used in this study (left) and soot-deposited piston after a month of operations (right).

Previous studies involving laser-based imaging diagnostics showed that for a “free jet” (*i.e.* in the absence of jet-wall interaction), soot is formed in the fuel-rich region downstream of the lifted flame base and enveloped by a layer of diffusion flame [6, 7]. Ideally, as long as the diffusion flame remains active, soot particles should complete oxidation together with other rich combustion products in the diffusion flame. However, diffusion flame could weaken or locally extinguish during the late-cycle burn-out stage of diesel combustion [8], resulting in exhaust soot emissions. In contrast to the free jet, the flame quenching of a wall-interacting jet could occur during the main combustion event, leading to soot deposition on the cylinder wall. Figure 2 illustrates this process together with the free jet schematic for comparison purposes. The figure shows that the wall impingement could lead to flame extinction allowing soot particles to escape the oxidation process [9]. These partially oxidised soot particles would be brought to the near-wall region and then deposit on the wall. Early works done by Kittelson *et al.* [10] and Suhre and Foster [11] suggested that the force triggered by a temperature gradient between a soot laden gas and a cold wall (*i.e.* positive thermophoresis or thermodiffusion) is a primary mechanism for the transportation and deposition of soot particles inside diesel engine cylinder, noting other mass transport mechanism such as inertial deposition and Brownian diffusion may play a part but are relatively insignificant compared to thermophoresis. Further details of soot wall-deposition were provided by Tree and Dec [12] where the initial soot deposition rate was found to correlate with the amount of soot within the flame and the degree of flame-wall contact.

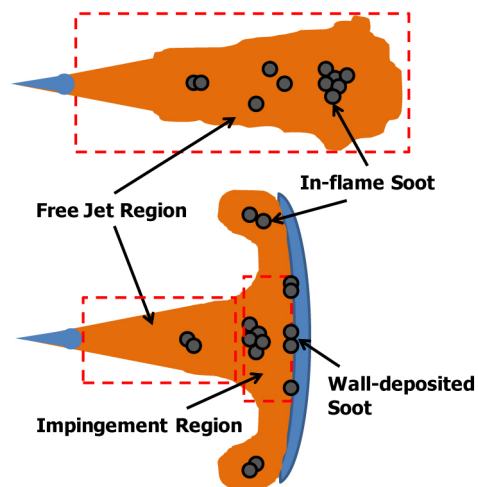


Figure 2. Conceptual drawing of a free jet (top) and a wall jet (bottom). Soot is formed within flame and its deposition occurs on the wall.

The present study aims to provide information of the size and structure of wall-deposited soot particles that are known to impact engine oil contamination and engine wear [3]. Also, size distribution and morphological details are compared between soot particles within the flame and soot particles

deposited on the wall, which would help understand the wall-deposition mechanism. Thermophoretic soot sampling followed by transmission electron microscope (TEM) imaging was used to this end. This technique has been widely used to investigate the structure and size distribution of soot particles sampled in a fundamental flame [13, 14], diesel engine exhaust [15, 16] and reacting diesel jet [17, 18, 19, 20, 21]. Recently, we further developed this technique to implement direct *in-flame* soot sampling in a working diesel engine [22]. Opposed to in-cylinder gas sampling [23, 24], the TEM grid was placed within the diesel flame and therefore directly exposed to in-flame soot particles. This approach allows sampling of high number of soot particles (>1000 aggregates), which is needed for statistical analysis. Also, possible morphological changes during the gas sampling processes can be avoided. Diagnostic details and techniques used to address issues raised by harsh engine environments are found in Ref. [22].

The same sampling method was used in this study to collect not only in-flame soot particles of a wall-interacting diesel jet but also those deposited on the cylinder-liner wall. In addition to a probe-type TEM grid holder used for in-flame soot sampling [22], a new in-liner-type TEM grid holder was designed for the wall-deposited soot sampling. Using these grids, TEM imaging was performed to clarify the structure and the shape of wall-deposited soot particles. Also, TEM images were post-processed to obtain the number of particles, soot particles projection area on the grid and size distribution.

EXPERIMENTS

Single-Cylinder Diesel Engine

An optically accessible, single-cylinder, direct-injection diesel engine was used in this study. Figure 3 shows schematic diagram of the combustion chamber. Detailed engine specifications and operating conditions are listed in Table 1. The engine has a single-cylinder displacement volume of 498 cm³ with 83 mm bore and 92 mm stroke, which is typical of an automotive-size diesel engine. Heated water with a temperature of 90°C was delivered to the cylinder liner, engine head and engine block to simulate warmed-up engine conditions. Temperature of naturally aspirated intake air was measured at 30°C throughout the experiments. The engine speed was fixed at 1200 revolutions per minute (rpm) using an electric motor. The compression ratio of the engine was originally 17.7, which was reduced to 15.2 because a portion of the piston bowl-rim was removed. Figure 3 shows the reacting diesel jet penetrates into the 30-mm-wide bowl-rim cut-out towards a probe-type soot sampler or in-liner-type sampler (two samplers were not installed simultaneously but one replaced the other). The bowl-rim cut-out was needed to place the probe-type sampler within the reacting diesel jet while avoiding potential collisions with the piston when it is at the top dead centre.

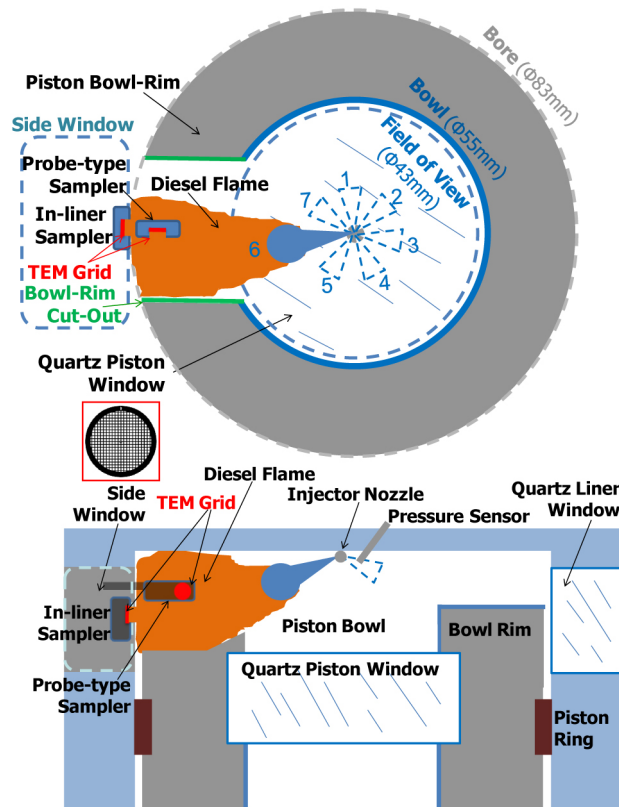


Figure 3. Schematics of the combustion chamber of the used optical diesel engine. Engine modifications for soot sampling and sooting diesel flame development relative to the sampling probe are illustrated for the bottom-view (top) and side-view (bottom) orientations.

the actual injection timing was fixed at -7°CA after top dead centre (aTDC).

Table 1. Engine specifications and operating conditions

Displaced volume	498 cc (single cylinder)
Bore	83 mm
Stroke	92 mm
Compression ratio	17.7 (original) 15.2 (modified)
Swirl ratio	1.4
Coolant temperature	90°C
Intake air temperature	30°C
Engine speed	1200 rpm
Fuel	Ultra low sulphur diesel
Cetane number	51
Common-rail	Second-generation Bosch
Nozzle	Mini-sac, hydro-grounded, K1.5/0.86
Number of holes	7 hole (original) 1 hole (modified)
Hydraulic fuelling rate for 7-hole nozzle	400 cc/30s at 10 MPa
Hole diameter	134 μm (nominal)
Included angle	150°
Rail pressure	70 MPa
Injection duration	1.2 ms (electronic) 2.34 ms (actual)
Fuel mass per injection	9 mg
Injection timing	-10°CA aTDC (electronic) -7°CA aTDC (actual)

Soot Particles Sampler

Figure 4 shows three-dimensional drawings of two different samplers used in this study. A probe-type sampler shown at the top was used to collect soot particles directly from the reacting diesel jet (*i.e.* in-flame soot particles). It comprises of three major components: 1) a metal dummy liner window serving as the base body of this sampler, 2) a sampling probe accommodating a 3-mm diameter, carbon-coated copper grid with 400 meshes, and 3) a back screw and washer set fixing the position of sampling probe and providing high pressure sealing.

Previous soot sampling study in constant volume combustion chambers provided information of soot progression along the axis of a reacting diesel jet [17, 19, 20, 25]. It was reported that near the nozzle, only precursor-like small particles were found. However, at further downstream location where the peak soot volume fraction was measured, a great mix of soot aggregates with long stretched chain-like structures and agglomerated shapes were evident. Then at the jet head region, aggregates with simpler and more compact structures were found, evidencing the soot oxidation. In the present study, however, the grid position was fixed at 5 mm from the cylinder liner wall to avoid the clash with moving parts such as the valves and piston. Therefore, the current