

Morphology Analysis of Wall-Deposited Diesel Soot Particles via Transmission Electron Microscope

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ABSTRACT

Wall-deposition of soot particles occurs due to the interaction between spray flame and cylinder liner wall/piston surface, which can potentially affect soot morphology after the in-flame formation/oxidation processes and before the exit from engine cylinder. In order to investigate these effects, flame wall impingement was simulated in a constant volume combustion vessel and thermophoretic soot sampling was conducted for Transmission Electron Microscopic analysis. A TEM grid for the sampling was exposed to a single-shot diesel spray flame multiple times and the variation of soot morphology (concentration, primary particle diameter and aggregate gyration radius) among the multiple exposures was compared. Furthermore, a newly designed impingement-type sampler vertically exposed the grid to the spray flame and sampled soot particles under different boundary condition from that of conventionally used skim-type sampler. The morphology of soot particles sampled by the impingement- and skim-type samplers were compared. The results showed that the multiple exposures increased both concentration and aggregate size but did not affect the primary particle size. On the other hand, flame wall impingement decreased both aggregate and primary particle sizes. It is suggested that cycle-to-cycle flame exposures to the wall cause soot coaggregation on wall surface but do not promote soot surface growth.

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INTRODUCTION

It is known that soot deposition on combustion chamber walls occurs during the jet-wall interaction in DI diesel engines. The fuel jet penetrates along cylinder liner wall and piston surface and the jet wall interaction repeatedly occurs during the engine operation. As a result, sooting diesel jets form a layer of soot particles on the wall/piston surface as seen in [Figure 1](#) (photos of piston surface before and after operation from Ref. [1]). These deposited soot particles possibly contaminate lubricant oil and deteriorate the engine performance as increasing the wear of liner wall and valve train [2,3]. Furthermore, the soot deposition and jet wall interaction itself may potentially affect the morphology of soot particles during in-cylinder sooting process. For example, the jet wall impingement causes soot deposition on the wall/piston surface and enables these deposited soot particles to escape from in-flame oxidation, then, subsequently the particles are blown off into the exhaust. Kittelson et al. [4] first discussed this pathway to soot emissions. Suhre and Foster [5] reported that several potential mechanisms might be a trigger of soot transportation through the boundary layer to the wall surface in DI diesel engines, which supported the idea, thermophoresis was the most possible source of the

mechanism suggested by Kittelson et al. [4]. Although these papers showed the in-cylinder soot deposition mechanisms, the morphology of wall-deposited soot particles has not been well investigated. Pungs et al. performed fast gas sampling and DMA-CNC measurement to obtain the size of both in-cylinder and tailpipe soot particles using a modern DI diesel engine [6]. From the results, it was found that the particle size distribution at the end of the expansion phase was similar to the tailpipe particle size distribution. However, the obtained particle size was mobility diameter and thus the details of soot morphology such as soot aggregate size and primary particle size were not clarified. Zhang et al. first visualized in-cylinder wall-deposited soot particles sampled from a single cylinder diesel engine and quantified their aggregate size via transmission electron microscopic (TEM) analysis [1]. The results showed that the aggregate of wall-deposited soot was more simple and compact cluster-like structure compared to in-flame stretched chain-like soot aggregates. In addition, both larger (radius of gyration > 100 nm) and smaller (radius of gyration < 10 nm) aggregates weren't observed in wall-deposited soot samples, which were observed in the in-flame samples. It was also found that the wall-deposited soot particles were significantly less than the in-flame soot particles in both number of particles

and soot projection area on a TEM grid. The above mentioned quantitative data are useful to understand the wall-deposited soot morphology, however, in the engine experiment, it is hard to extract the effect of jet wall impingement on the soot morphology from other factors, mainly due to the complex experimental configuration and limitation in an actual engine cylinder.

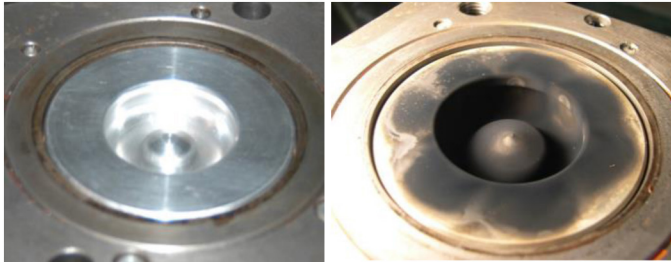


Figure 1. Photos showing a new piston installed in a single-cylinder diesel engine (left) and soot-deposited piston after a month operation (right). These photos were provided by UNSW [1].

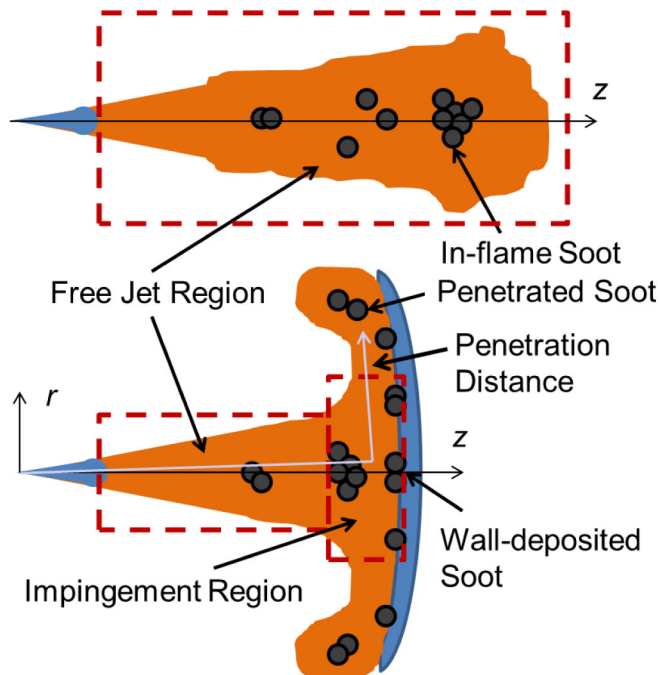


Figure 2. Conceptual drawing of a free jet (top) and a wall jet (bottom) provided by UNSW [1].

The present study aims to investigate the effects of in-cylinder process including jet wall impingement and repeated exposures to jets on the soot morphology without complexity of actual engine experiments. This paper especially focuses on the following three effects on soot morphology. First, the effect of multiple time exposures to reacting jets will be described, which clarifies the morphology change of soot particles deposited on the wall/piston surface during the multiple cycles in a real engine cylinder. Second, the effect of jet wall impingement will be discussed. Jet wall impingement causes flame stagnation and changes parameters such as flame temperature and in-flame particle residence time which have great impact on the soot formation and oxidation processes, thus the effect needs to be

understood to estimate engine out soot morphology. Third, this paper will present the effect of distance from the stagnation point after the jet wall impingement which includes the effects of both radial distribution in a reacting jet and penetration distance corresponding to $z + r$ seen in Figure 2. This will show the morphology of soot existing at the periphery of a reacting jet and at the same time wall penetrated soot morphology, which is also useful to predict the engine out soot morphology. For these purposes, the jet wall impingement and repeated exposures to jets were simulated in a constant volume combustion vessel which has wide flexibility for geometric configuration and measurements. The soot particles were thermophoretically sampled using two different types of soot sampler and their morphology was analyzed quantitatively via TEM.

EXPERIMENTAL METHOD

Constant Volume Combustion Chamber

Diesel combustion for soot sampling was achieved in a constant volume combustion chamber as seen in Figure 3. The chamber has three quartz windows for optical access and its displacement is 560 cm³. A common-rail fuel injector with a single-hole nozzle was mounted on its head. Diesel-like high pressure and high temperature conditions (2.55 MPa, 1000 K) were simulated by spark-ignited combustion of a premixture of acetylene, oxygen and nitrogen. The pressure was set below a typical modern diesel in-cylinder condition mainly for the safety limitations of the experimental device used in the present study. However the analysis of soot particles sampled in a higher pressure condition (6.7 MPa) [7] did not show significant difference in general trend of soot formation and oxidation and its morphology compared with the previous analysis conducted under lower pressure condition [8]. The distance between the injector nozzle tip and the soot sampling location could be varied by changing the spacer between the head and the chamber.

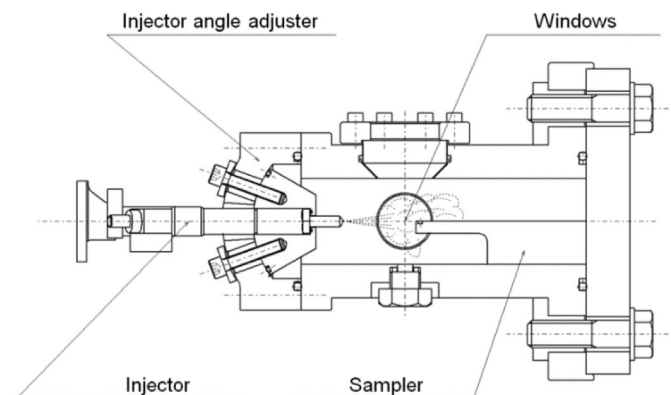


Figure 3. Constant volume combustion chamber

Soot Sampler

Figure 4 shows schematics of two different samplers used in the present study. A skim-type soot sampler shown in Figure 4 (a) which was conventionally used in the previous studies [8,9,10] was designed to fix a 3 mm-diameter TEM grid parallel to the spray axis and minimize the flame stagnation. Thus the

sampled soot particles are thought to keep in-flame soot property. On the other hand, a newly designed impingement-type soot sampler seen in Figure 4 (b) perpendicularly exposed the grid to the spray flame to simulate the jet wall impingement occurring in an engine cylinder. In order to see the soot particles existing in a penetrated jet, this sampler holds three grids as seen in Figure 4 (b). The grid placed at the bottom called “r0” is located on the flame centerline whose samples show the morphology of soot particles in the spray core region right after the wall impingement. The other two grids are placed 10 mm (“r10”) and 20 mm (“r20”) far from the flame centerline, respectively, which show penetrated soot properties. The both types of sampler and the grids were heated to 373 K together with the combustion chamber. Soot particles were sampled onto the grid surface mainly by the thermophoretic force due to the temperature gradient between the grid and the reacting jet.

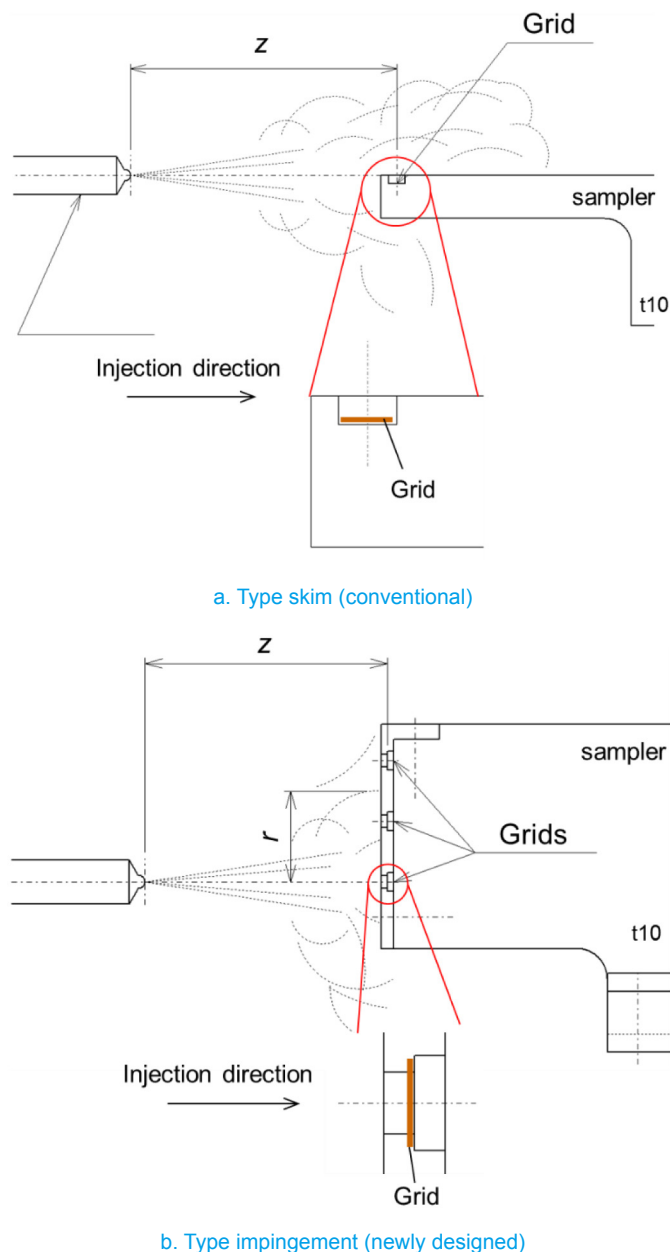


Figure 4. Side view of soot samplers

Experimental Conditions

Table 1 shows the experimental conditions. Diesel like high pressure and high temperature conditions were achieved by a premixed combustion as explained in the section of “Constant Volume Combustion Chamber”. The fuel used in this study is JIS#2 Japanese conventional diesel fuel. This study employed two different sampling conditions for different purposes. Sampling condition 1 is employed to investigate the effect of multiple exposures to reacting jets on the wall-deposited soot morphology. In order to eliminate the effects of jet wall impingement on the sampled soot morphology, the skim-type sampler was used. The sampling location was set to 60 mm away from the nozzle tip which corresponds to the peak sooting region in this spray [8]. To see the effect, an identical TEM grid was exposed to the flame three times and the variation of soot morphology among the multiple exposures was compared.

Table 1. Experimental Conditions

Surrounding Conditions	
Ambient gas density: ρ_a	9.5 kg/m ³
Temperature: T_a	1000 K
Pressure: P_a	2.55 MPa
O ₂ concentration: X_{O_2}	21%
Injection conditions	
Nozzle	ϕ 0.14 mm x 1
Injection pressure: P_{inj}	80 MPa
Injection duration: t_{inj}	2.5 ms
Fuel	JIS#2
Injection amount: M_f	10.3 mg
Sampling condition 1	
Sampler type	skim
Distance from orifice: z	60 mm
Grid type	Carbon coated copper grid
Temperature of sampler: $T_{sampler}$	373 K
Number of flame exposures	1, 2 and 3
Sampling condition 2	
Sampler type	skim and impingement
Distance from orifice: z	40 and 60 mm
Distance from stagnation point: r	0, 10 and 20 mm (impingement only)
Grid type	Carbon coated copper grid
Temperature of sampler: $T_{sampler}$	373 K

The combustion experiments for simulating the jet wall impingement were conducted under sampling condition 2 seen in Table 1. The morphology of soot particles sampled by the impingement-type sampler was compared to that by skim-type sampler. The distance between the nozzle tip and sampling location was set to 40 mm and 60 mm, which correspond to a typical piston bowl-wall dimension in heavy duty diesel engines and the above mentioned peak sooting location in this spray, respectively. The distance from stagnation point was set to 0, 10 and 20 mm. The radius of this jet at $z = 40$ mm and 60 mm