Evolution of nano-scale particle structures within a pilot-main injected jet fuel flame in a small-bore optical diesel engine

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Background and motivation

For a surrogate jet fuel specifically formulated for nanoparticle studies in an optically accessible small-bore diesel engine (Figure 1), combustion generated soot particles are sampled from multiple in-flame points and their structural evolution is analysed. The fuel contains 24% aromatics ("AR24"), similar with a conventional diesel fuel; however, its cetane number is only 40, posing a significant challenge for ignition and combustion control. It is a type of low-reactivity jet fuel used in unmanned aerial vehicles for various tactical reasons, which requires pilot injection prior to the main injection and thus produces more soot particles during combustion.

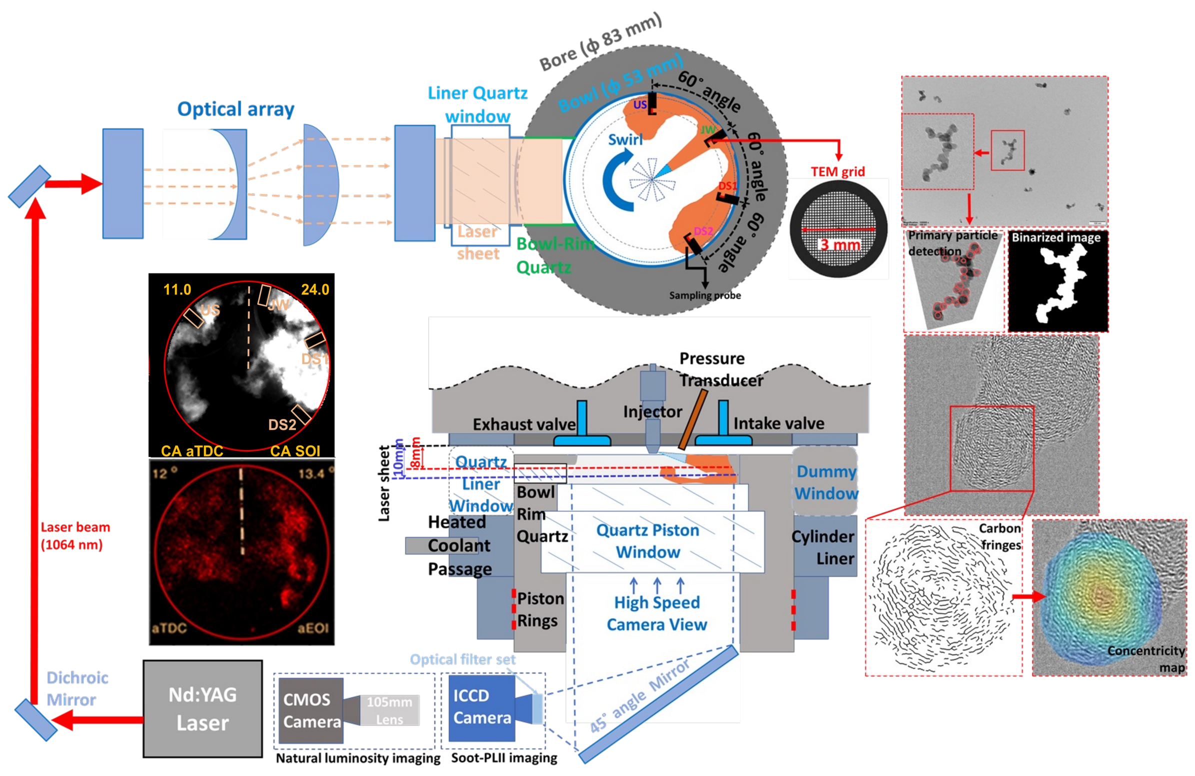

Figure 1 Engine setup for in-flame soot sampling and optical diagnostics

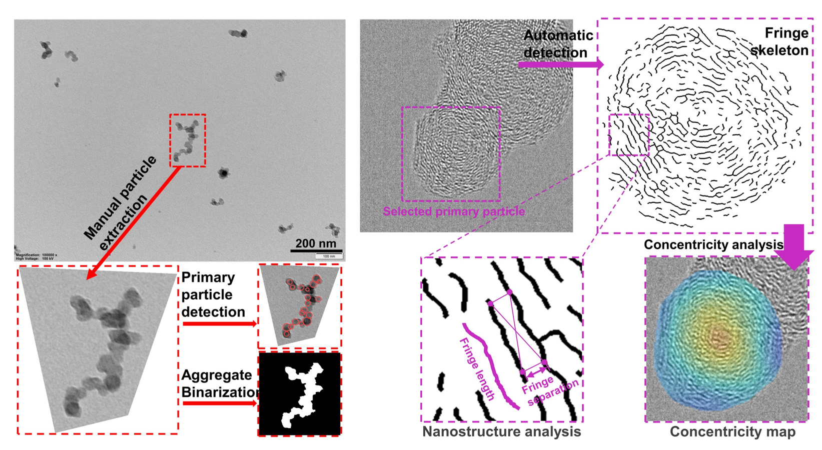

Figure 2. Soot particles morphology and nanostructure analysis

Approach

The soot particles deposited on transmission electron microscope (TEM) grids via thermophoresis are image post-processed to extract various morphology parameters such as the size of soot aggregates, primary particles and fractal dimension as well as concentricity, length, tortuosity and gap of the carbon-layer fringes (Figure 2).

The sooting flame trajectory is first identified by performing planar laser-induced incandescence imaging and high-speed soot luminosity movie recording (Figure 3). Along this trajectory, four soot sampling probes are installed on the piston-bowl wall with 60° spacing angles for simultaneous sampling from the same firing cycles. The first sampling point represents a jet-wall impingement region (JW) from which a jet flame starts to travel along the bowl wall while interacting with the swirl flow to both up-swirl and down-swirl directions. Three more sampling points therefore are selected for an up-swirl point (US), a down-swirl point 1 (DS1) and a down-swirl point 2 (DS2).

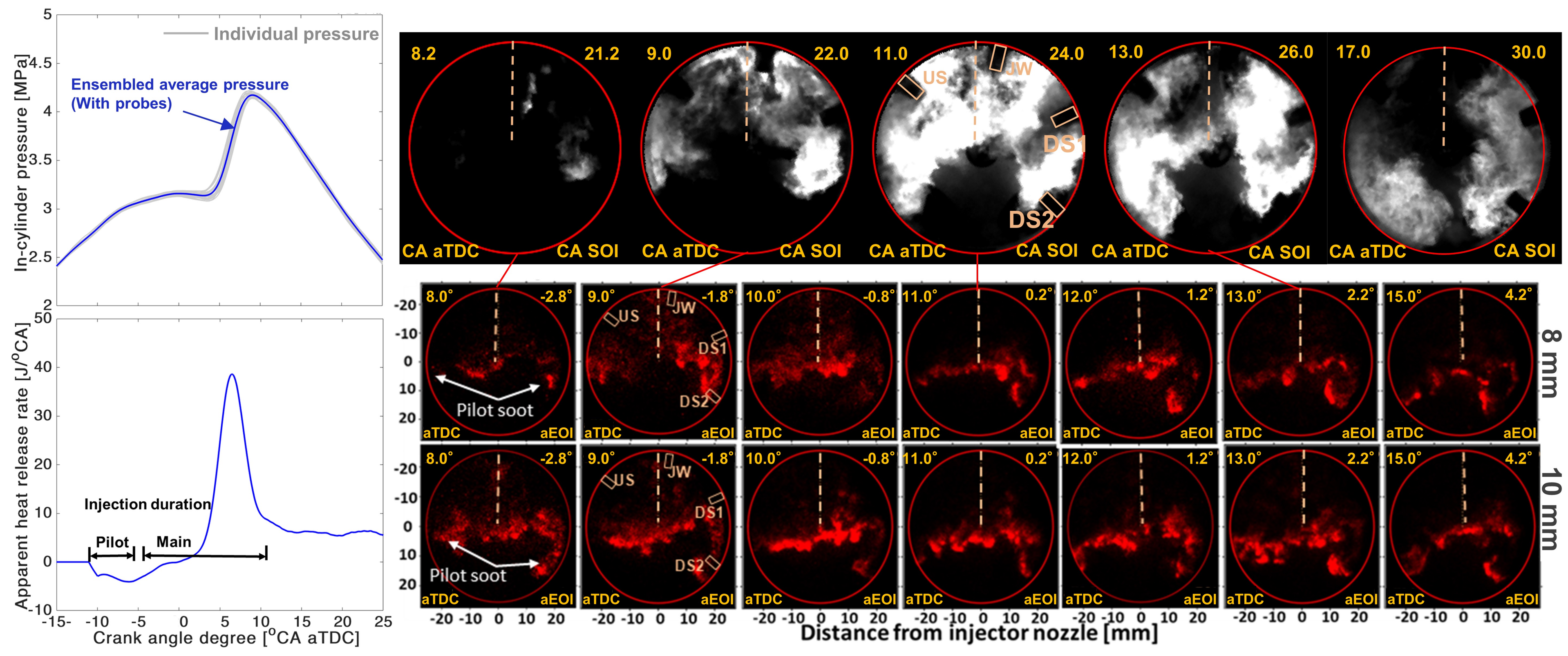

Figure 3. In-cylinder conditions, selected high-speed soot luminosity images, and planar laser induced incandescence images taken at 8 and 10 mm below the cylinder head for a high-sooting pilot-main injection condition of AR24 fuel.

Key Findings

The results indicate a large amount of small soot aggregates form at JW point due to fuel-rich mixtures (Figure 4 and Figure 5). These aggregates grow in size while the number counts decline, suggesting the aggregate-to-aggregate agglomeration and soot oxidation occur at the same time. This process is accelerated on the up-swirl side due to the counter-flow condition, showing similar parameter values between US and DS2 points. Interestingly, the primary particles show minimal changes on both up-swirl and down-swirl points; however, the significant soot particle oxidation is evident in the subnano-scale carbon layer fringes with increased length and decreased tortuosity/gap (Figure 6). The concentricity also indicates the soot particles become a clearer core-shell structure as they flow along the bowl wall (Figure 7). This trend is also more evident on the up-swirl side, indicating a significant effect of increased flow/turbulence on soot evolution.

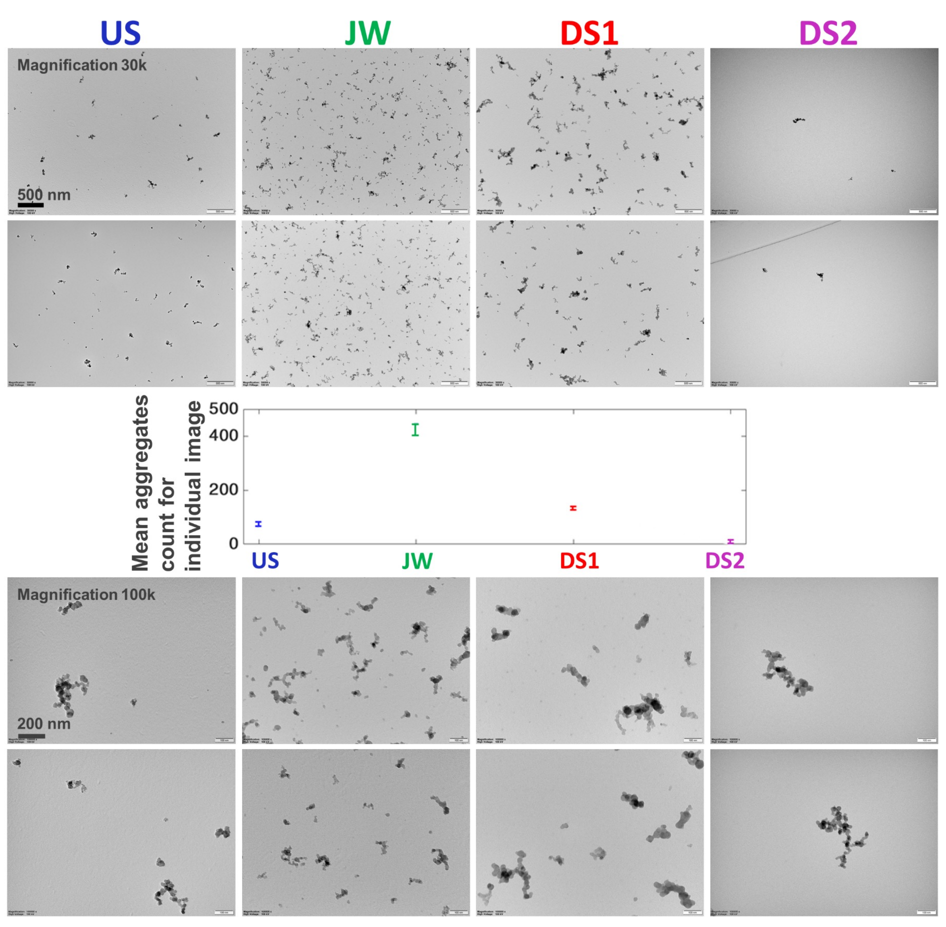

Figure 4. Example TEM images of the four sampling locations of the high-sooting pilot-main injection condition for AR24 fuel. A 30k TEM magnification is used for the soot aggregate number counting with the mean value plotted with error margins of 95% confidence while a 100k magnification is used for morphology analysis.

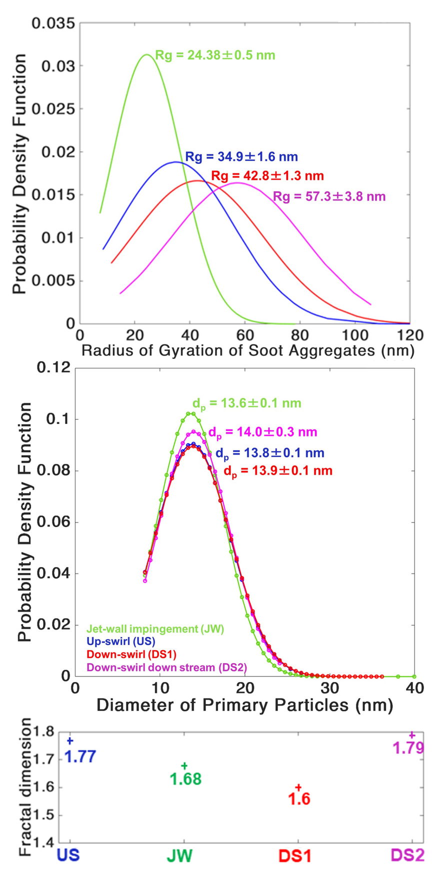

Figure 5. Size distribution of the soot aggregate radius of gyration and primary particles of the four sampling locations of the high-sooting pilot-main injection condition for AR24 fuel. The estimated fractal dimension is shown at the bottom.

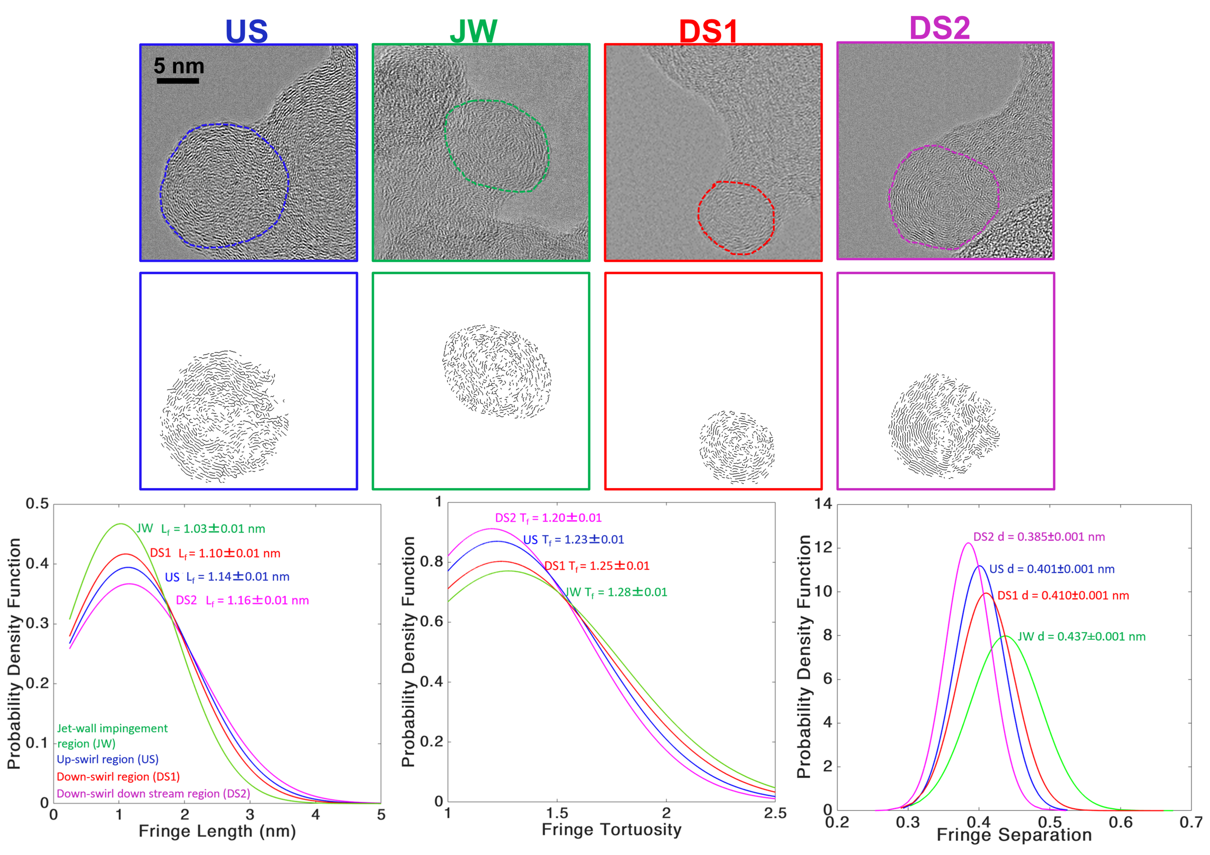

Figure 6. Example HR-TEM images of AR24 fuel at varied sampling locations (top). The results are shown for the pilot-main injection condition. Shown in the middle are the corresponding carbon-layer fringes. The PDF profiles of the fringe length, tortuosity and separation are presented at the bottom row.

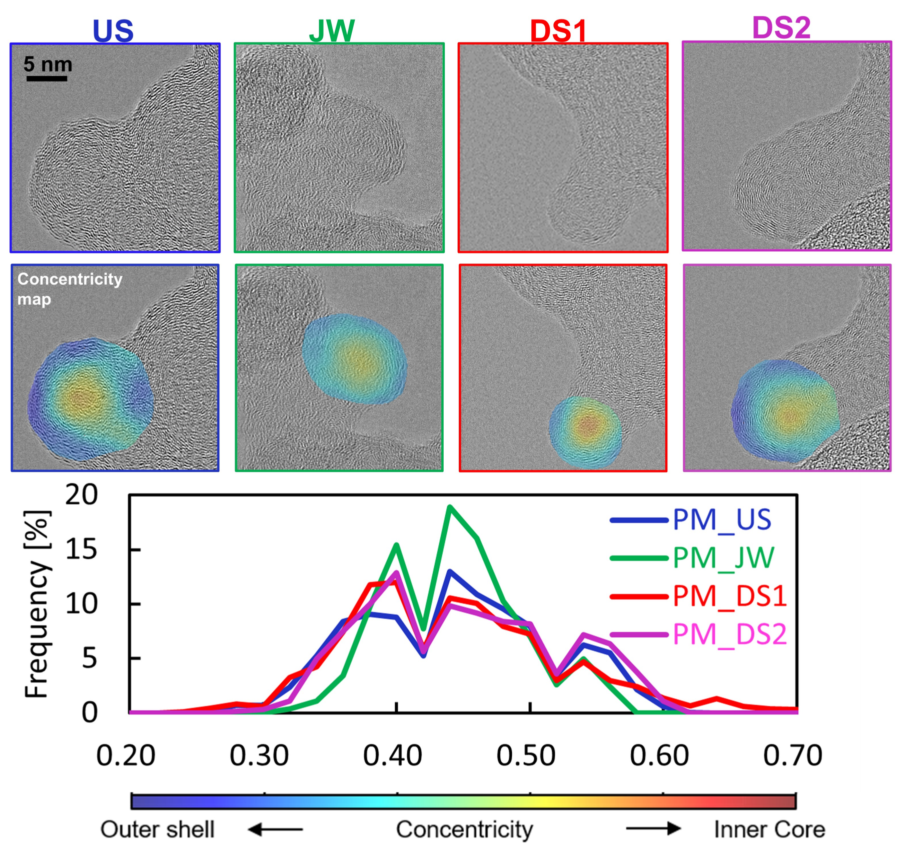

Figure 7. Example HR-TEM images of a soot primary particle and overlaid concentricity colormap for four sampling locations of the pilot-main injection condition of AR24 fuel. The frequency plot of the concentricity calculated from five primary particles is shown at the bottom.