July 2018 Progress Report for Sandia National Laboratories on DE-EE0007300, Development and Validation of a Lagrangian Soot Model Considering Detailed Gas Phase Kinetics and Surface Chemistry

The role of Sandia National Laboratories to this project is to image in-cylinder soot and PAH under conditions where PAH and soot are on the threshold of formation due to dilution by excess nitrogen gas. The primary effect of dilution is to lower the combustion temperatures, and if sufficient dilution is provided, soot and/or PAH formation can be completely inhibited. Hence, these experimental data are useful for validation of CFD predictions of initial soot and PAH formation.

The previous progress report described the experimental setup. As a brief summary, the in-cylinder soot and PAH were probed essentially simultaneously by laser sheet diagnostics using two lasers with different wavelengths. PAHs of different size ranges absorb light of different wavelengths, and hence different PAH size classes can be probed by planar laser-induced fluorescence (PAH-PLIF) using different laser-light colors. The second laser operates in the infrared where PAHs do not absorb, and yields a laser-induced soot incandescence (soot-PLII). The two laser beams were formed into thin sheets and were spatially overlapped with each other. Three different laser sheet heights were employed, at 11, 15, or 18 mm below the cylinder fire deck.

Figure 1 shows an overview of the crank-angle resolved 633-nm PAH-PLIF and soot-PLII imaging results across a wide range of intake air dilution levels from 7.5% to 15.0% charge oxygen concentrations (by volume). Each image in Figure 1 is a false-colored composite of the two diagnostics. The 633-nm PAH-PLIF images (false colored green) represent relatively large PAH (greater than 10 aromatic rings), while the 1064-nm soot-PLII images (false colored red) represent soot particles. The images in Figure 1 show that at 7.5% charge O_2, no PAH or soot is formed, even though ignition and combustion do occur. With charge dilution down to 7.5% O_2, the post-combustion temperatures are most likely too low for PAH and soot formation, even if local mixtures are sufficiently fuel-rich. As the charge O_2 concentration is increased, first PAH (at 9.0% charge O_2) and then soot (at 10% O_2, circled in red) begin to form earlier and earlier in the cycle as the post-combustion temperature increases. When soot does form, it appears on the jet periphery, and with little overlap with the large PAH, which would appear as yellow in the false-colored images. This suggests that under these conditions, soot forms only where the temperatures are sufficiently high, apparently near the diffusion flame that likely surrounds the fuel-rich core of the jet. Within the central core of the jet, only PAH is observed (green). Furthermore, the minimal amount of overlap (yellow) suggests that PAH rapidly convert to soot and do not persist along with the soot.

Figure 2 shows a different composite image, showing ensemble-averaged images 355-nm, 532-nm, and 633-nm, PAH-PLIF at three different sheet elevations and at two different times during the engine cycle (258 and 360 CAD) near the onset of PAH formation for a close-coupled split-injection operating condition. Note that the split-injection condition adds a pilot injection before the main injection, such that ignition (and subsequent PAH formation) occurs earlier in Figure 2 than in Figure 1. The images at 358 CAD show that small PAH excited by 355-nm PLIF (3-4 aromatic rings) form first. The images at 360 CAD show that larger PAH excited by 532-nm (~10 aromatic rings) and 633-nm (>10 rings) form later. In addition, varying the dwell between injections (not shown) also affects the timing of PAH formation, with later PAH formation for conditions with a longer dwell between injections.

These and other imaging results provide validation data for modeling of PAH and soot.

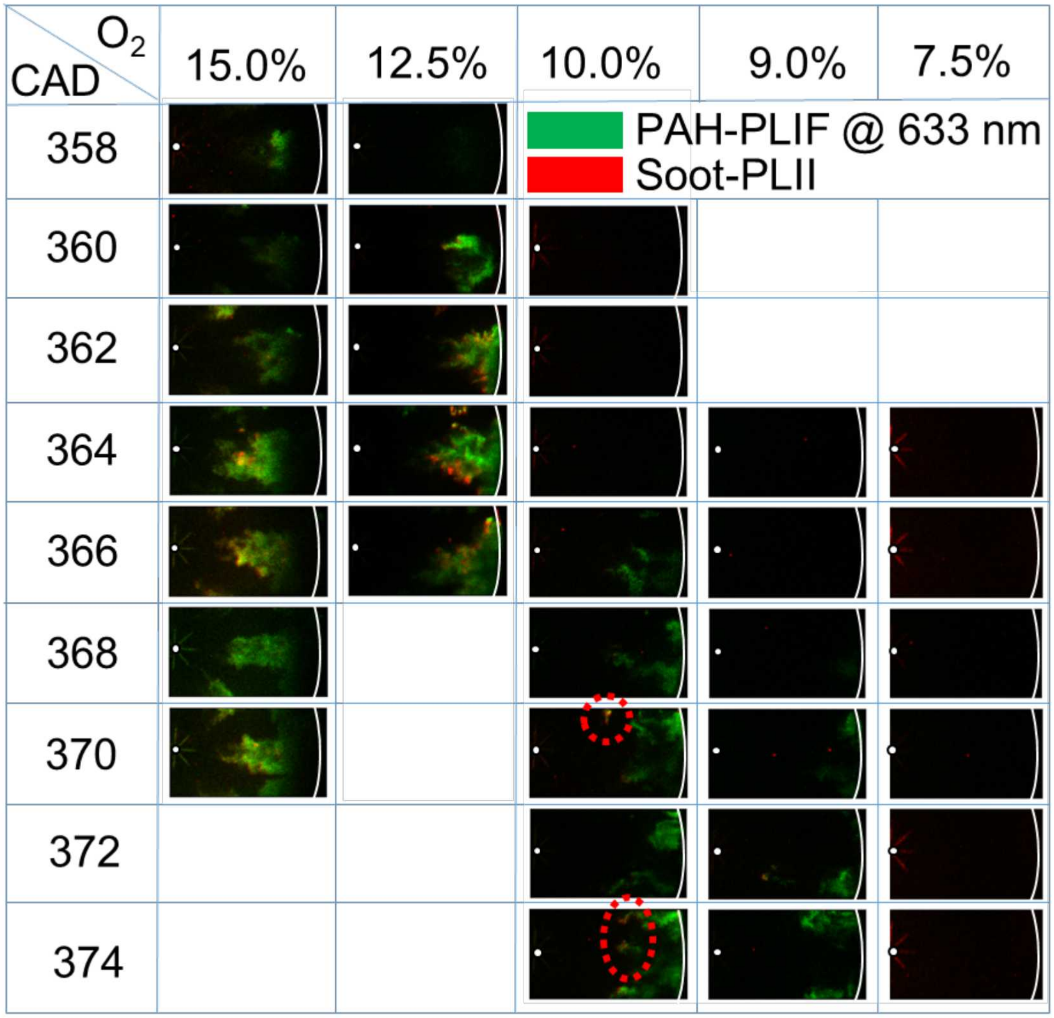

Figure 1: Composite images of 633-nm PAH-PLIF (green) and soot-PLII (red) for a single injection operating condition.

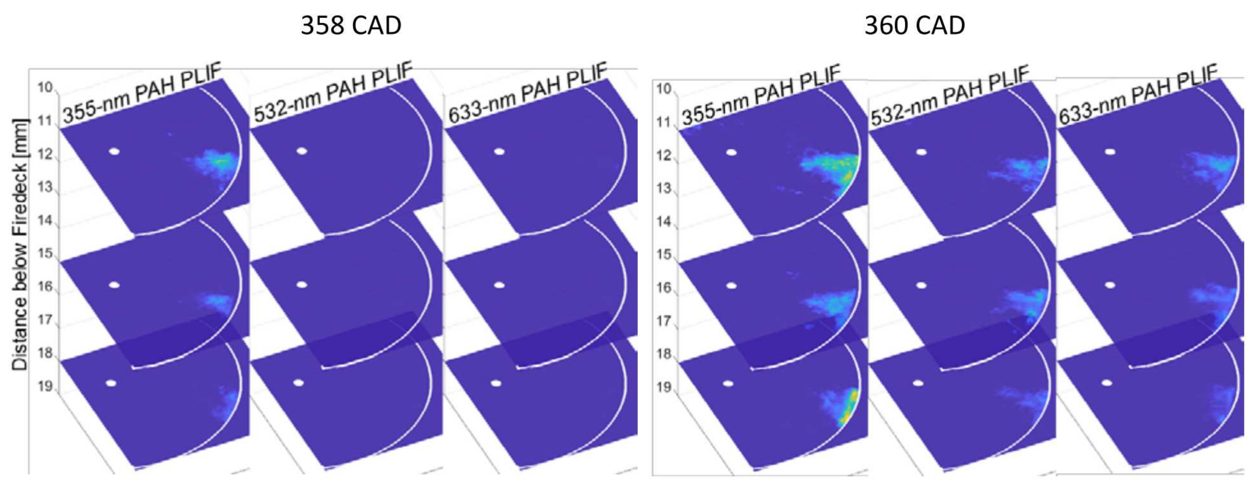

Figure 2: Multi-wavelength ensemble-averaged PAH-PLIF for a close-coupled split injection condition at 10% charge O_2 at multiple laser-sheet elevations.