Size, Charge, and Volatility Characteristics of Particles Generated by a Full Scale Aeroengine Fuel Injector

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The reduction of particulate matter emissions from internal combustion engines positively impacts ambient air quality. To date, large gains have been realized in many industries: for example, the use of aftertreatment devices like diesel particulate filters in diesel engine exhaust has resulted in reductions of particle mass and number of 99% or greater. To some extent, this technology can also be applied to gasoline direct injection engines and stationary power generation. Likewise, advances in the aviation industry over the past 40 years have resulted in significant reductions of smoke and NOx emissions from gas turbine engines. A straightforward "aftertreatment" solution that would enable emissions from these engines to be reduced to background levels is not obvious, but the industry is still moving forward. For example, current research is focused on the development of a methodology to measure particle mass and number concentration. Such methodology may be used to help support mandatory emission reporting or later, even enforceable emission standards. Candidate techniques for reducing particle number and mass emissions include the use of alternative fuels, advanced fuel injection design and techniques, and modification of the combustion chamber. While these show promise, the problem is complex, both from a modeling and experimental perspective.

This presentation offers a first look at the characteristics of particles generated from a representative, full-scale aeroengine injector that was operated using the University of Cambridge's intermediate pressure combustion facility as shown in Figure 1. This facility partially simulates the combustion process that occurs in a turbine by burning liquid fuel at typical high temperatures and pressures. Rather than expansion through a turbine, the products of combustion are mixed with cooling air and expanded through a nozzle. The purpose of these tests was to further elucidate the impact of operating condition such as inlet pressure and air-fuel ratio on the nature of particle and gas emissions. Such direct combustor measurement results can be used to better understand the effect of operating variables and methods for control of particulate matter emissions compared to measurements performed downstream of the gas turbine exhaust.

The combustion facility was configured to evaluate particle emissions by using a short transfer line to extract a sample from the region indicated in Figure 1. The sample was diluted with cold air and then aged for ~1 s before being diluted again to quench growth processes. This dilution scheme provides results that are atmospherically relevant because prevailing conditions are simulated. Next, a nano-SMPS was used to measure particles in the size range 4 to 160 nm and a catalytic stripper was used to determine the volatility characteristics of these particles. Finally, particles were collected electrostatically to determine morphology characteristics via TEM and they were also separated electrostatically so that the charged and neutral fractions could be measured.

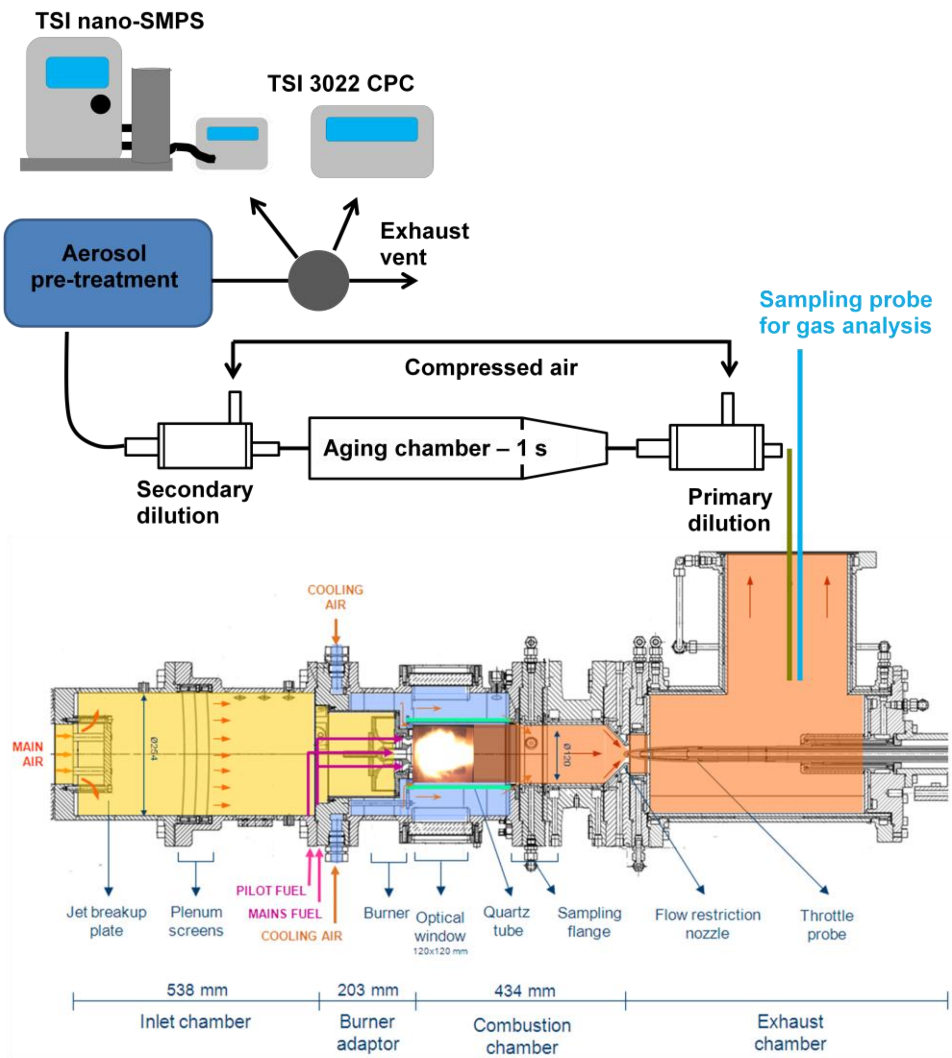

Figure 1 Figure 1. Cambridge Intermediate Pressure Combustion Facility (CIPCF) with two stage particle dilution system that extracts an exhaust sample at atmospheric pressure. Aerosol pre-treatment included a catalytic stripper to distinguish between solid and volatile particles and an electrostatic precipitator to measured particle charged and neutral fractions.

Preliminary tests were conducted to evaluate the thermal stability of the nickel chromium transfer line tube to ensure particles were not produced at exhaust gas temperatures, which exceeded 800°C during testing. Results suggested that conditioning the tube for an hour in a tube furnace at 1200°C resulted in the formation of a protective oxide layer that prevented contaminant particle formation in the tube at exhaust temperature. This finding enabled us to proceed with combustor tests.

Combustor results showed that air-fuel ratio, inlet air temperature, and inlet pressure affect particle size and concentration. Figure 2 shows representative size distributions with and without a catalytic stripper. For all test conditions, the particle number size distribution was approximately lognormal and unimodal with a geometric mean size that depended on conditions but was always smaller than 35 nm. Use of the catalytic stripper demonstrated that these modes always consisted entirely of solid particles. The relationships between particle size and AFR for different conditions are shown in Figure 3.

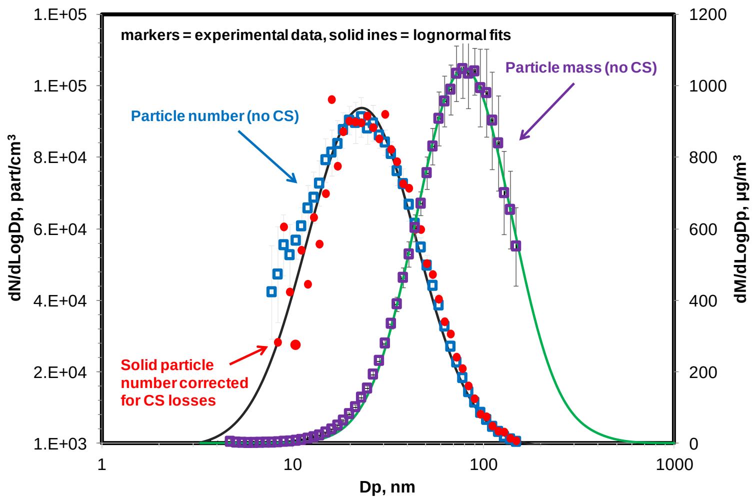

Figure 2 Representative experimental data and fitted mass and number distributions with and without a catalytic stripper. Results not corrected for exhaust dilution ratio.

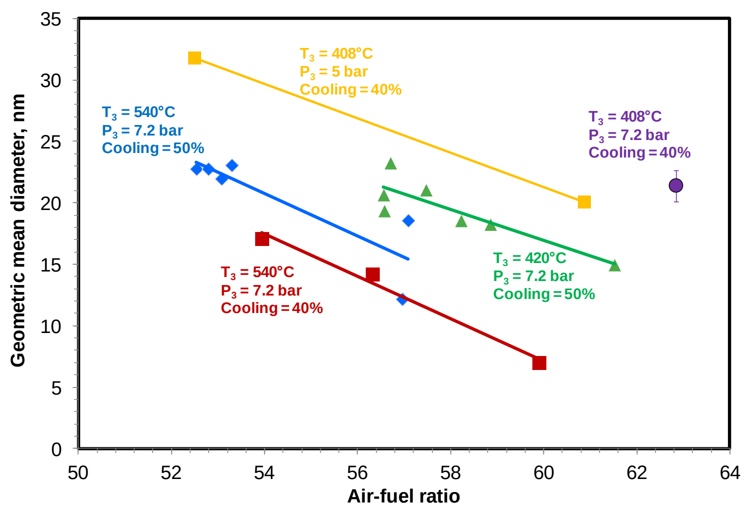

Figure 3 Effect of operating condition on mean particle size

Conclusions

- The absence of semi-volatile particle formation for all test conditions despite standard sampling and dilution conditions may be related to the operation of the nozzle in pilot mode only, the absence of lubricating oil in the system, and/or the lack of growth species in the dilution air that are present in outdoor field studies (i.e., APEX). Future tests include the use of the mains injector, which may also alter the characteristics of particle formation
- That fact that smaller particles are associated with lower cooling air fractions suggests soot burnout is occurring downstream of the flame. Cooling air reduces bulk mixture temperatures, which reduces oxidation rates. This effect must be better quantified to connect the formation of particles in a combustor to emissions from a gas turbine
- The test apparatus and methodology proved to be an effective means to characterize the impact of operating conditions on emissions. Such results may lead to the development of predictive tools that enable the use of cost-effective combustor research to understand the performance of prototype fuel injectors in a gas turbine

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BACKGROUND

This presentation offers a first look at the characteristics of particles generated from a representative, full-scale aeroengine injector that was operated using the University of Cambridge's intermediate pressure combustion facility as shown in Figure 1. This facility partially simulates the combustion process that occurs in a turbine by burning liquid fuel at typical high temperatures and pressures. Rather than expansion through a turbine, the products of combustion are mixed with cooling air and expanded through a nozzle.

The purpose of the tests was to further elucidate the impact of operating conditions such as inlet pressure and temperature and air-fuel ratio on the nature of particle emissions. Such direct combustor measurement results can be used to better understand the effect of operating variables and methods for control of particulate matter emissions directly from the combustor rather than measurements performed downstream of gas turbine exhaust.

EXPERIMENTAL APPARATUS

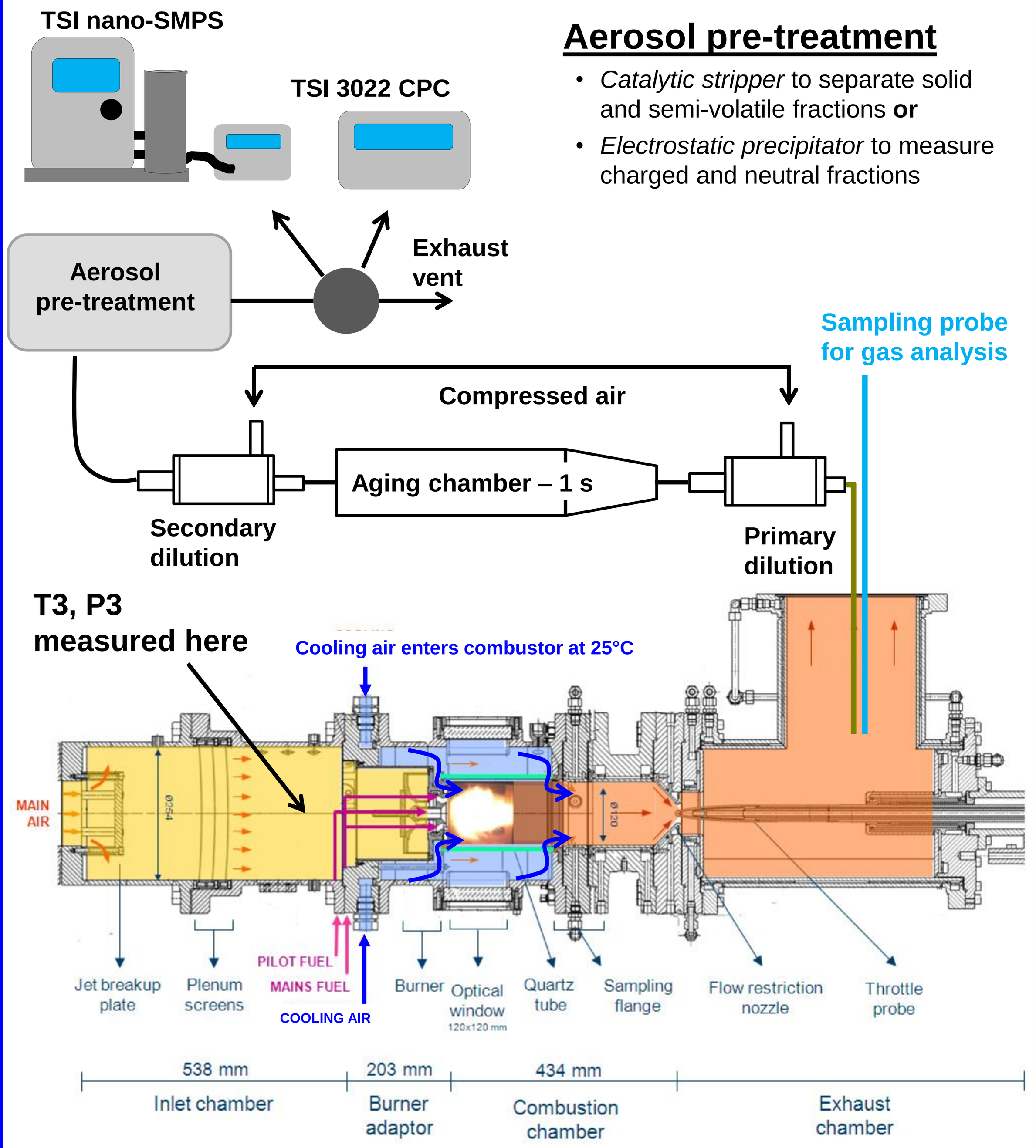

Figure 1. Cambridge Intermediate Pressure Combustion Facility (CIPCF) with two stage particle dilution system that extracts an exhaust sample at atmospheric pressure

CIPCF: designed to operate at inlet temperatures up to 873 K, pressures of up to 10 bar, and air mass flow rates through the injector of up to 0.7 kg/s at full pressure.

Fuel injector: full-scale, prototype, swirl-stabilized lean-direct injection (LDI) spray nozzle operated on kerosene. The radially staged fuel delivery system includes two concentric prefilming airblast injectors: a central stream for the pilot fuel and an outer stream for the main fuel. The nozzle houses various stages of air and fuel swirlers for fuel atomization and mixing. The present work was conducted with the pilot burner only. This operation scheme was selected to provide a rich flame, representing an "approach" condition as an initial trial to study particle emissions.

TEST CONDITIONS

Dilution and sampling

- Air-Vac Engineering ejector dilutors
- Insulated transfer line to primary dilutor ~20 cm
- Primary dilution
  - –DR = 16-18
  - –Temperature = 25°C
  - –Determined from raw/dilute NO
- Particle aging and growth ~1 s
- Secondary dilution
  - –DR = 12.5
  - –Temperature = 25°C
  - –Determined from flowrates

Combustor

AFR	P3	T3	Injector air flow	Cooling air
-	bar	°C	g/s	%
59.9	7.2	540	530	40
56.3	7.2	540	530	40
53.9	7.2	540	530	40
57.0	7.2	540	530	50
53.3	7.2	540	530	50
52.5	7.2	540	530	50
53.1	7.2	540	530	50
52.8	7.2	540	530	50
57.1	7.2	540	530	50
61.5	7.2	420	570	50
58.8	7.2	420	570	50
58.2	7.2	420	570	50
56.6	7.2	420	570	50
57.5	7.2	420	570	50
56.6	7.2	420	570	50
56.7	7.2	420	570	50
62.7	7.2	408	530	40
60.9	5	408	421	40
52.5	5	408	402	40

RESULTS – SIZE & VOLATILITY

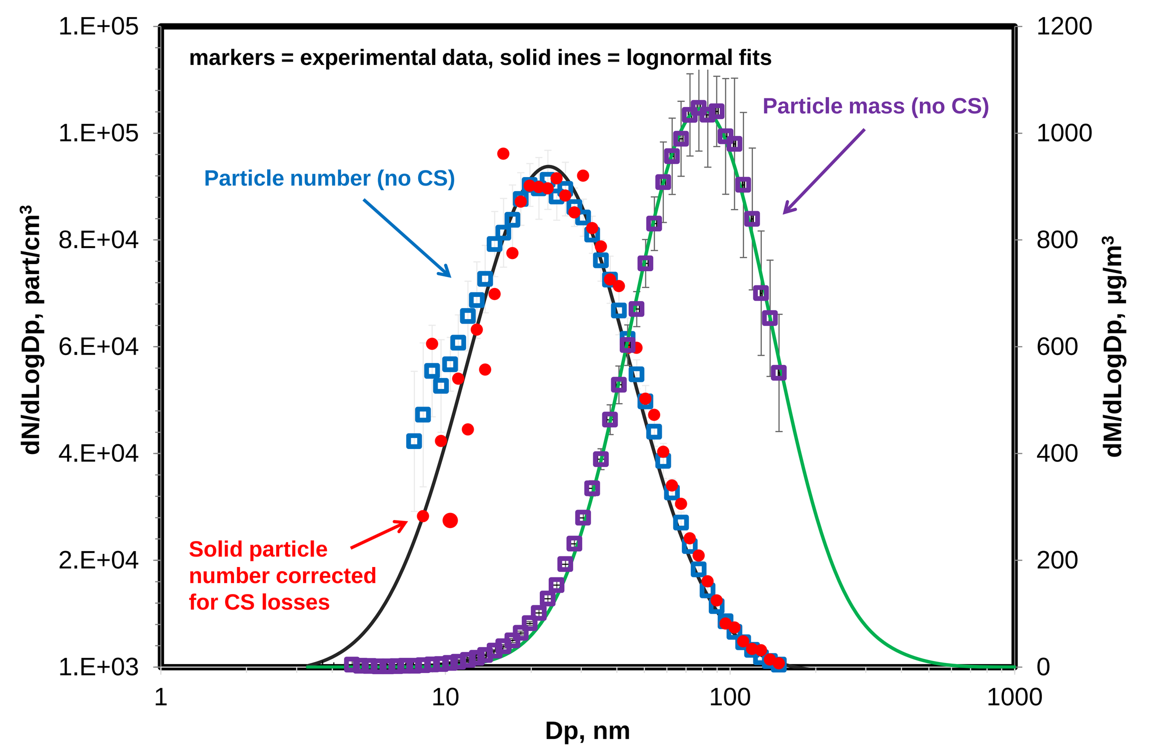

Figure 2. Representative experimental data and fitted mass and number distributions with and without a catalytic stripper

- For all conditions, particle distributions were *unimodal* and lognormally distributed.
- Use of the catalytic stripper did not affect the size distribution for any operating condition
- Mean particle size (GMD) was ~20 ± 10 nm, depending on AFR and operating condition

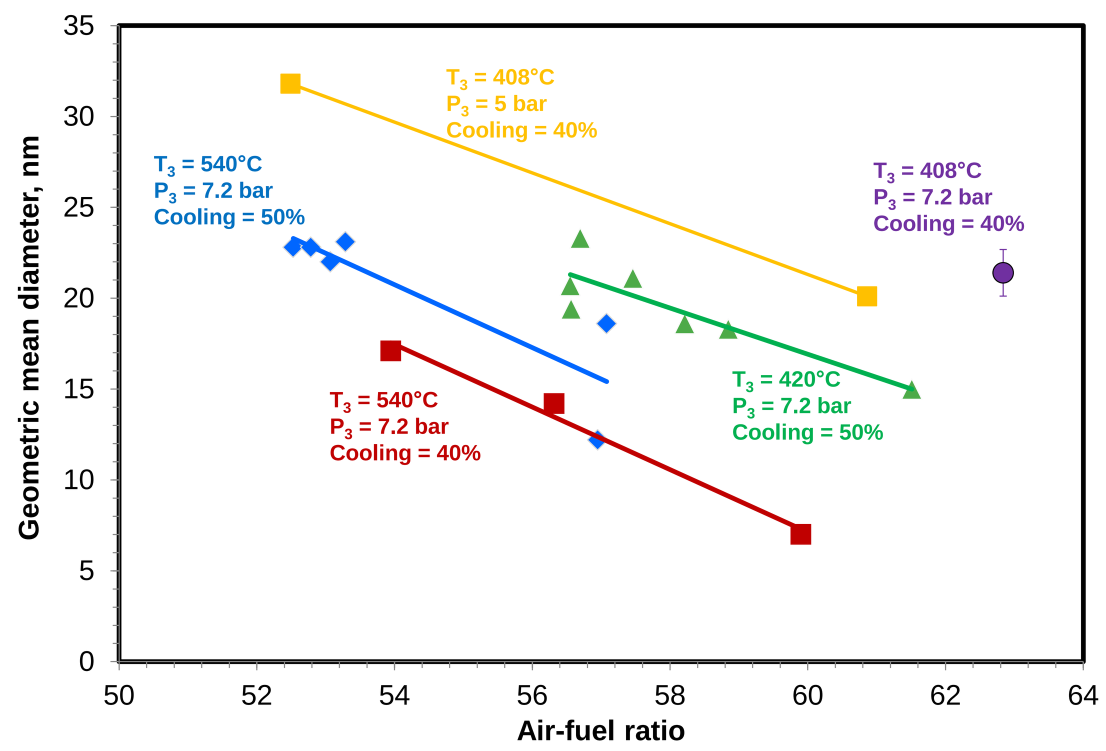

Figure 3. Effect of operating condition on particle size

RESULTS – CHARGED FRACTION

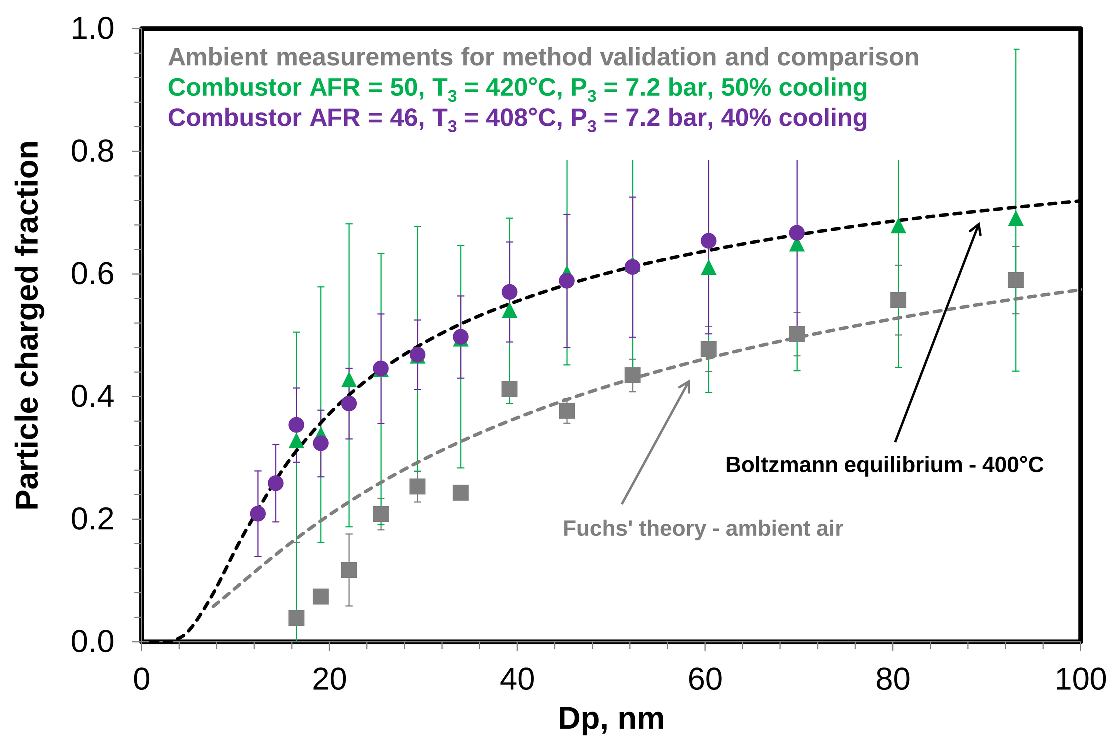

Figure 4. Measured particle charged fractions. Ambient data is consistent with Fuchs' theory and the combustor data best fits a high temperature (400ºC) Boltzmann distribution

RESULTS – NOx EMISSIONS

NOx emissions were comprised of primarily NO (>95%). Trends showed some dependence on inlet temperature and cooling air but generally less dependence on AFR in the range evaluated

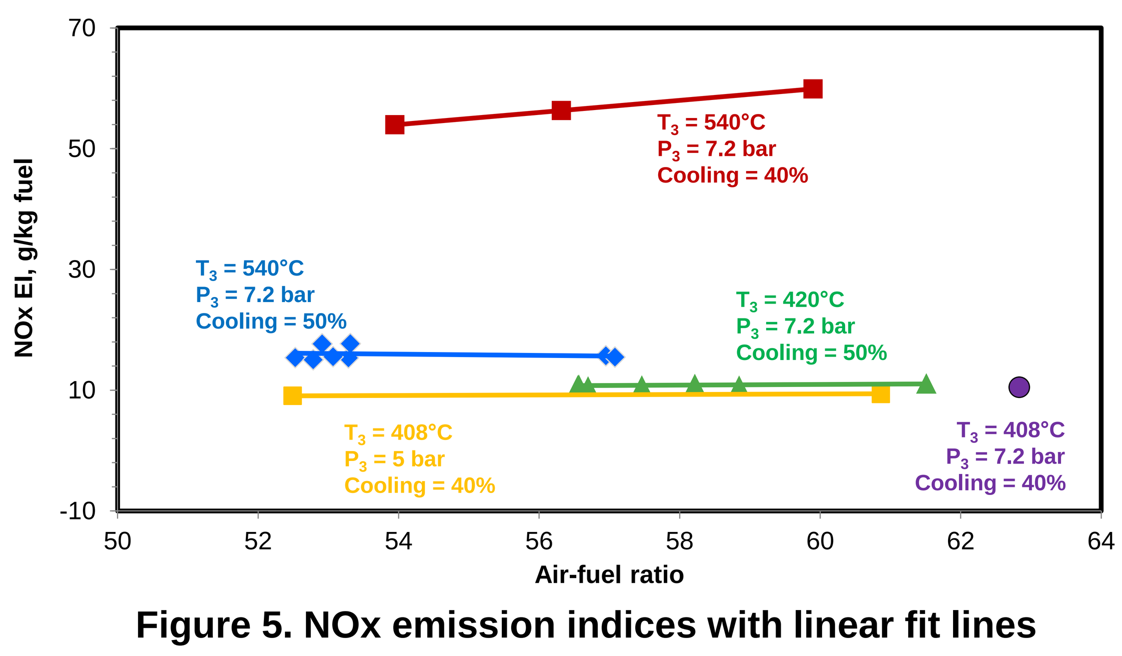

Figure 5. NOx emission indices with linear fit lines

RESULTS – PM EMISSION INDICES

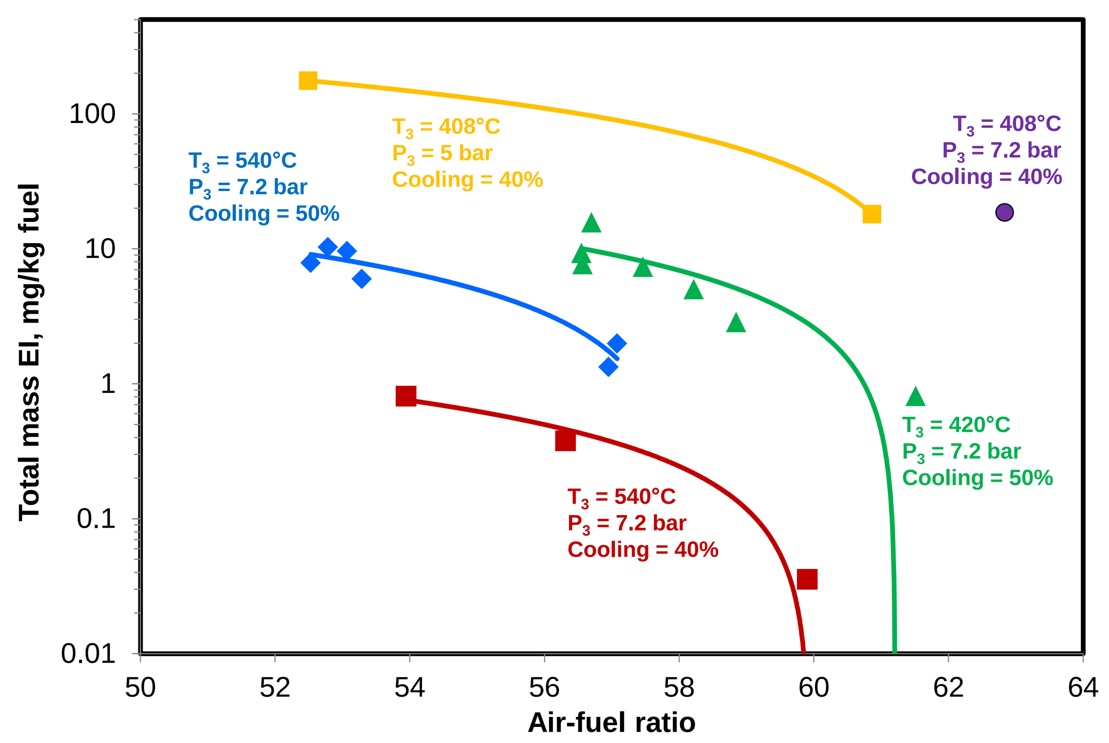

Figure 6. Total PM mass emission indices with linear fit lines

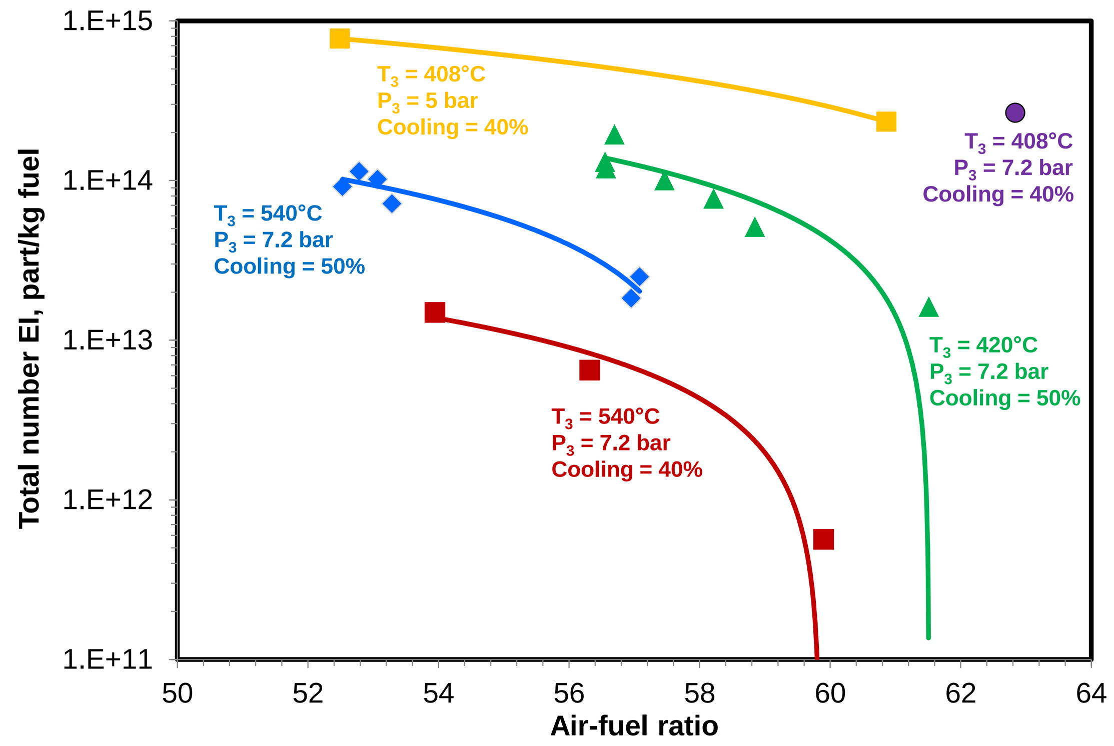

Figure 7. Total PM number emission indices with linear fit lines

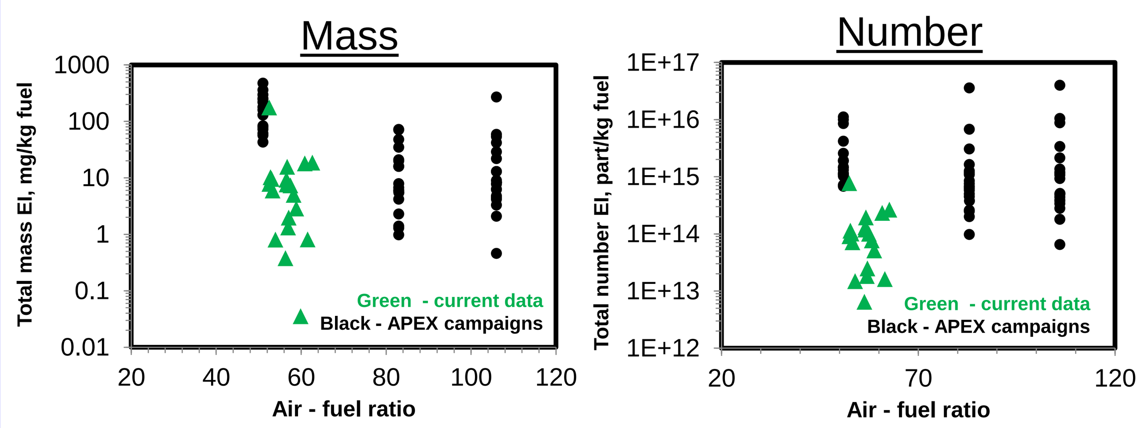

Figure 8. Comparison of current combustor data (green triangles) with mass and number indices (black circles) from the APEX Series of commercial gas turbine measurement campaigns [1]. For comparison, thrust values of 7, 30, and 85% corresponding to idle, approach, and climb-out were converted to fleet average air-fuel ratios of 106, 83, and 51, respectively [2]. Total mass concentration was calculated using a constant particle effective density value of 0.5 g/cm³

[1] Whitefield, P., Lobo, P., Hagen, H., et al. (2008). Summarizing and interpreting aircraft gaseous and particulate emissions data. *Environmental Protection*, 3, 1-52. ISBN: 9780309117609.

[2] Wayson, R.L., Fleming, G.G., Lovinelli R. (2009). Methodology to estimate particulate matter emissions from certified commercial aircraft engines. *J Air Waste Manag. Assoc.* 59, 1, 91-100.

DISCUSSION

- The absence of semi-volatile particle formation for all test conditions despite standard sampling and dilution conditions may be related to the operation of the nozzle in pilot mode only, the absence of lubricating oil in the system, and/or the lack of growth species in the dilution air that are present in outdoor field studies (i.e., APEX). Future tests include the use of the mains injector, which may also alter the characteristics of particle formation
- High particle charged fractions suggests that solid carbonaceous particles were charged by combustion ions or thermionically during the combustion process
- That fact that smaller particles are associated with lower cooling air fractions suggests soot burnout is occurring downstream of the flame. Cooling air reduces bulk mixture temperatures, which reduces oxidation rates. This effect must be better quantified to connect the formation of particles in a combustor to emissions from a gas turbine
- The test apparatus and methodology proved to be an effective means to characterize the impact of operating conditions on emissions. Such results may lead to the development of predictive tools that enable the low-cost, effective combustor research to understand the performance of prototype fuel injectors in a gas turbine

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