Size Dependence of Morphology and Nanostructure in Ultrafine Particles Emitted by a GDI Engine Operated with Various Fuel Injection Strategies

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Background and Motivation

- GDI engines emit large numbers of particles
  - Cold start, passing acceleration
  - Significant fraction of number lies in size range < 100 nm, but this contributes very little mass
- Like all IC engines, these particles have complex behavior:
  - Multiple sizes; temporal, chemical, and physical dynamics
- Regardless of the metric (PM, PN, SA, etc.), there is concern that these particles can be harmful to human health
  - There is a desire to reduce these emissions

Background and Motivation

- Mitigation strategies:
  - Filters, fuel additives, calibration, geometrical tuning (e.g., injector placement), etc.
- Multiple fuel injection events is one solution likely to increase in prevalence
  - Has shown success in diesel engines
  - Plenty of examples of reductions in fuel consumption, gaseous emissions in the literature
- Has not been studied as extensively with regard to particulate matter emissions

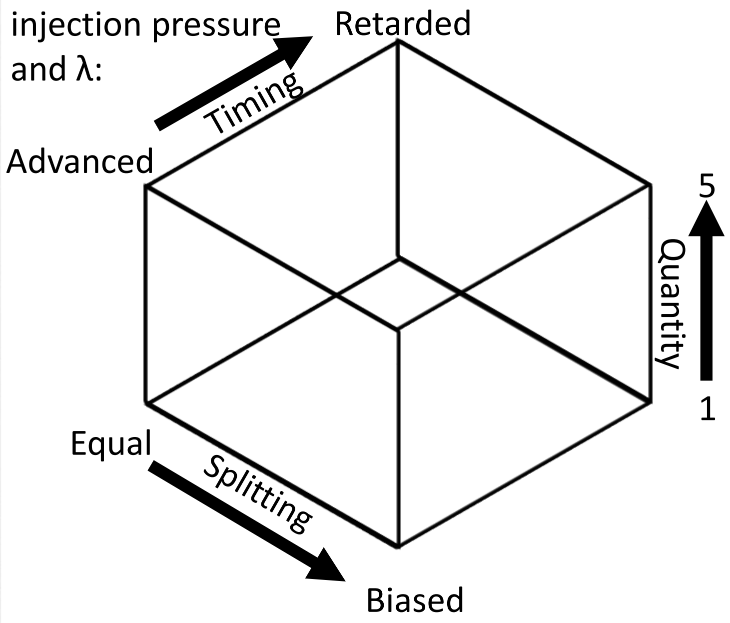
Goals

- Show how fuel injection strategy affects some physical characteristics of the particulate matter produced by a GDI engine
  - “Coarse”: fractal dimension
  - “Fine”: Fringe length, tortuosity, and spacing

Racing Against Time

There is a limited amount of time for fuel delivery, preparation, and conversion to occur!

For a given injection pressure and λ:



The number, spacing, and splitting can give any number of behaviors:

- Turbulence/mixing enhancement
- Stratification
- Late burn-up
- Change combustion regime (premixed – partially premixed – diffusion-limited)

Further, it is well-known that:

- Early injection timings give more homogeneous charge
- Higher pressure results in jets with more momentum; many times with higher penetration and better mixing
- Coupled injections can reduce droplet pileup

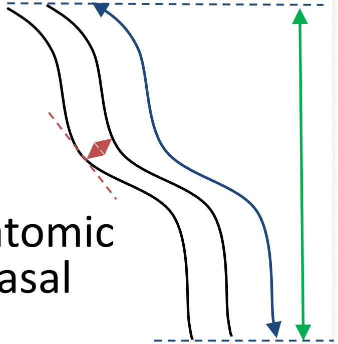
Some Definitions: LR

$$n_{p,o} = k_f \left(\frac{d_g}{d_{p,o}} \right)^{d_f}$$

$n_{p,o}$: number of primary particles
k_f: fractal prefactor - lacunarity
d_g: diameter of gyration – "size"
$d_{p,o}$: primary particle diameter
d_f: fractal dimension – space filling

M. Lapuerta, F. J. Martos, and G. Martín-González, "Geometrical determination of the lacunarity of agglomerates with integer fractal dimension," *J. Colloid Interface Sci.*, vol. 346, no. 1, pp. 23–31, 2010.

Some Definitions: HR

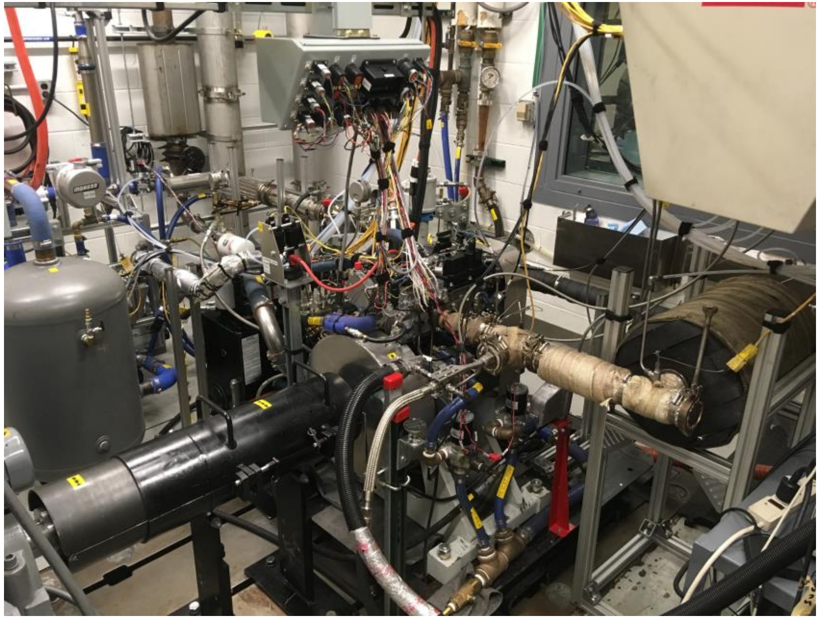


- A **fringe** is a plane of atoms visible in a TEM image.
- “**Lattice fringe length** is a measure of the physical extent of the atomic carbon layer planes … The length reflects the dimension of the basal plane diameter… carbon material having larger fringe lengths is considered to have a higher degree of in-plane similarity with graphite.”
- “**Tortuosity** is a measure of the curvature of the fringes. It reflects the extent of odd-numbered 5- and 7-membered carbon rings within the material. Tortuosity is [therefore] a measure of disorder in the material.” It correlates with oxidative reactivity.
- **Fringe separation** is measure of the distance between adjacent planes of carbon atoms.

Yehliu, K., Vander Wal, R. L., & Boehman, A. L. (2011). Development of an HRTEM image analysis method to quantify carbon nanostructure. *Combustion and Flame*, *158*(9), 1837–1851.

Apparatus

- 1.6L SGDI Ford EcoBoost-based single-cylinder engine
- TSI 3082 classifier with 3081A DMA
- TSI 3776 CPC
- Naneos Partector TEM sampler
- Two-stage dilution system



Test Procedures

- CA50: -10 °BTDC – adjust spark to meet this
- 8 bar $IMEP_g$ – adjust throttle to meet this – no boost
- 1500 rpm
- 3 equally-apportioned injections
- λ = 1
- Tier II E0 certification gasoline
- Cam phasing at 10° from park (i.e., unphased) position

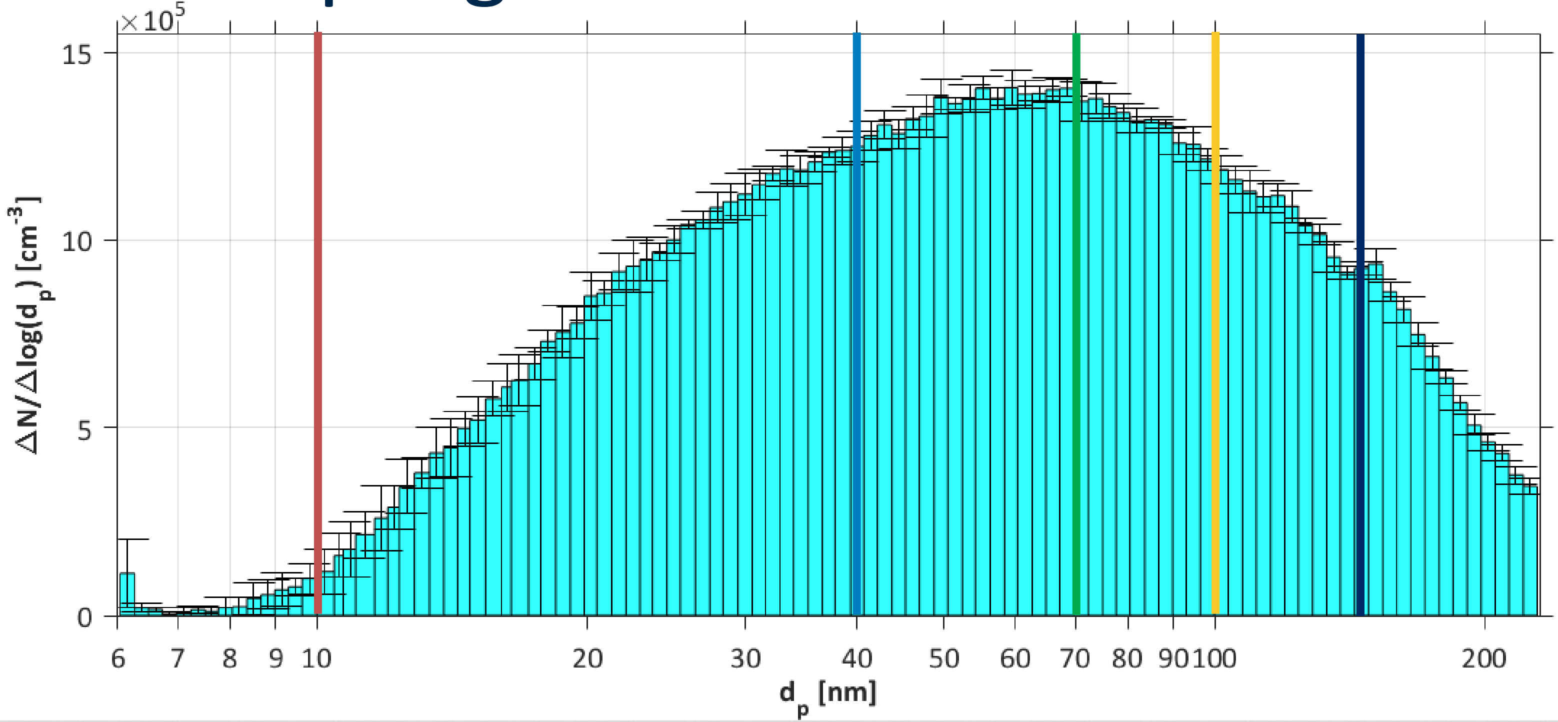
Injection Strategy

	Injection timing [CAD BTDC]								
Injection pressure [bar]	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
50	330	270	200	270	200	120	180	120	60
200	330	270	200	270	200	120	180	120	60

8 bar Triple 1	**8 bar Triple 2**	**8 bar Triple 3**	**8 bar Triple 4**	**8 bar Triple 5**	**8 bar Triple 6**

Premixed; mixing-enhancing	Column 1
Straddle premixed/turbulence-enhancing	Column 2
Stratified; turbulence-enhancing	Column 3

Sampling Procedures



Size Distribution Statistics

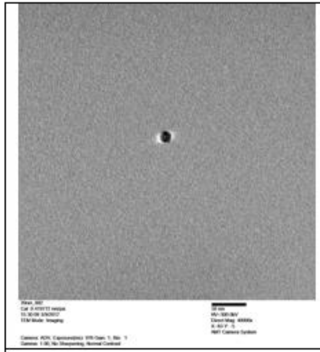
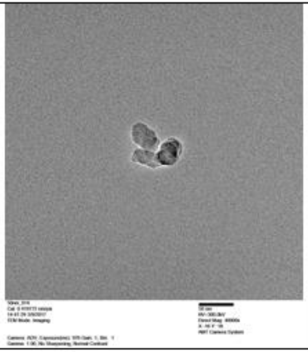
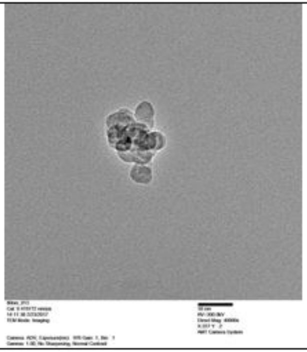
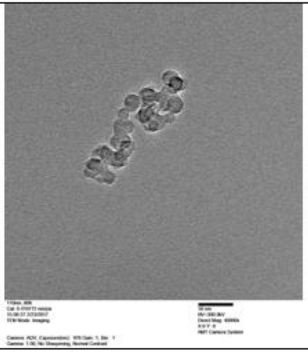
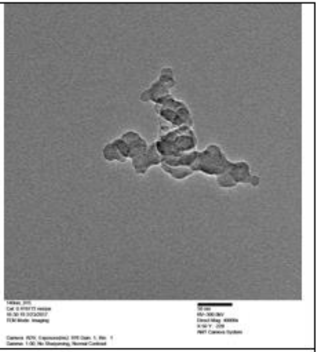
	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6
LR Mode [nm]	90	90	90	80	70	80
HR Mode [nm]	90	110	100	70	60	70

- Approximately 10 nm mode repeatability day-to-day
- Less than 10 % difference in peak concentrations day-to-day
- O(1×10^6) cm^{-3} total concentrations

Image Analysis Procedures

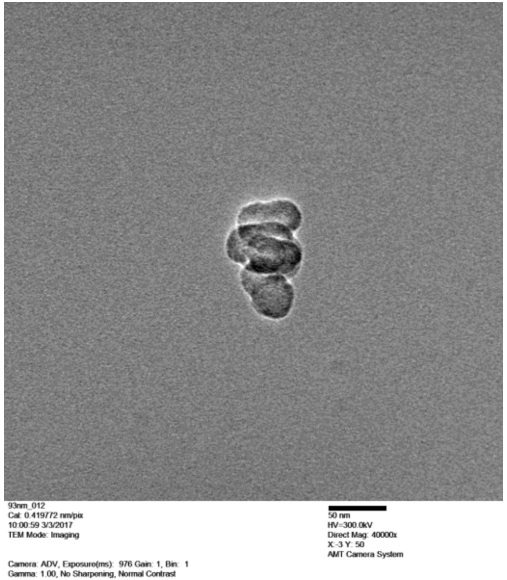
- Images were taken using a JEOL 3011 TEM at the Michigan Center for Materials Characterization, $(MC)^2$
- Low resolution (LR) analysis done using modified codes originally developed by students at the University of Antioquia (Colombia) and University of Castilla - La Mancha (Spain)
- High resolution (HR) analysis done using a modified code originally developed by Kuen Yehliu at the Pennsylvania State University (USA)

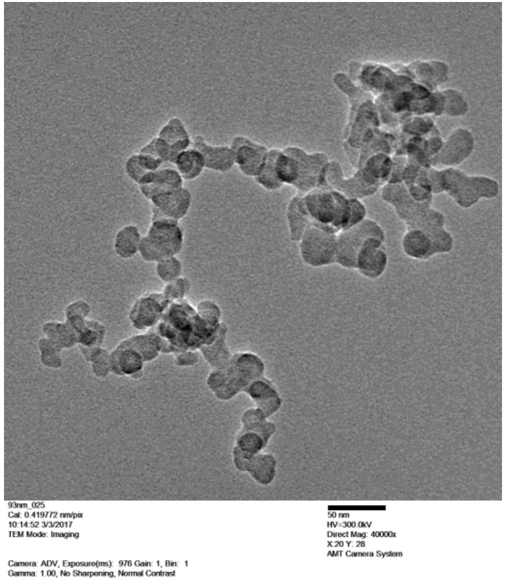
Low Resolution Results: Images

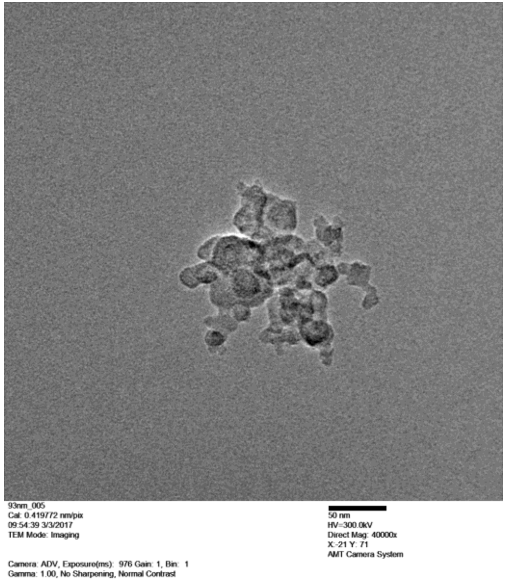
				
Mode – 60 nm = 20 nm	Mode – 30 nm = 50 nm	Mode = 80 nm	Mode + 30 nm = 110 nm	Mode + 60 nm = 140 nm

8 bar Triple 4

Low Resolution Results: Images

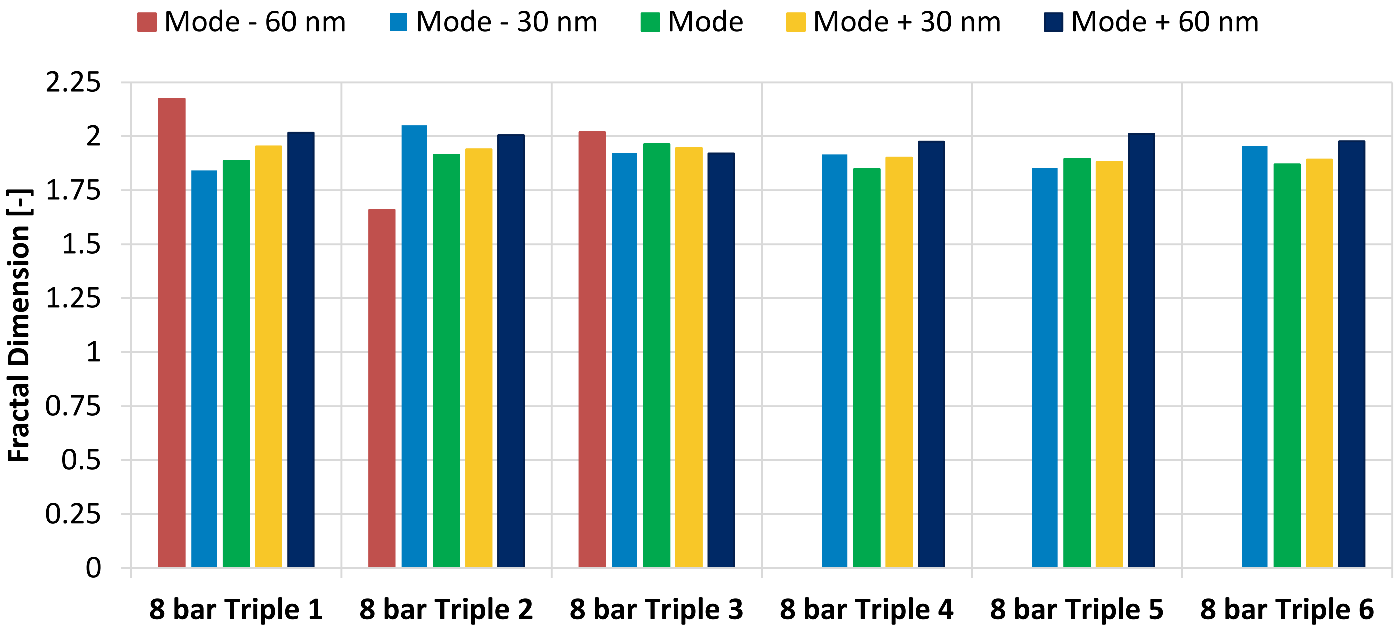




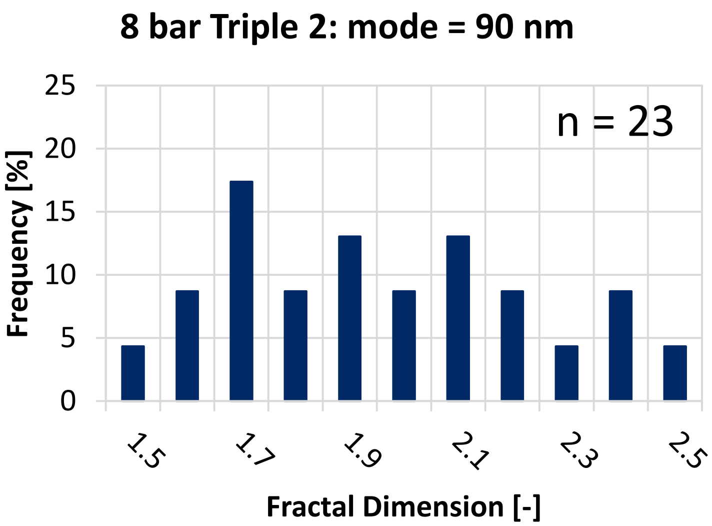


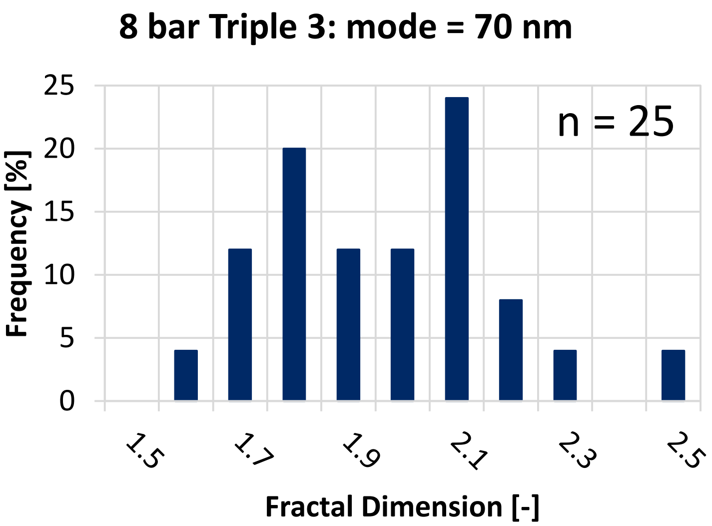
8 bar Triple 1: Mode = 90 nm

Low Resolution Results: Quantitation

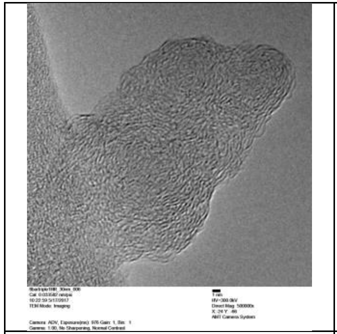
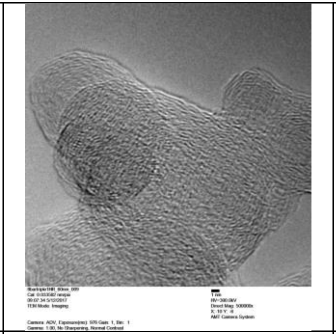
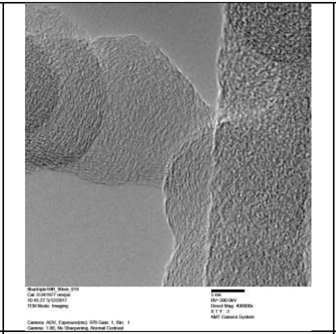
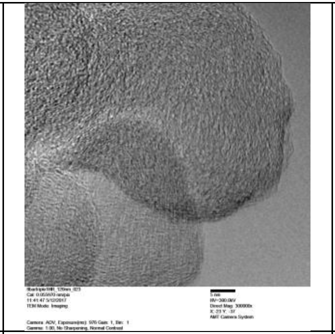
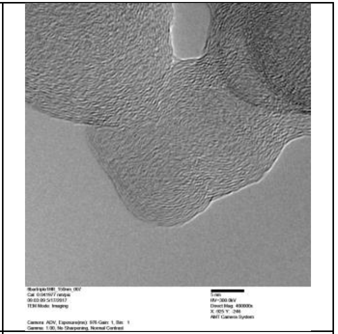


Low Resolution Results: Quantitation



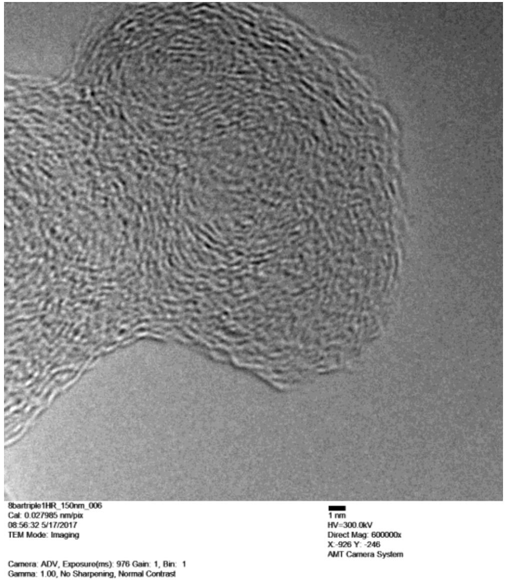


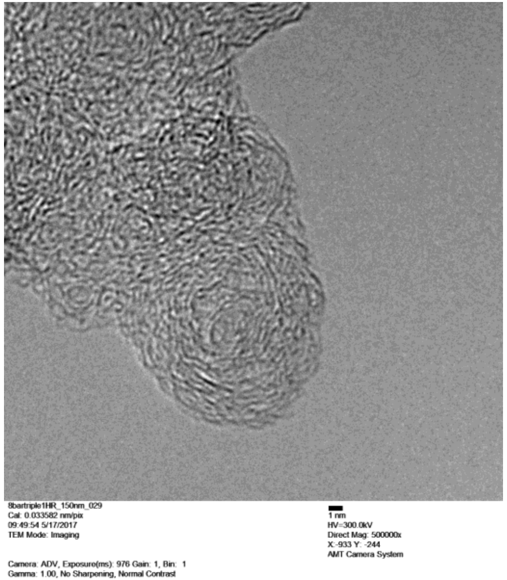
High Resolution Results: Images

				
Mode – 60 nm = 30 nm	Mode – 30 nm = 60 nm	Mode = 90 nm	Mode + 30 nm = 120 nm	Mode + 60 nm = 150 nm

8 Bar Triple 1

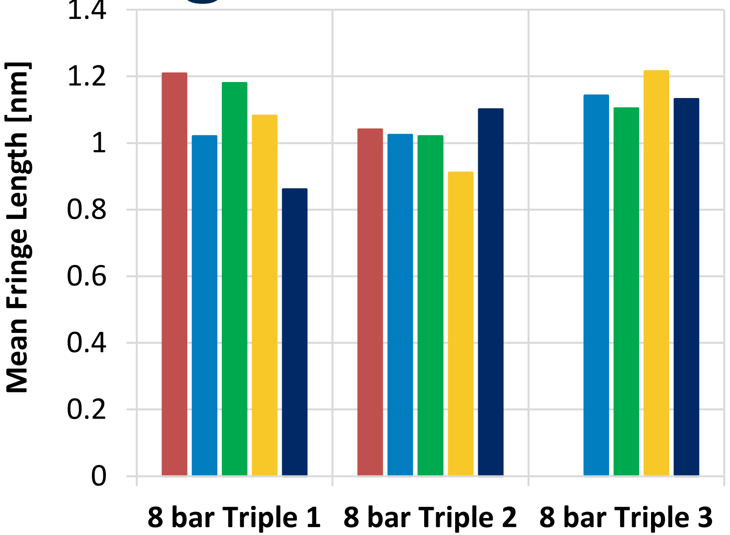
High Resolution Results: Images

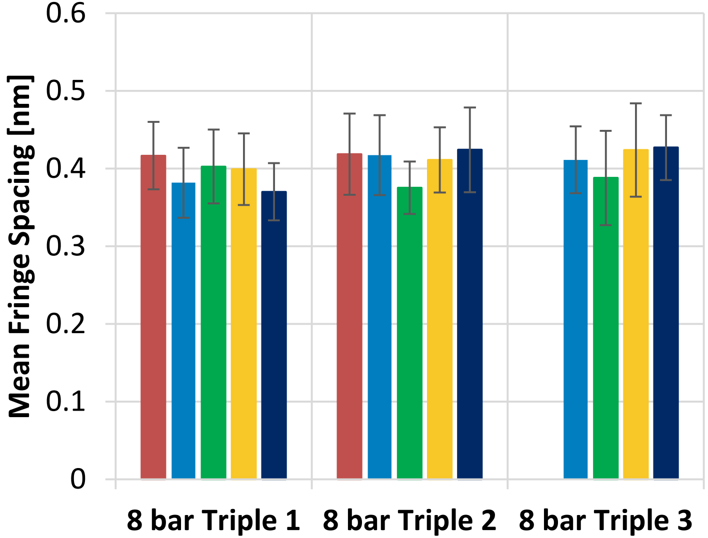




8 Bar Triple 1, Mode + 60 nm = 150 nm

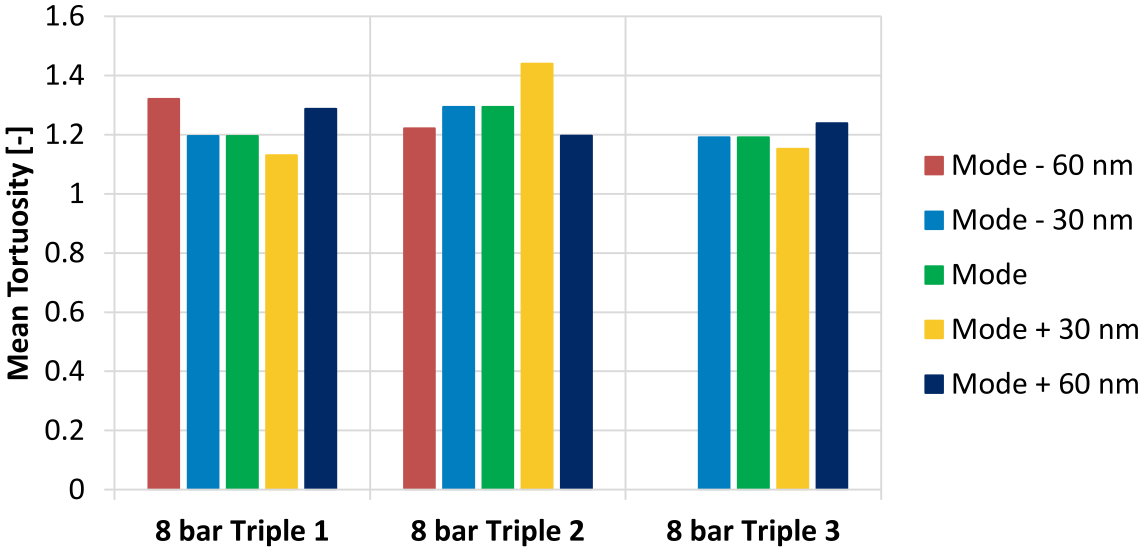
High Resolution Results: Quantitation



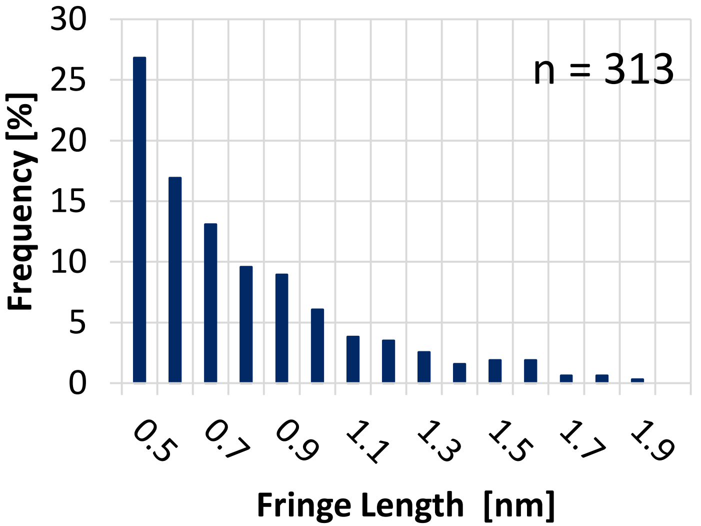


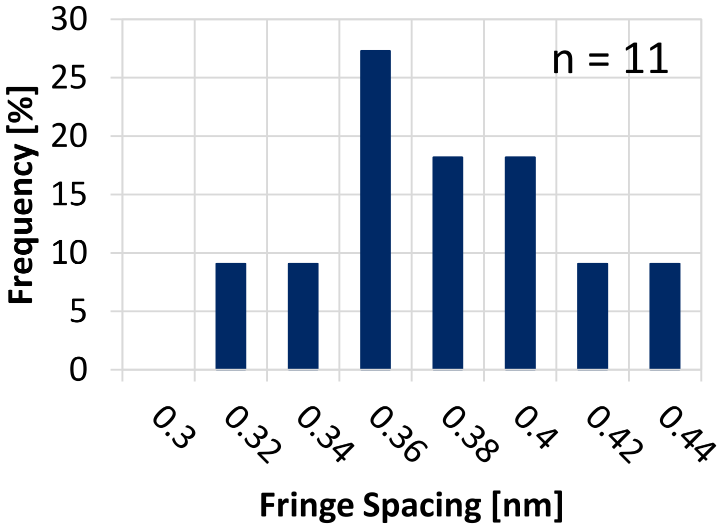
Mode – 60 nm	Mode – 30 nm	Mode	Mode + 30 nm	Mode + 60 nm

High Resolution Results: Quantitation



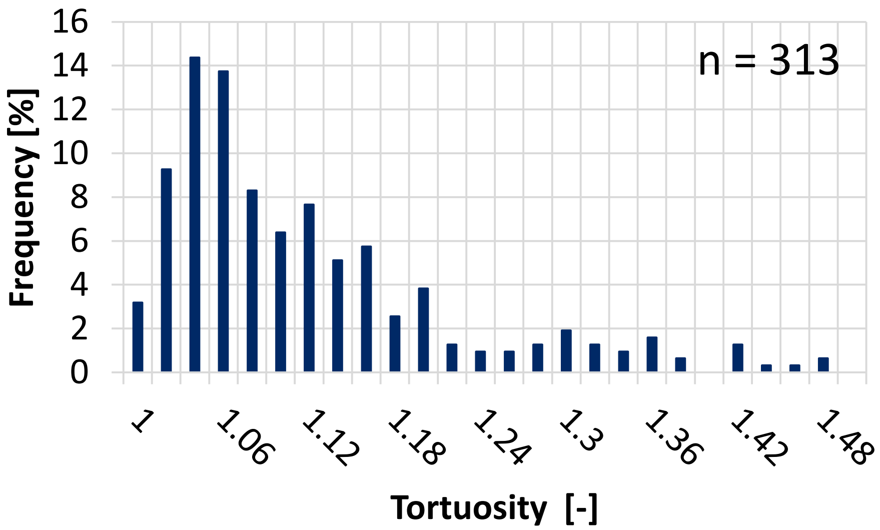
High Resolution Results: Quantitation





8 bar Triple 1 mode + 60 nm = 150 nm

High Resolution Results: Quantitation



8 bar Triple 1
mode + 60 nm = 150 nm

Conclusions

- The mean fraction dimensions around 2 suggest that the particles were very likely to be branched rather than linear
- Large standard deviations in the measurements (30 % or more) suggest that one number (e.g., the mean) is not optimal to summarize the results
- There were few clear tends, indicating a low sensitivity to the injection strategy that were selected
- The small fringe lengths and tortuosities indicates that, on average, there was a lack of long-range order in the soots

Future Work

- Examine other dimensions (i.e., number and splitting) of the fuel injection space
- Investigate the size-specific chemistry
  - TEM–EELS
  - TEM–EDXS
  - Perhaps some bulk analysis (e.g., TGA, XPS)
- Explore some fuel effects on size-specific composition

Acknowledgements

- Special thanks to
  - Staff at $(MC)^2$
  - Staff at US EPA
  - Boehman research group (and visitors) at UM
- This work was supported by the Student Program for Excellence in Environmental Design (SPEED), a grant funded by the US EPA

Thank you for your attention!

Questions?

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UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Supporting Slides

Further Background and Motivation

- The gasoline direct injection (GDI) engine is becoming a more popular power plant choice for light duty vehicles
  - Increased fuel economy (lower greenhouse gas emissions)
  - Higher power density
- GDI engines emit large numbers of particles
  - Cold start, passing acceleration
  - Significant fraction of number lies in size range < 100 nm, but this contributes very little mass
- Particulate emissions are regulated by mass in the US, by number in the EU
- Regardless of the metric (PM, PN, SA, etc.), there is concern that these particles can be harmful to human health
  - There is a desire to reduce these emissions

Further Background and Motivation

- Engine aerosols have complex physical and chemical dynamics
  - One number is often not enough to quantify these behaviors
  - Health effects research has suggested toxicity may be size-dependent
- There is a need for more information on chemical and physical information of the particles with regards to size, ideally in real time

Further Background and Motivation

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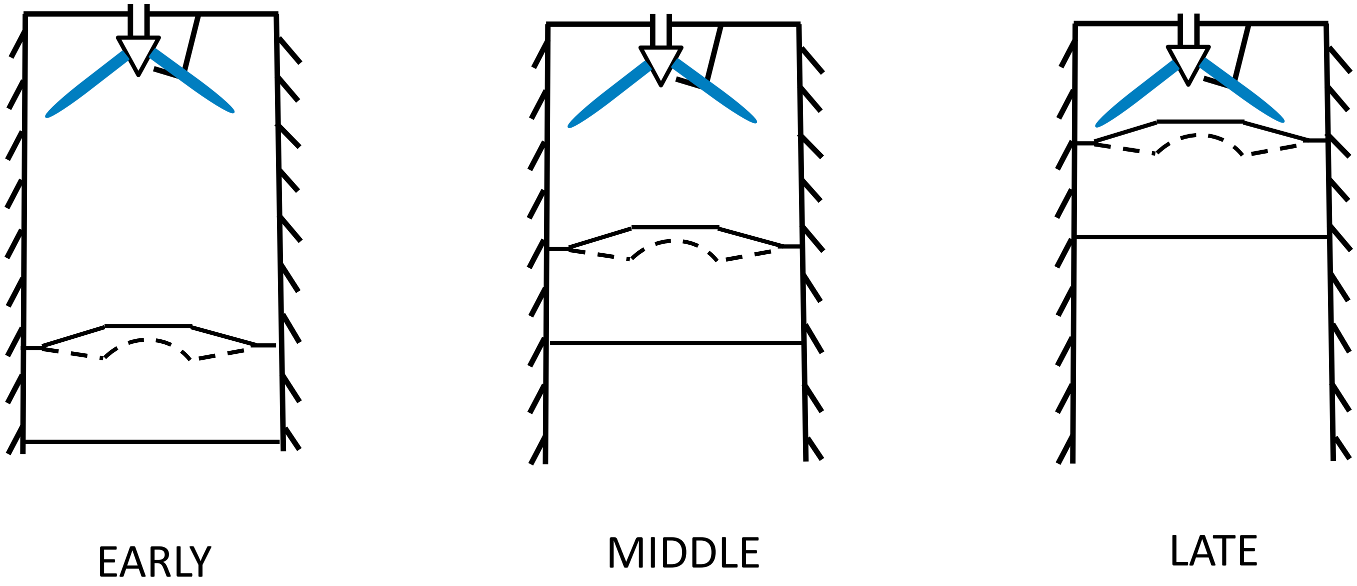
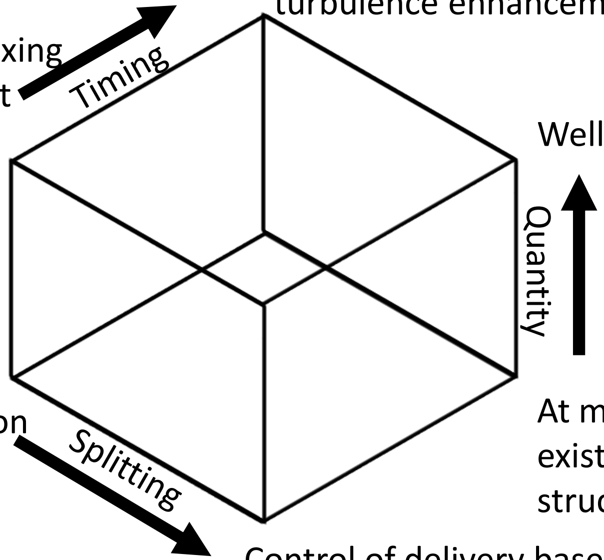
Impact of Injection Strategy on PM

- Want to see how fuel injection strategy affects the particles
  - Expect high pressures to improve mixing, supposedly producing fewer particles
- Early injections can lead well-premixed conditions, but can cause sooting pool fires (an example of impingement)
  - Turbulence cascade also ends early
- Late injections associated with high PM production, but can help with catalyst light-off for cold start emissions
  - Insufficient mixing time
- Post-injections can sustain combustion to burn up residual PM, at risk of increasing UHC
- Fuel stratification can yield thermodynamic benefits (primarily with lean operation), but can generate more PM (e.g., localized λ effect, diffusion combustion)
- Improving combustion efficiency and thermal efficiency through optimization of heat release would ostensibly also reduce PM
  - Kinetics require elevated temperatures and pressures to increase reaction rates; also need adequate species concentrations
- Unknown: overall shape, surface area, internal structure differences as a result of the strategy?
  - These are important for health, filtration, etc.

Fluid Mechanics in the Cylinder



Physical Effects of Injection Strategy



Also some practical considerations:

- Hardware and software-driven limitations
  - Injection profile
  - Minimum spacing between injections

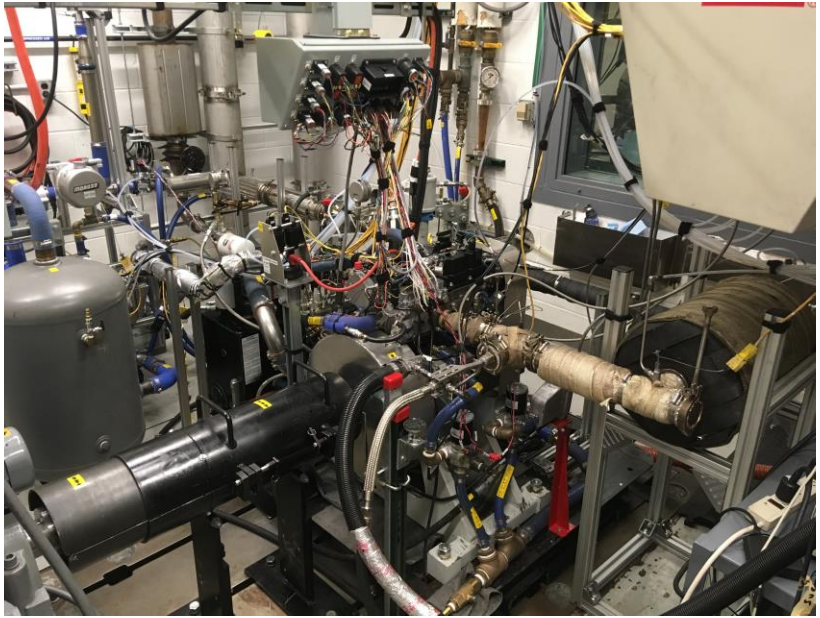
Pressure

Increased penetration, smaller droplet size, higher momentum

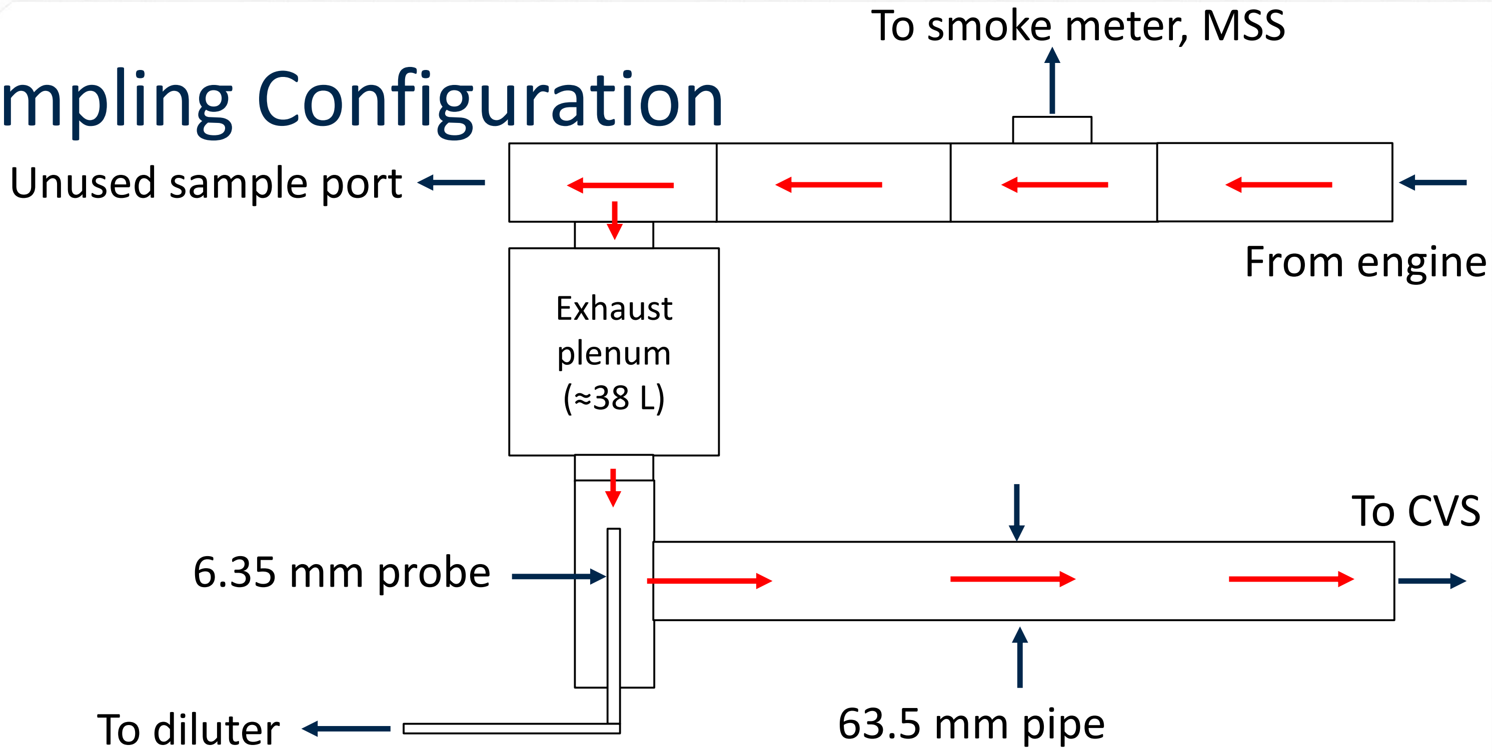
Larger droplet size, less penetration

More Apparatus

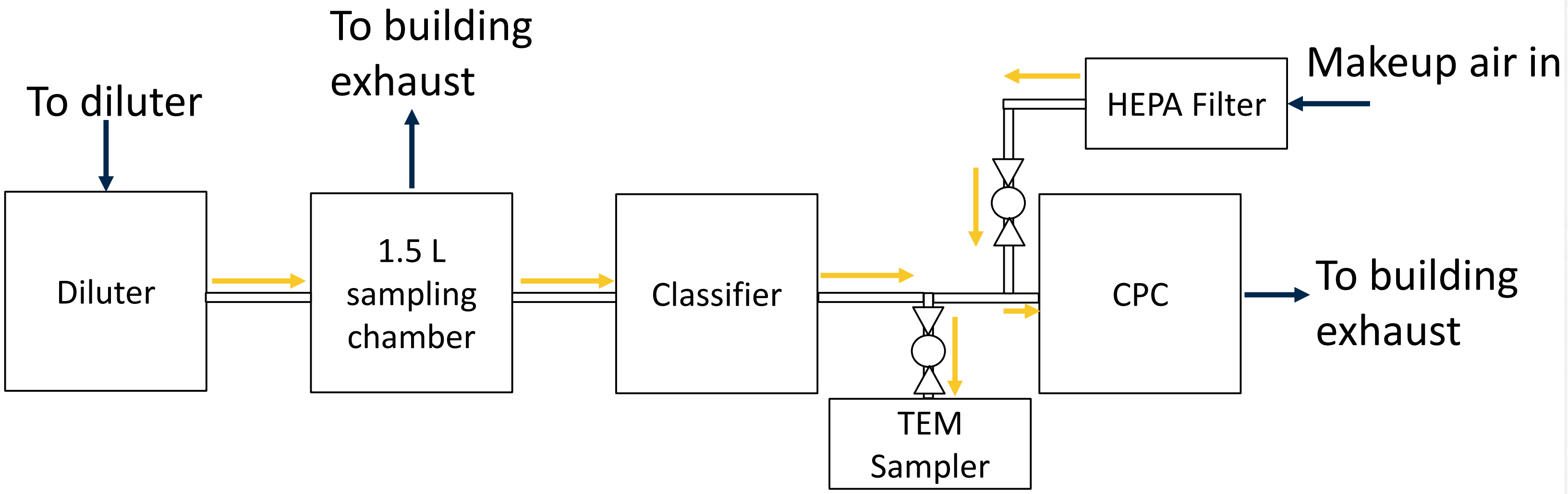
- 2013 1.6L SGDI Ford EcoBoost-based engine:
- Single cylinder
- FEV Systemmotor crankcase
- Instrumented production cylinder head
- SwRI DCO ignition system
- SwRI RPECS engine control system



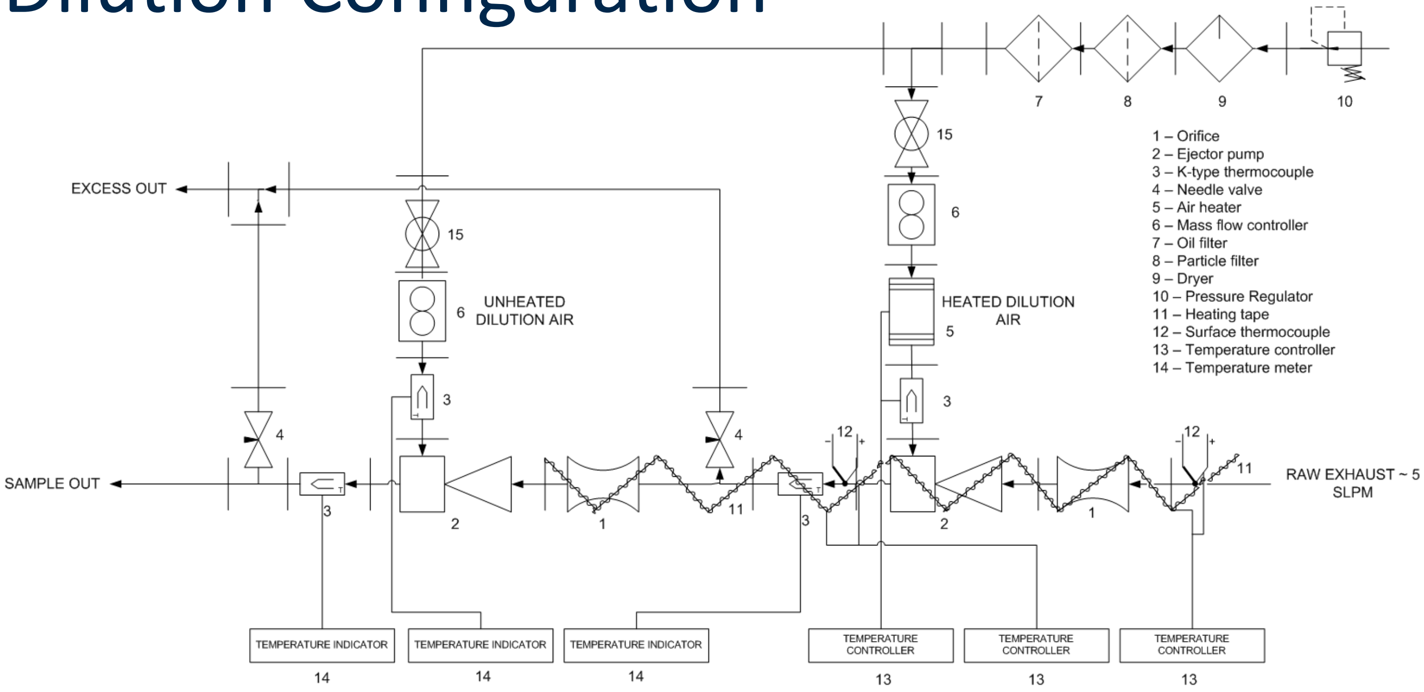
Sampling Configuration



Sampling Configuration

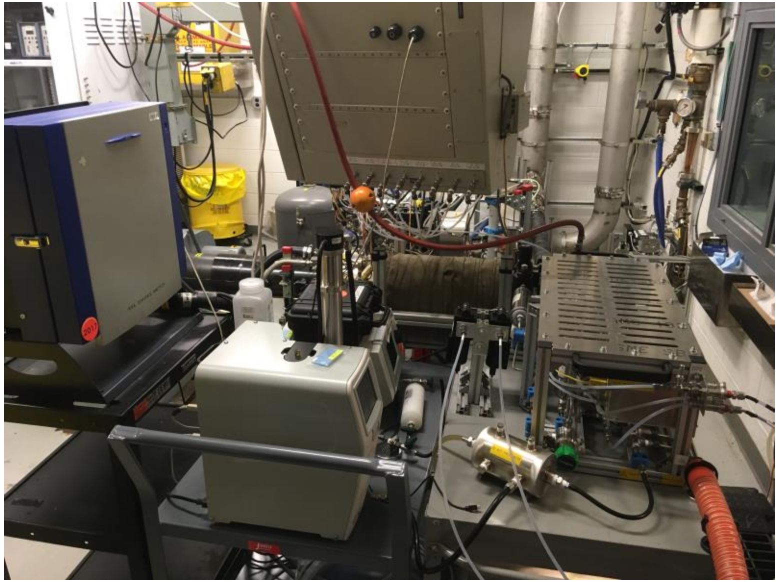


Dilution Configuration

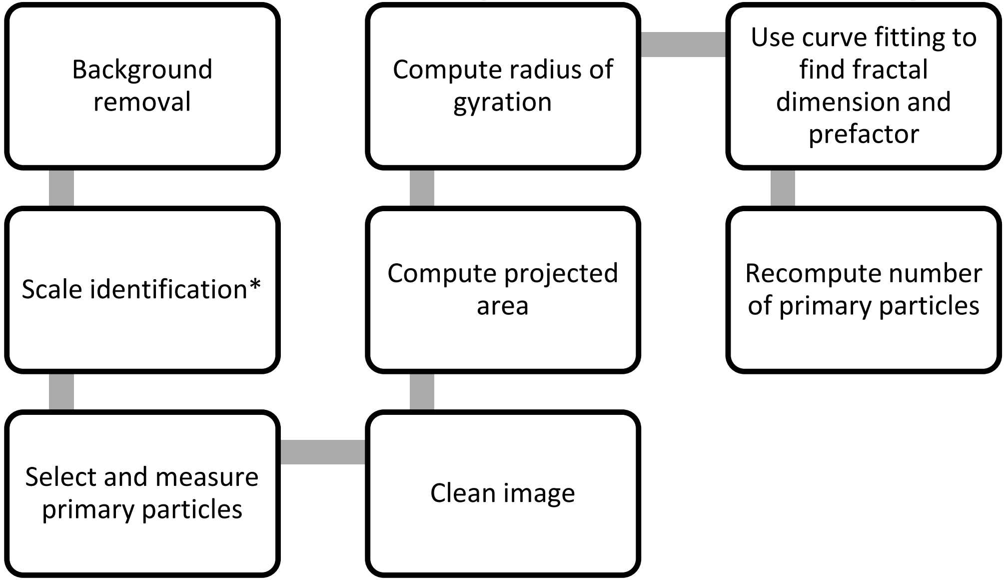


Particle Instrumentation

- TSI 3082 classifier with Po 210 neutralizer and 3081A long DMA
- TSI 3776 CPC
- Custom-built 2-stage ejector diluter system
  - CAI 602 dual-bench CO_2 analyzer to monitor dilution ratio
- Naneos Partector TEM sampler

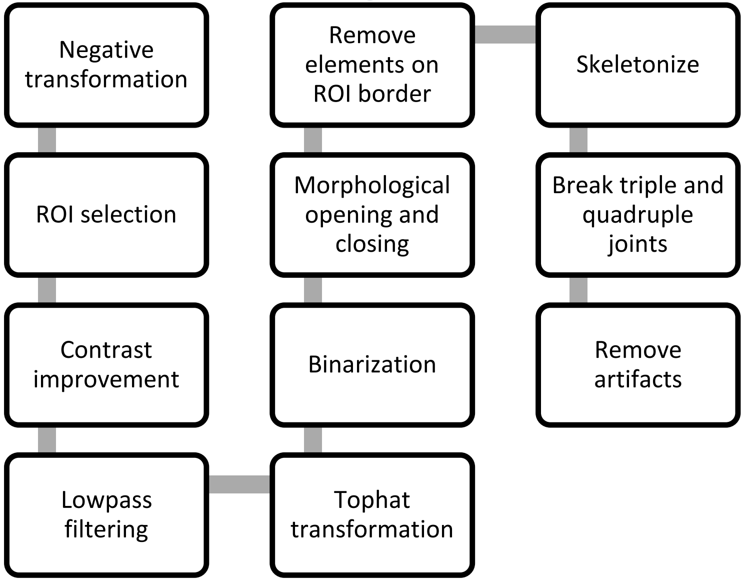


Low Resolution Image Processing



E. V. Luis, “Desarrollo de una Interfaz de Usuario para la Determinación de la Dimensión Fractal de Aglomerados,” Universidad de Castilla - la Mancha, 2014.

High Resolution Image Processing



Yehliu, K., Vander Wal, R. L., & Boehman, A. L. (2011). Development of an HRTEM image analysis method to quantify carbon nanostructure. *Combustion and Flame*, *158*(9), 1837–1851.

Examples of Multiple Injections in GDI in the Literature

J. Su, M. Xu, P. Yin, Y. Gao, and D. Hung, “Particle Number Emissions Reduction Using Multiple Injection Strategies in a Boosted Spark-Ignition Direct-Injection (SIDI) Gasoline Engine,” SAE Int. J. Engines, vol. 8, pp. 20–29, 2014.

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I. Pielecha, “Diagnostics of stratified charge combustion under the conditions of multiple gasoline direct injection,” J. Therm. Anal. Calorim., vol. 118, no. 1, pp. 217–225, 2014.

Dahlander, P. and Hemdal, S., "High-Speed Photography of Stratified Combustion in an Optical GDI Engine for Different Triple Injection Strategies," SAE Technical Paper 2015-01-0745, 2015, doi:10.4271/2015-01-0745.

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T. Kim, J. Song, and S. Park, “Effects of turbulence enhancement on combustion process using a double injection strategy in direct-injection spark-ignition (DISI) gasoline engines,” Int. J. Heat Fluid Flow, vol. 56, pp. 124–136, 2015.

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J. Seo, J. S. Lee, K. H. Choi, H. Y. Kim, and S. S. Yoon, “Numerical investigation of the combustion characteristics and wall impingement with dependence on split-injection strategies from a gasoline direct-injection spark ignition engine,” Proc. Inst. Mech. Eng. Part D J. Automob. Eng., vol. 227, no. 11, pp. 1518–1535, 2013.

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