Measuring Particle Mass and Other Properties with the Couette Centrifugal Particle Mass Analyzer

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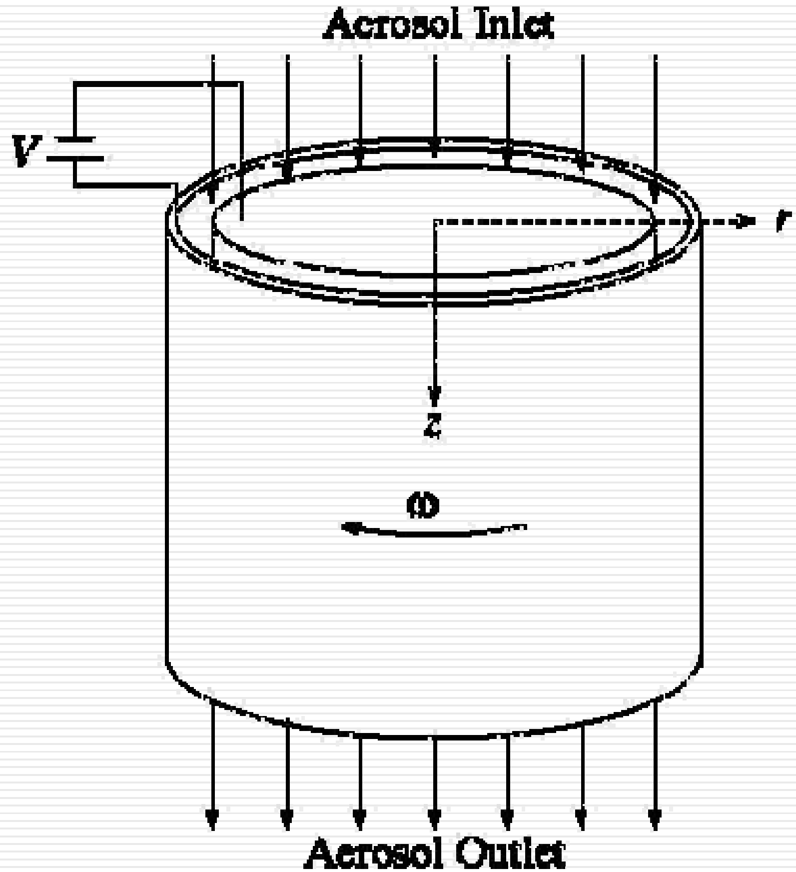
Outline

- Introduction
  - Description of the Aerosol Particle Mass (APM) Analyzer.
  - Motivation for using particle mass classification.
- A new method for particle mass classification – the Couette CPMA.
- ‘Proof of Concept’ experimental results for the Couette CPMA.
- Measuring particle properties with the CPMA.

Operation of the Aerosol Particle Mass Analyzer (APM)

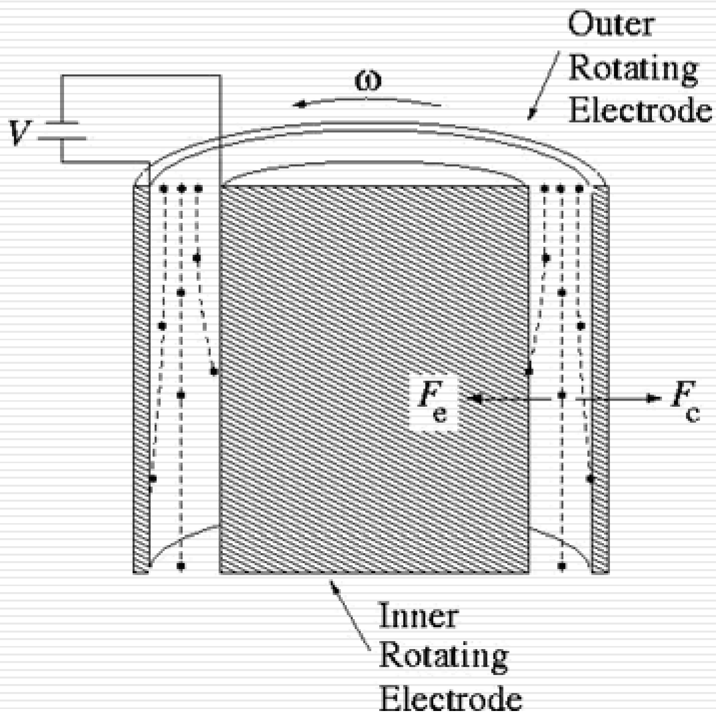
- Developed by Ehara *et al.*
- Charged particles pass through two cylindrical electrodes.
- The cylindrical electrodes rotate - creating a centrifugal force on the particles. In Ehara's APM both cylinders rotate at constant ω.
- Voltage is applied between the cylindrical electrodes – creating an electrostatic force on the particles.



- Particles of a certain mass-to-charge ratio will pass through the APM.

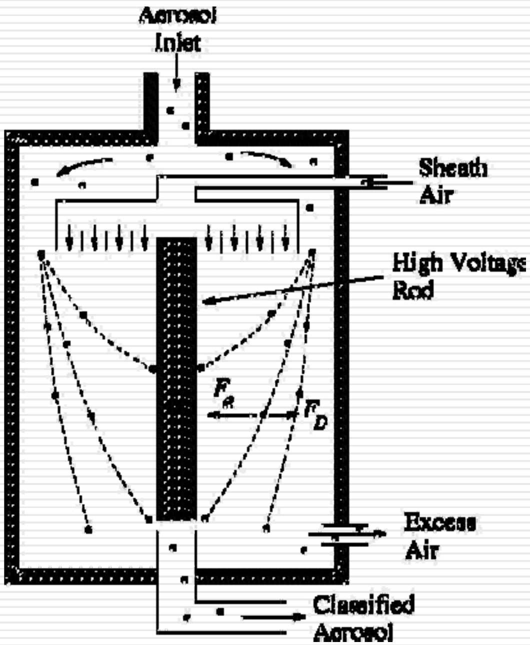
APM & DMA

Aerosol Particle Mass Analyzer



- Particles are classified by balancing electrostatic and centrifugal forces.
- Particles are classified by mass.

Differential Mobility Analyzer



- Particles are classified using electrostatic and drag forces.
- Particles are classified by size.

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Motivation for Classifying Particles by Mass

- Measure particle density and fractal dimension
  - Using the DMA-APM technique (McMurry *et al*., 2002)
    - For spherical particles – the true particle density is found
    - For non-spherical particles – the effective density is found

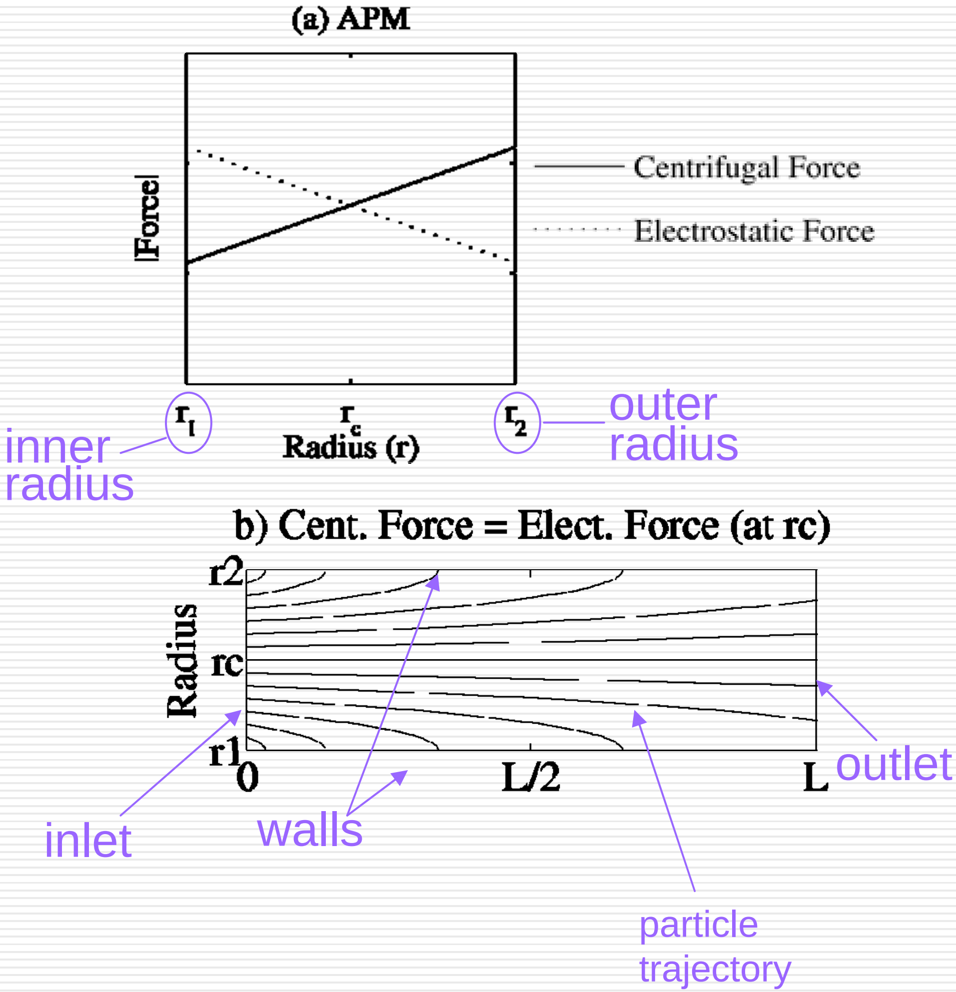
- Measure inherent material density
  - Using APM to measure mass and TEM to measure volume (Park *et al.,* 2004)

- Measure dynamic shape factor
  - Using the DMA-APM technique (McMurry *et al*., 2002), where the DMA is used to measure the mobility diameter and the APM is used to measure the volume equivalent diameter.

- Measure particle mass distributions
  - Using the DMA-APM technique and an SMPS (Park *et al*., 2003)
  - APM is not affected by volatilization or adsorption (unlike filter measurements)

Poor Transfer Function of the APM

- The centrifugal force is proportional to r and the electrostatic force is proportional to $1/r$.
- When the forces are equal the particle will move in a straight line.
- When forces are unequal the particles will move toward the electrodes.
- The forces are unstable.



A New Method of Particle Mass Classification

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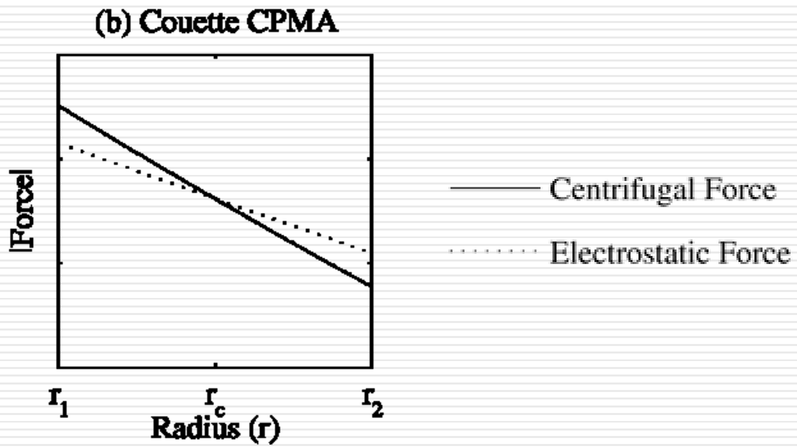
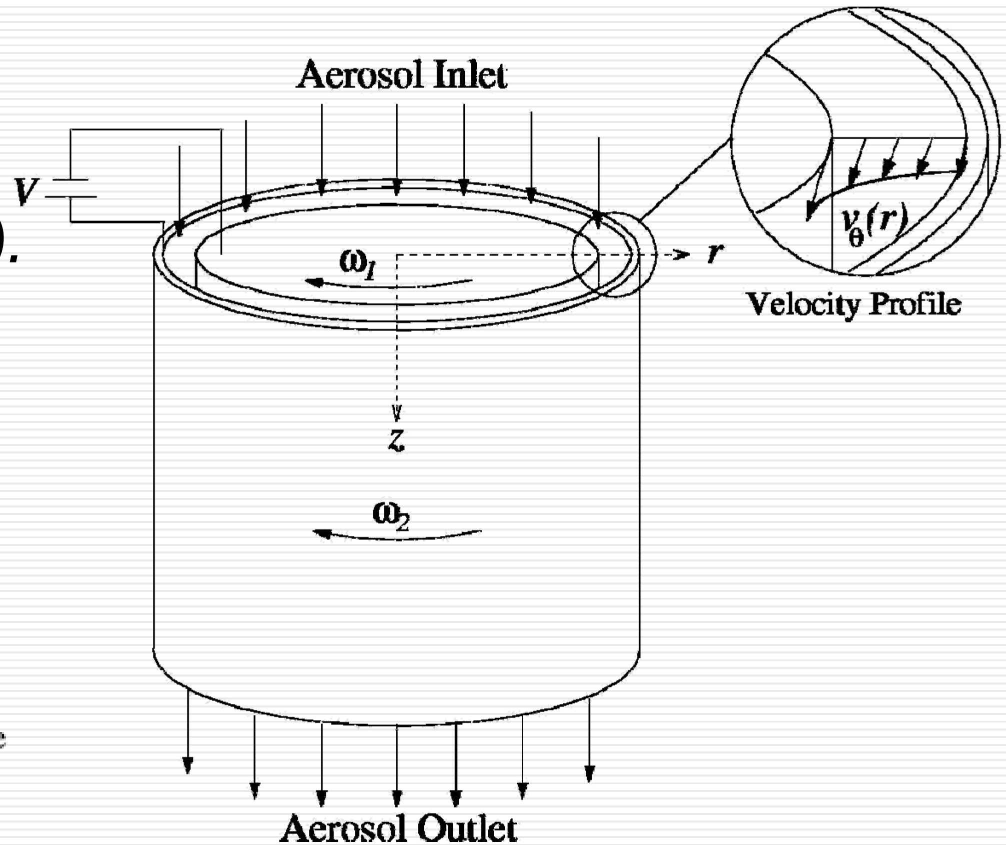
The Couette Centrifugal Particle Mass Analyzer (Conceived by Reavell & Rushton)

- Inner cylinder rotates faster than the outer cylinder (centrifugal force decreases with *r*).
- A stable system is created:

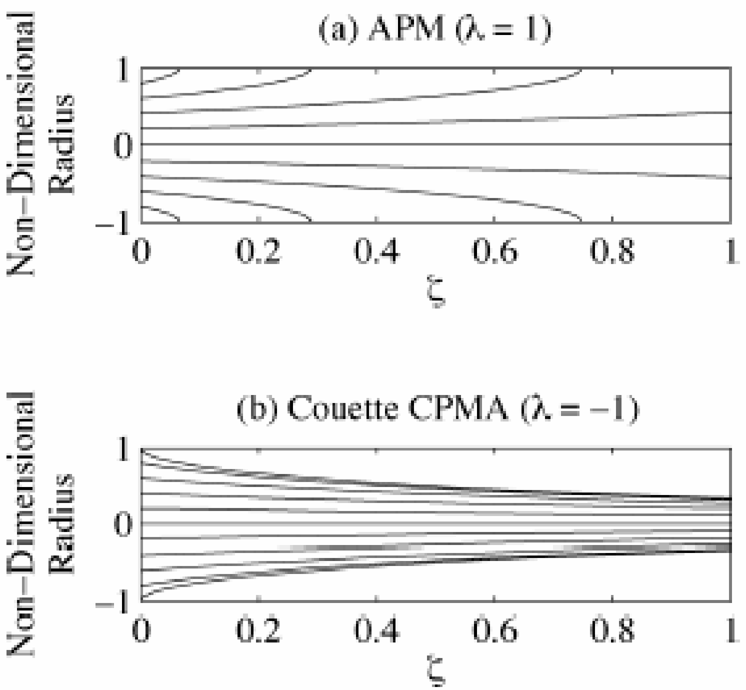




See: Olfert & Collings (2005). *J. Aero. Sci.*

Particle trajectories in the APM and the Couette CPMA

- The equilibrium radius is the radius where the centrifugal and electrostatic forces are balanced.
- In the APM, particles move *away* from the equilibrium radius.
- In the Couette CPMA, particles move *toward* the equilibrium radius.



Transfer Function of CPMAs

- The transfer function, Ω, is determined by one non-dimensional constant:

Always positive

Time to travel length of classifier

$$\lambda_{APM} = \frac{L/\bar{v}}{1/(2\tau\omega^2)}$$

Time to travel across the gap

Always negative

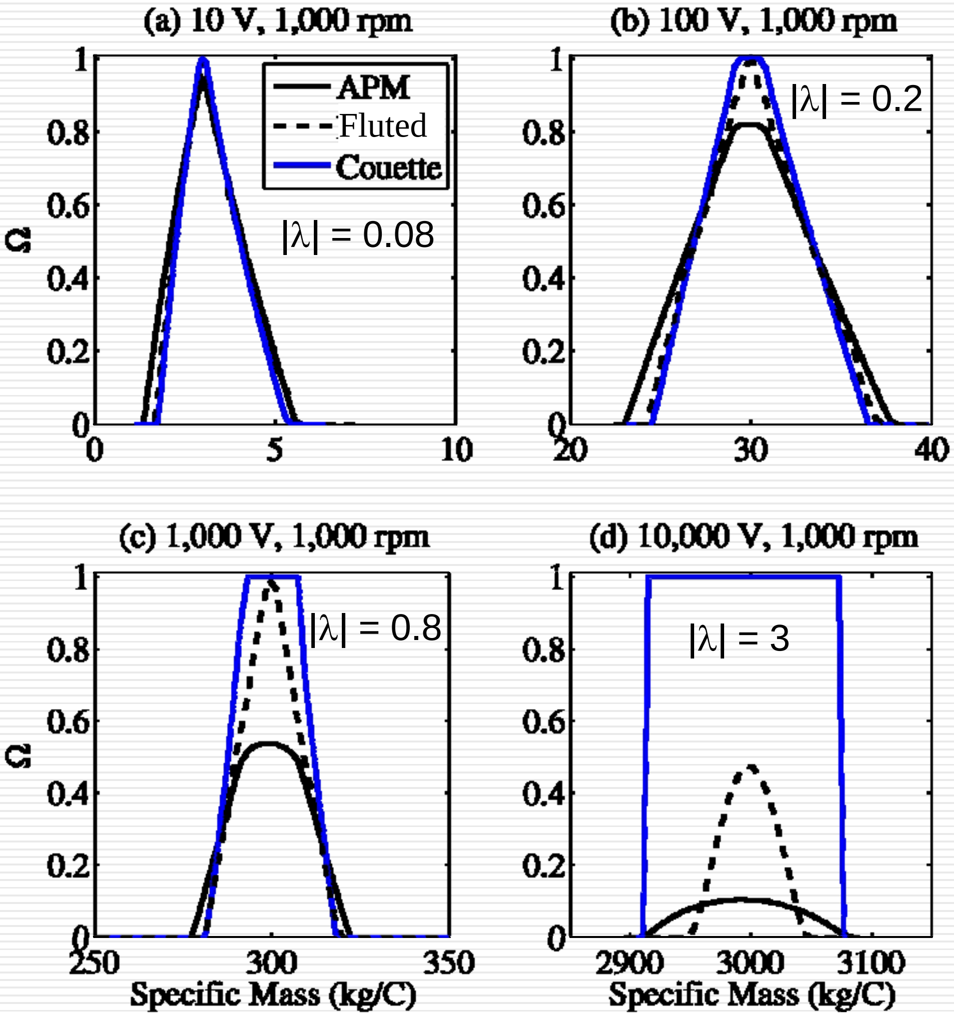
$$\lambda_{Couette} = \frac{L/\bar{v}}{1/[2\tau(\hat{\alpha}^2 - \hat{\beta}^2/r^{*4})]}$$

Term dealing with rotational speed
and ratio between inner ω and outer ω

- A relatively long classifier, slow flow rate, large angular velocity, or large particle will result in a large |λ| and a narrow transfer function.

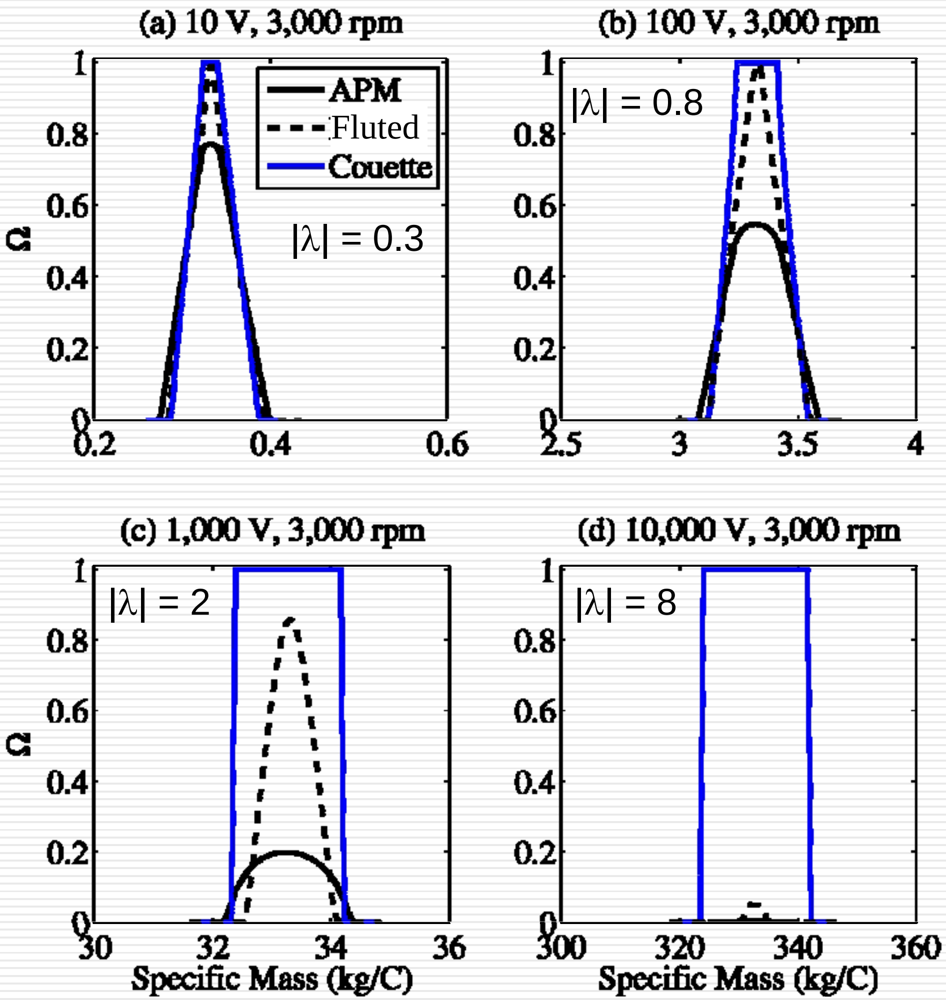
Performance Comparison

- The classifiers can be compared by comparing the transfer functions.
- The Ω's are similar when |λ| is small. See (a).
- As |λ| increases, the Ω of APM decreases.



Performance Comparison

- If |λ| is too high the Ω may be very small for the APM.
- The best classifier is the Couette CPMA – nearly ideal classification for all conditions



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The Prototype Couette CPMA

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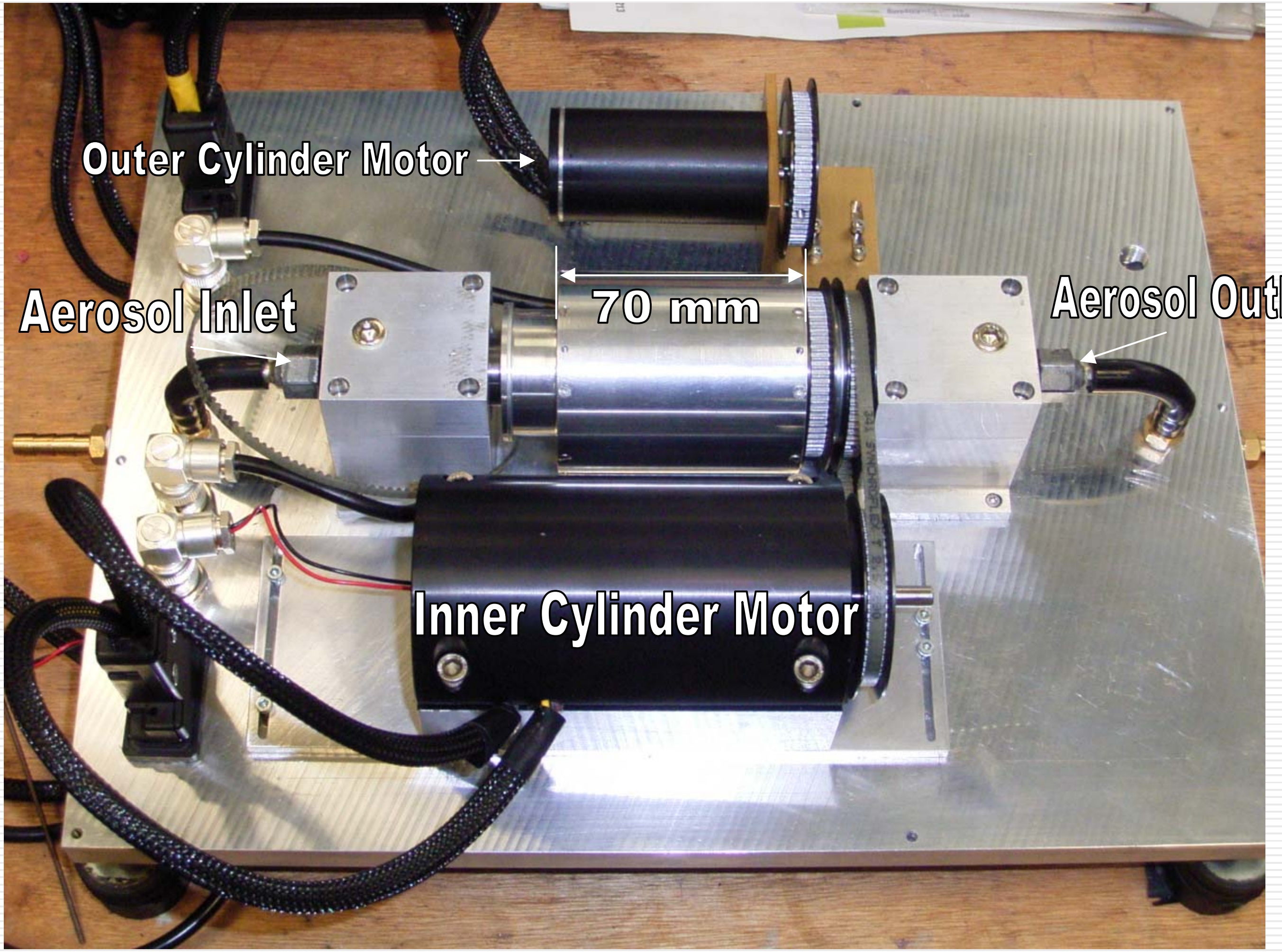
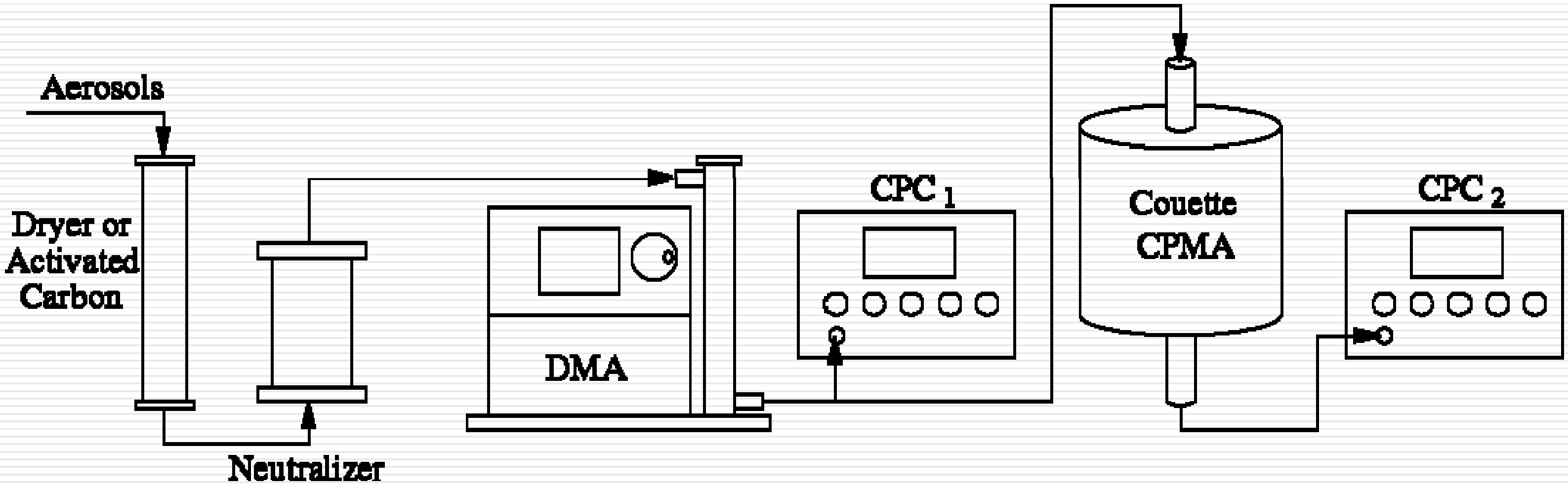
The Couette CPMA Prototype



The DMA-CPMA system

- A DMA and Couette CPMA can be used to measure particle densities, fractal dimensions, and dynamic shape factors.
- The experimental set-up used in this work is shown below:



Measuring the Mass of PSL Particles

- Use PSL particles to compare the theoretical and experimental transfer function of the Couette CPMA.
- In the Couette CPMA (like the APM) the mass of a classified particle is:

$$m = \frac{qV_{\text{peak}}}{r_c^2 \omega_c^2 \ln(r_2 / r_1)}$$

Particle charge

Voltage at maximum concentration

Radius at center of gap

Rotational speed at center of gap

Outer and inner radii

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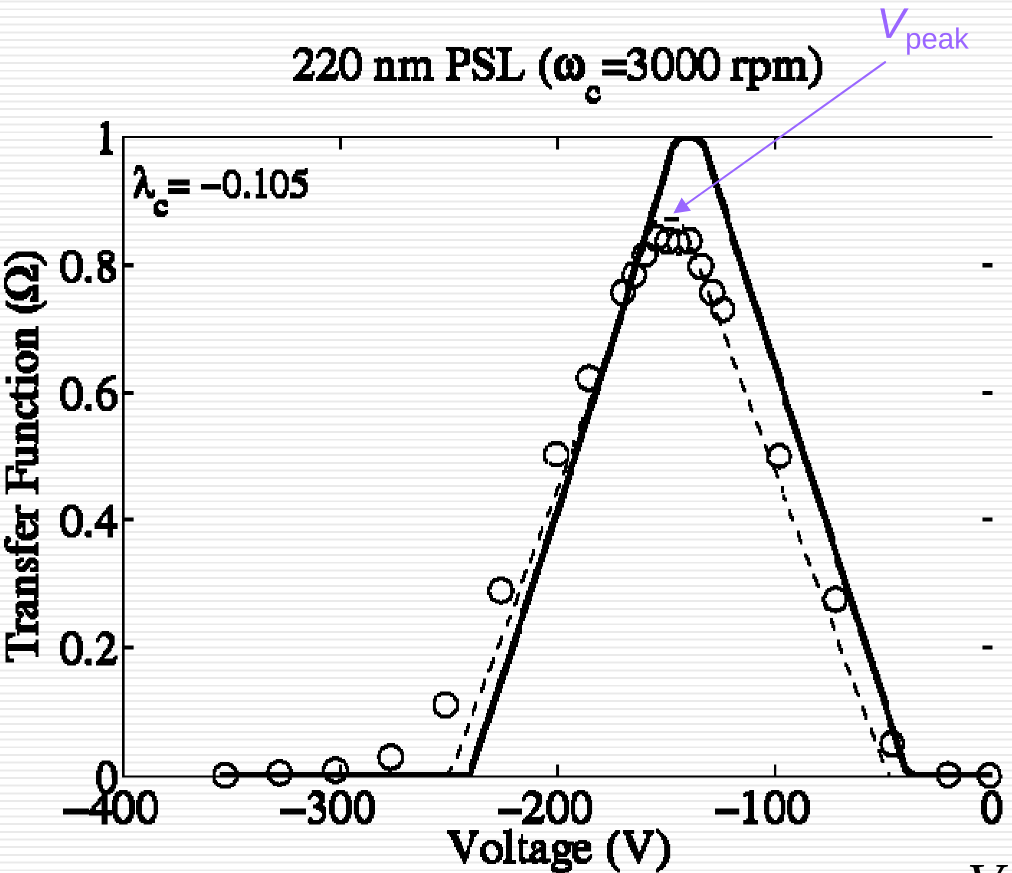
Measuring the Mass of PSL Particles



- m_{exp}= 6.25 femtograms
- m_{theo}= 5.85 fg (7% error)
- Error mostly likely due to uncertainty in ω.
- Some particles losses; mostly likely due to impaction before and after classifying region.

$$m = \frac{qV_{\text{peak}}}{r_c^2 \omega_c^2 \ln(r_2 / r_1)}$$

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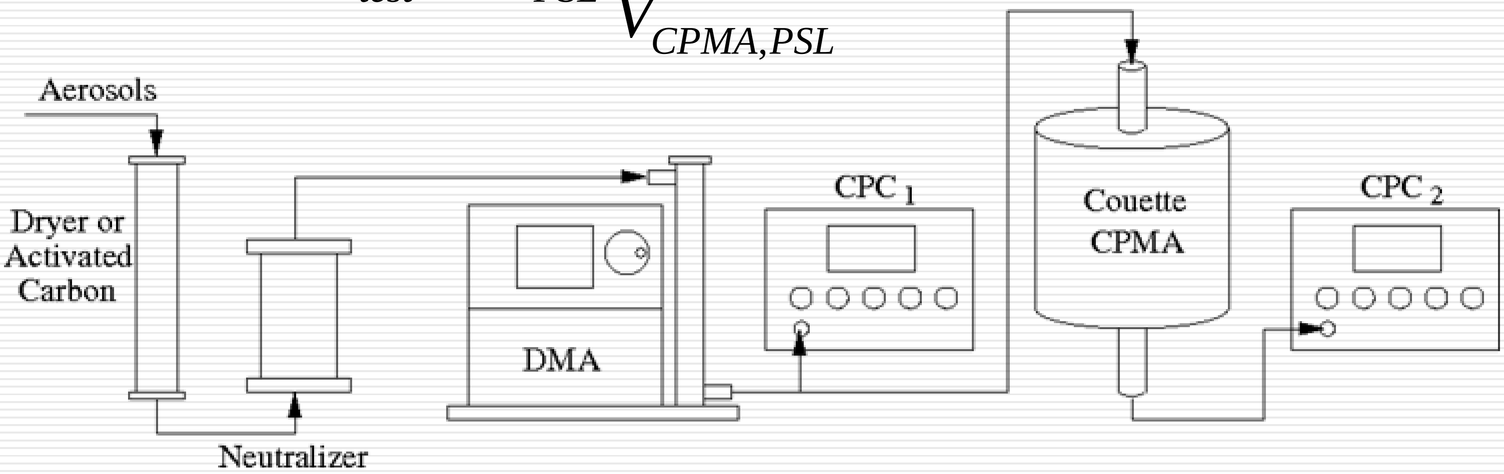
Experimental Results: Measuring Particle Properties

Measuring the density of spherical particles

- A DMA and a Couette CPMA can be used to find the density of spherical particles.
- A accurate way to measure density is to calibrate the DMA-CPMA system with PSL particles. Where the density of the spherical particles is calculated by:

$$\rho_{test} = \rho_{PSL} \frac{V_{CPMA,test}}{V_{CPMA,PSL}}$$



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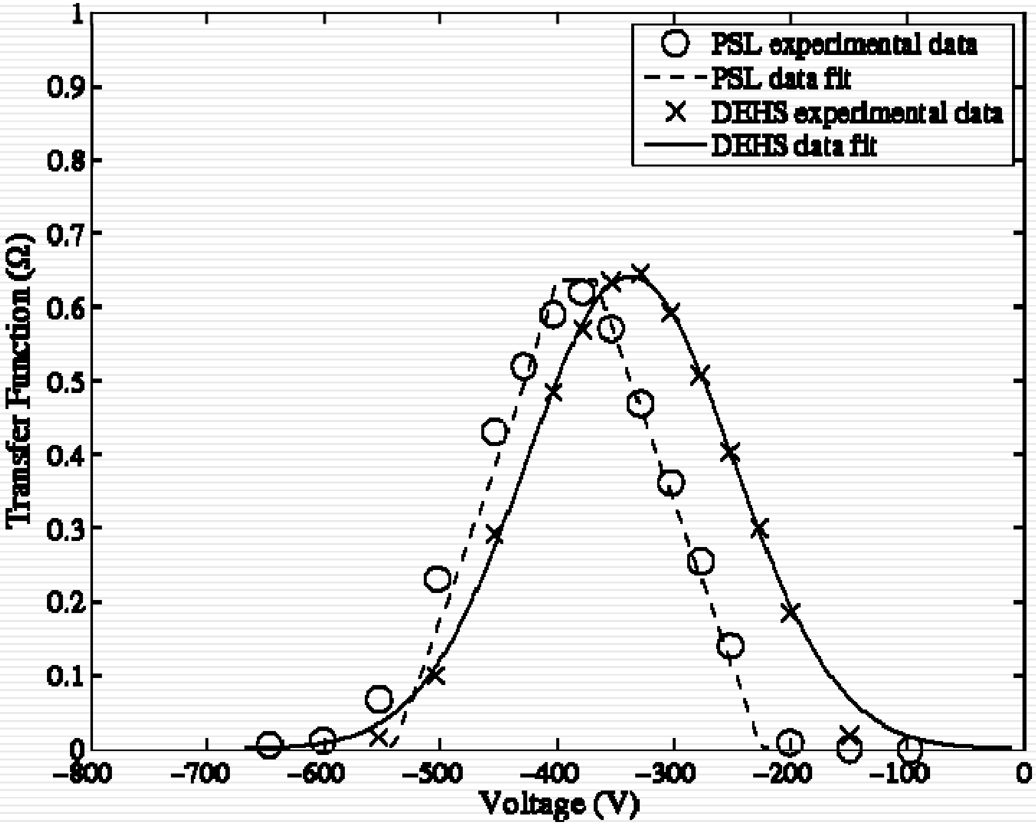
Density of DEHS particles



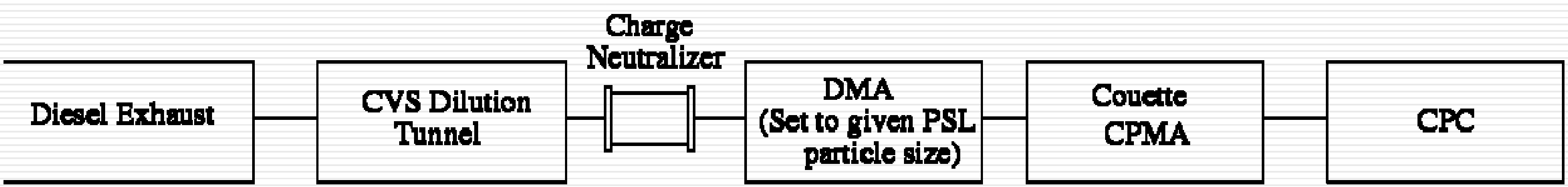
- Using this method the density of DEHS was measured to be 0.926 g/cm^3 compared to the actual density of 0.914 g/cm^3 (1.3% error).
- Repeating this experiment at different sizes showed that the DMA-CPMA can measure density to within ±3%.

Measuring the Effective Density of Diesel Particles

- The Couette CPMA can be used to find the effective density of Diesel particles.
- The effective density can be found from:

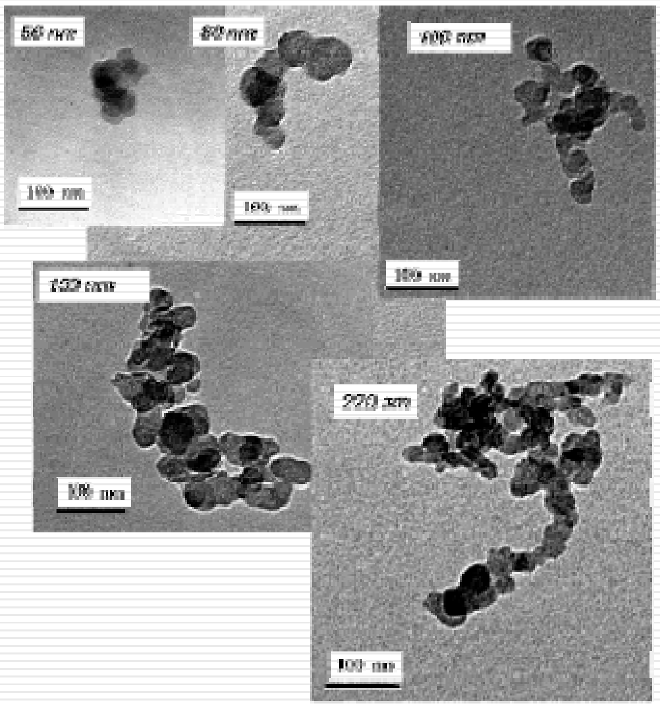
$$\rho_{eff} = \rho_{PSL} \frac{V_{CPMA,soot}}{V_{CPMA,PSL}}$$

- Vehicle tested: 2002 Peugeot 406 (2.2L common rail Diesel with oxidation catalyst; Euro III)
- Experimental Set-up:



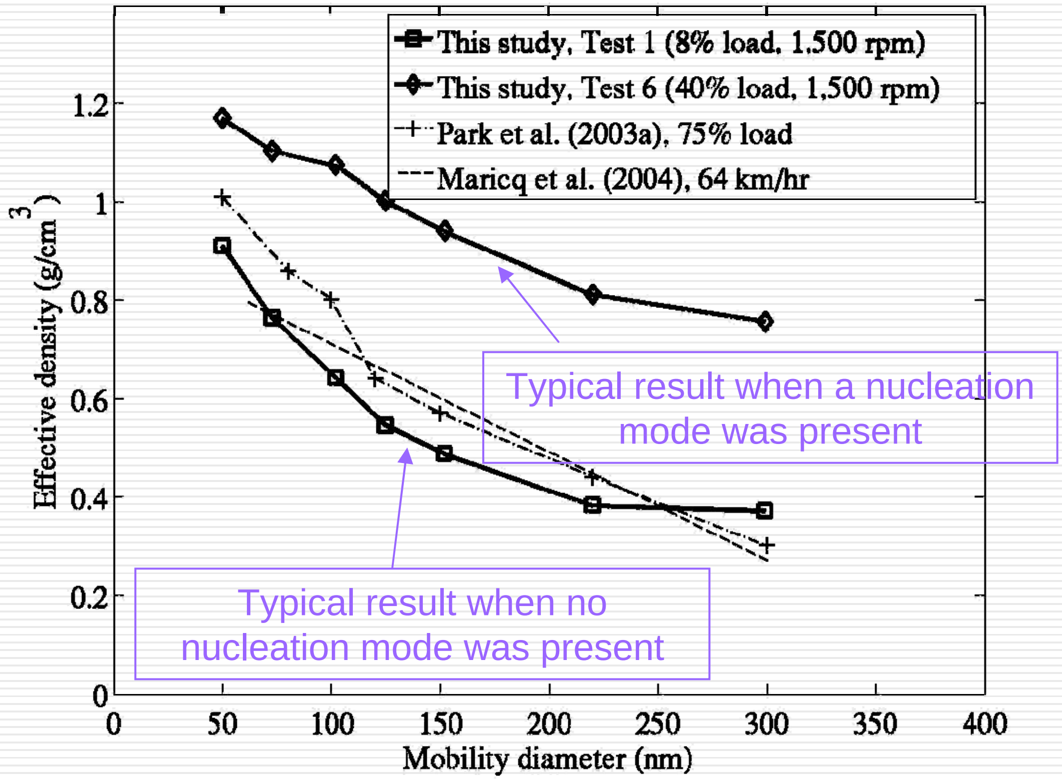
Effective density of diesel particles

- By measuring size (DMA) and mass (CPMA) the effective density can be determined.



TEM images of diesel particles

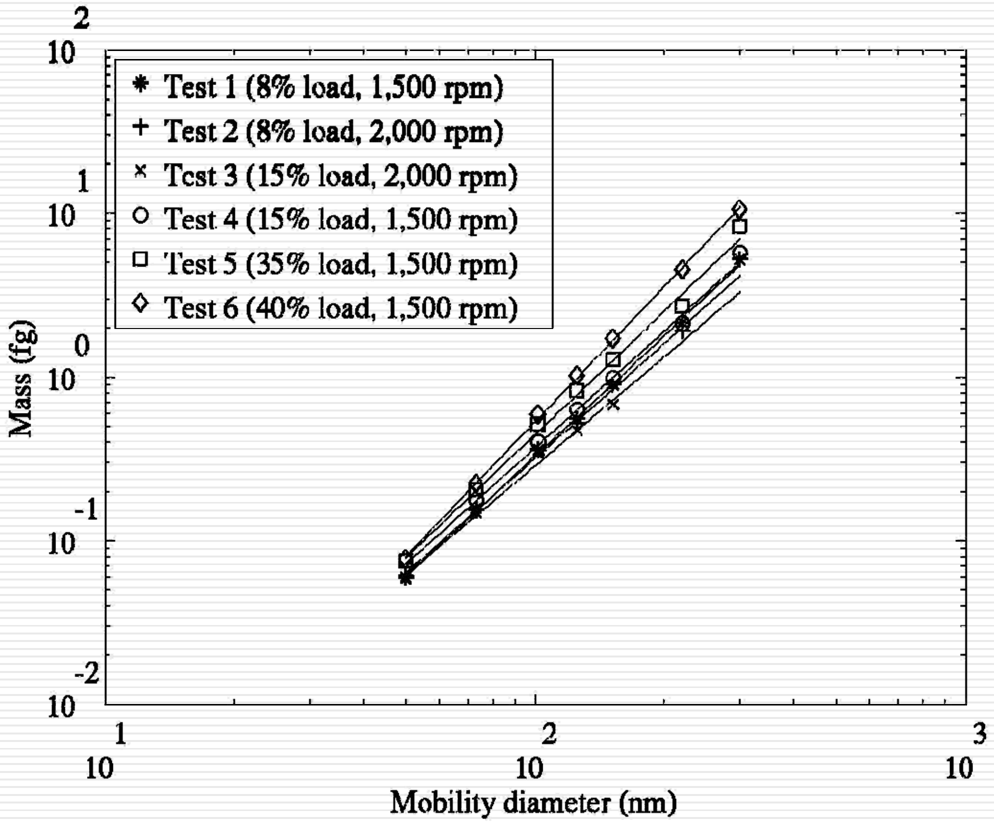
(Park, Kittelson, McMurry)



Effective density of diesel particles

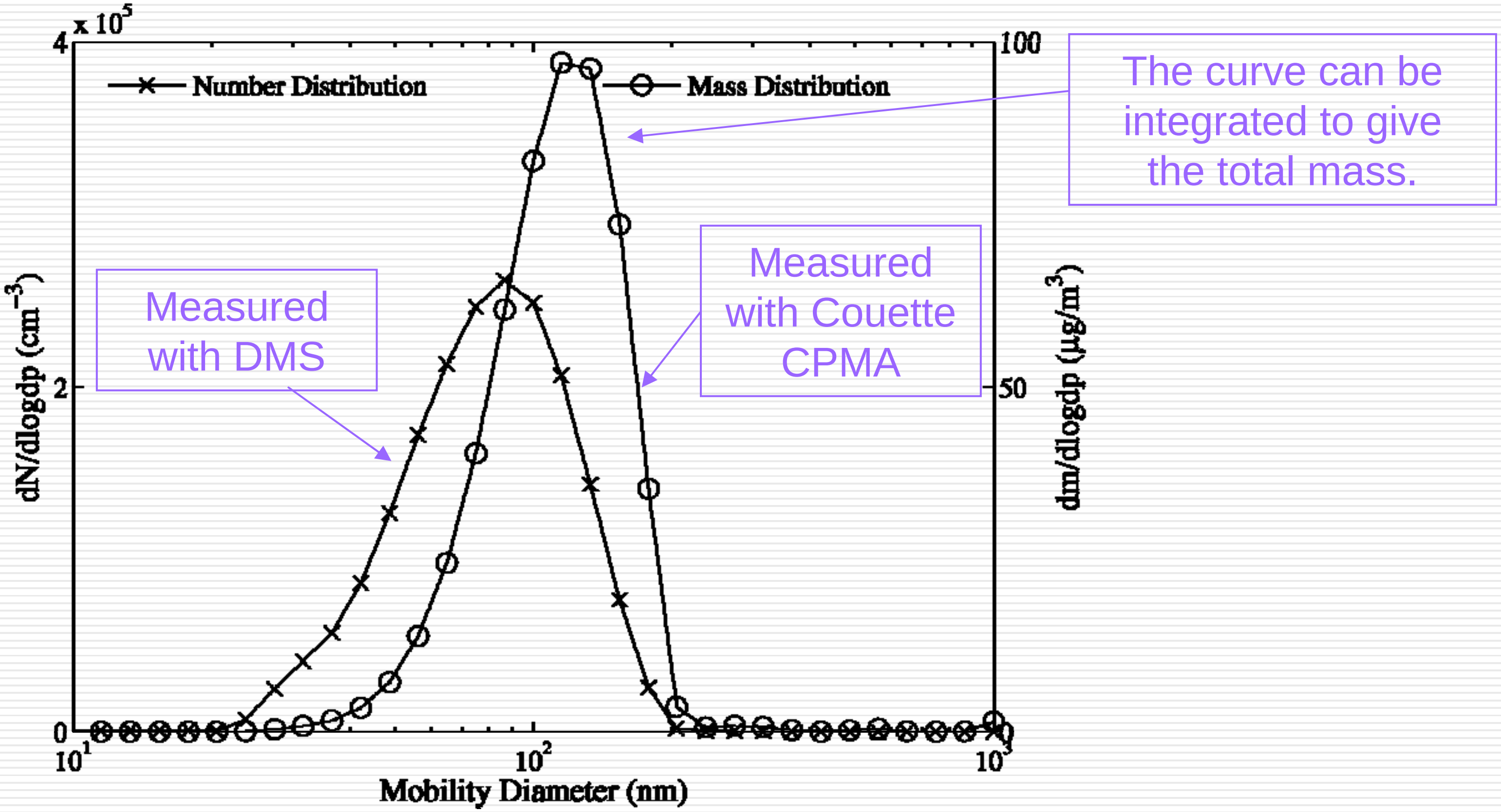
Fractal dimension of diesel particles

- The fractal dimension is a measure of the 'stringiness' of a particle ($m \propto d_{me}^{D_f}$).
- The fractal dimension of the diesel particles when no nucleation mode was present ranged from 2.22-2.45.
- The fractal dimension was 2.51-2.74 when a nucleation mode was present (high load).



Mass distribution of diesel particles

Mass distributions can be found by multiplying the number distribution (from DMS) by the particle mass (CPMA).



Number and mass distribution of diesel particles

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Summary (1)

- A new method for particle mass classification have been introduced – the Couette CPMA.
- Theoretically the transfer function of the Couette CPMA is better than the APM.
- The prototype Couette CPMA can accurately measure the mass of particles.

Summary (2)

- Particle mass and mobility diameter measurements can be combined to measure the properties of particles (i.e. effective density, fractal dimension, dynamic shape factor, mass distributions etc.)

Questions/Comments?

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