Optical Levitation of Absorbing Particles for Fuels Characterization

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“An expert is a person who has made all the mistakes that can be made in a very narrow field.”

– Niels Bohr

Why single particle studies?

- Particles of interest in combustion processes:
  - Pulverized coal (~40-70 µm)
  - Biomass (~40 µm – several mm)
  - Ash particles
  - Energetic materials
  - Metals

Background

- Electrodynamic levitation
  - Charged particles trapped in an electrodynamic chamber
    - Particles lose their charge at elevated temperatures
- Optical manipulation of *transparent* particles reported by Arthur Ashkin in 1970
  - Developed optical tweezers used in aerosol and biological research
- Optical levitation of *opaque* particles reported in the early 1980's
  - To date, no mechanism has been established
  - Not necessary to charge particles

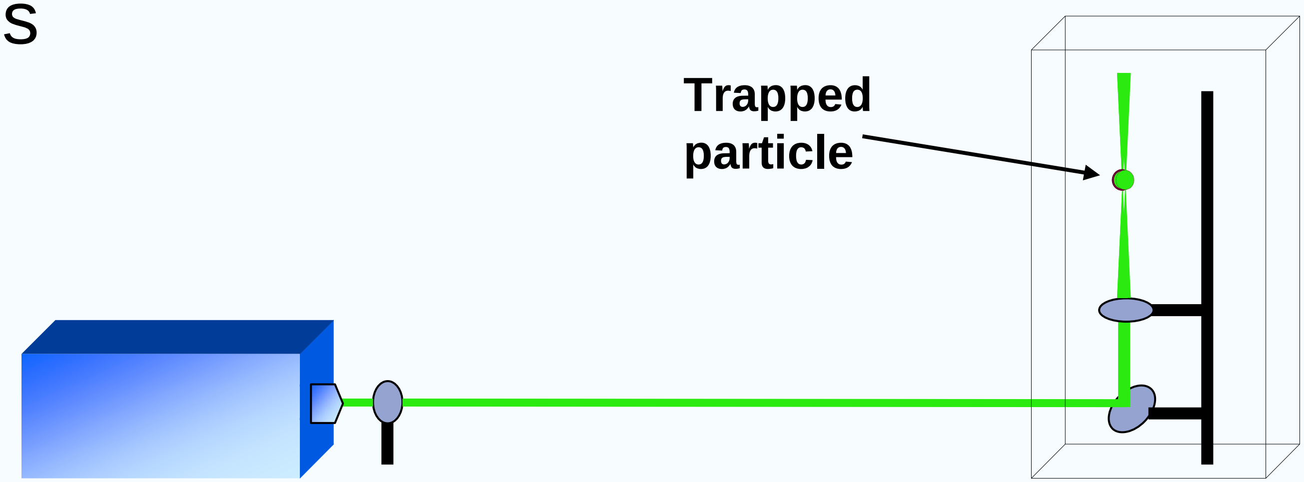
Project Objectives

1) Establish comprehensive opaque-particle trapping mechanism

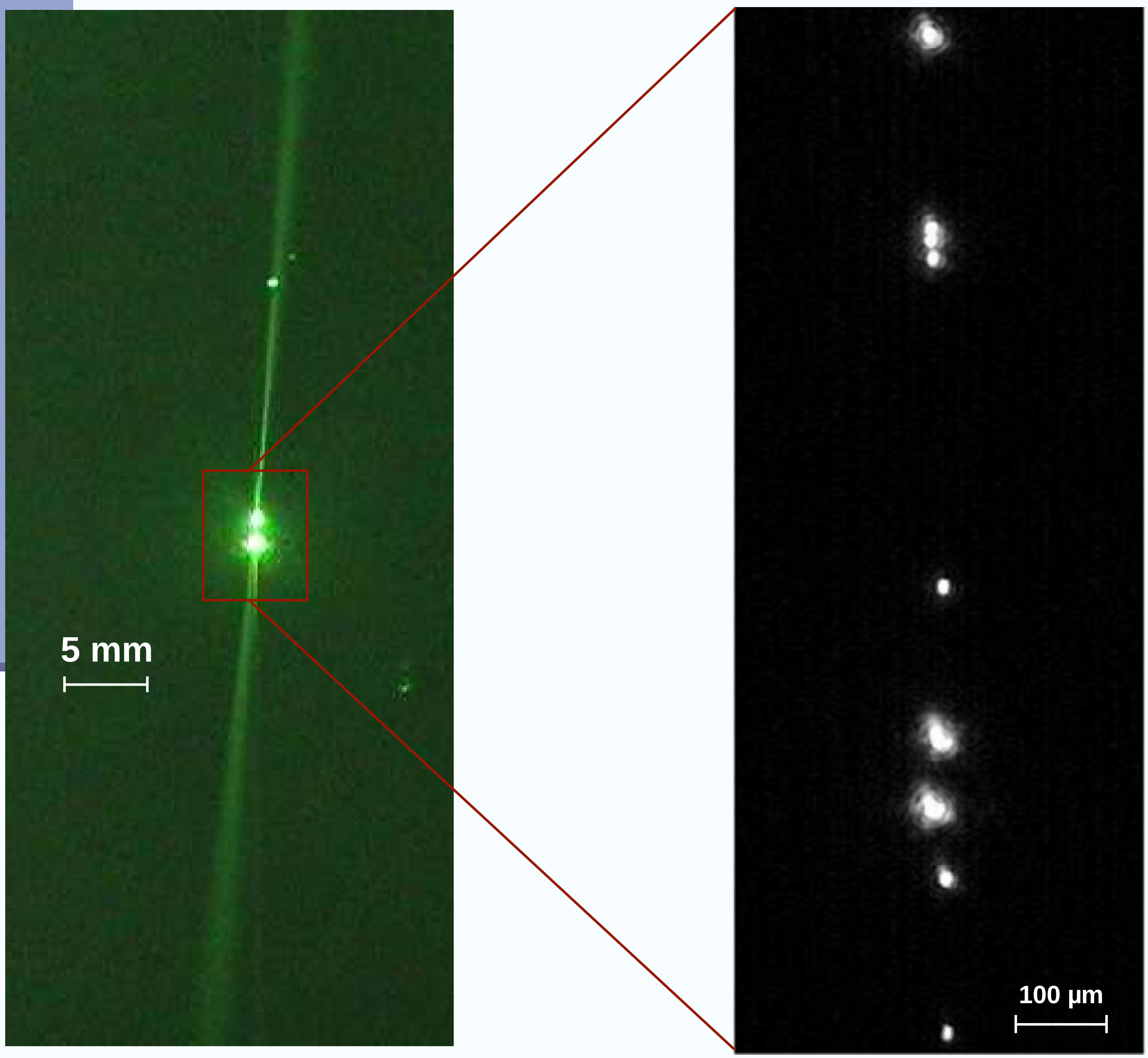
2) Develop *in situ* diagnostic tool to study single-particle reactivities of solid fuels

Experimental Methods

- $NdYVO_4$: Solid state cw, 532 nm
  - Variable power output up to 10.5 watts
- A lens focuses the beam
- A needle coated with particles and passed through the beam near the focal point suspends particles



Trapped Particles



- Black liquor particles trapped at 2 watts
- All particles shown are optically trapped

Experimental Observations

- Ar+, Nd:YAG, and Nd:YVO_4 laser beams oriented in any direction successfully levitate particles
  - Even when directed downward or angled
  - Vertical beams propagating upward are the most effective
- Experiments have been performed at ambient pressures as well as under vacuum
  - Cannot trap below ~1 Torr

Experimental Observations

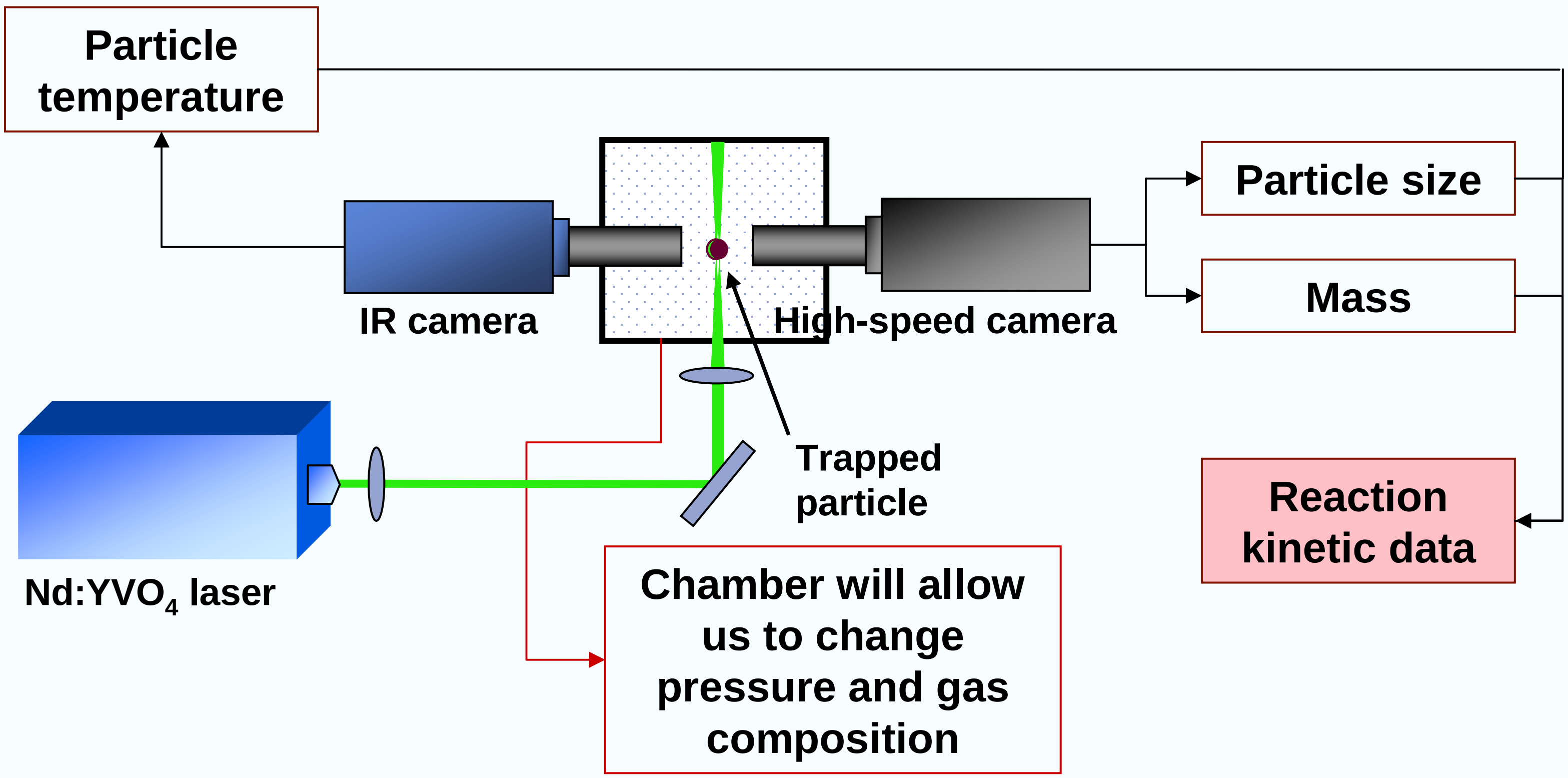
- Most particles do not react while trapped and will stay trapped indefinitely with no apparent change in size or shape
- Trapped particles include:
  - silver, nickel, iron, magnesium oxide, tungsten, charcoal, carbon black, graphite, aluminum, wood dust, and black liquor

Progress

- Developed Particle Levitation Model
  - Establishes trapping mechanism
- Experimental work
  - Particle size measurements
  - Particle temperature measured by Flir SC6000 IR camera (InSb, 640x512, 120 fps)
  - Mass loss measurements made by force balance from particle's position with respect to focal point

Diagnostic Tool

- Determine single particle reaction kinetics from d_p, T_p, and m_p



Particle Levitation Model

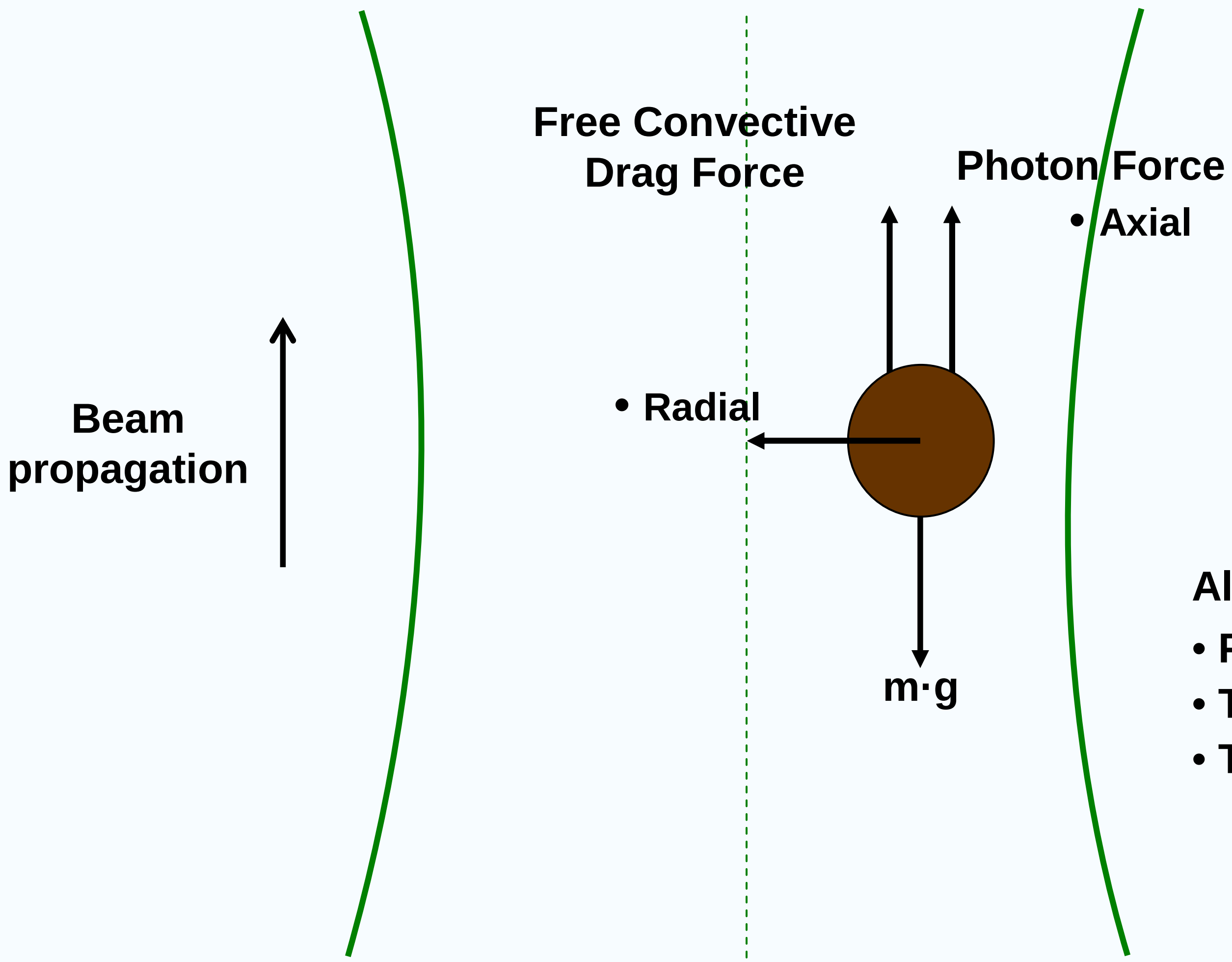
Energy Balance

- An energy balance estimates particle surface temperature
  - Assumptions:
    - The only energy source is the incident laser light
    - The particles are inert
- Equates the heat from the laser light to the heat lost through convection and radiation

$$P_L \iint_{A_{p,cs}} S_L \, dA = A_{p,s} h \left(T_p - T_\infty\right) + A_{p,s} \varepsilon\sigma \left(T_p^4 - T_\infty^4\right)$$

Force Balance

- Two major forces counteract gravity:

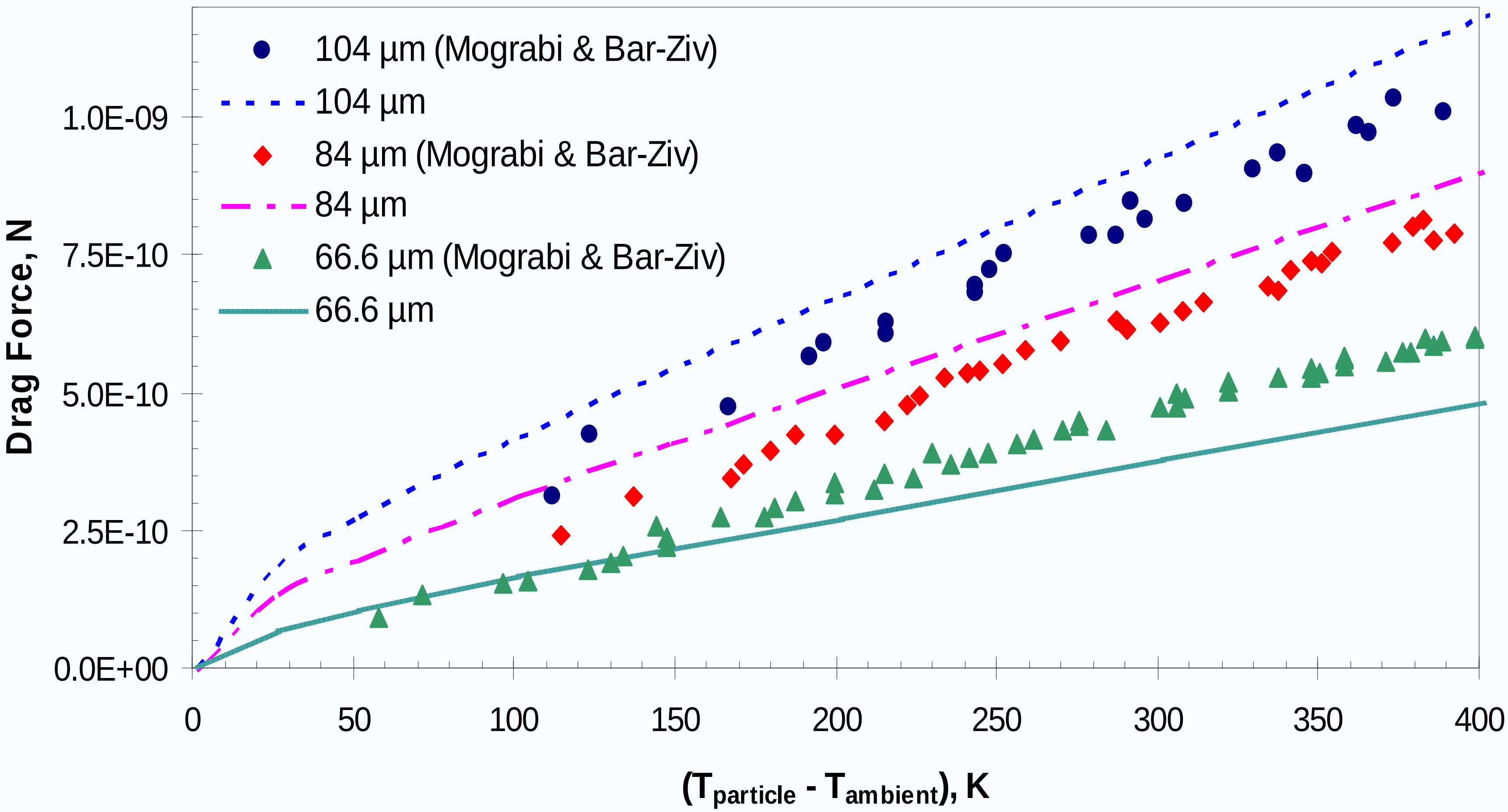


Also considered:
- **Photophoresis**
- **Thermophoresis**
- **Thermal transpiration**

Drag/Photon Force Models

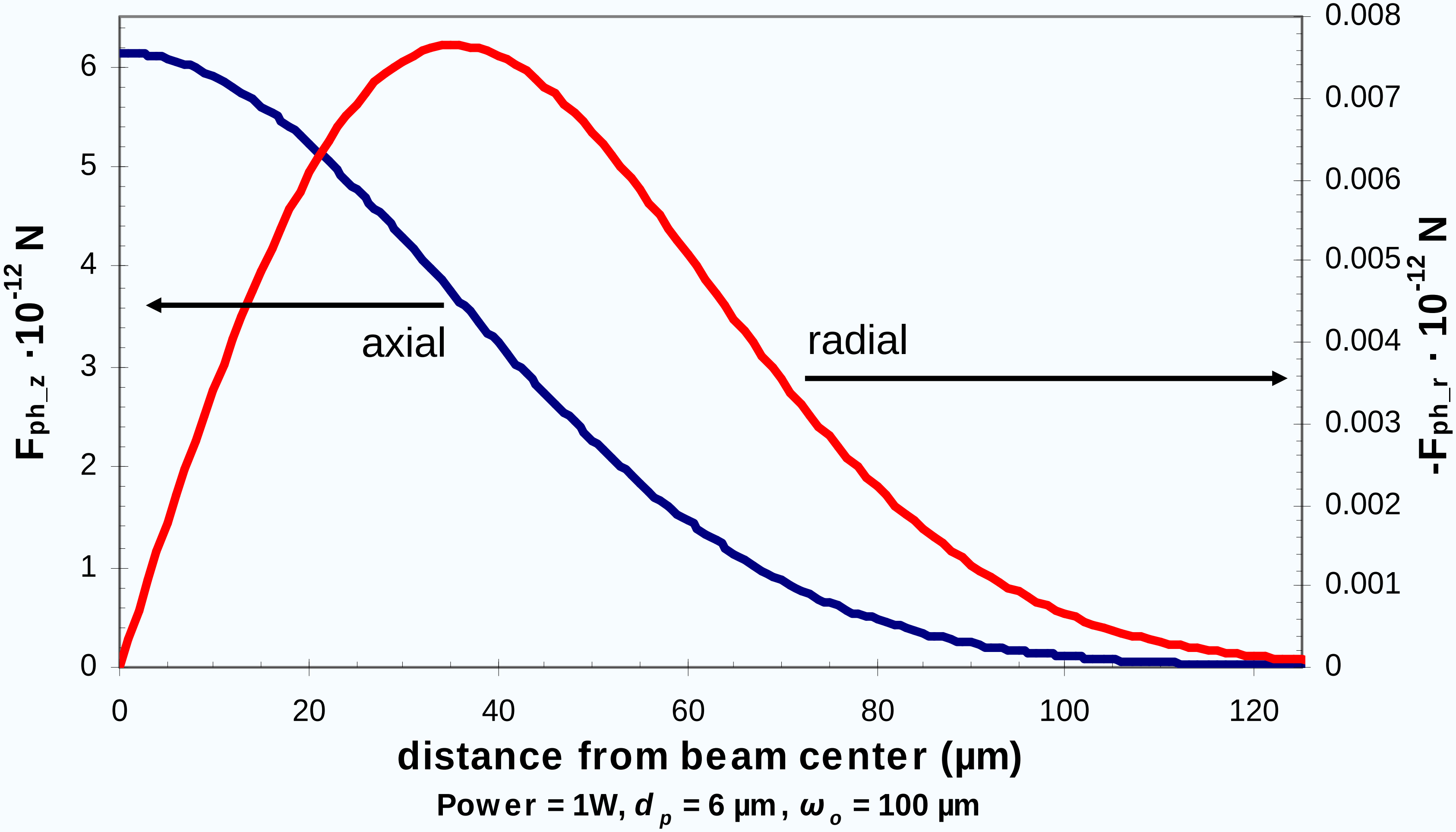
- Fluent predicts F_{drag} as a function of d_p and T_p
  - Modeled 8 particle diameters (5-200 µm) at 9 different temperatures (400-1700 K)
  - ~18,000 nodes in axisymmetric grid
  - Grid-independent solution
- Amsterdam Discrete Dipole Approximation (ADDA) predicts F_{photon}
  - Axial component
    - Always in direction of beam propagation
  - Radial component
    - Acts as a restoring force – pulls particles to center of beam

Drag Force Model vs. Data

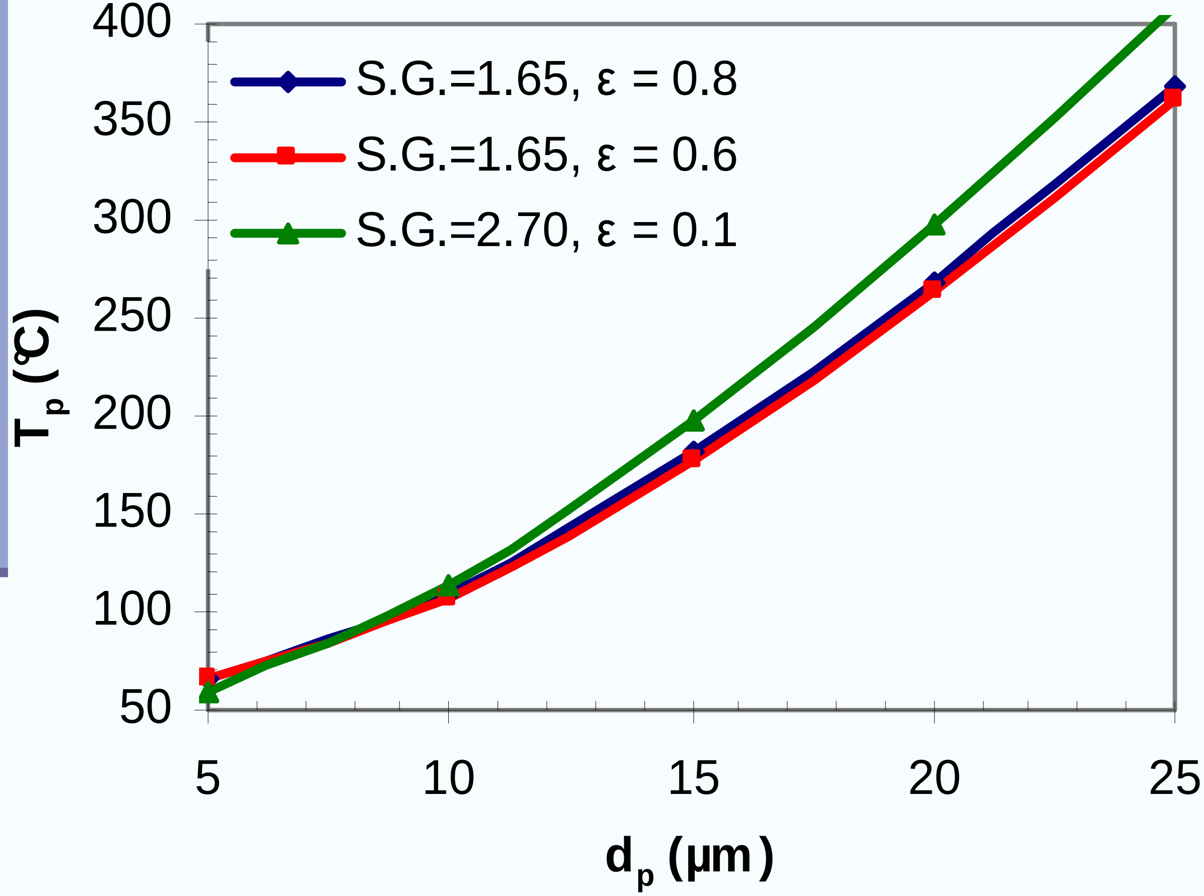


Comparison of Fluent™ predictions with experimental results of the free-convective drag force (Mograbi & Bar-Ziv, 2005)

Photon Force Model

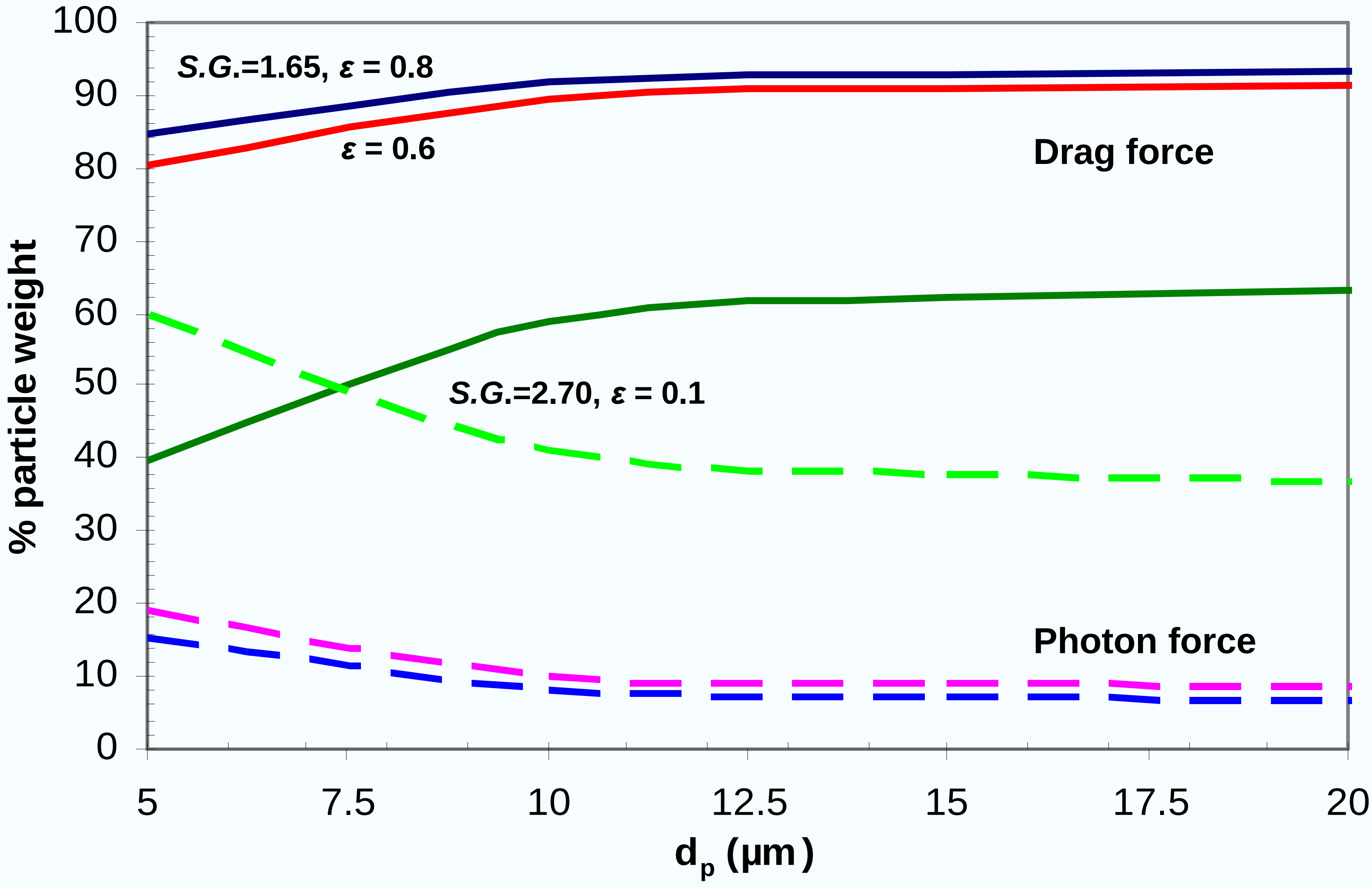


Temperature Predictions



- T_p only a function of particle properties
- Particles <25µm do not react without external heating

Force Predictions



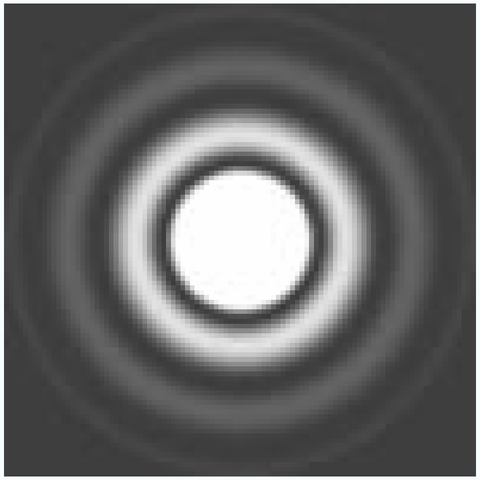
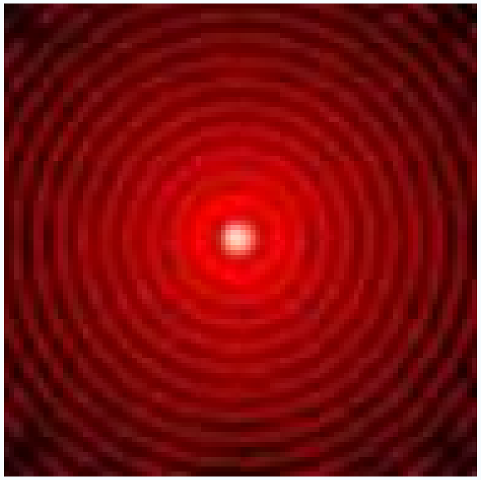
Opaque Particle Trapping Mechanism

- Two major forces:
  - Free-convective drag force
  - Photon force
- Drag force dominates trapping mechanism for large particles, high emissivities
- Photon force much smaller but not negligible
  - Importance of photon force decreases as particle size and emissivity increase

Particle Sizing Procedure

Particle Sizing

- Measure Airy rings
  - Measurements using Mie scattering provide a very accurate size measurement technique

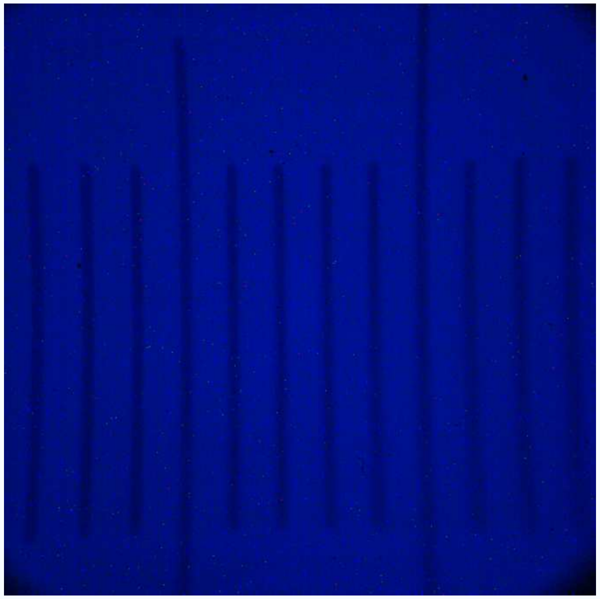


[1,2]

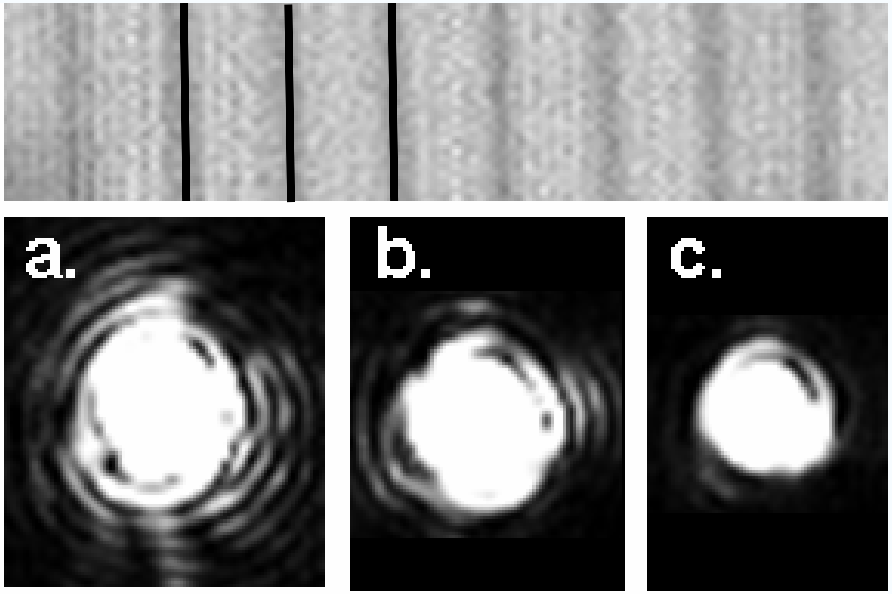
  - Knowing angle between each ring gives particle size

[1] http://www.cambridgeincolour.com/tutorials/diffraction-photography.htm
[2] http://www.ugr.es/~jadiaz/docencia.htm

Particle Sizing

- Image particles and compare to measured field of view

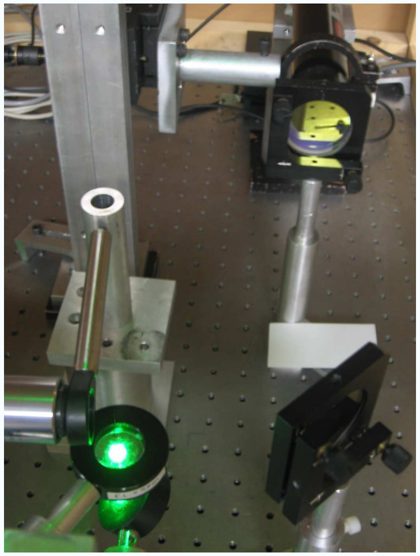




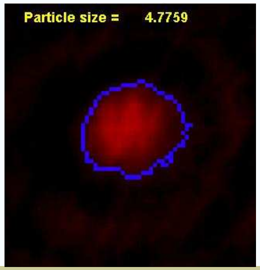
- Because of reflected laser light, particle size changed based upon shutter speed

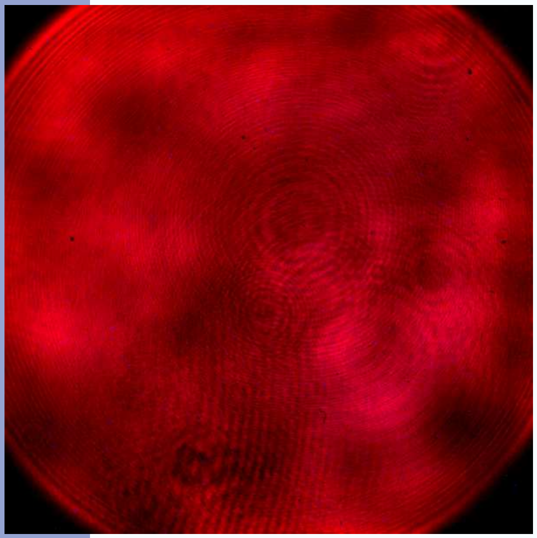
Particle Size

- He-Ne (633 nm) beam traverses particle and enters camera, creates shadow
- Filters attenuate beam, block 532 nm light
- Focusing upon shadow allows particle size measurement



Particle Size





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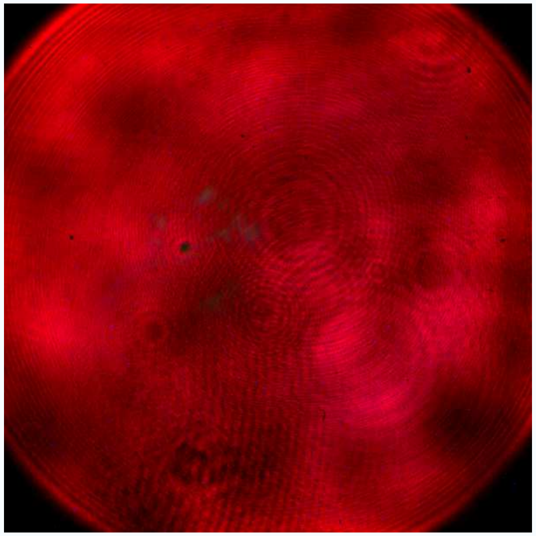

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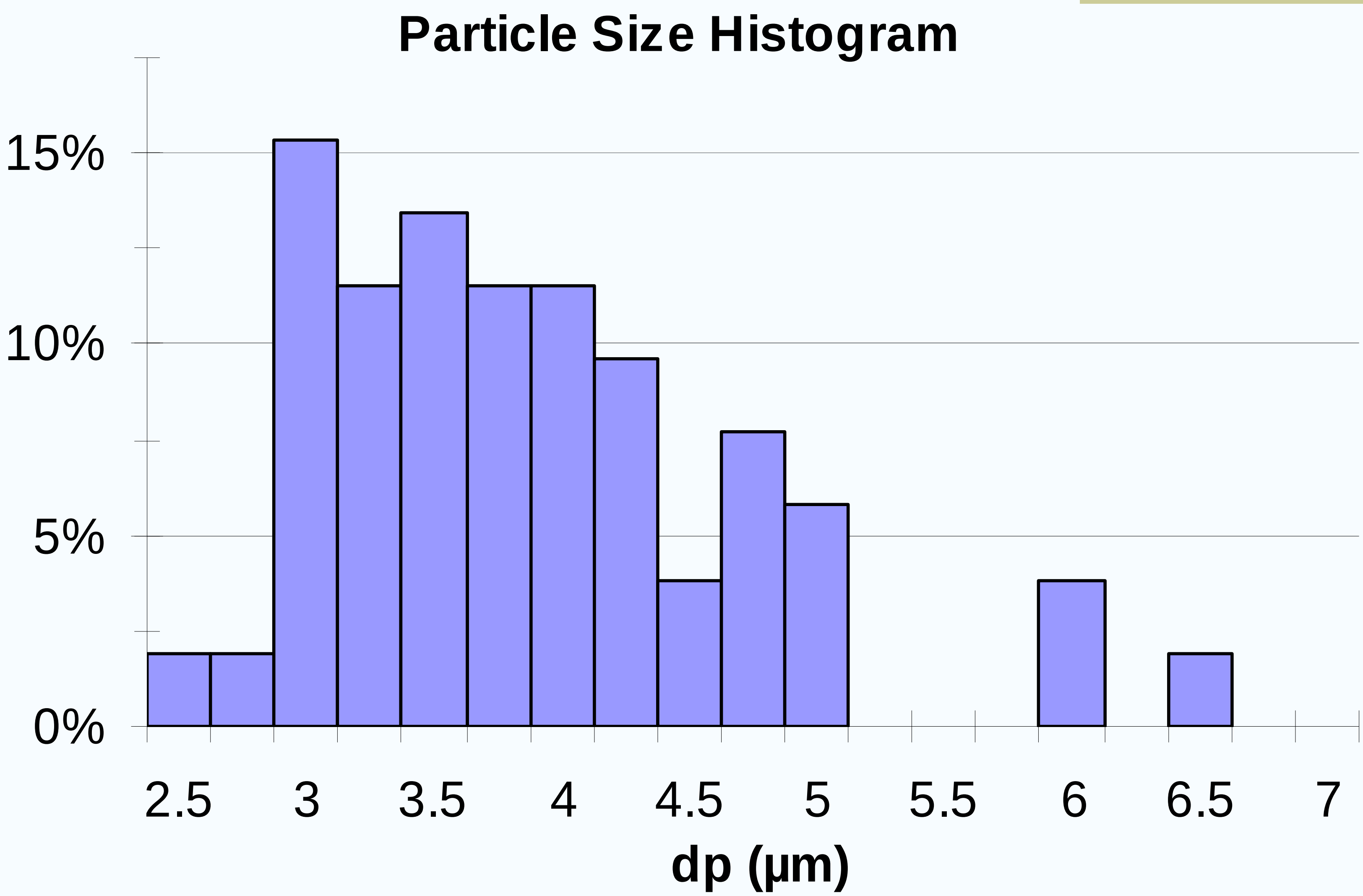
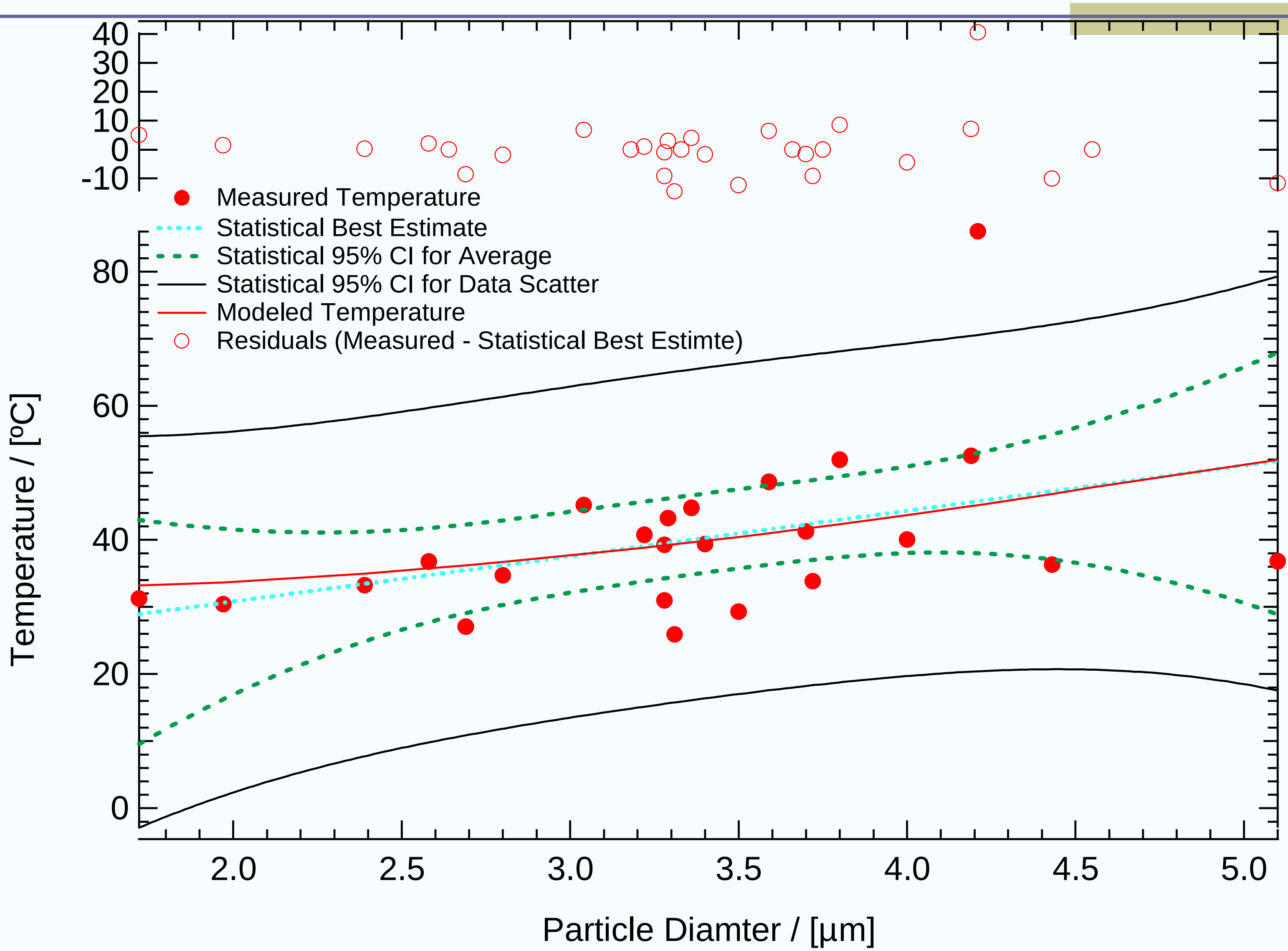
- Matlab detects particle edge at 20% of maximum pixel intensity
- Sums number of pixels and determines diameter corresponding to cross-sectional area

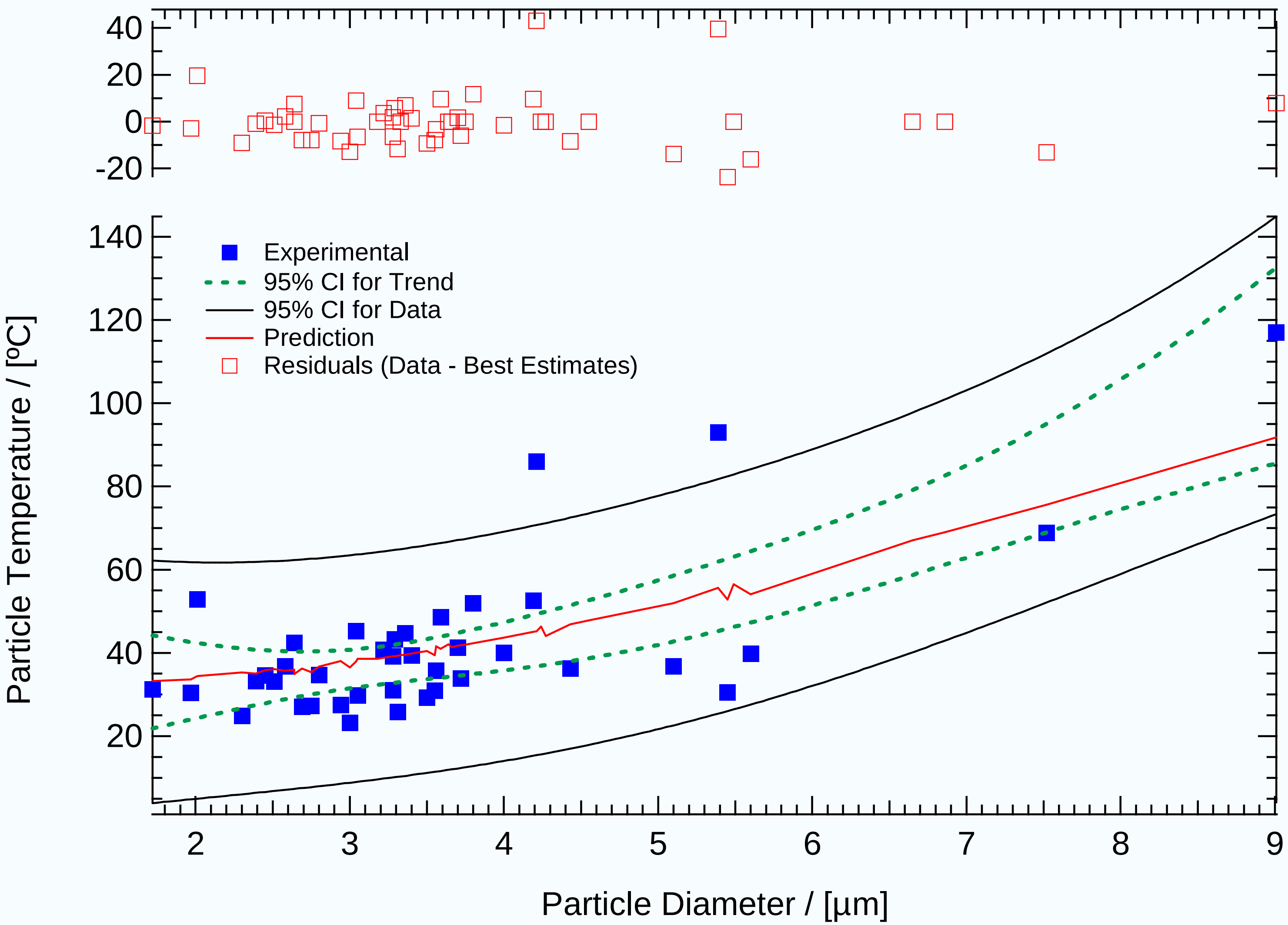
Particle Size Results



Verification Results



Validation Results



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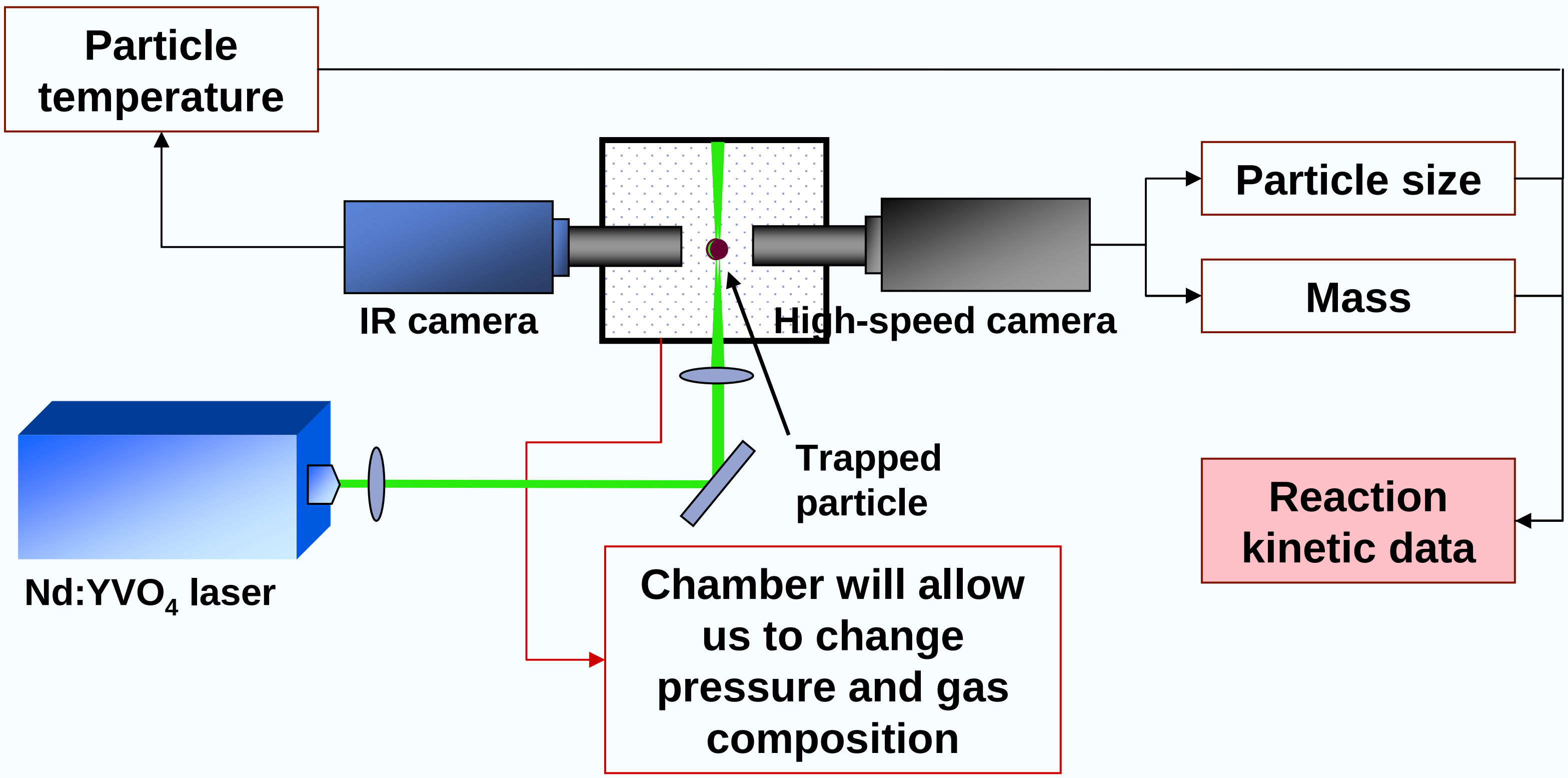


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Possible Limitations

- **Limitations**
  - Particle size
  - Studies may be limited to char particles in some cases
  - Cannot simulate boiler conditions

Advantages/Application

- **Advantages**
  - Single particle studies
  - Distinguish changing reactivities
  - Access to gas pressure and composition regimes previously difficult to study
  - Enable studies of reaction kinetics at conditions similar to commercial processes (gasification, oxyfuel)
- May be used to study light scattering, thermobaric weapons

Acknowledgments

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Levitation Model

- For a given d_p, Φ_p, *and* r_c
- Estimate ω_o
- Determine T_p from energy balance:
  - $T_p(\Phi_p, I, d_p)$
- Determine F_{drag} and F_{photon}:
  - $F_{drag}(\Phi_p, T_p)$
  - $F_{photon}(\Phi_p, I, d_p)$
- Iterate until $\Sigma F = F_{mg} + F_{drag} + F_{photon} = 0$

- Φ_p = particle optical/physical properties