Optical Levitation of Absorbing Particles for Fuels Characterization

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Overview

- Why study single particles?
- Project background and objectives
- Experimental methods
- Experimental observations
- Particle levitation model
  - Drag force model
  - Photon force model
- Particle diagnostics

Background

- Millikan oil drop experiment (1909)
  - Suspended oil droplets between electrical plates to measure the charge of an electron
    - Experiment actually performed by Harvey Fletcher (PhD student, 1st Dean of College of Eng. at BYU)
- Electrodynamic levitation
  - Initially developed by Ezra Bar-Ziv and Adel Sarofim to do combustion studies
  - Charged particles trapped in an electrodynamic chamber
    - Particles lose their charge at elevated temperatures

Background

- 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
  - Not necessary to charge particles
  - To date, no mechanism has been established

Background

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

Project Objectives

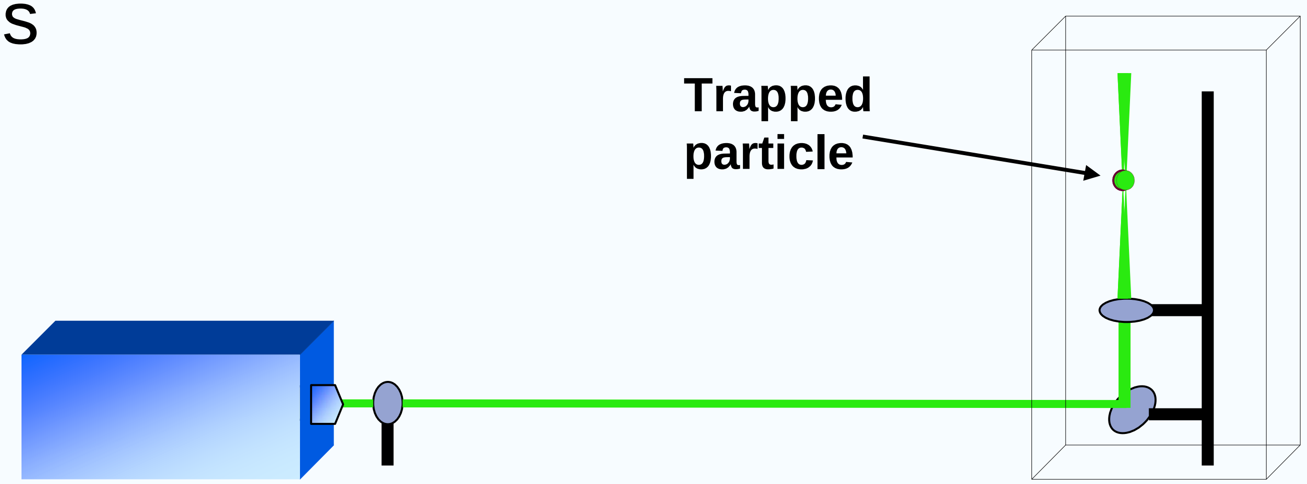
1) Explain opaque-particle trapping mechanism

2) Observe and model particle properties as functions of time during combustion

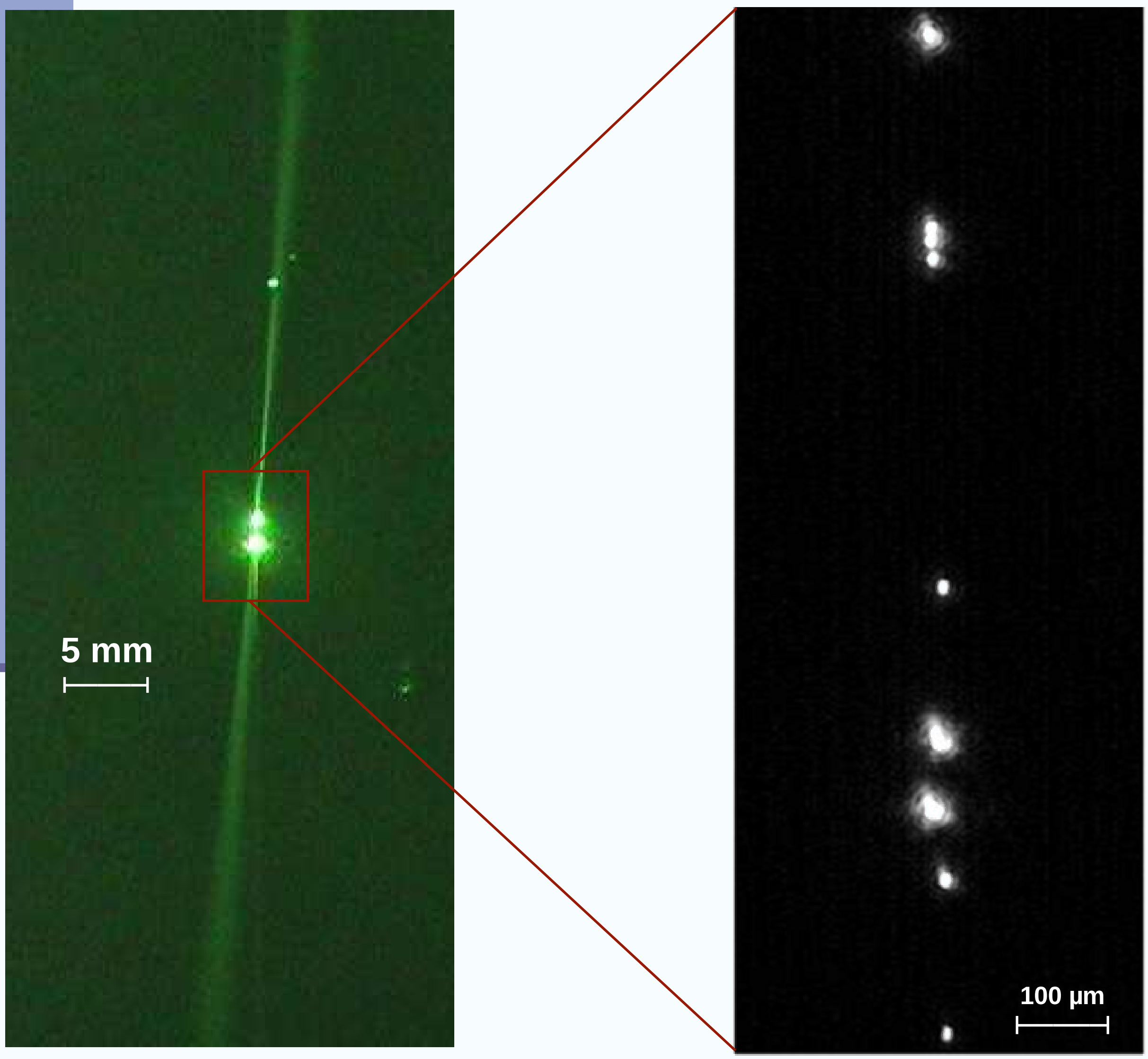
3) Develop *in situ* diagnostic technique for fuels characterization

Experimental Methods

- 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

- Particles with higher emissivities and lower densities levitate more easily
- 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, and black liquor

Particle Levitation Model

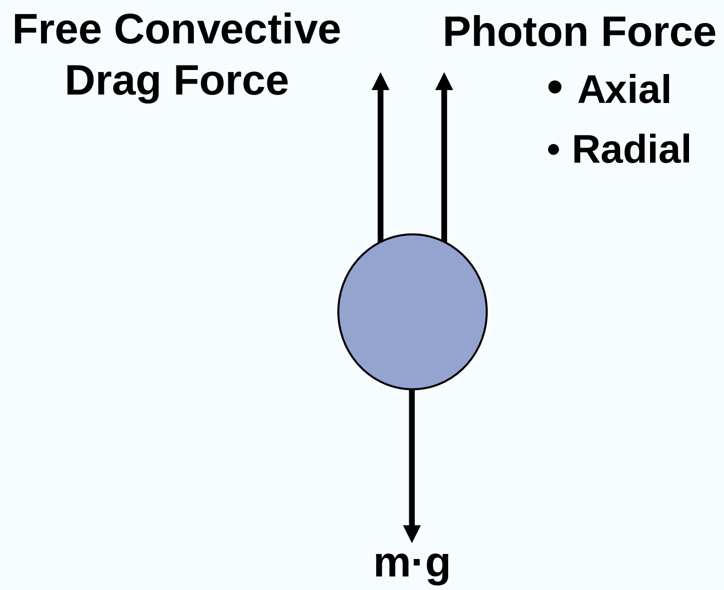
Energy Balance

- 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

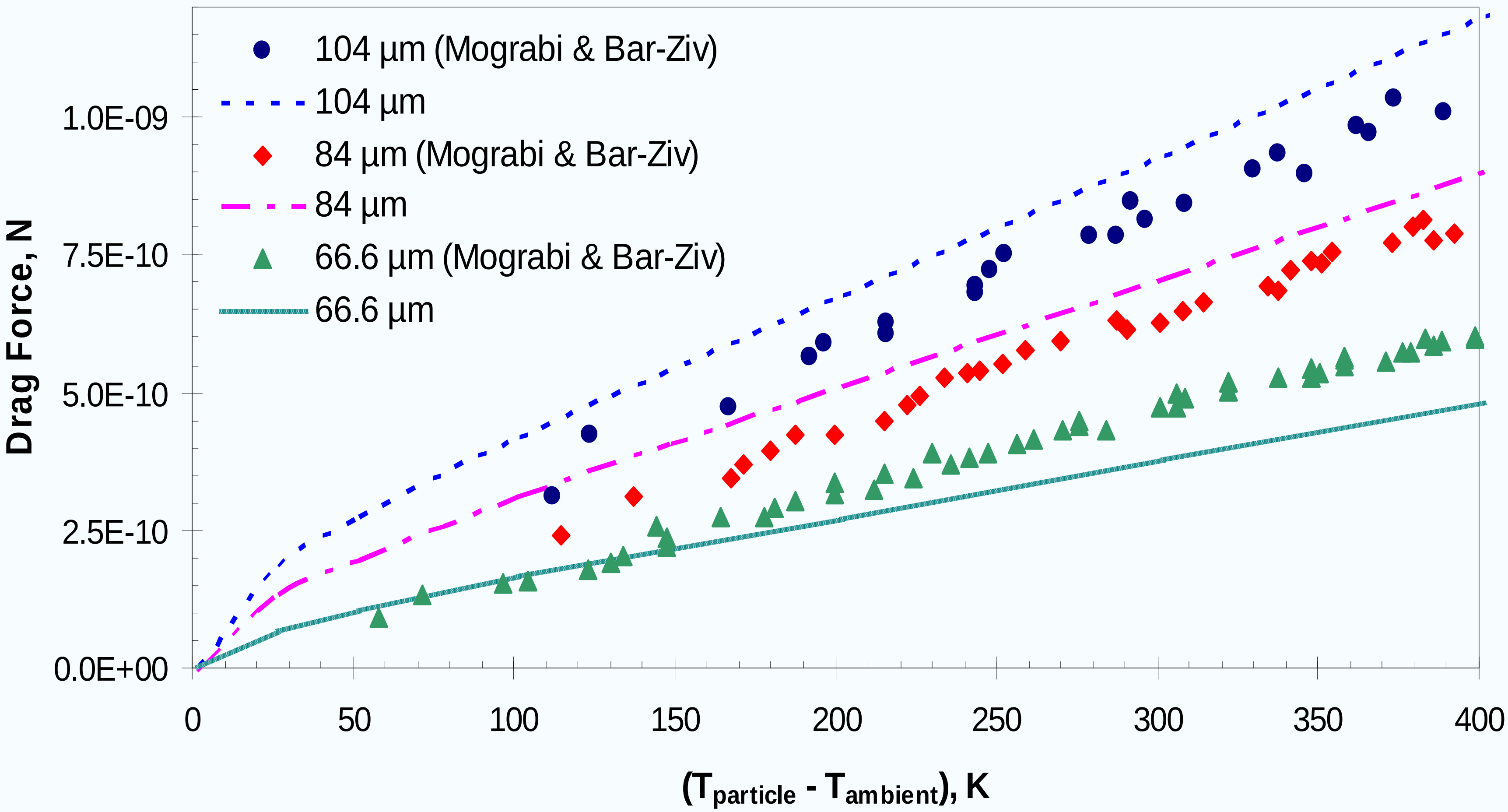
- Two major forces counteract gravity:
  1) Free convective drag force
  2) Photon force



Drag Force Model

- Free convective drag
  - Particle heats up due to incident laser light inducing a convective flow around the particle
  - This flow generates a natural convective drag force
- 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)

Drag Force Model vs. Data

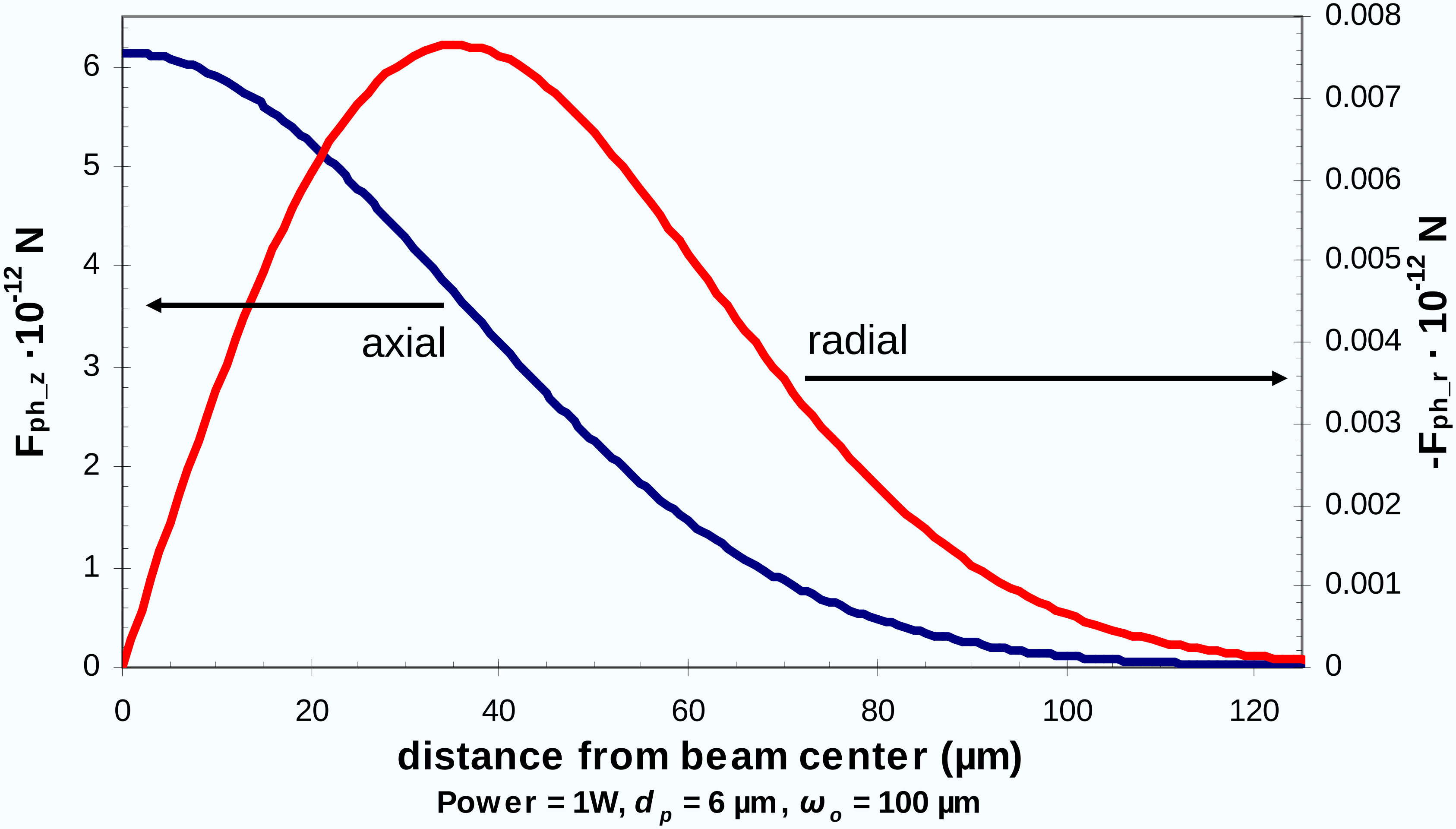


Comparison of Fluent™ predictions with experimental results of the free-convective drag force (Mograbi & Bar-Ziv, 2005)

Photon Force Model

- Each incident photon transfers momentum equal to *h/λ*
  - Function of d_{p}, laser intensity, and scattering properties
- Estimated by Amsterdam Discrete Dipole Approximation (ADDA)
  - Axial component
    - Always in direction of beam propagation
  - Radial component
    - Acts as a restoring force – pulls particles to center of beam

Photon Force Model

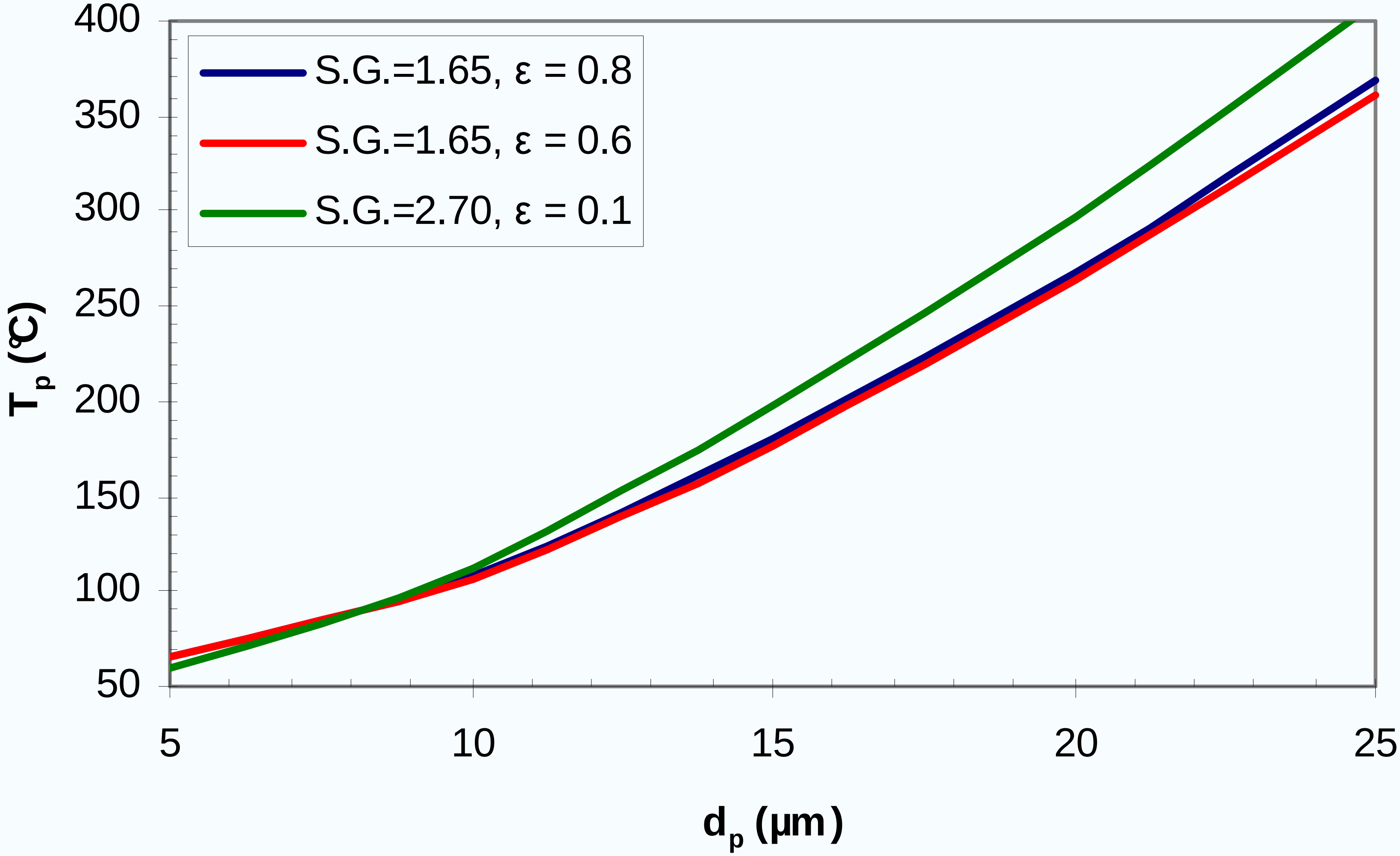


Levitation Model

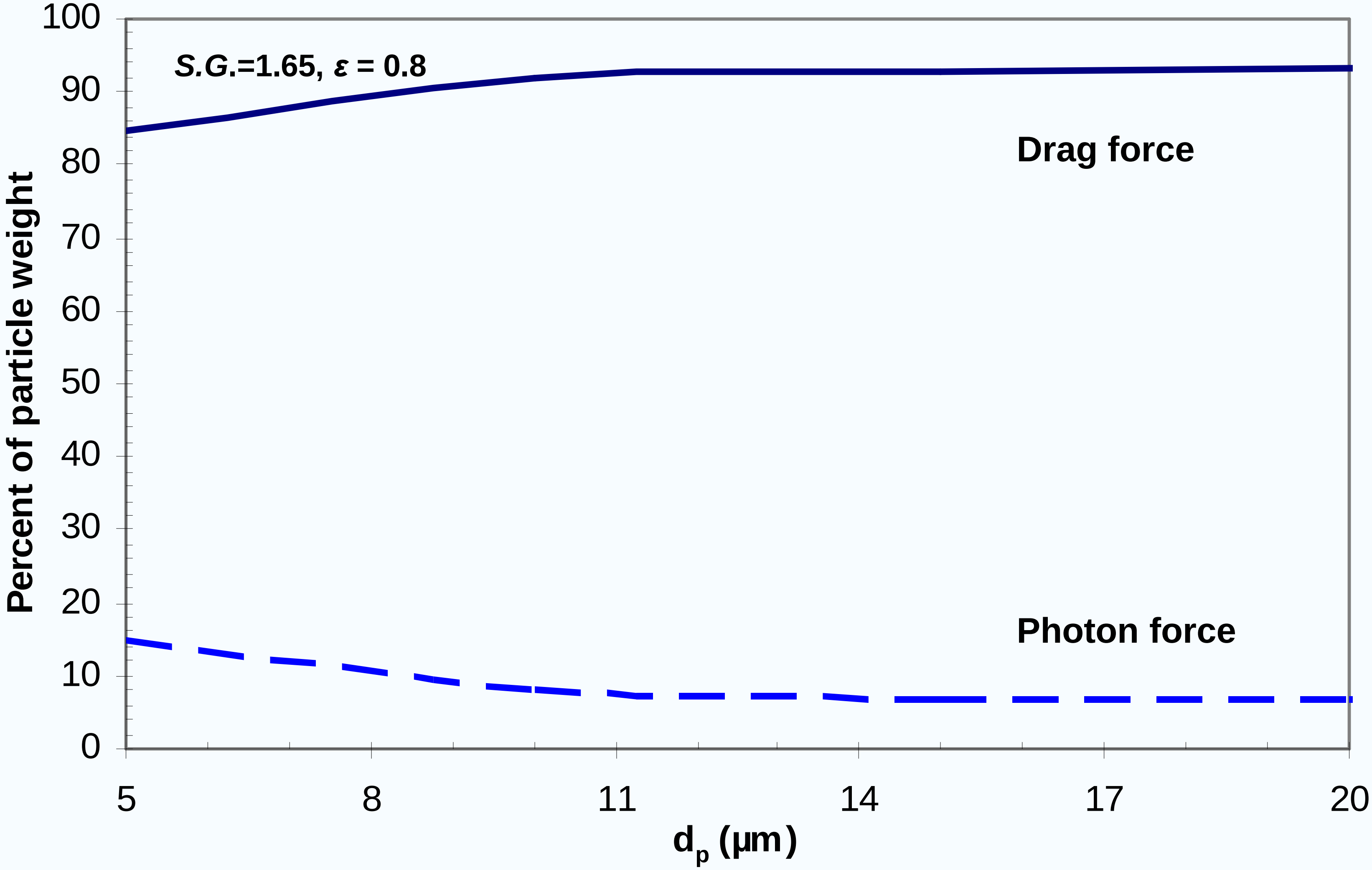
- For a given d_p
- Estimate laser intensity ($\omega_o \rightarrow I$)
- Determine T_p from energy balance:
  - $T_p(\Phi_p, I, d_p)$
- Determine F_{drag} and F_{photon}:
  - $F_{drag}(\Phi_p, T_p)$
  - $F_{photon}(\Phi_p, I, d_p)$
- Iterate until $\Sigma F = F_{mg} + F_{drag} + F_{photon} = 0$

  - Φ_p = particle optical properties

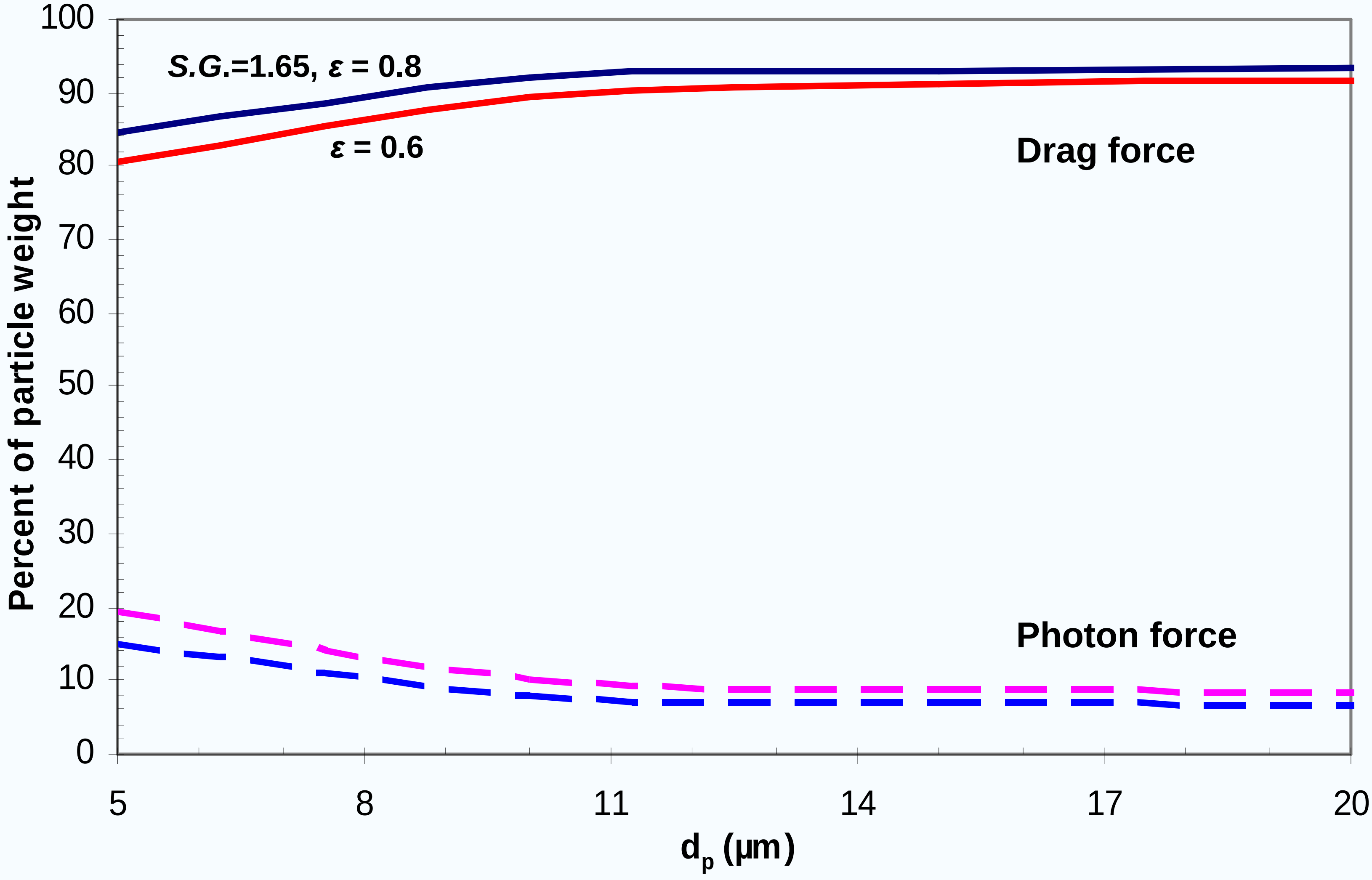
Levitation Model Predictions



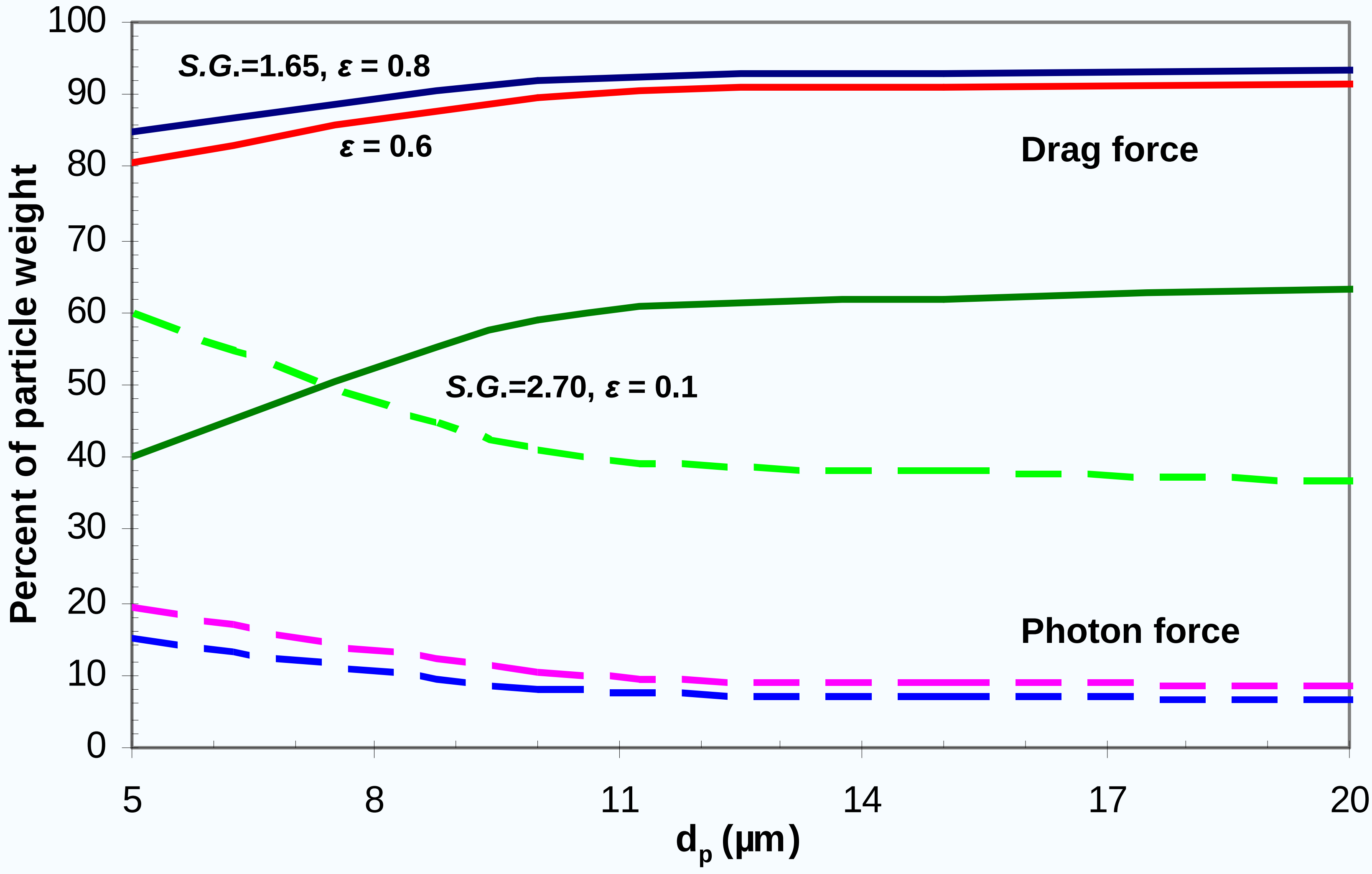
Levitation Model Predictions



Levitation Model Predictions



Levitation Model Predictions

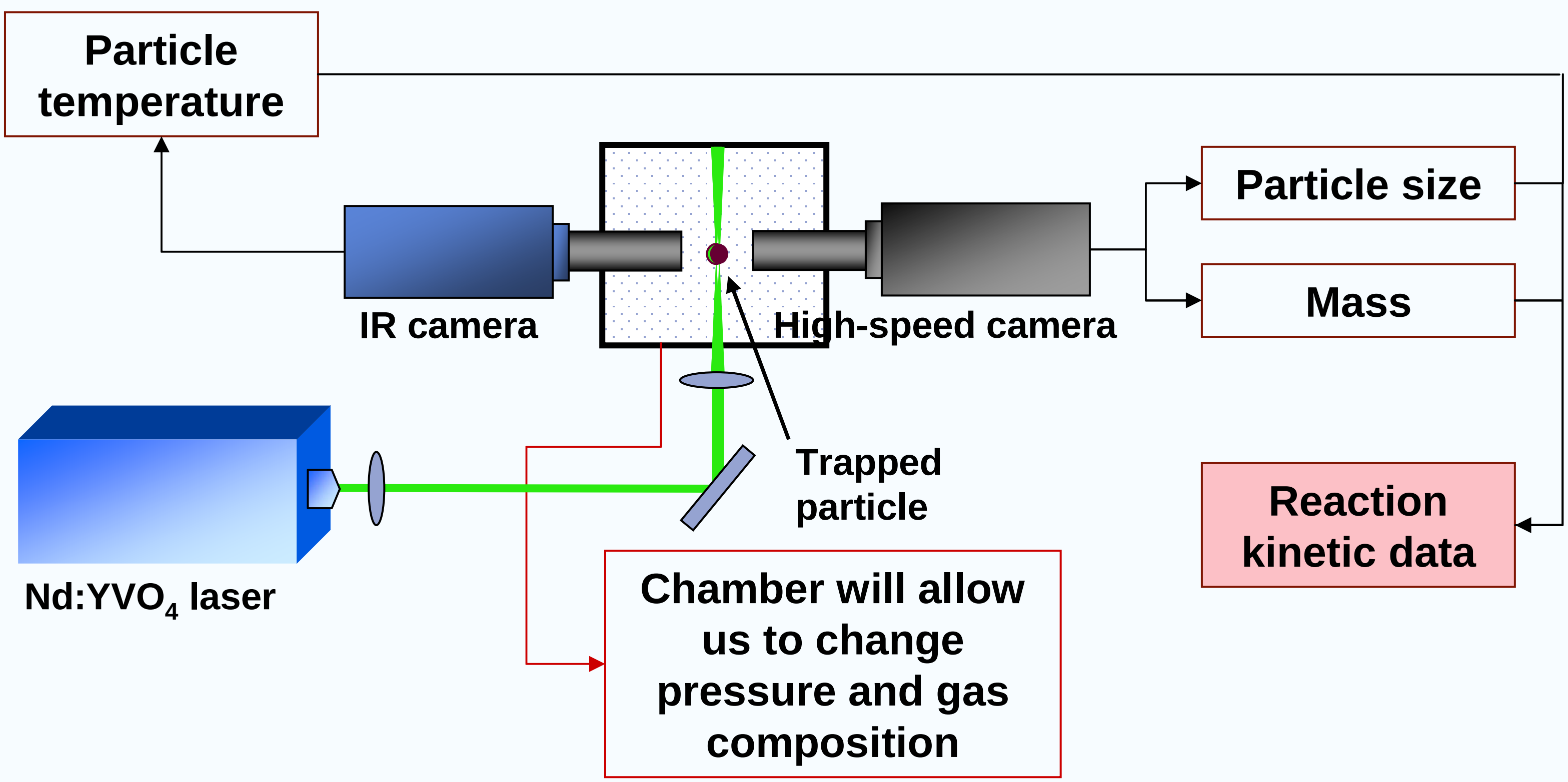


Levitation Model Conclusions

- Particle temperature is only a function of particle properties
  - A given particle reaches the same temperature regardless of overall beam power
- Drag force dominates trapping mechanism at high emissivities
- Importance of photon force decreases as particle size and emissivity increase
- Particles less than 25 µm in diameter do not react significantly without external heating

Diagnostic Tool

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

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Conclusion/Application

- Established comprehensive optical trapping mechanism
- How can we use this information?
  - Diagnostic may provide more accurate, cheaper, safer, and faster access to gas pressure and composition regimes previously difficult to study
  - Possibly most significant is the possibility of studying reaction kinetics at conditions similar to commercial processes (gasification, oxyfuel)

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