

Droplet condensation/evaporation in a turbulent free shear flow: mixing-induced supersaturation and inertial droplet dynamics at the turbulent/non-turbulent interface

SAND2016-4854C

ICMF 2016

Florence, Italy
May 26, 2016

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Turbulent Condensation

- Turbulent condensation is a relatively common phenomenon
- Jet is quite inhomogeneous in the instantaneous sense
- Non-linear effects at the turbulent/non-turbulent interface
- Results in complex droplet diameter distributions that are relevant to additional dynamics
- Goal is to bridge the gap between simple models and DNS



PDF Method

- Probability density function (PDF) methods were developed as an alternative method to model turbulence
- Theory for determining velocities is not widely adopted
- Composition PDF is used because it allows scalars/reactions to be treated explicitly
 - Use traditional CFD for velocity field, but PDF for scalar advection

Computational Algorithm

- Stochastic particle advection

$$dx_i = u_i dt + \frac{1}{\langle \rho \rangle} \frac{\partial \Gamma}{\partial x} dt + \left(\frac{1}{\langle \rho \rangle} \Gamma \right)^{0.5} dW_i$$

- Stochastic particle mixing (modified Curl's method)

- Number of particles to mix

$$C_\phi N \omega dt$$

- Degree of mixing is random

- Cell balancing

- Particles must be split combined to maintain appropriate count

- Particle flux at the domain

- Thermodynamics

- Supersaturation-driven growth or shrinkage of droplets

Diameter Growth/Shrinkage

- Supersaturation is computed

- Water vapor pressure

$$\log_{10} p_{sat} = A - \frac{B}{C + T}$$

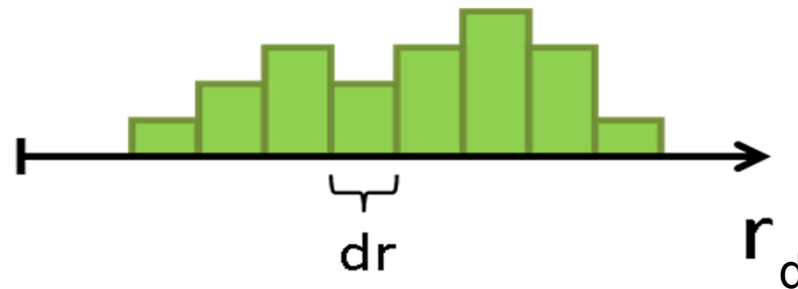
- Supersaturation

$$s = \frac{p_v}{p_{sat}} - 1$$

- Droplet growth is computed via multi-step Runge-Kutta

$$\frac{dr}{dt} = \gamma \frac{s}{r}$$

- Droplets are redistributed such that water droplet volume is conserved

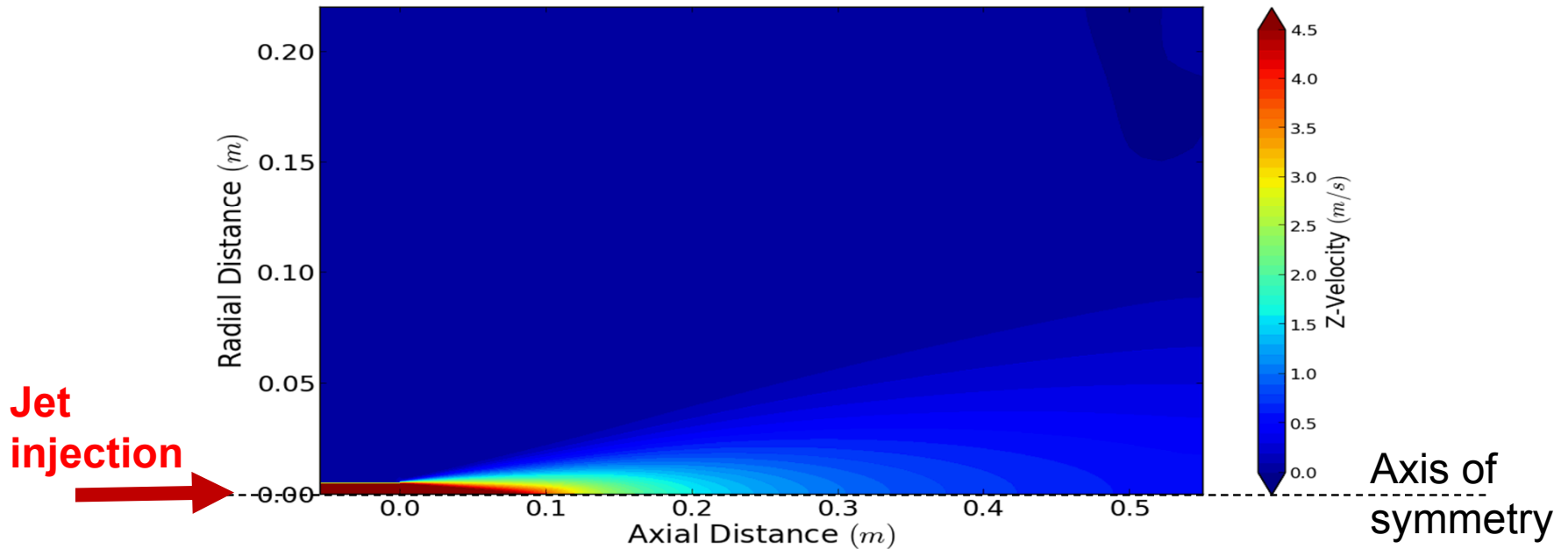
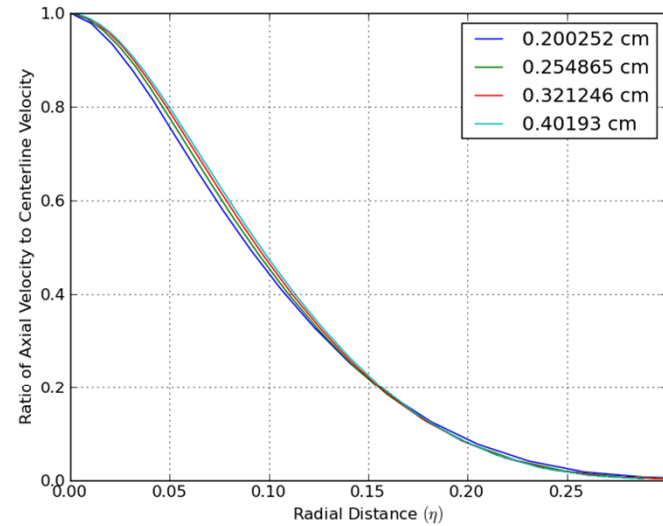
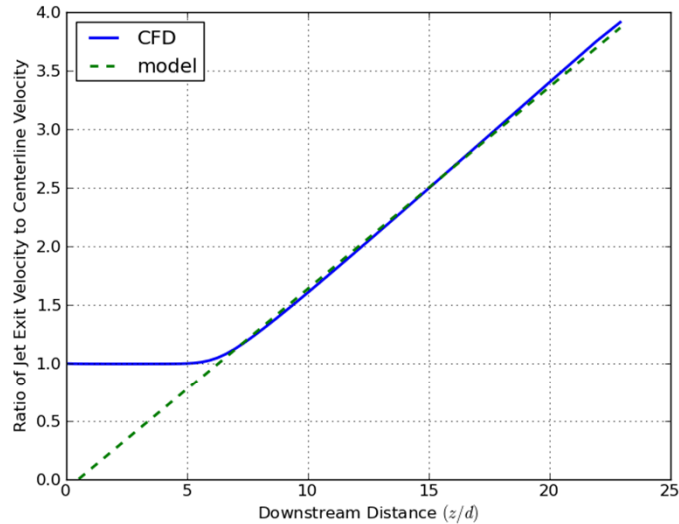


Computation with GPU

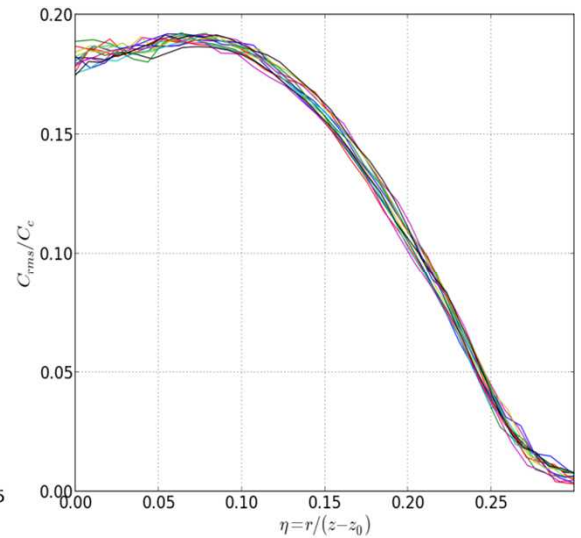
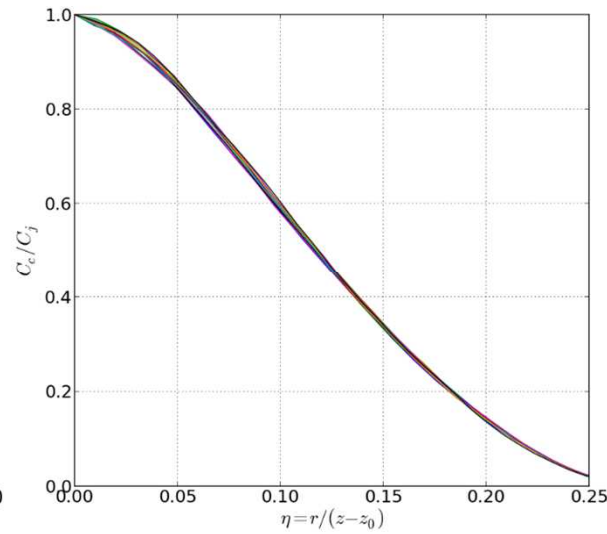
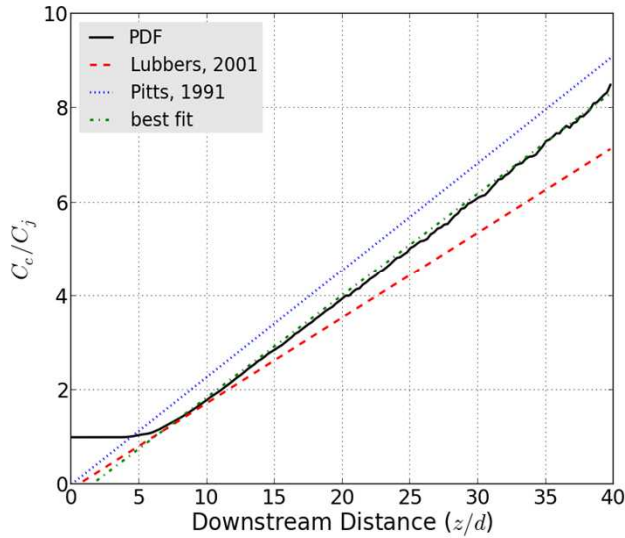
- Problems well-suited to being solved with Graphical Processing Units (GPUs)¹
 - Computational requirements are large
 - Parallelism is substantial
 - Throughput is more important than latency
- Lagrangian Monte Carlo particle code hits all three points

¹ Owens, et al (2008), *GPU Computing*.

OpenFOAM Results



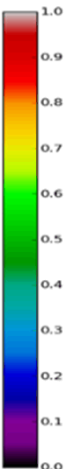
Scalar Transport Validation



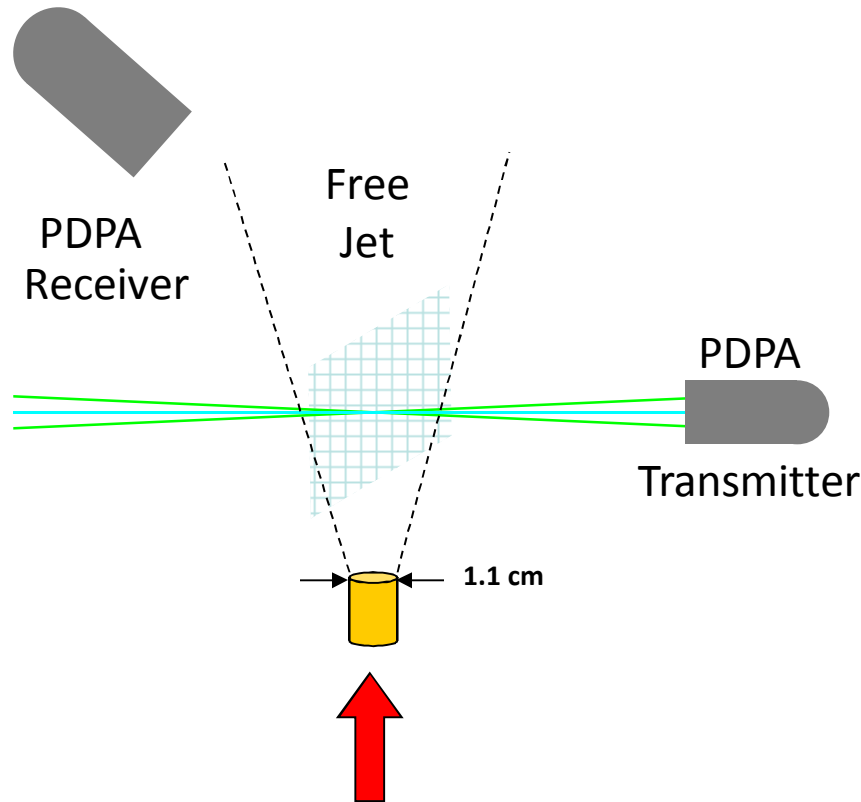
Jet injection →



Axis of symmetry

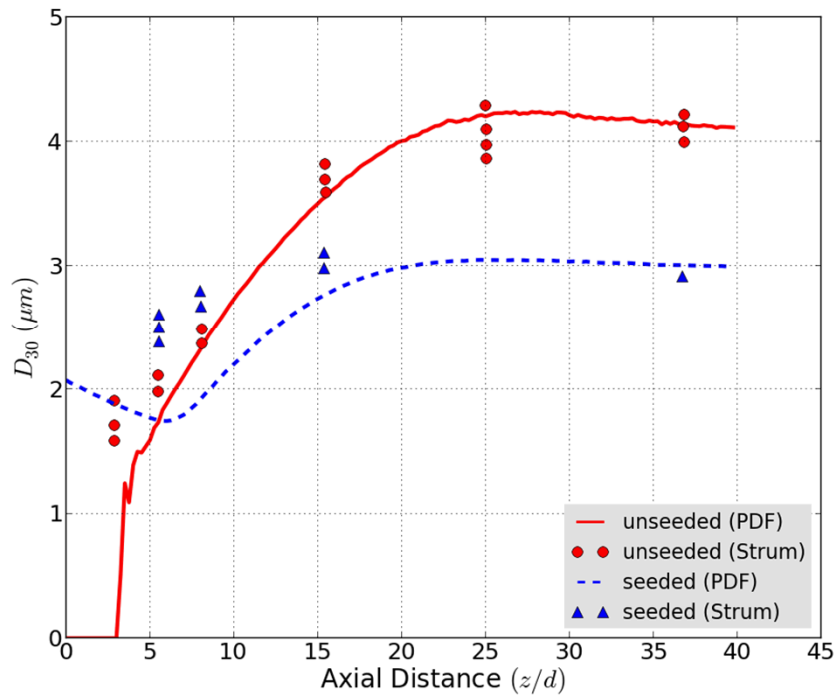


Strum & Toor Experiments

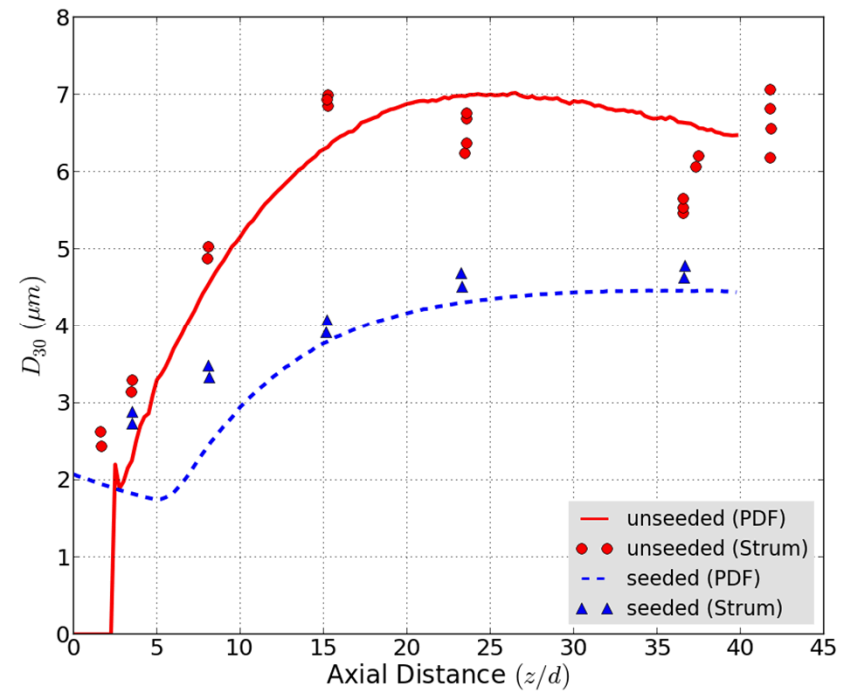


- Emerging jet had 100% humidity
 - 85 °C
 - 62 °C
- Measurements taken at various radial and axial locations
 - Development region as well as near-field

D_{30} Comparison

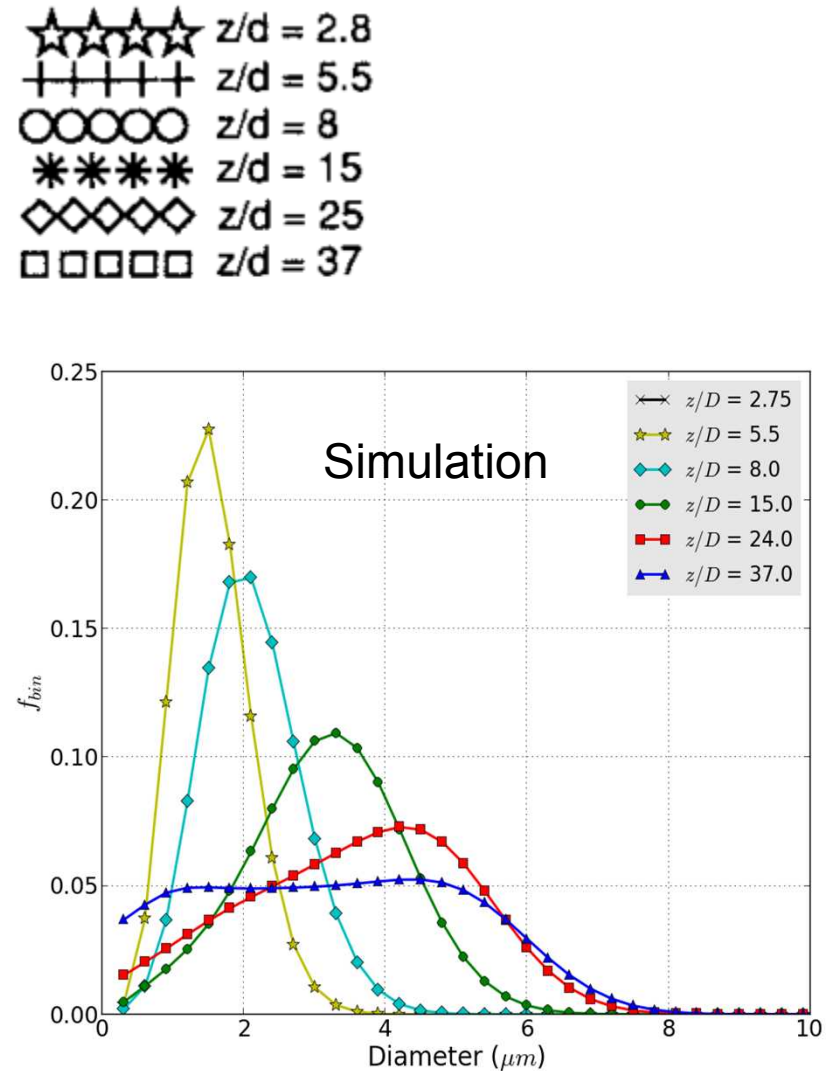
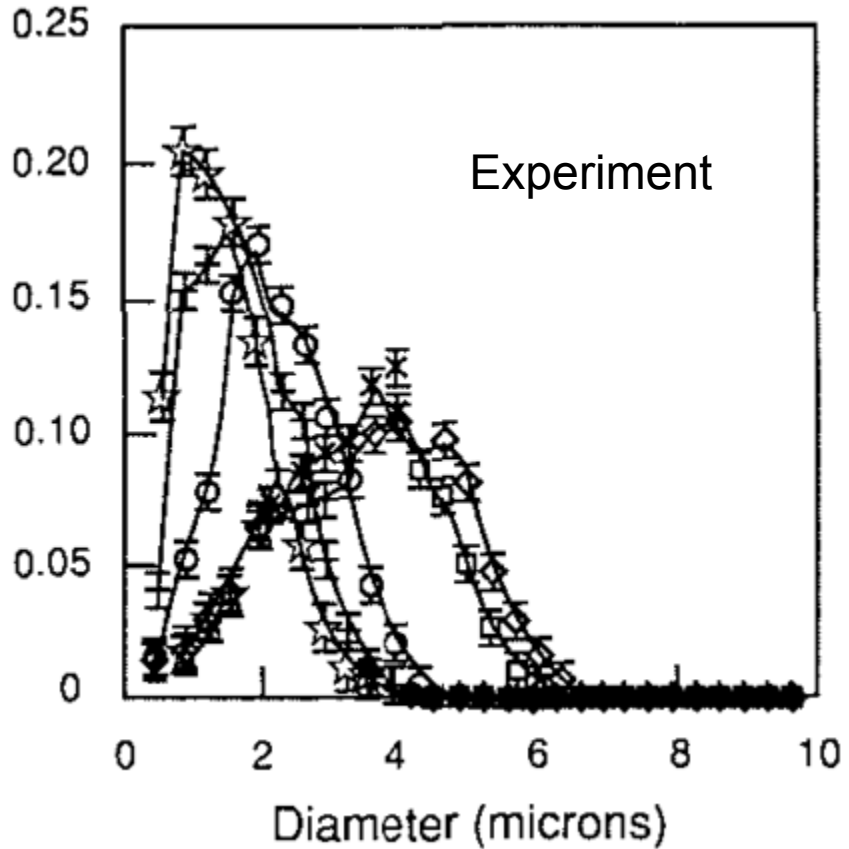


62 °C

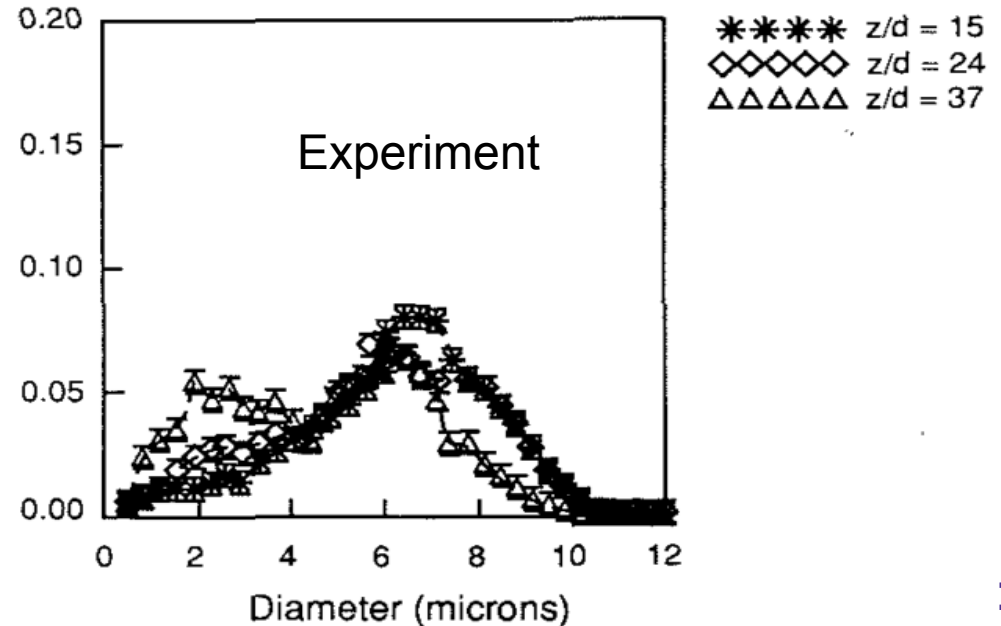
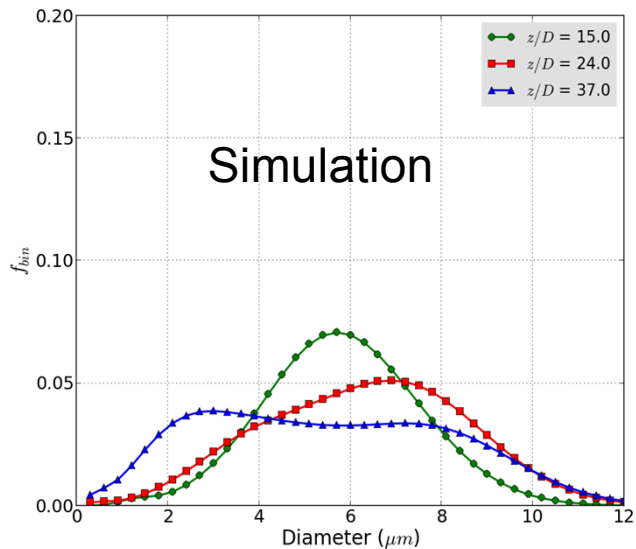
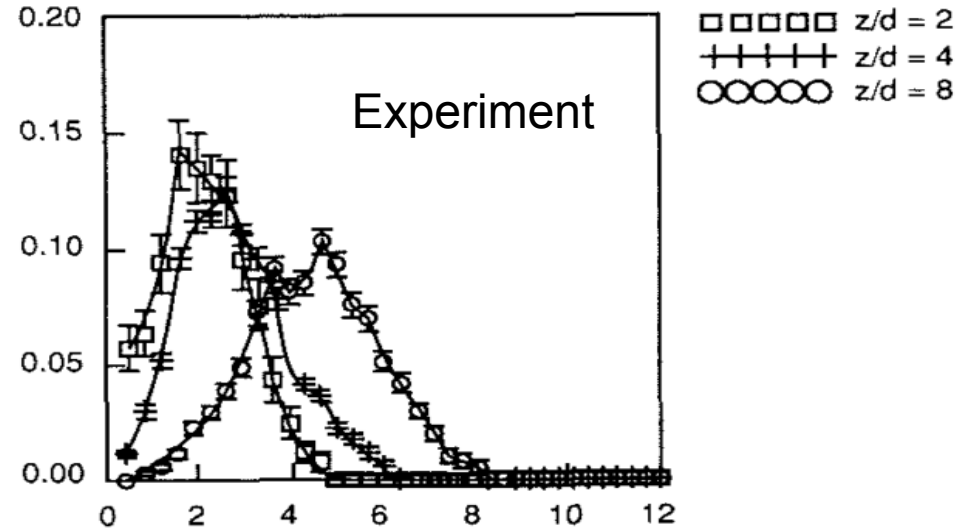
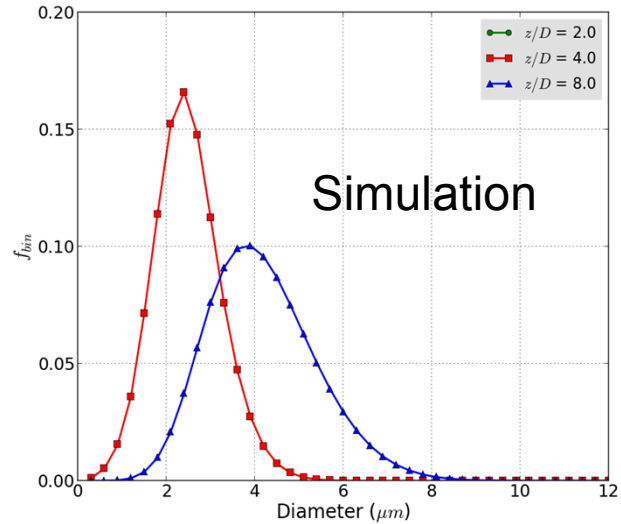


85 °C

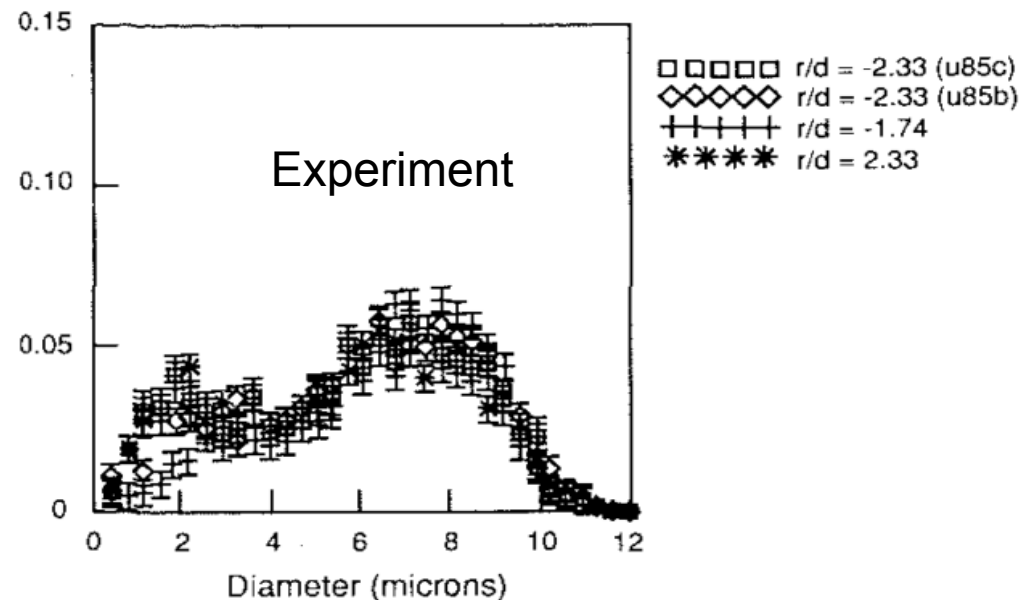
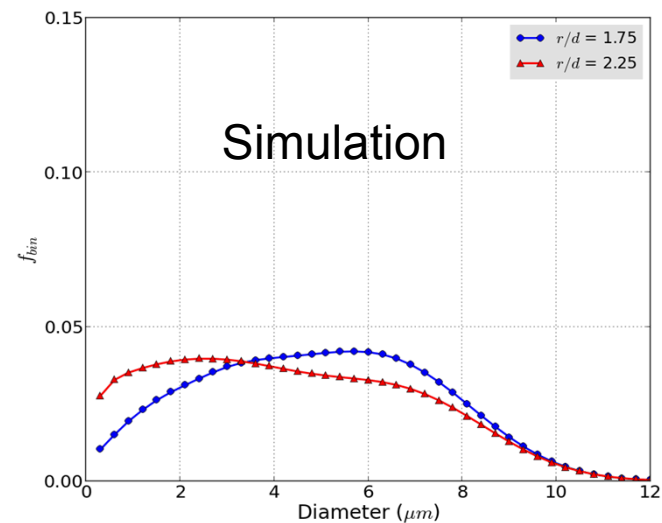
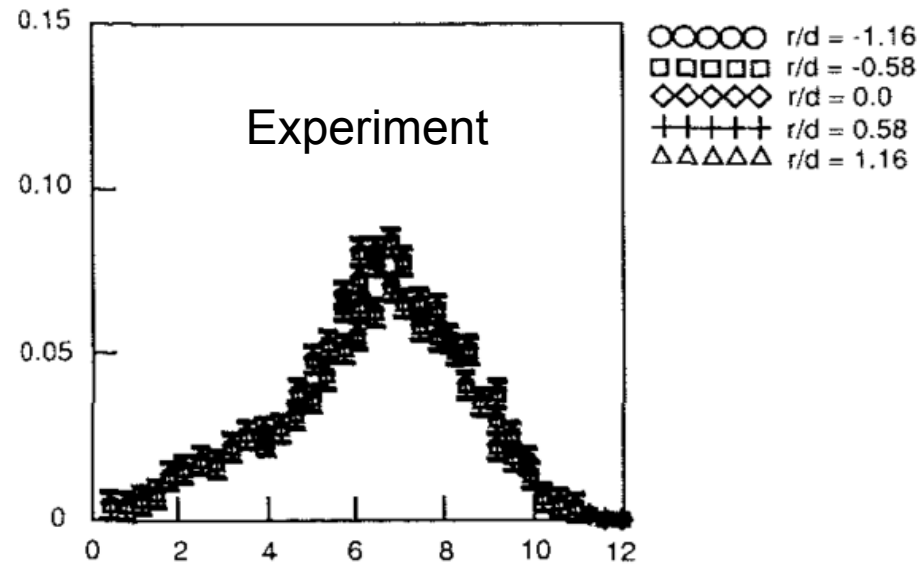
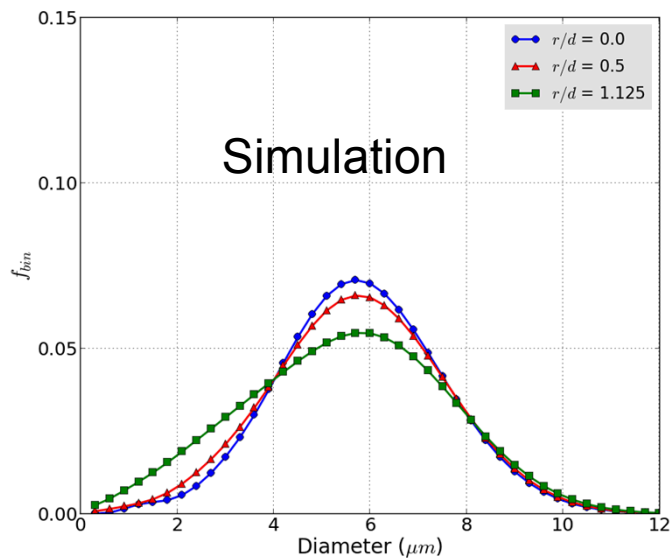
62 °C Turbulent Jet



85 °C Turbulent Jet



85 °C Turbulent Jet ($z/d=15$)



Conclusions & Future Work

- PDF composition method used to model turbulent condensation
 - Monte Carlo approach is implemented
 - Particle thermodynamics tracked with enthalpy
- Speed-up with GPU is considerable ($\sim 30x$)
- Possibilities for future code improvements
 - 3-D
 - Flexible meshing/discretization
 - Coupling with flow solver
 - Different evolving quantities

Monte Carlo Treatment

- Continuous PDFs are represented as an computational particles
 - Stochastic particles are advected through the domain
 - Each particle is a different realization of the flow
- Each particle tracks a diameter-discretized distribution of water droplets
- Domain is subdivided into particle-containing cells