SAND2014-20245C

PDF Study of Round Turbulent Condensing Jet using GPU Hardware

APS DFD 2014
November 25, 2014

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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

Thermodynamics

- Particles are assumed to have constant enthalpy between mixing events
- Total enthalpy consists of three components:

$$h_p = (1-x)c_{cp}T + (x-x_l)(c_{pw}T + h_{we}) + x_l c_w T$$

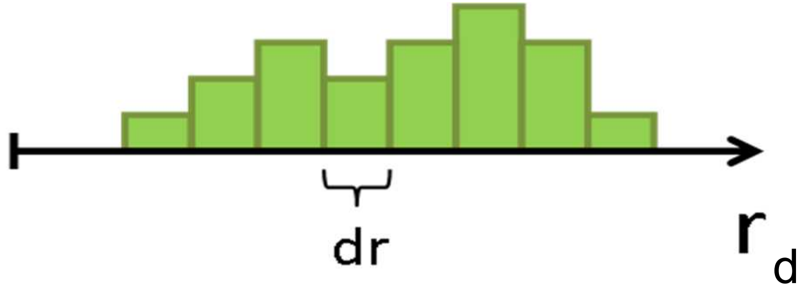
air — water vapor — liquid

- Temperature is function of the fraction of condensed water

$$T = \frac{h_p - (x-x_l)h_{we}}{(1-x)c_{pa} + (x-x_l)c_{pw} + x_l c_w}$$

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

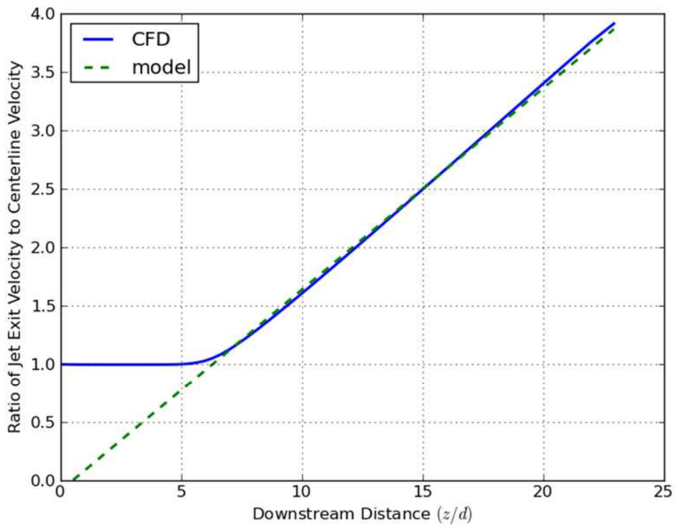


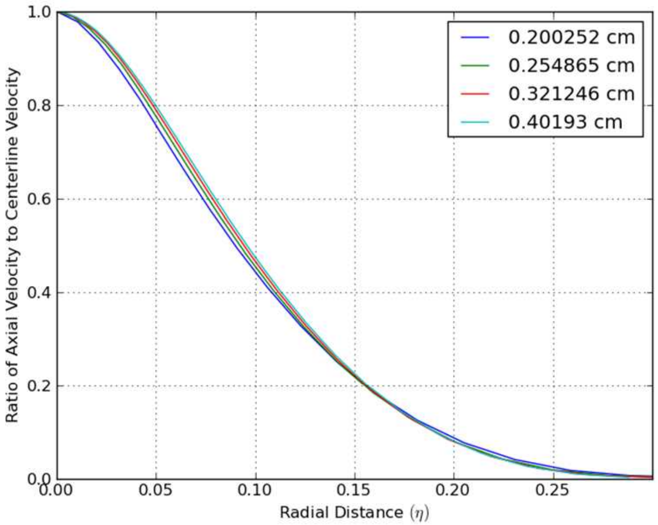
Computation with GPU

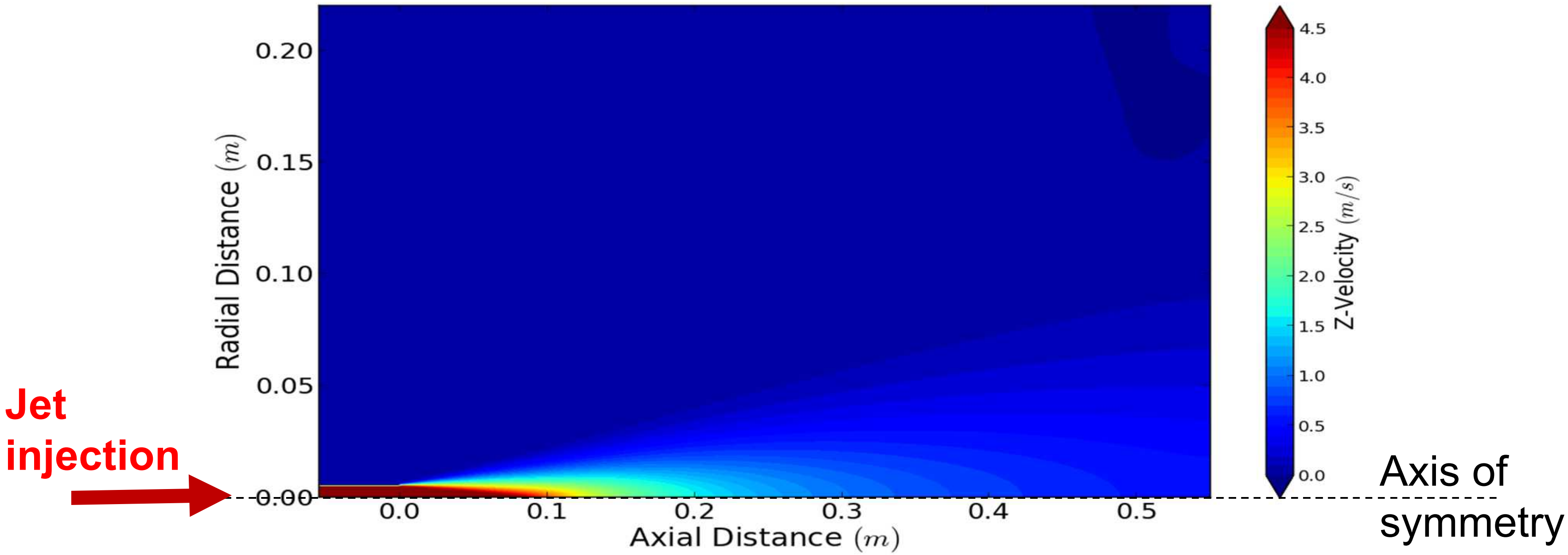
- Problems well-suited to being solved with Graphical Processing Units (GPUs)[1]
  - Computational requirements are large
  - Parallelism is substantial
  - Throughput is more important than latency
- Lagrangian Monte Carlo particle code hits all three points

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

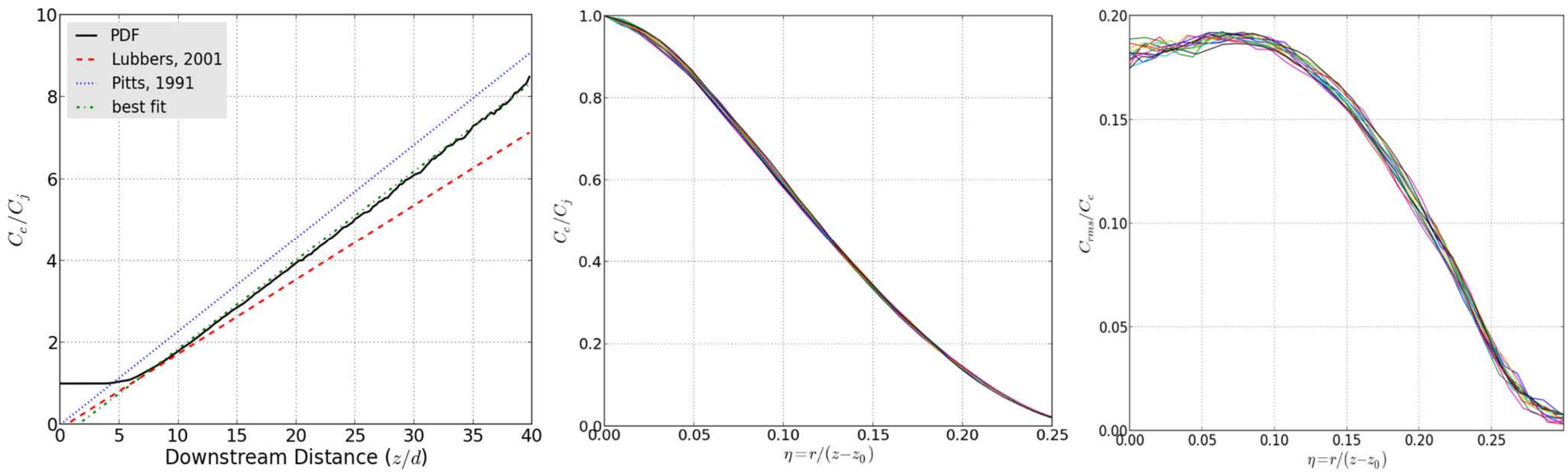
OpenFOAM Results



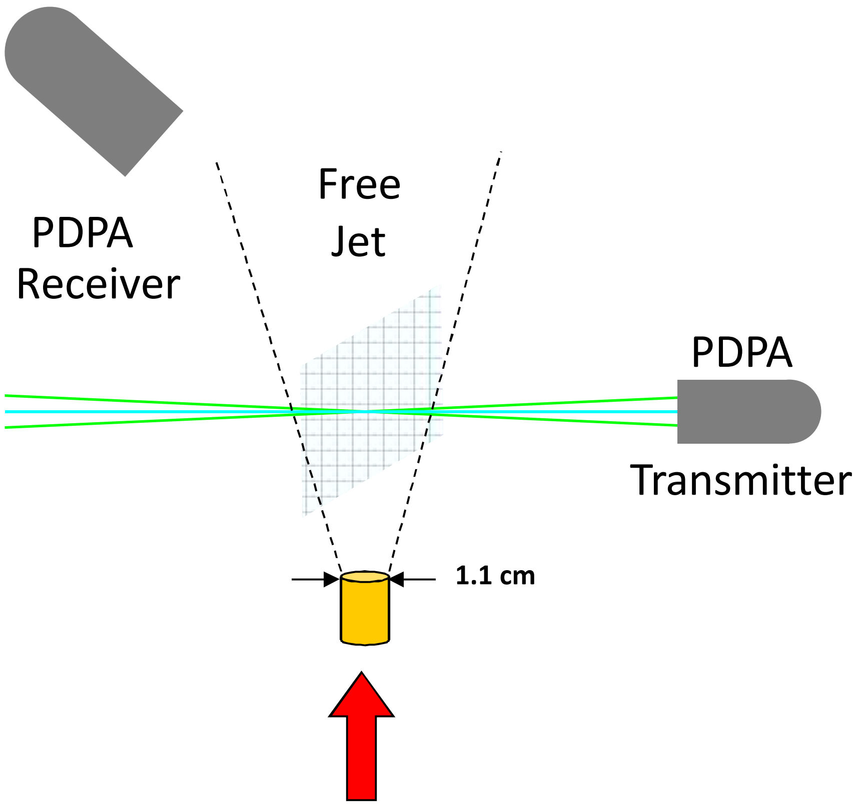




Scalar Transport Validation



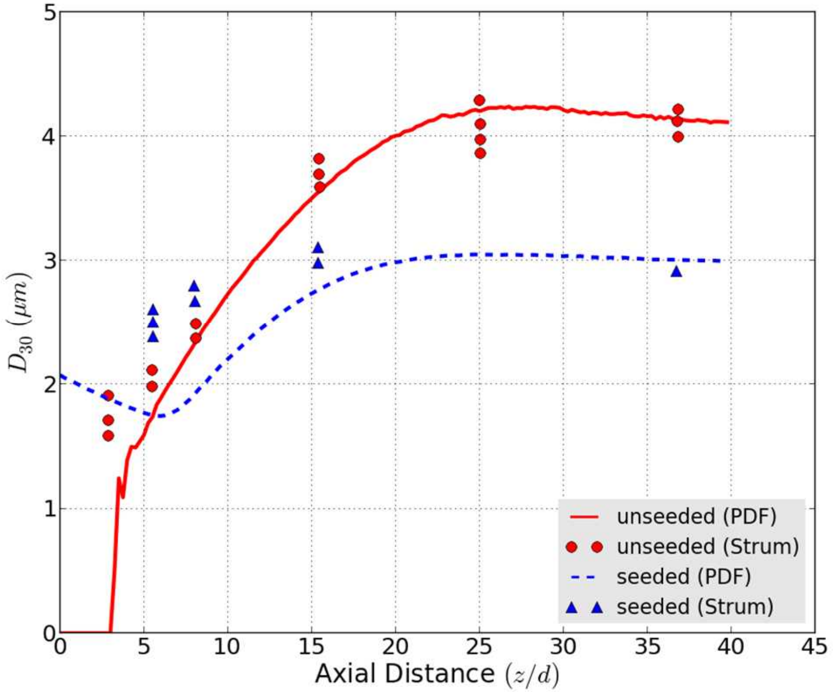
Strum & Toor Experiments



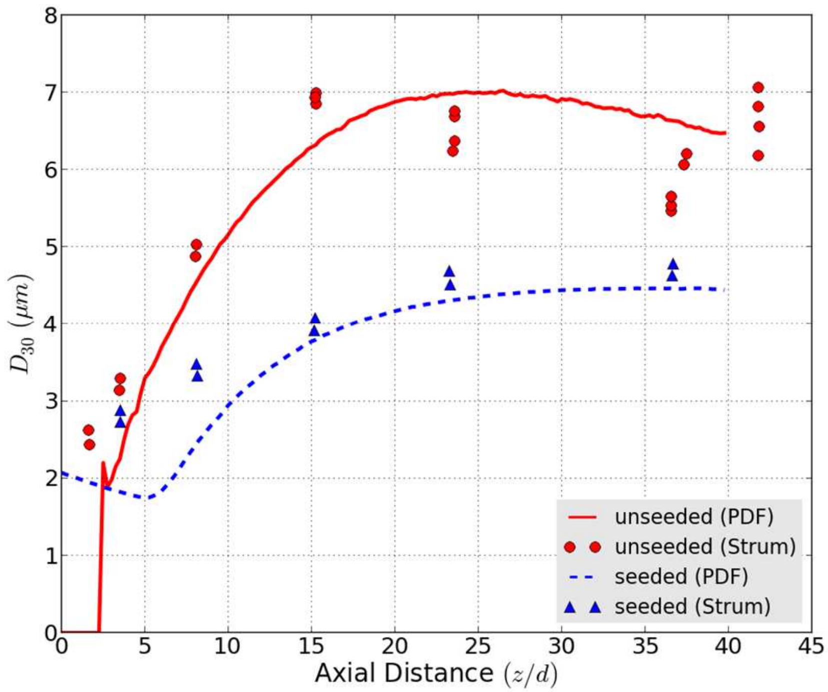
- Emerging jet had 100% humidity
  - 85 °C
  - 62 °C
- Measurements taken at various radial and axial locations
  - Development region as well as near-field

from Strum & Toor, 1992

D_{30} Comparison

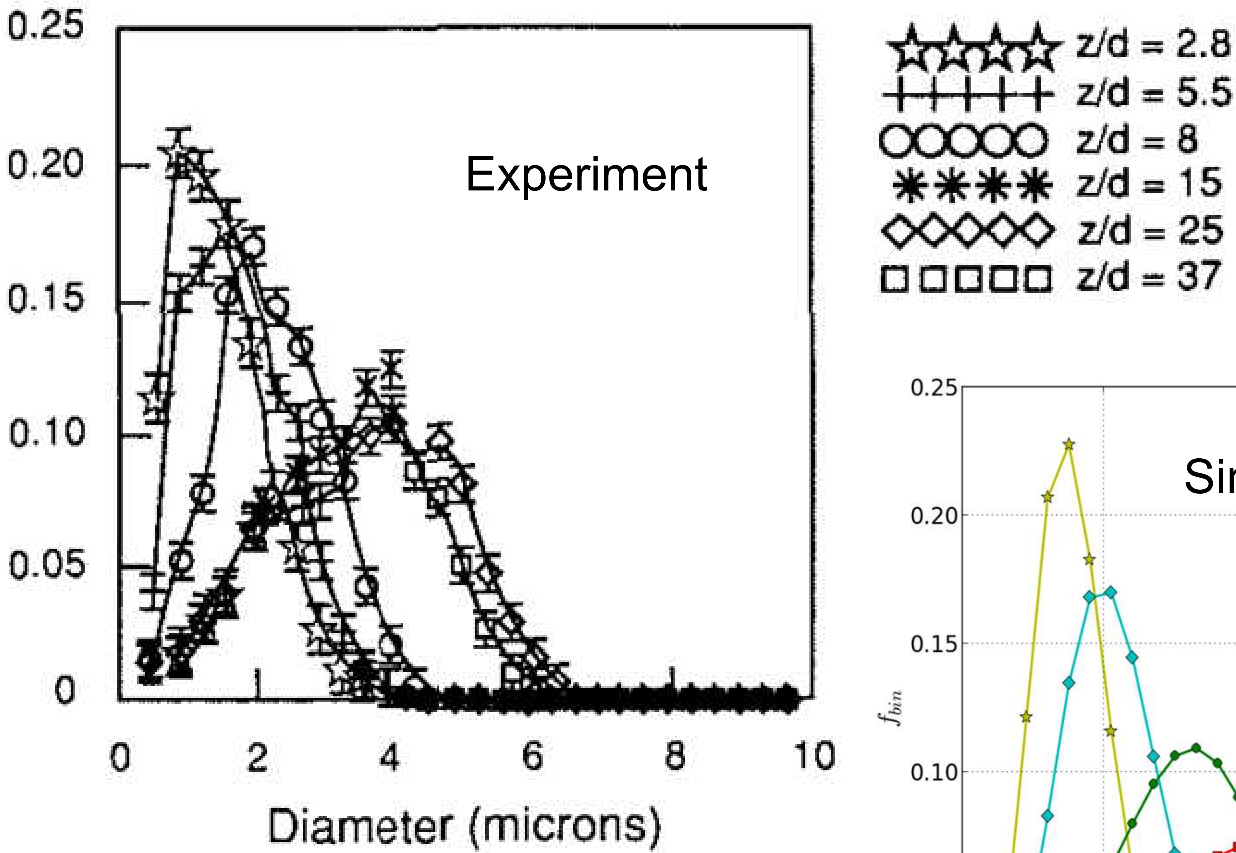


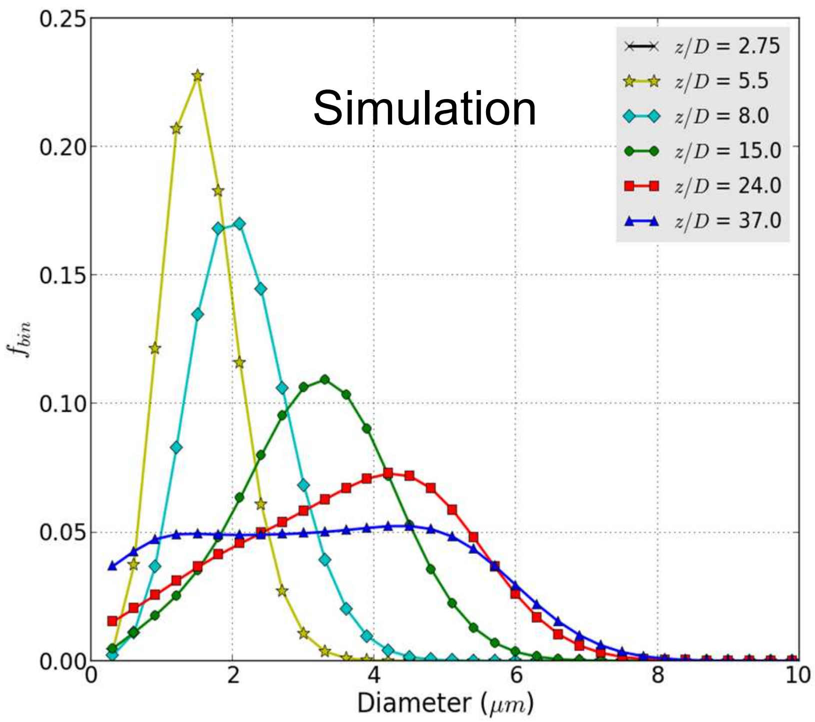
62 ºC



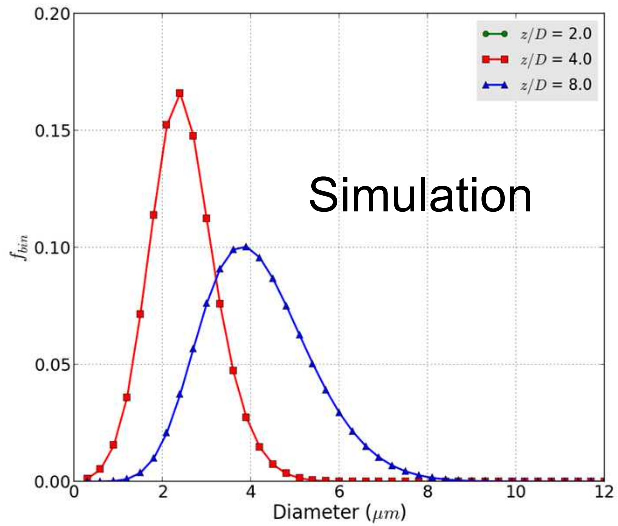
85 ºC

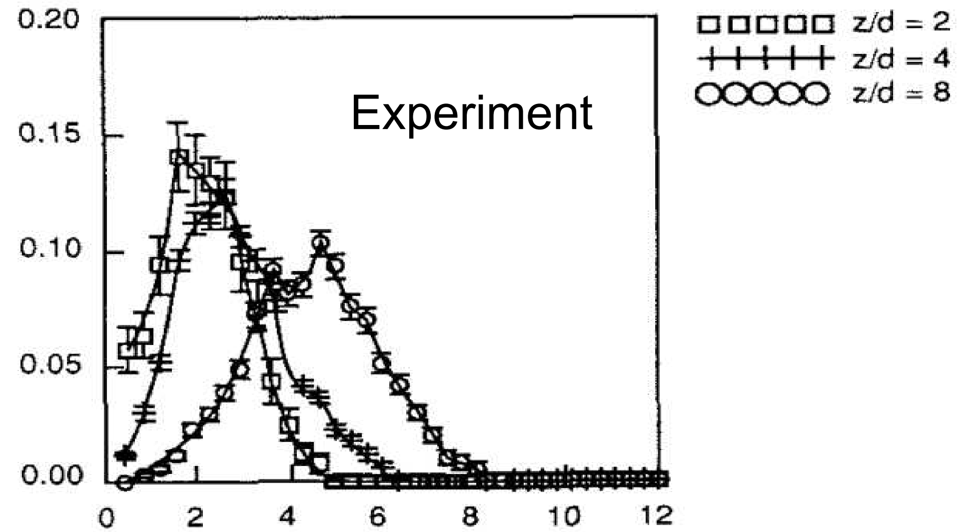
62 °C Turbulent Jet

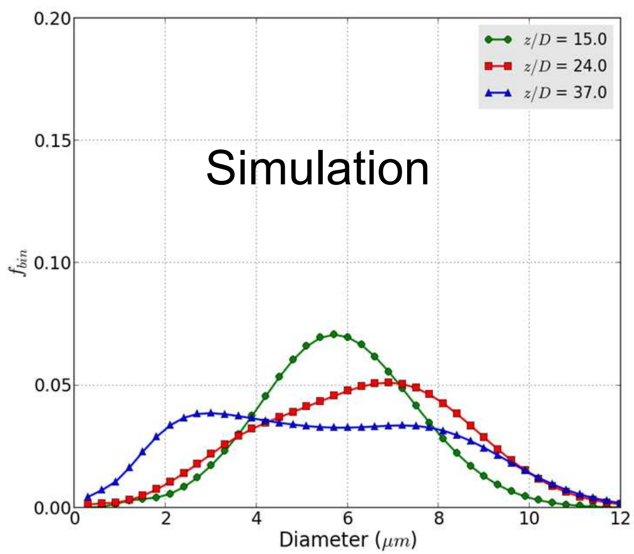


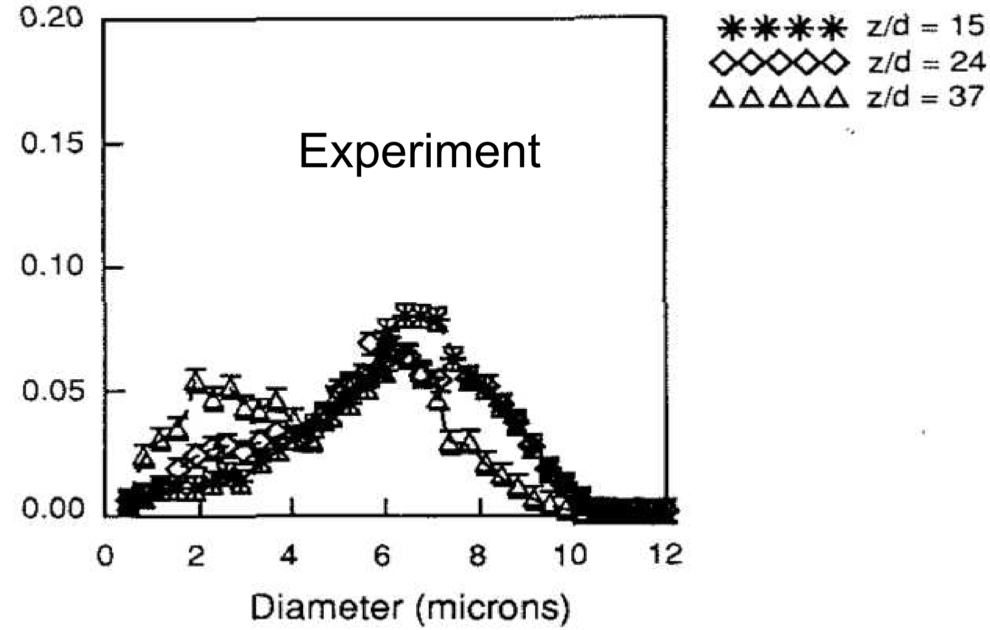


85 ºC Turbulent Jet

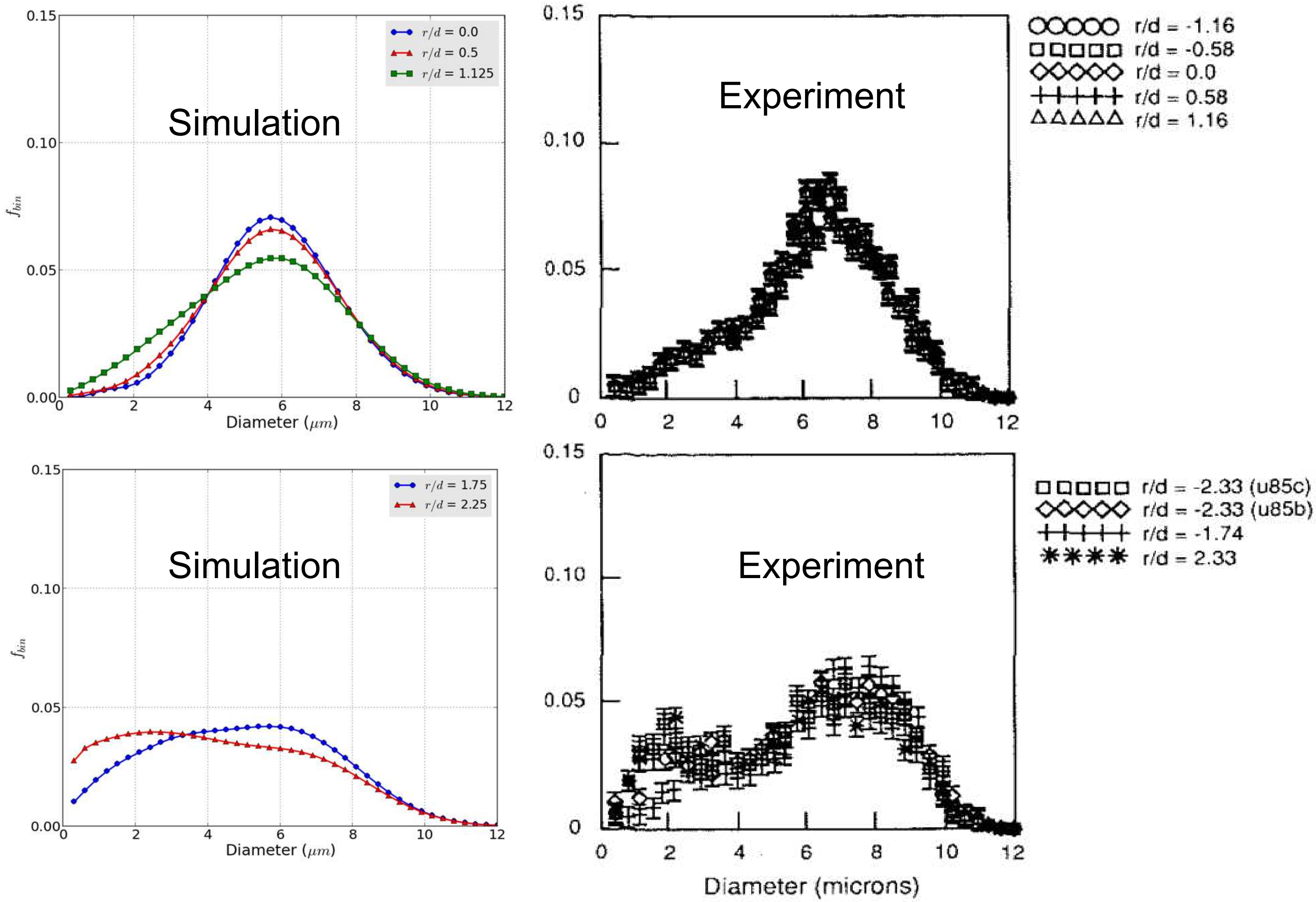








85 ºC Turbulent Jet (z/d=15)



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 (~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