Recent Activities in the Flowphy Project

Effect of Droplet Size and Breakup on Spray Shape: A Priori Study Using Large-Eddy Simulation

Aalto-yliopisto
Teknillinen korkeakoulu

V. Vuorinen, H. Hillamo, O. Kaario and M. Larmi
Internal Combustion Engine Research Group
Department of Energy Technology, TKK

Tekes

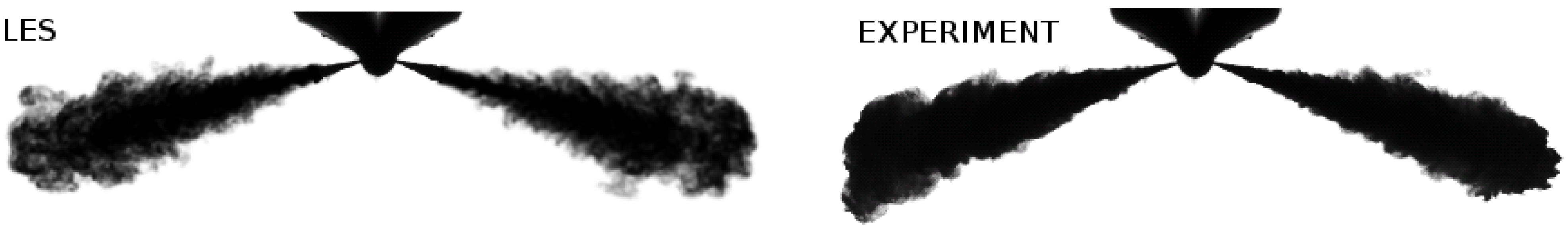
MASI

IEA Task Leader's Meeting, Nara, Japan, July 2010

Other Recent Work

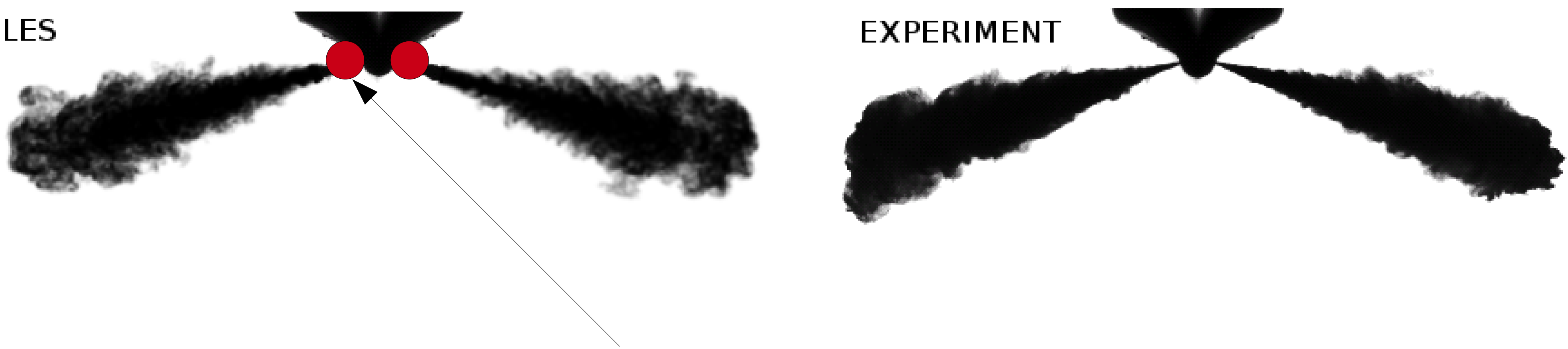
- Hillamo et al. *Diesel Spray Visualization and Shockwaves, Atomization and Sprays*, **20**, 3, 177-189, (2010).
- Vuorinen et al. *Large Eddy Simulation of Droplet Stokes Number Effects on Turbulent Spray Shape*, Atomization and Sprays, **20**, 2, 93-114, (2010).
- Vuorinen et al. *Large-Eddy Simulation of Droplet Stokes Number Effects on Mixing in Transient Sprays*, Atomization and Sprays, in Print (2010).
- Vuorinen, *LES of Certain Droplet Size Effects in Fuel Sprays*, PHD Thesis (2010).
- Hillamo, *Diesel Spray Measurements*, PHD Thesis, to be defended (2011).

Qualitative Comparison of LES and Experiments



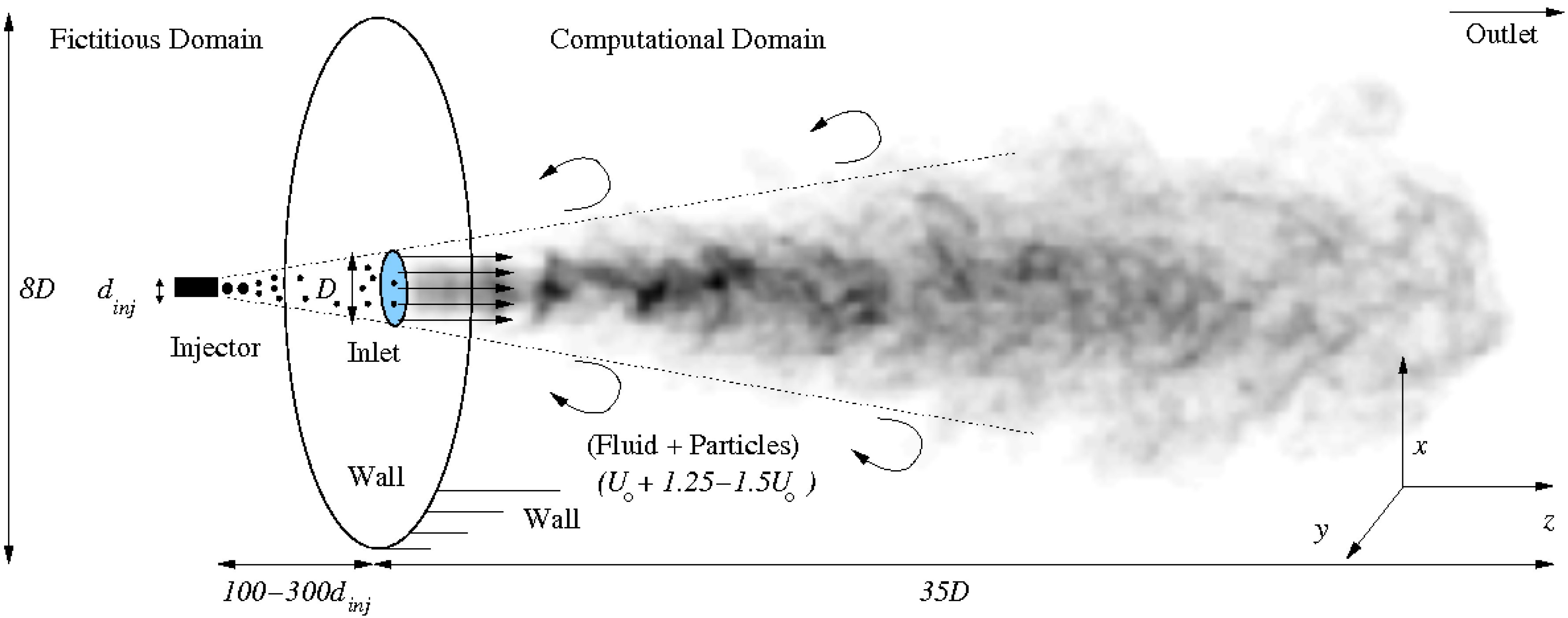
Vuorinen et al., Atomization and Sprays, **20**, 2, 93-114, (2010).

The Dense Region is Problematic



Not simulated in LES

Simulation Model: Gaseous Jet with Fuel Droplets



MAIN PARAMETER DROPLET DIAMETER
I.E. STOKES NUMBER ~ DIAMETER^2

Large-Eddy Simulation (LES) + Lagrangian Particles (LPT)

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_j} = -\frac{\partial}{\partial x_j}(-p\delta_{ij} + \sigma_{ij}) + \mathcal{M}_{spray}$$

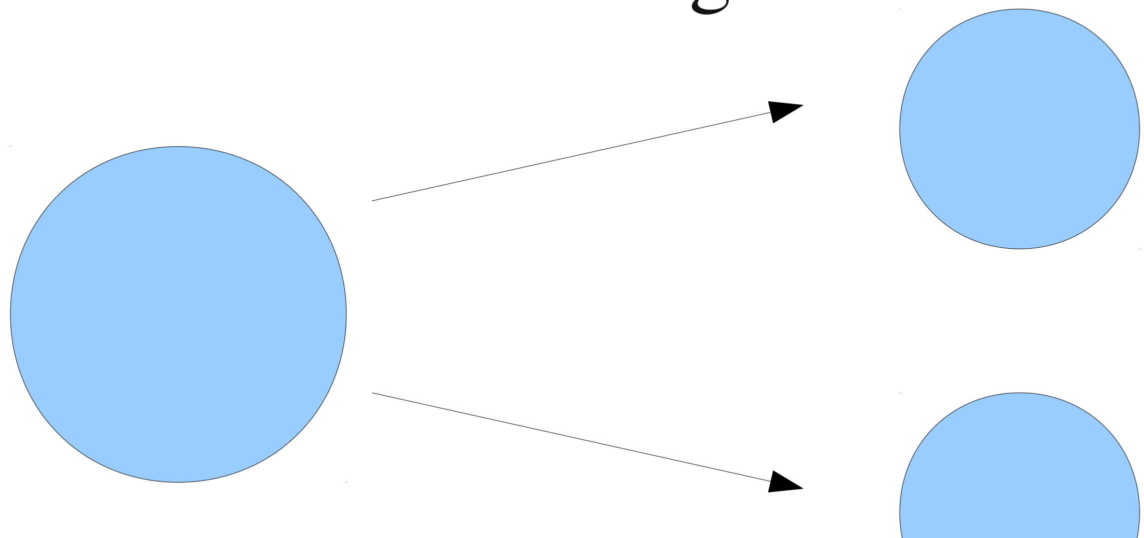
$$\mathcal{M}_{spray} = -C_D(u_i - u_{d,i})|u_i - u_{d,i}|\delta_{r,r_d}$$

- No turbulence model (implicit LES), simulation carried out on a fine grid.
- The OpenFOAM code is in key role: no lisence fees, open source code, many existing solvers, parallel processing, LES and DNS capability.

Droplet Breakup

- The state-of-the-art breakup models in commercial codes assume that droplet are stable if their Weber number is below 13.
- The limit is based on laminar flow measurements.
- Is this a good assumption?
- Breakup in turbulence is different and we investigate the “potential” consequences.
- 5 simulations carried out at maximum Weber numbers 13.
- 3: SMALL, MEDIUM, LARGE stable droplets.
- 2: LARGE droplets break SLOW/FAST

Population Balance Equation and Droplet Breakup Modeling



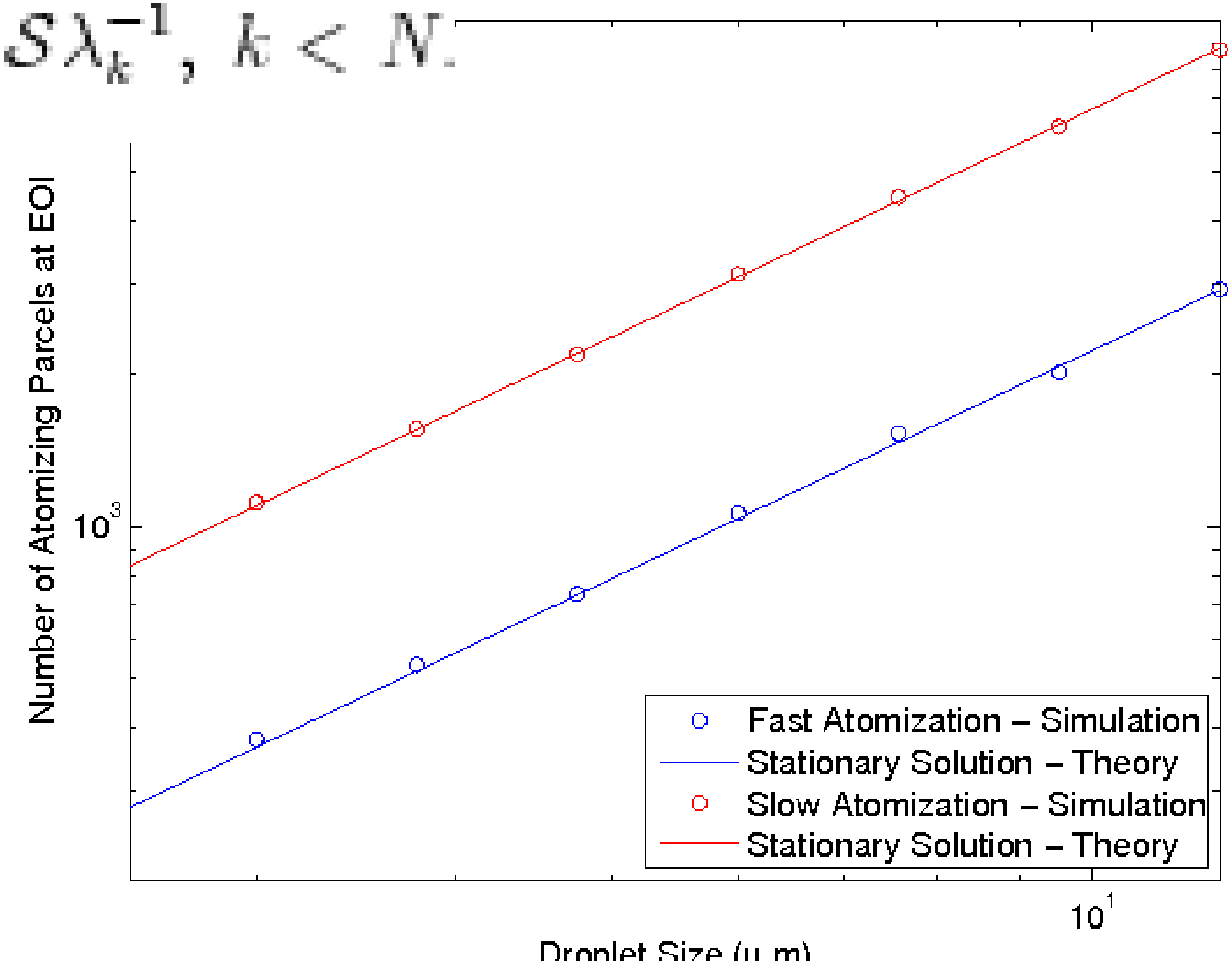
Droplet breakup triggered by turbulent resonance Sevik & Park (1973).

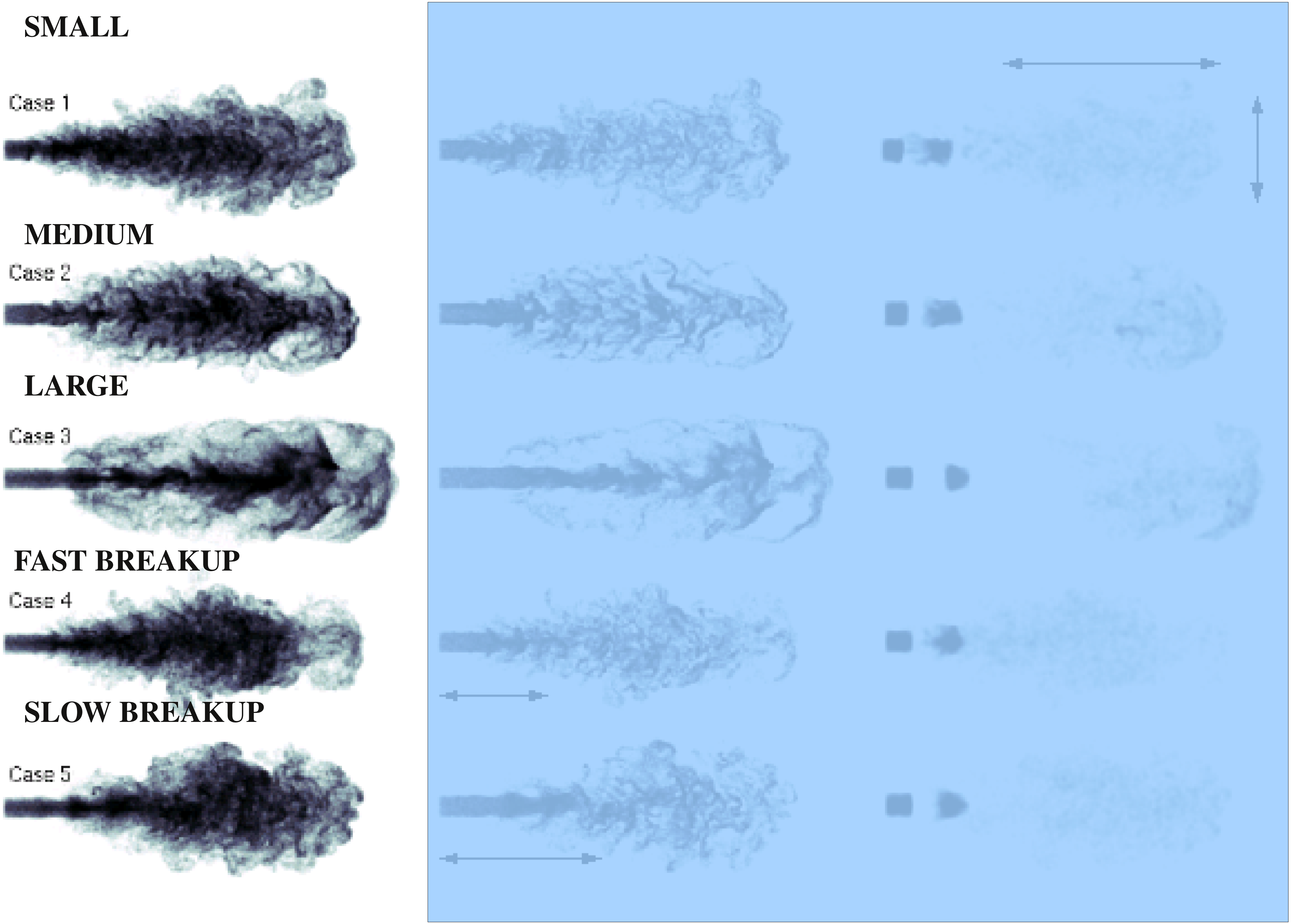
$$\lambda_d = \gamma \frac{\omega}{2\pi} = \gamma \frac{2}{d\pi^2} \left(\frac{\sigma_p}{\rho_p d} \right)^{0.5}$$

$$\begin{cases} \frac{dn_0}{dt} = -\lambda_0 n_0(t) + S \\ \frac{dn_k}{dt} = +\lambda_{k-1} n_{k-1}(t) - \lambda_k n_k(t) \\ \frac{dn_N}{dt} = +\lambda_{N-1} n_{N-1}(t), \end{cases}$$

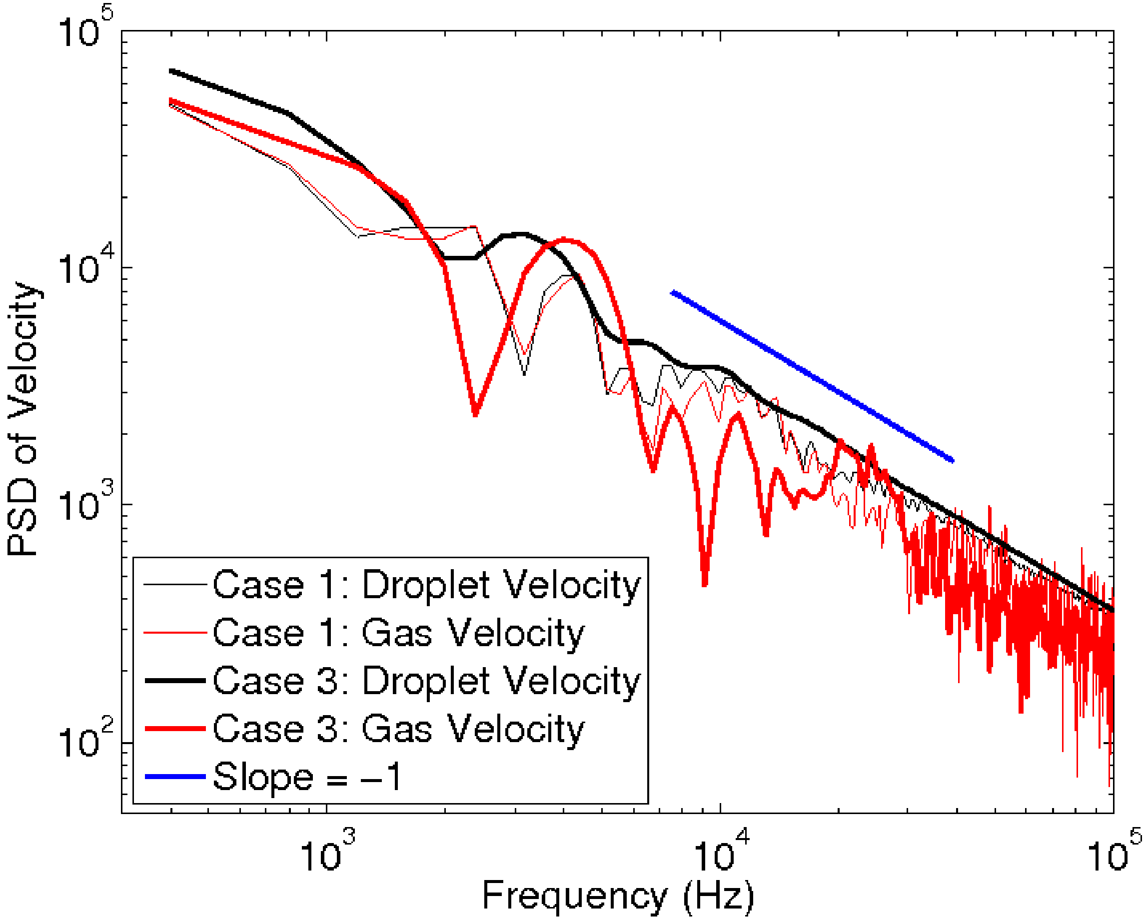
Analytic Steady State Distribution for Droplet Sizes

$$\langle n_k \rangle = S\lambda_k^{-1},\ k < N.$$

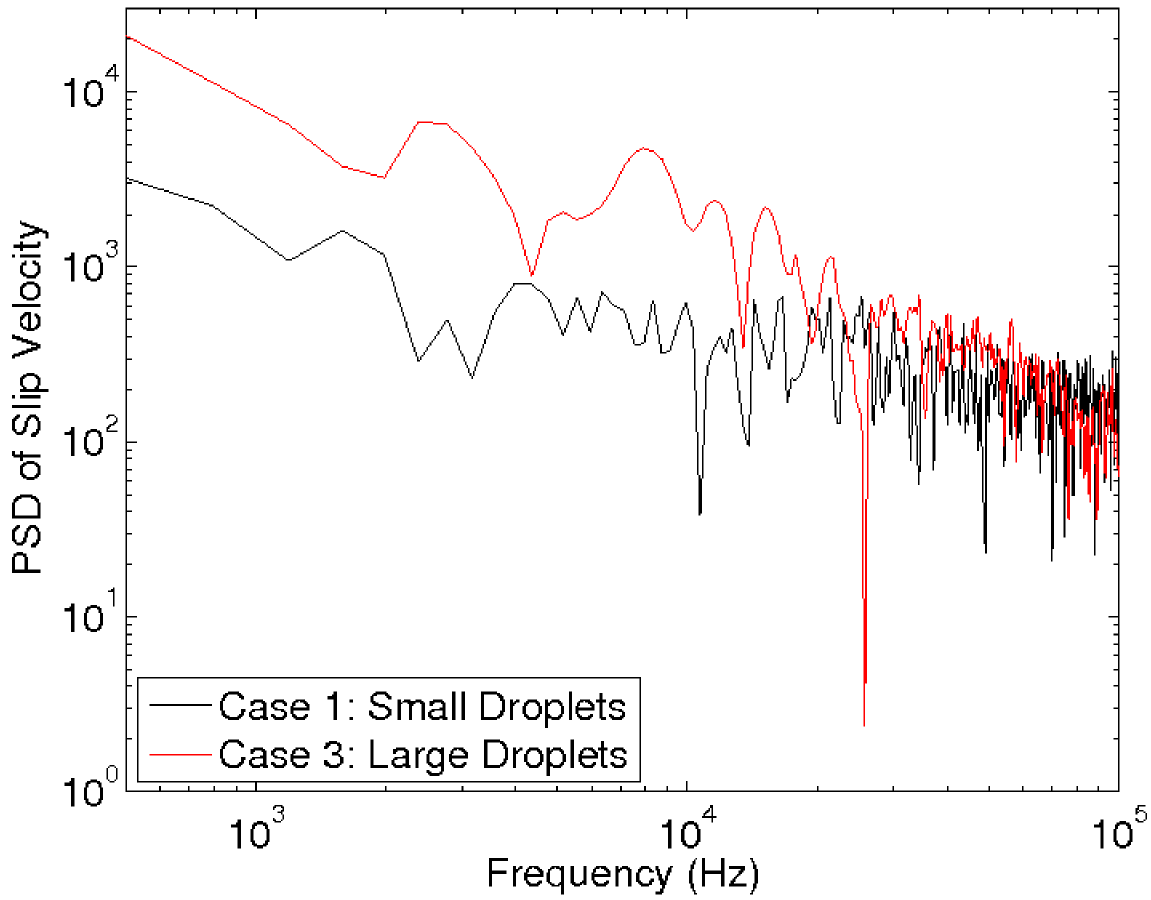


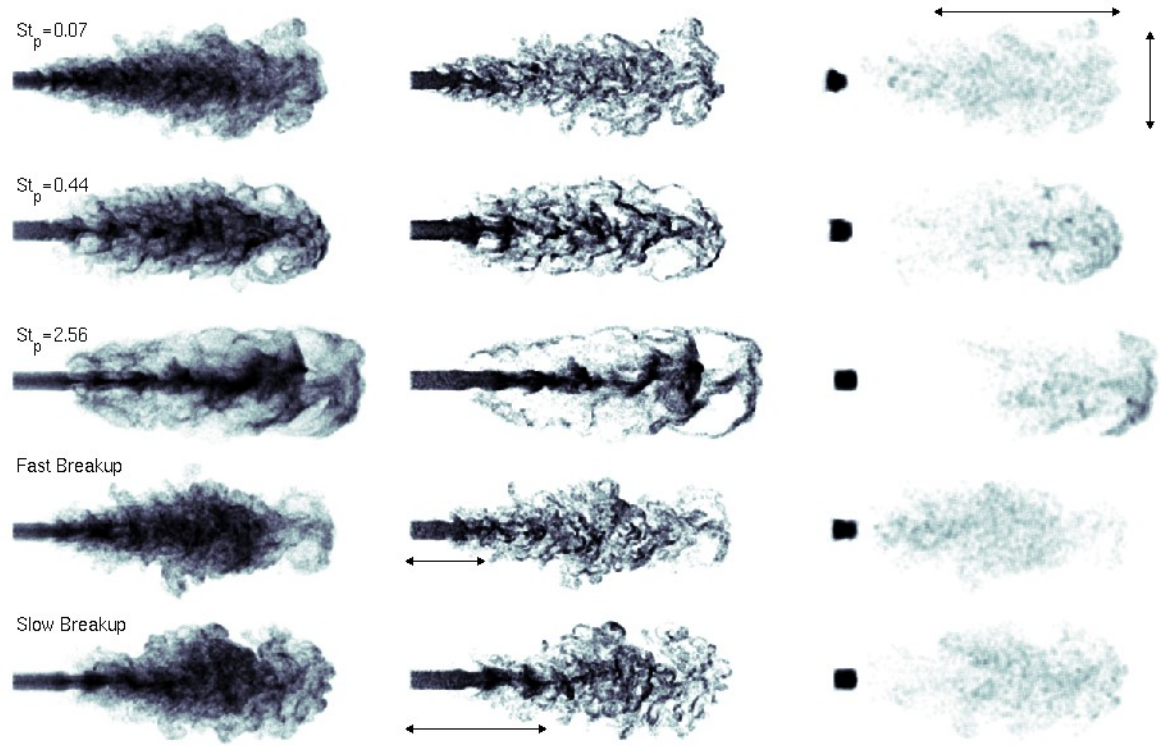

SMALL
Case 1
MEDIUM
Case 2
LARGE
Case 3
FAST BREAKUP
Case 4
SLOW BREAKUP
Case 5

Droplet Experiences Locally: Velocity vs Gas Velocity



Spectrum of Slip Velocity: Large vs Small Droplets





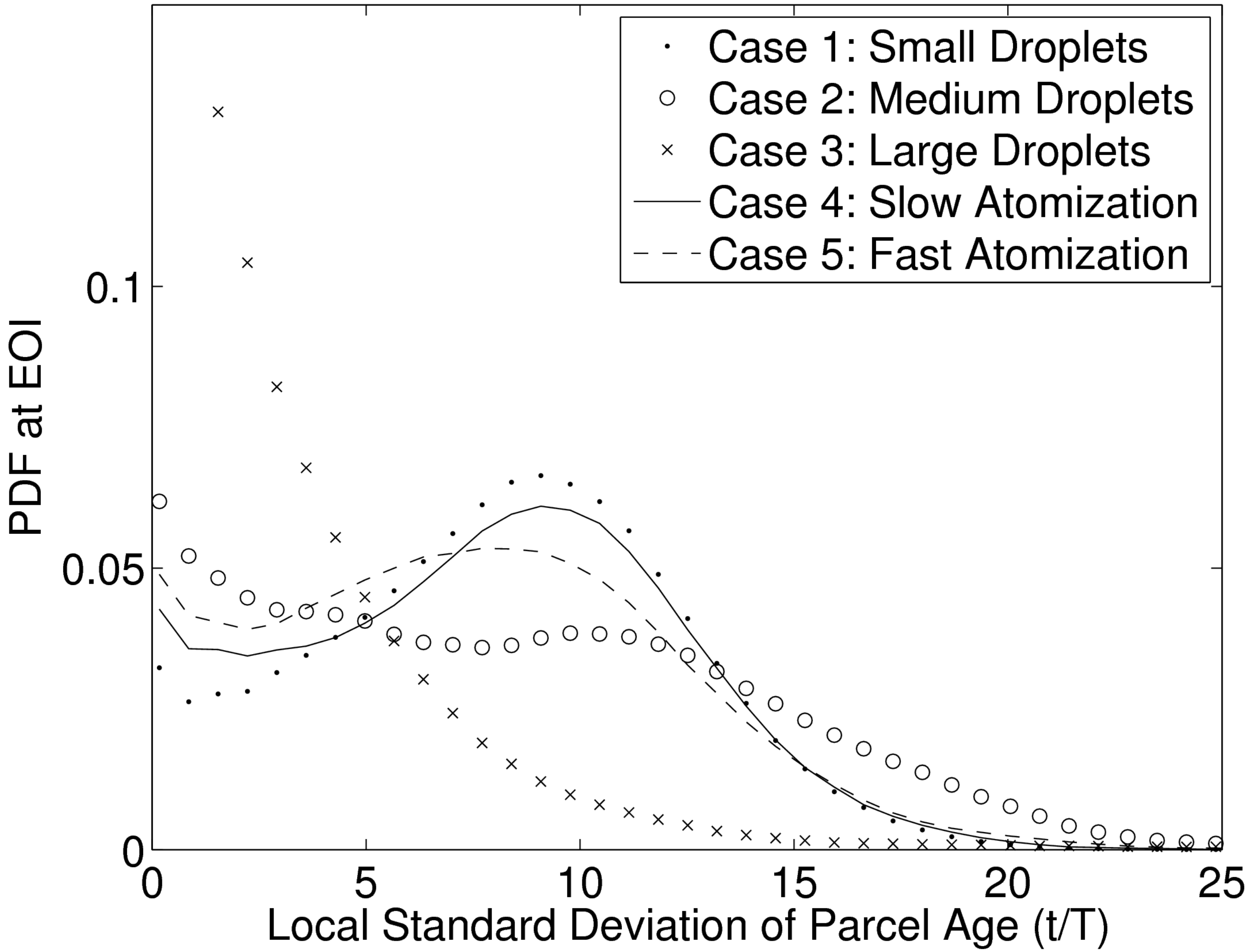
St$_p$=0.07
St$_p$=0.44
St$_p$=2.56
Fast Breakup
Slow Breakup

Local Measures for Mixing

Poor mixing -> nearby sphere numbers are "CLOSE" -> small standard deviation of droplet index number.

Good mixing -> nearby sphere index numbers are "NOT CLOSE". -> large standard deviation of droplet index number

Structural Analysis of Sprays Shows the Differences in Mixing



Conclusions

- Mixing indicators to quantify the spray shapes were developed.
- Small droplets mix better because: (i) Mass loading is rather small – no significant dissipation. (ii) Small timescale and hence strong interaction with turbulence.
- Here a simple resonance breakup model was developed.
- The results show that, potentially, if resonance breakup (even at low Weber numbers; $We < 13$) would be modeled then the consequences to mixing can be drastic.