Large-Eddy Simulation of Droplet Size Effects on Turbulent Fuel Spray Shape

How does drop size affect mixing?

Drop size?

How do we make a very realistic simulation of a spray?

Internal structure?

What is good mixing?

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Background objective A: Understand the effect of droplet size (Stokes number) on spray dynamics using LES.

St = (Momentum Relaxation Timescale)/(Flow Timescale)

St ~ (Droplet Diameter)^2

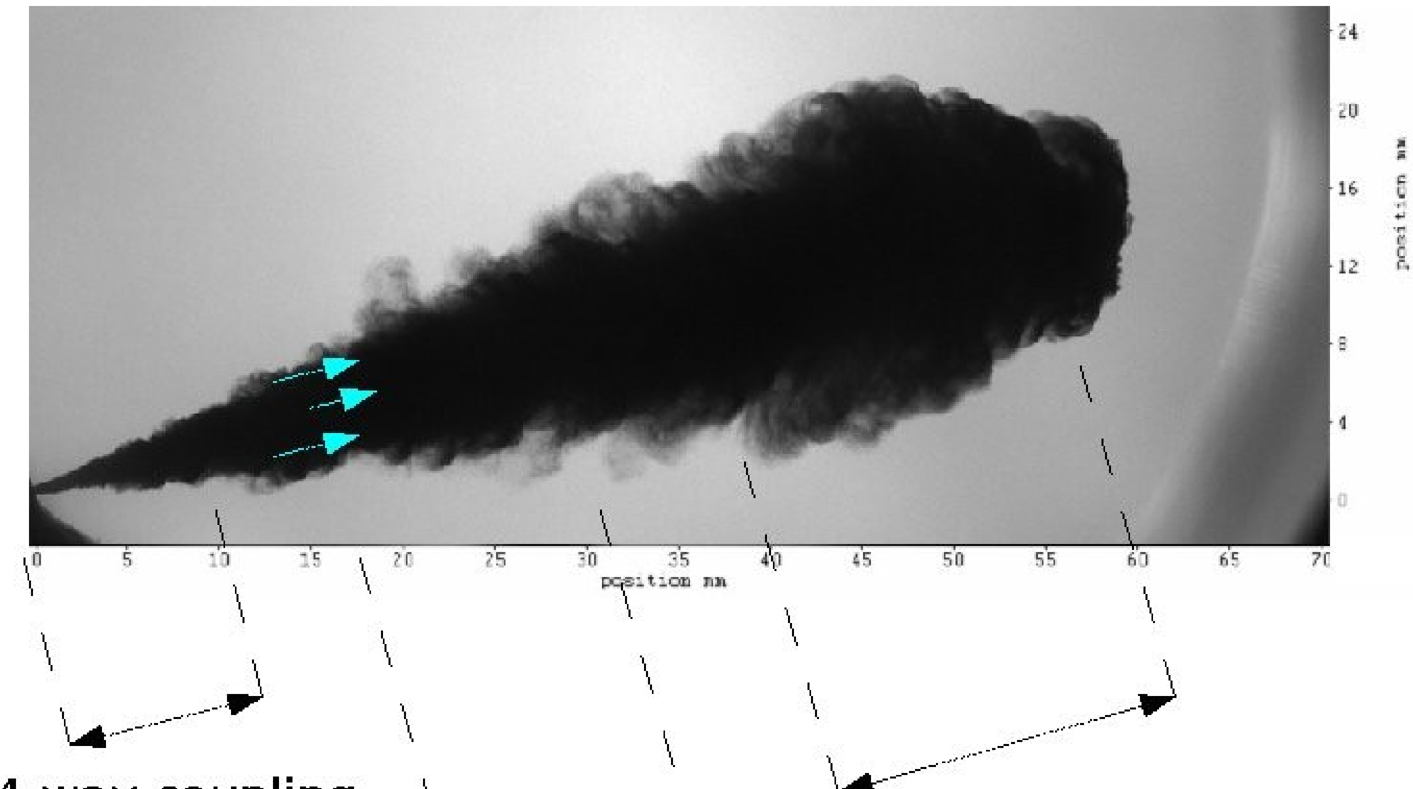
Case 1: St << 1 -> droplets follow the flow

Case 2: St~1 -> droplets interact with large scale

Case 3: St >> 1 -> droplets are nearly ignorant

Background objective B: To profoundly understand the phenomena that are related to **the physics** of spray formation.

The Object of Interest: Physics of Diesel Fuel Sprays



4-way coupling
vol. fraction ~ 1
COMPLEX INTERACTIONS, LIGAMENTS, DROPLET COLLISION ETC

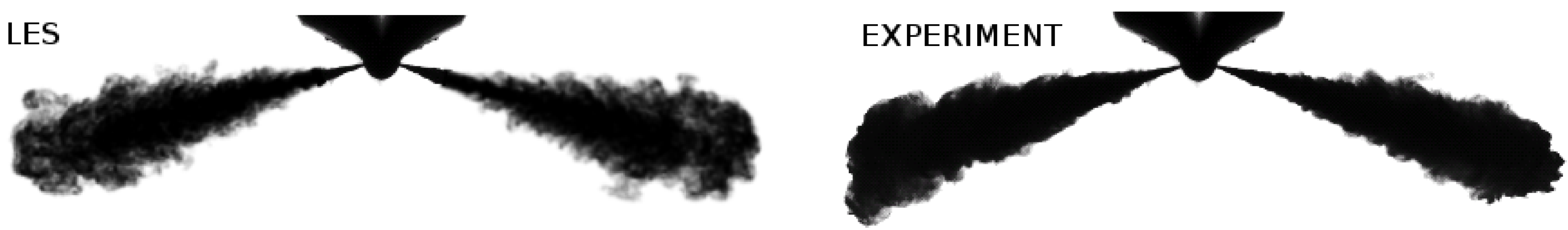
2-way coupling
vol. fraction ~ 0.001
GASEOUS JET WITH FUEL DROPLETS

1-way coupling
vol. fraction << 0.001

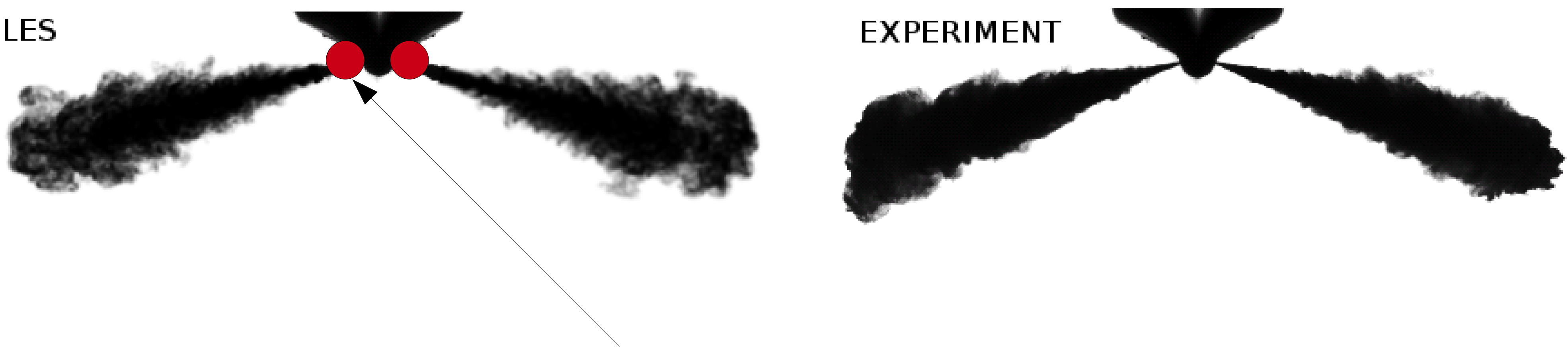
Recent Background Work

- Hillamo et al. *Particle Image Velocimetry Measurements of a Diesel Spray*, SAE 2008-01-0942 (2008).
- Hillamo et al. *Diesel Spray Studies: Near-Nozzle Shock Waves and Entrainment*, to be submitted (10/2009).
- Vuorinen et al. *Large-Eddy Simulation of Droplet Stokes Number Effects on Turbulent Spray Shape*, submitted to Atomization and Sprays (8/2009).
- Vuorinen et al. *Large-Eddy Simulation of Droplet Stokes Number Effects on Mixing in Transient Sprays*, submitted to International Journal of Multiphase Flow (6/2009).
- Vuorinen, *LES of Certain Droplet Size Effects in Fuel Sprays*, PHD Thesis, submitted to pre-examination 9/2009.

Qualitative Comparison of LES and Experiments

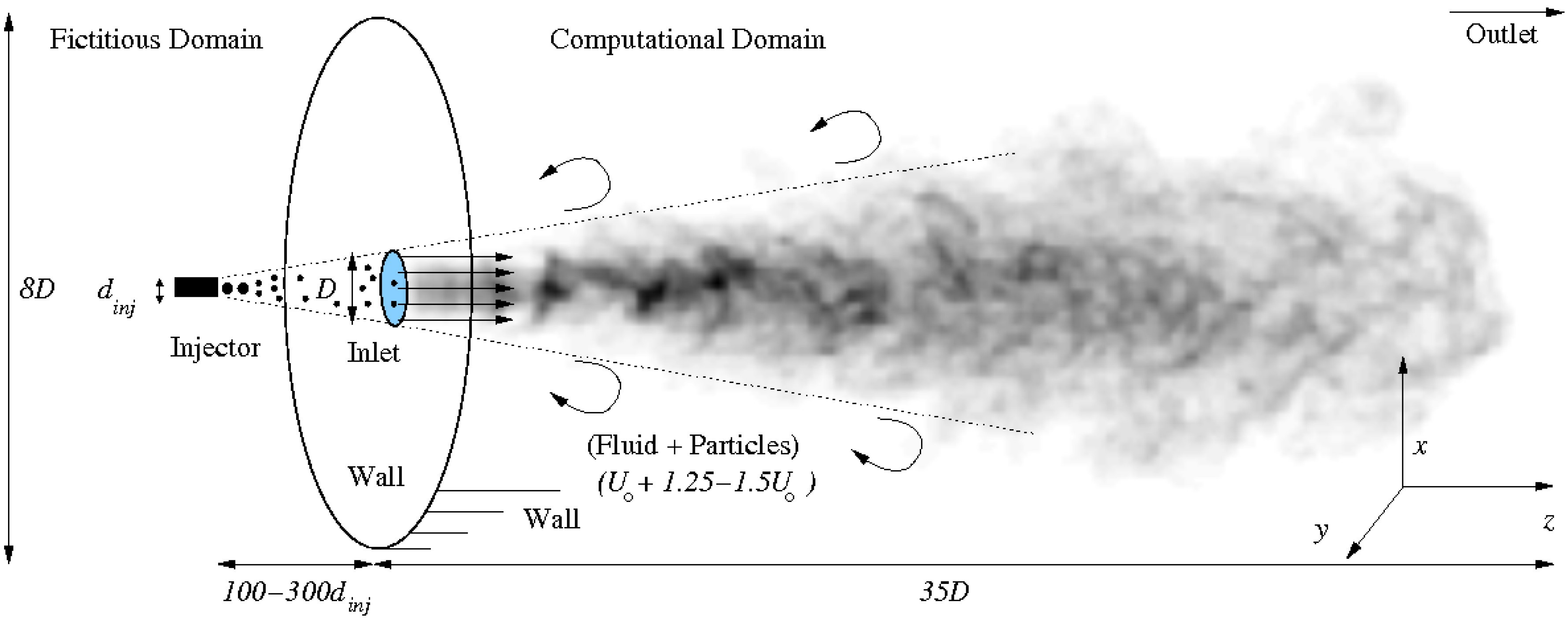


The Dense Region is Not Simulated in LES

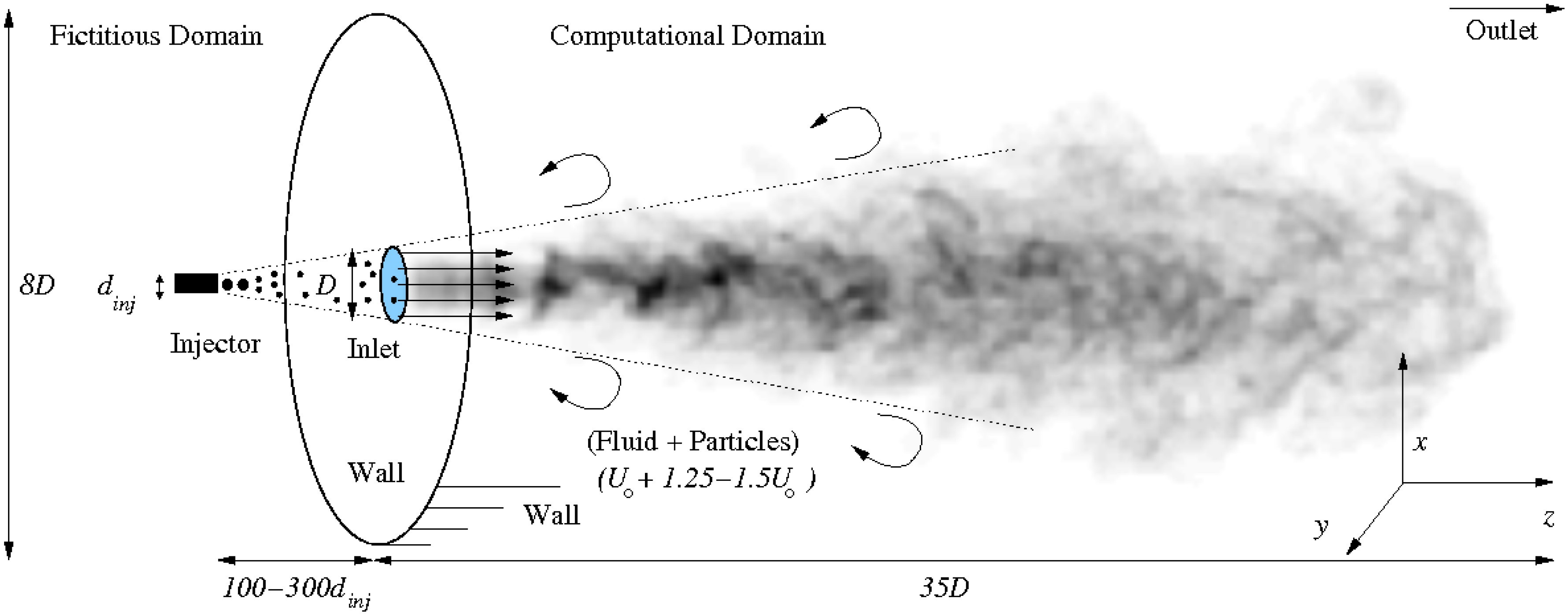


Not simulated in LES

Simulation Model: Gaseous Jet with Fuel Droplets



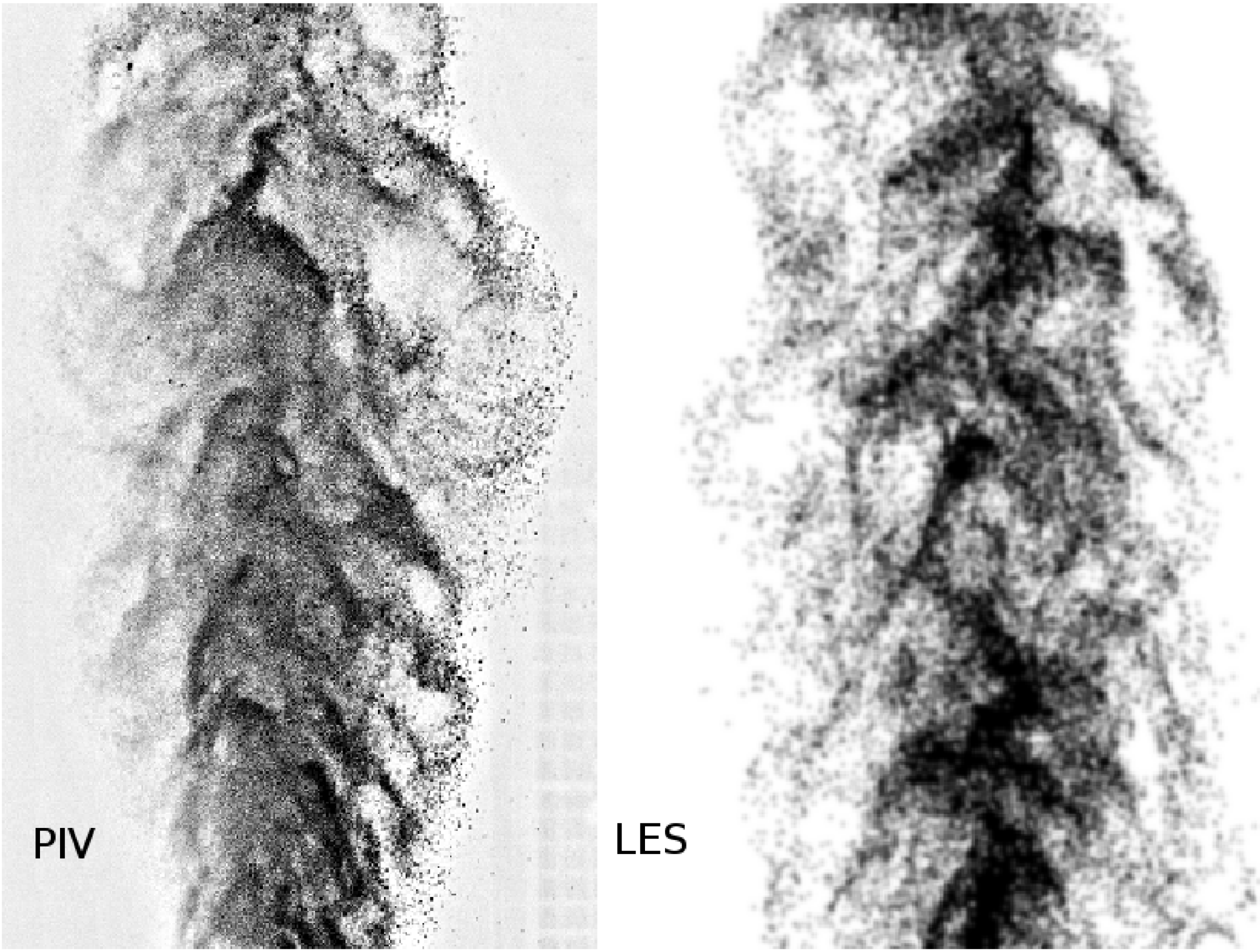
Simulation Model: Gaseous Jet with Fuel Droplets



MAIN PARAMETER DROPLET DIAMETER

I.E. STOKES NUMBER ~ DIAMETER^2

LES Reproduces the Internal Branch-Like Structures (e.g. Cao et al. 2000)



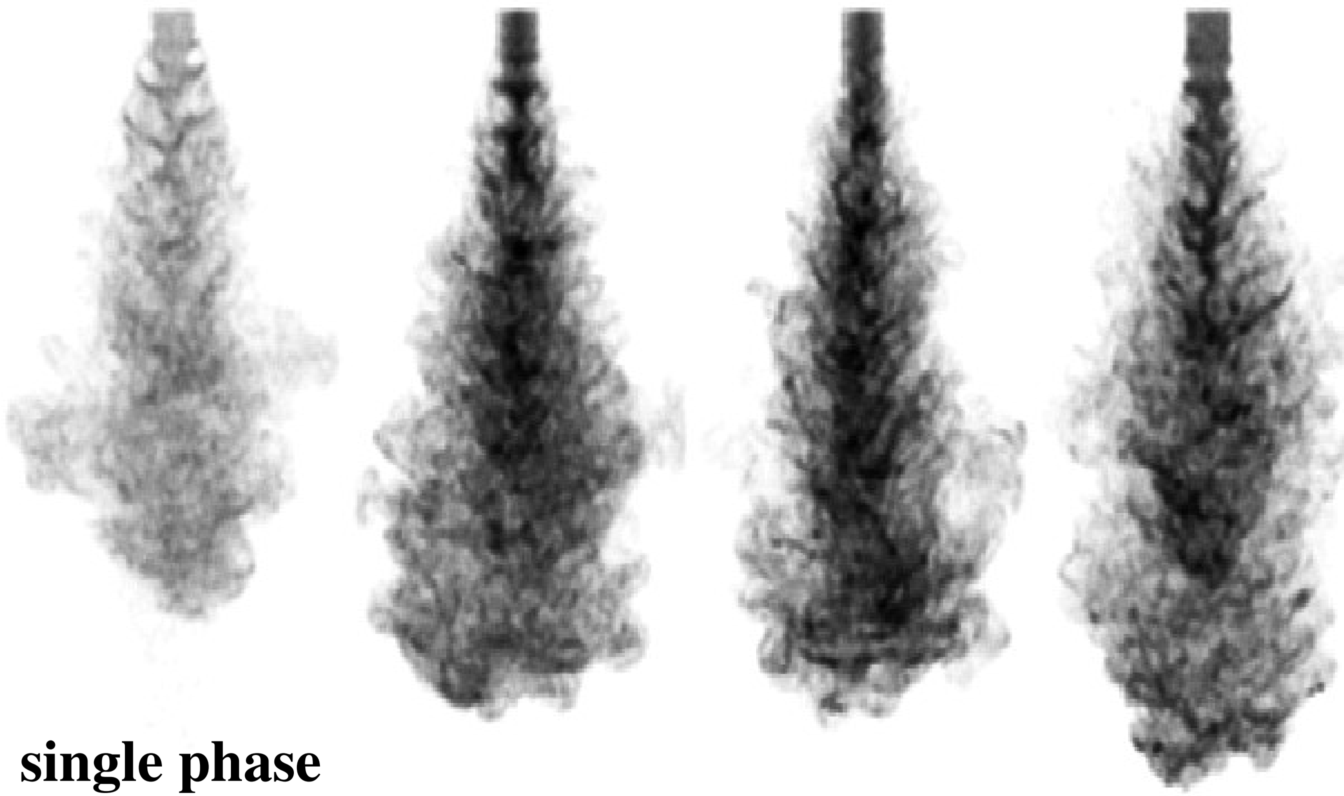
Large-Eddy Simulation (LES) + Lagrangian Particles (LPT)

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

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

- 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.

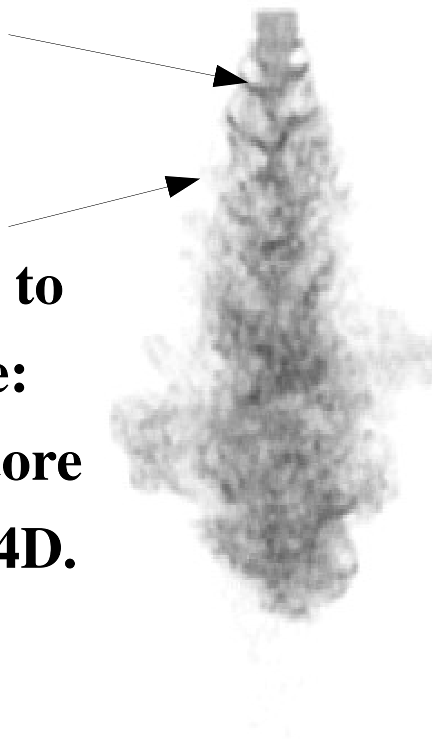
Constant Size Droplets: 0.07 < St < 0.5



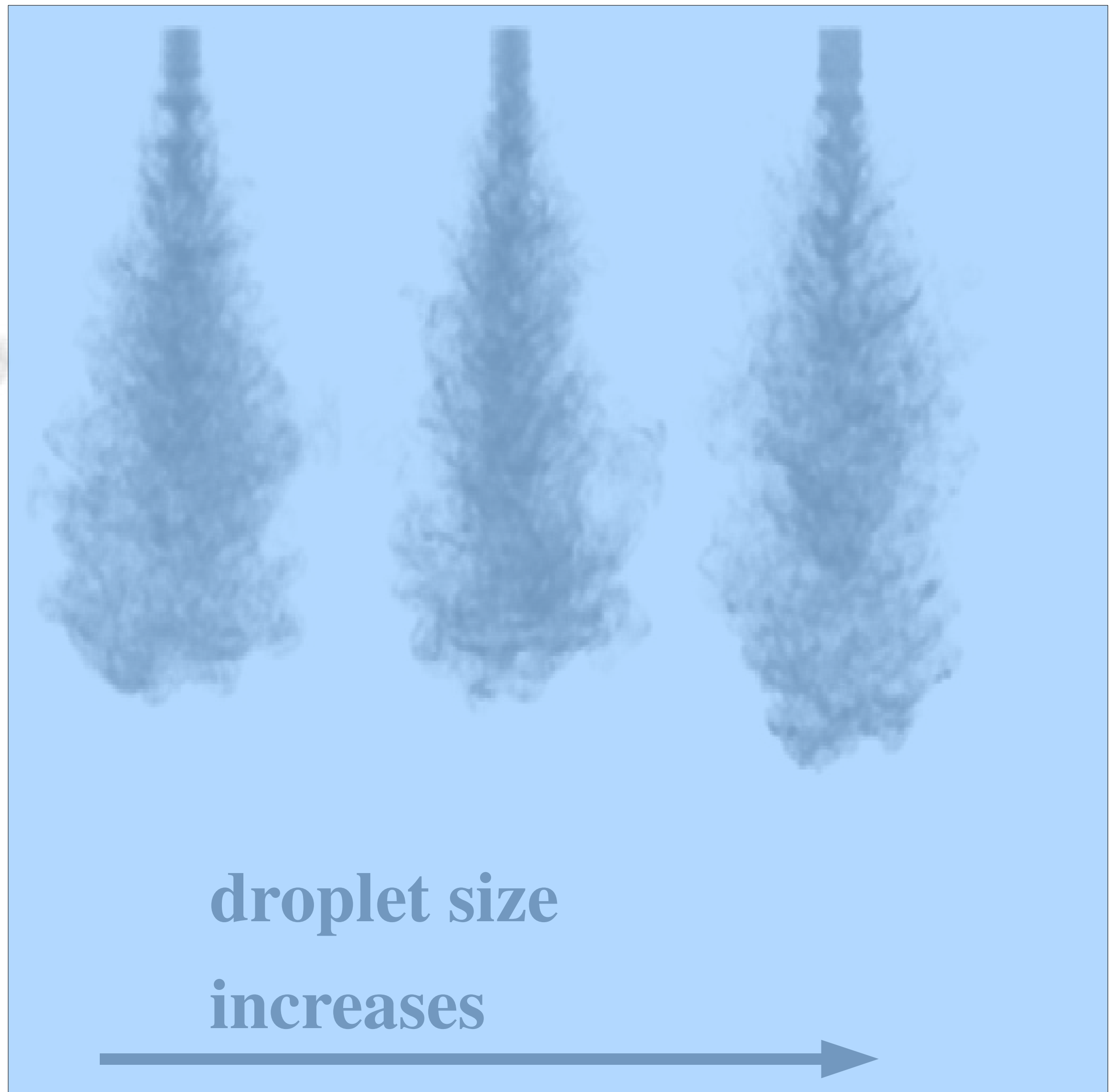
single phase
jet + tracers

Single Phase Gas Jet: St=0.07

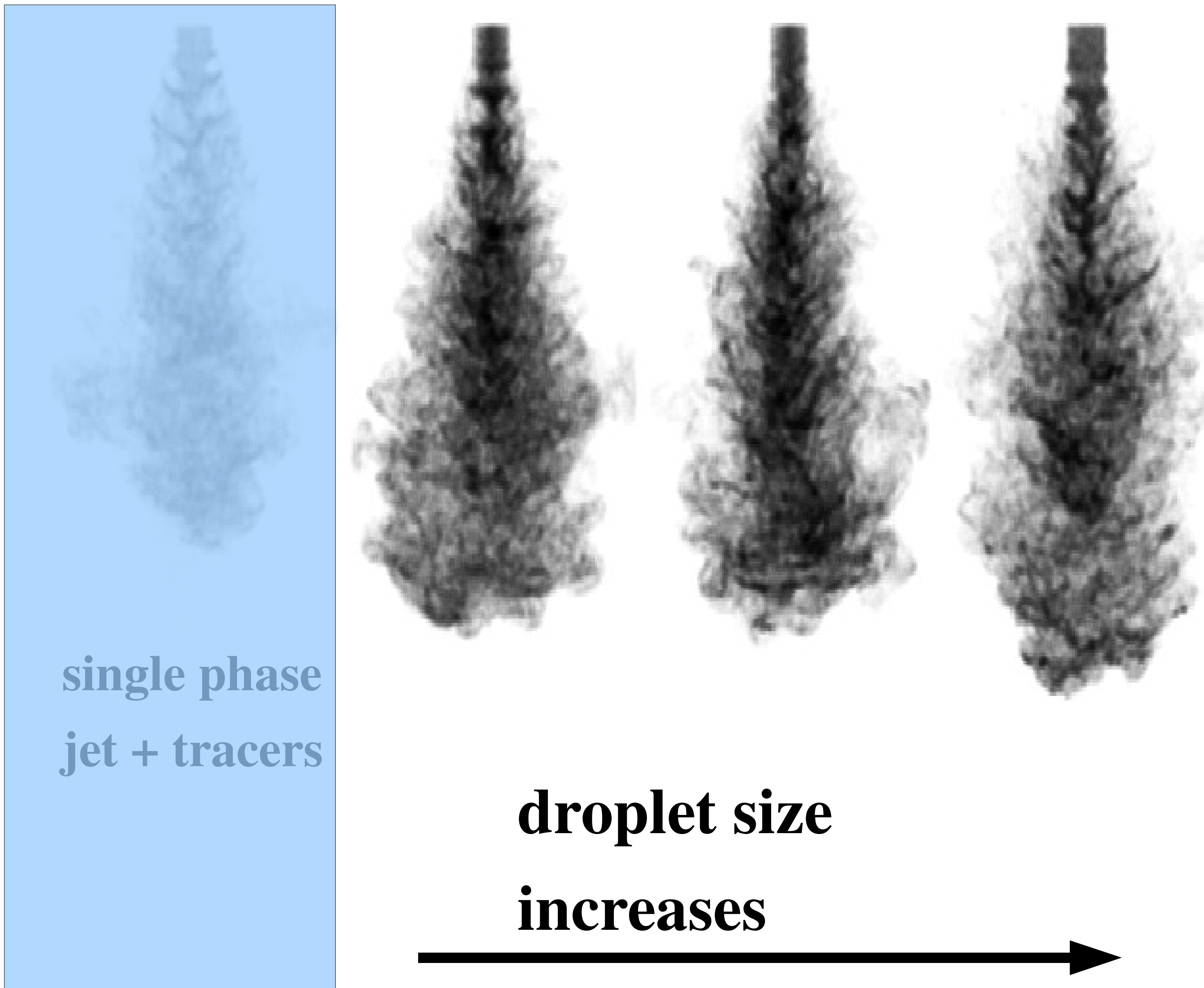
Kelvin-Helmholtz instability



Transition to turbulence: potential core ends at z=4D.



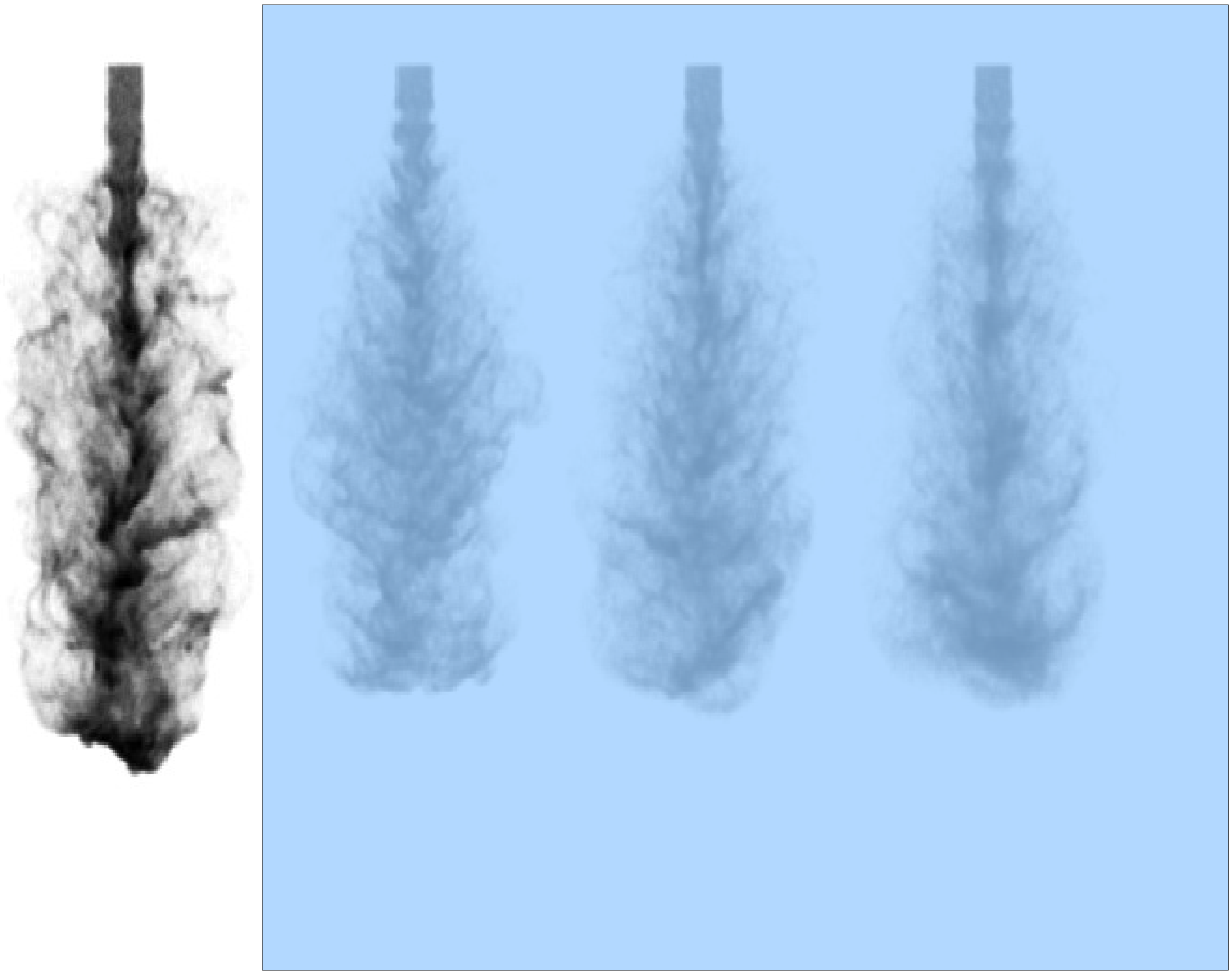
Monodisperse Sprays, Intermediate Mass Loading:
0.07 < St < 0.5



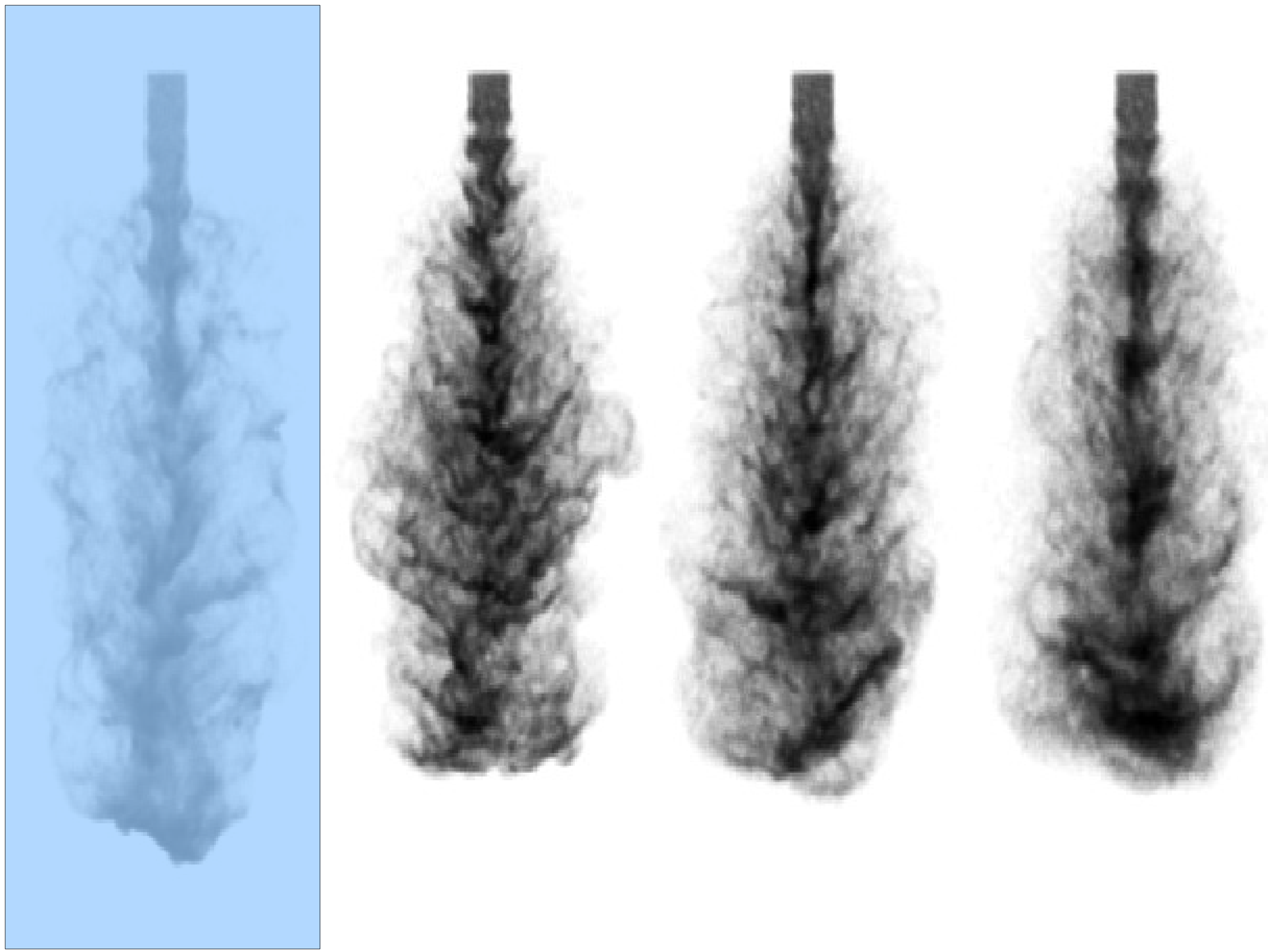
Monodisperse Sprays: $0.5 < St < 2$

droplet size increases

Largest Droplets: St = 2.56



Polydisperse Sprays: <St>=0.3, 1.2, 2.5



Qualitative Stokes Number Comparison to Yan et al. (2008) on DNS Study on Plane Jet at Re=3000

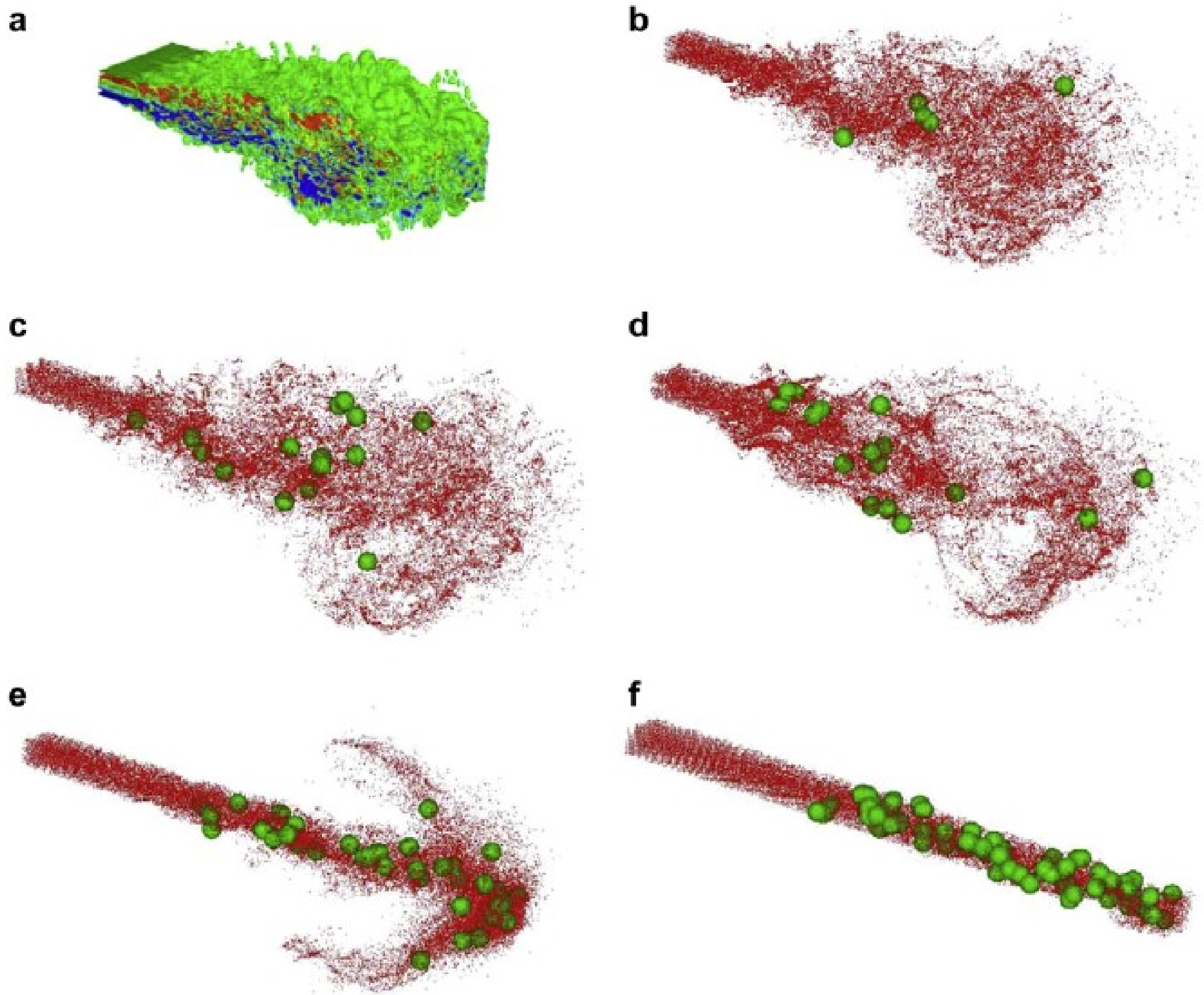
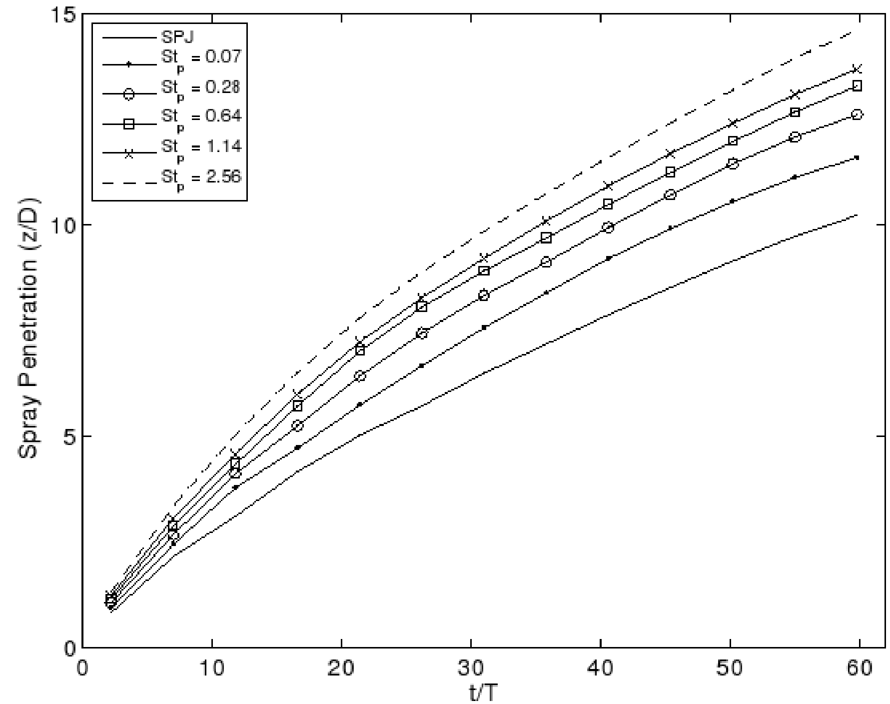
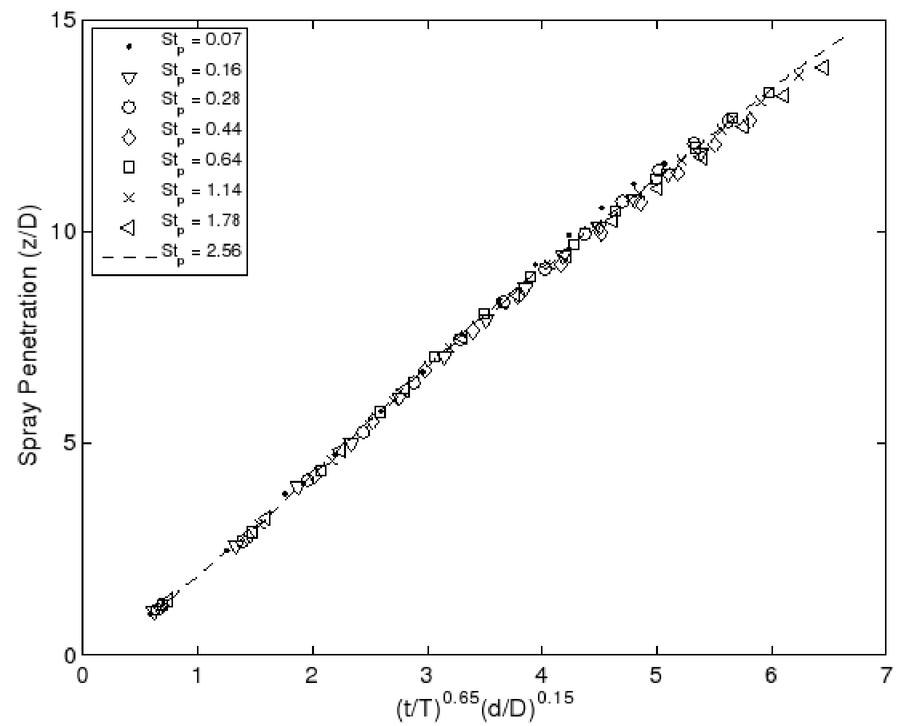


Fig. 4. Spatial distribution of inter-particle collision for particles at different Stokes numbers at the time $t = 42$. (a) Lateral vorticity, (b) $St = 0.01$, (c) $St = 0.1$, (d) $St = 1$, (e) $St = 10$, (f) $St = 100$.

Spray Penetration Depth

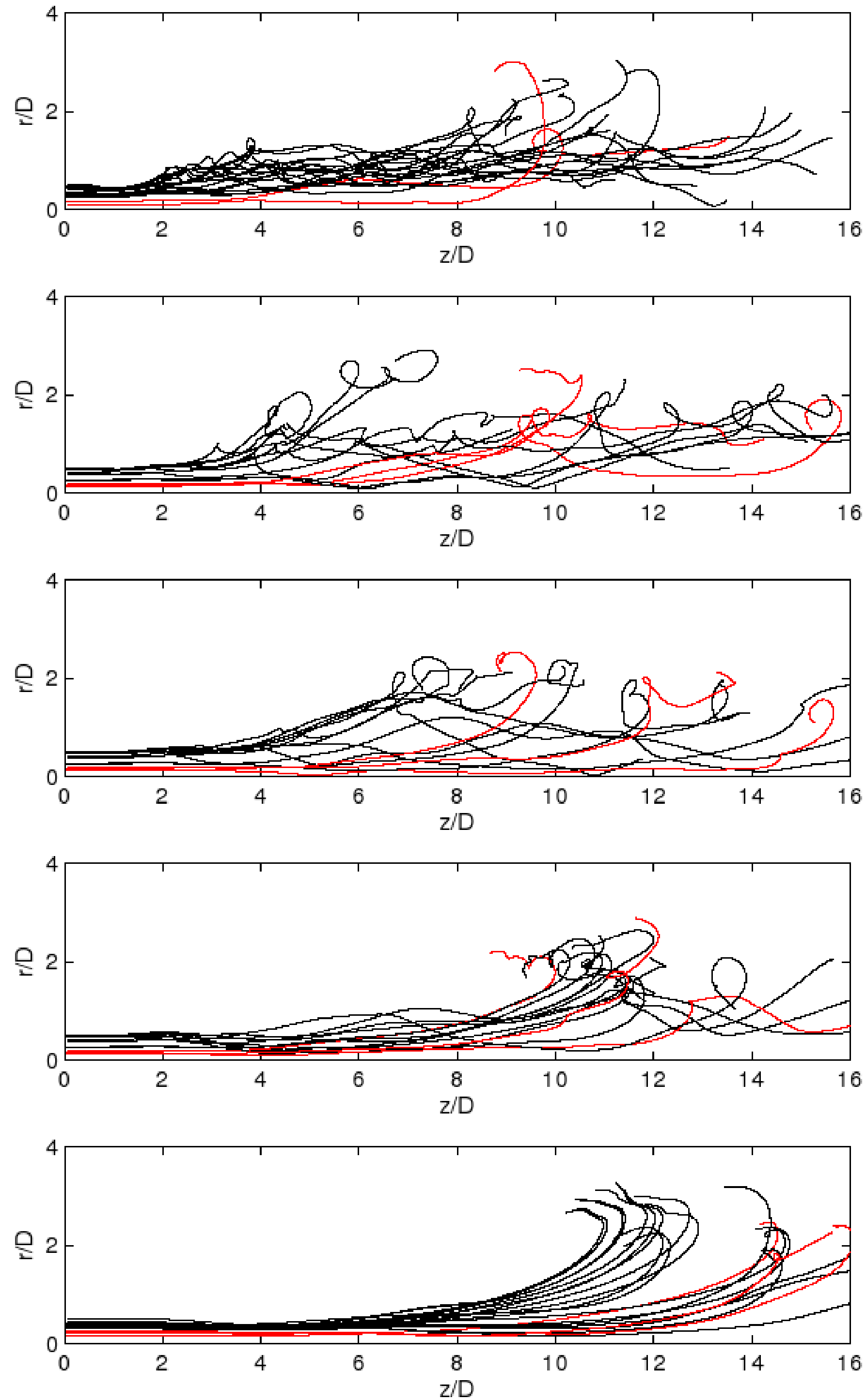
-



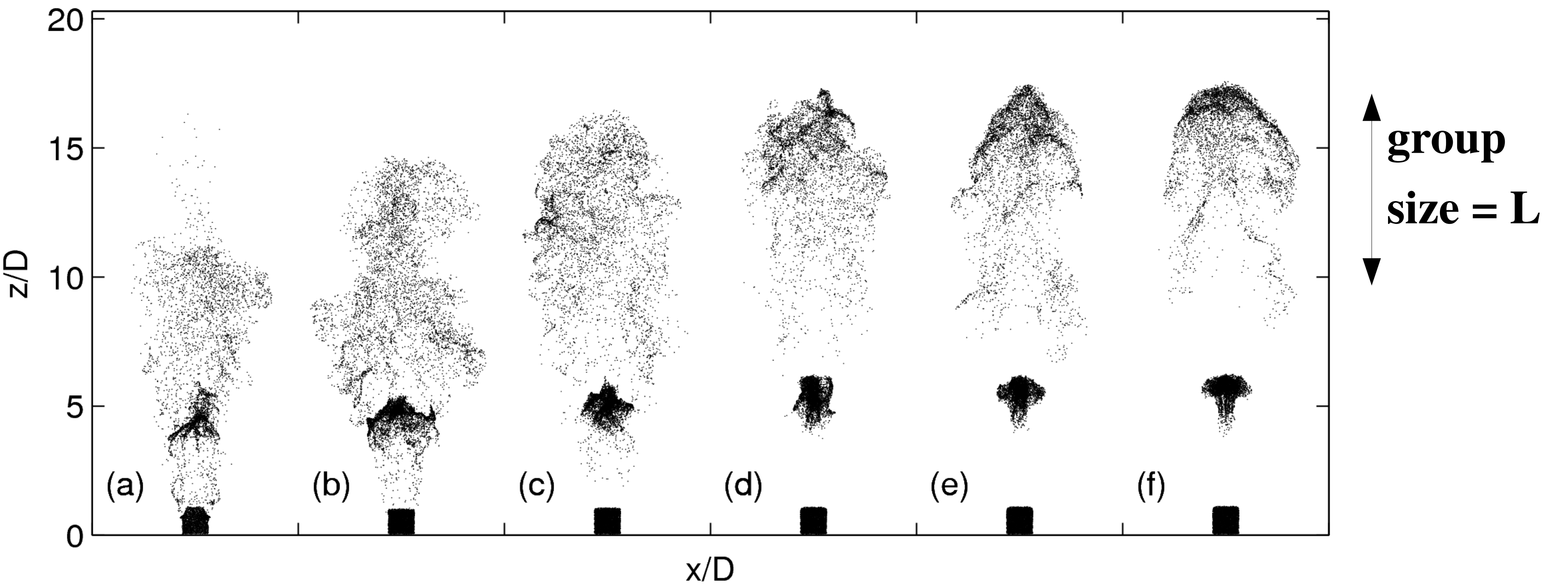


Droplet Trajectories

droplet size increases

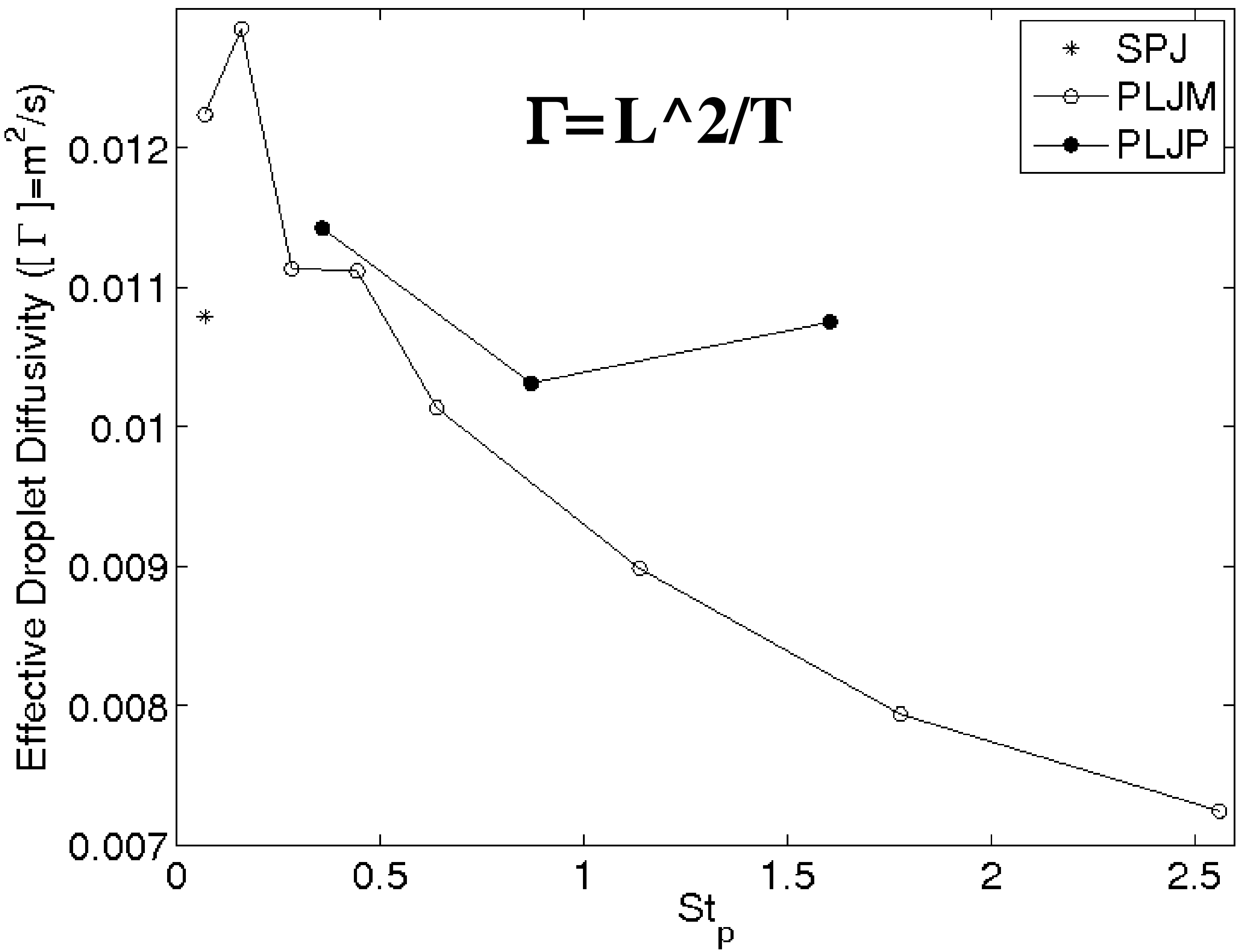


Visualization of **ONLY Small Part of Spray** i.e. How **Droplet Groups** Mix

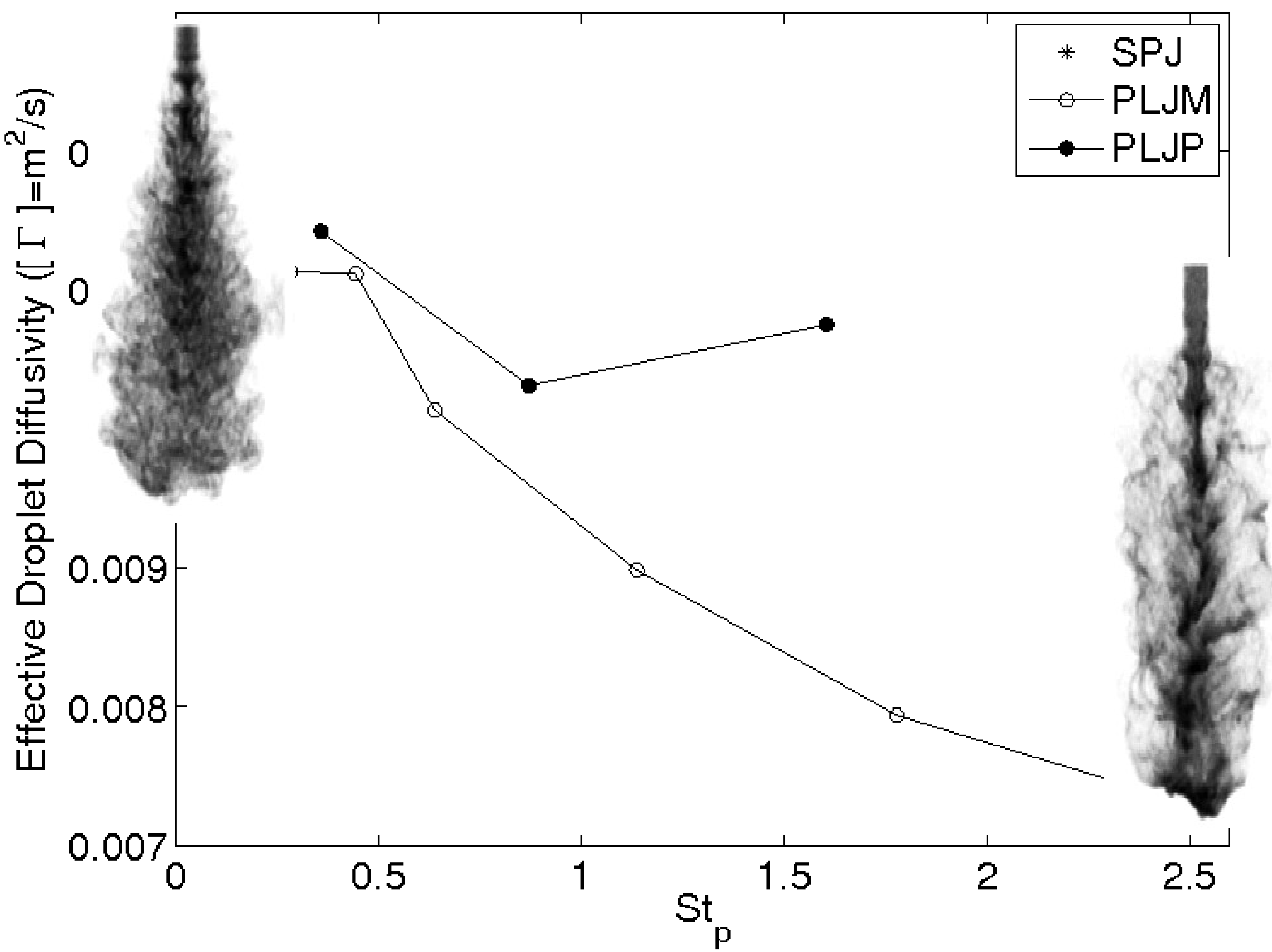


droplet size increases

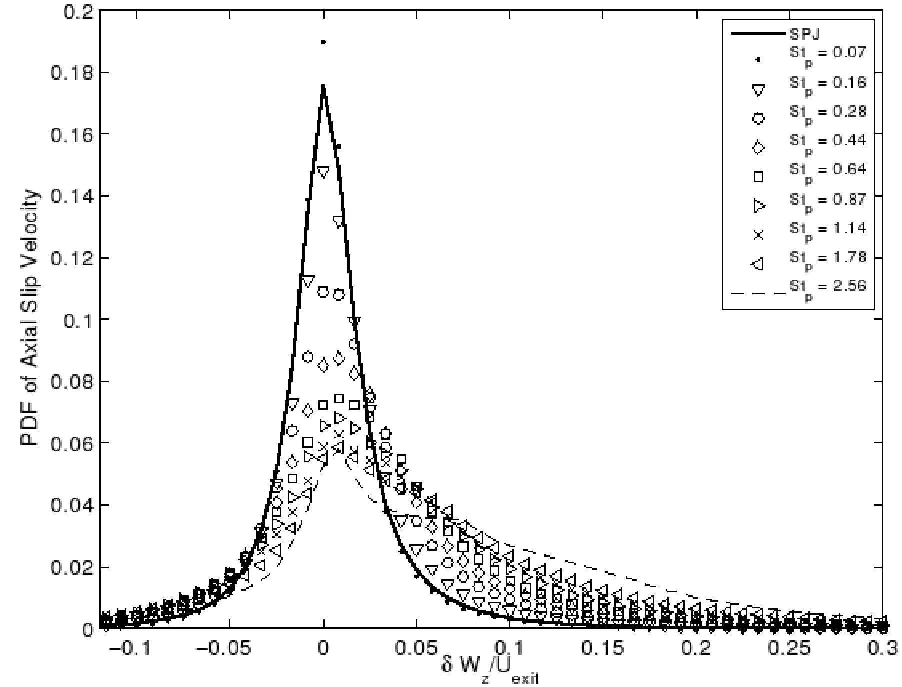
Spreading of Droplet Groups i.e. Mixing Can Be Quantified in Terms of a Droplet Diffusivity

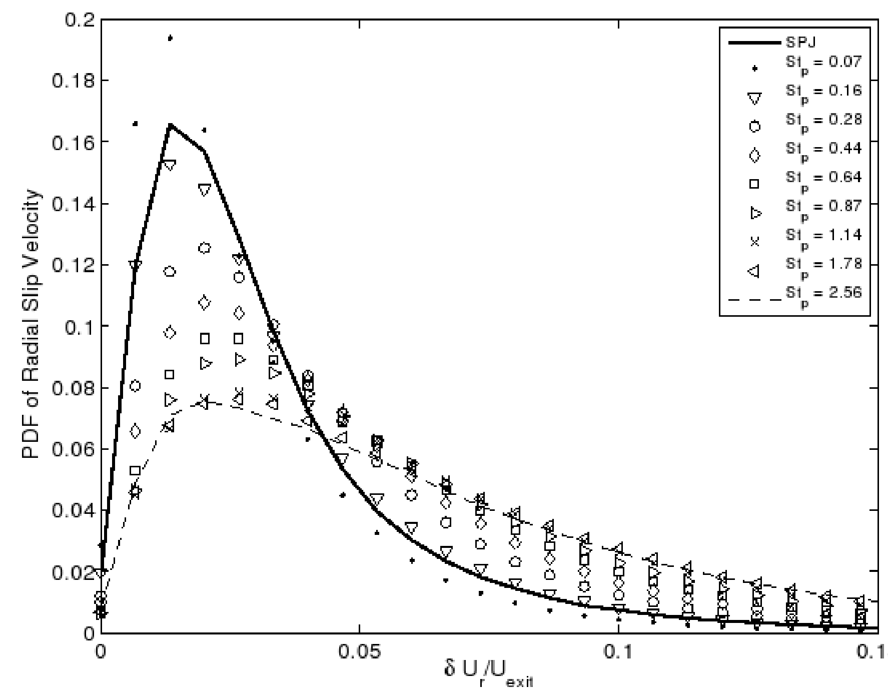


Spray Shapes are Clearly Explained and Quantified: Implications to Dispersion Models?

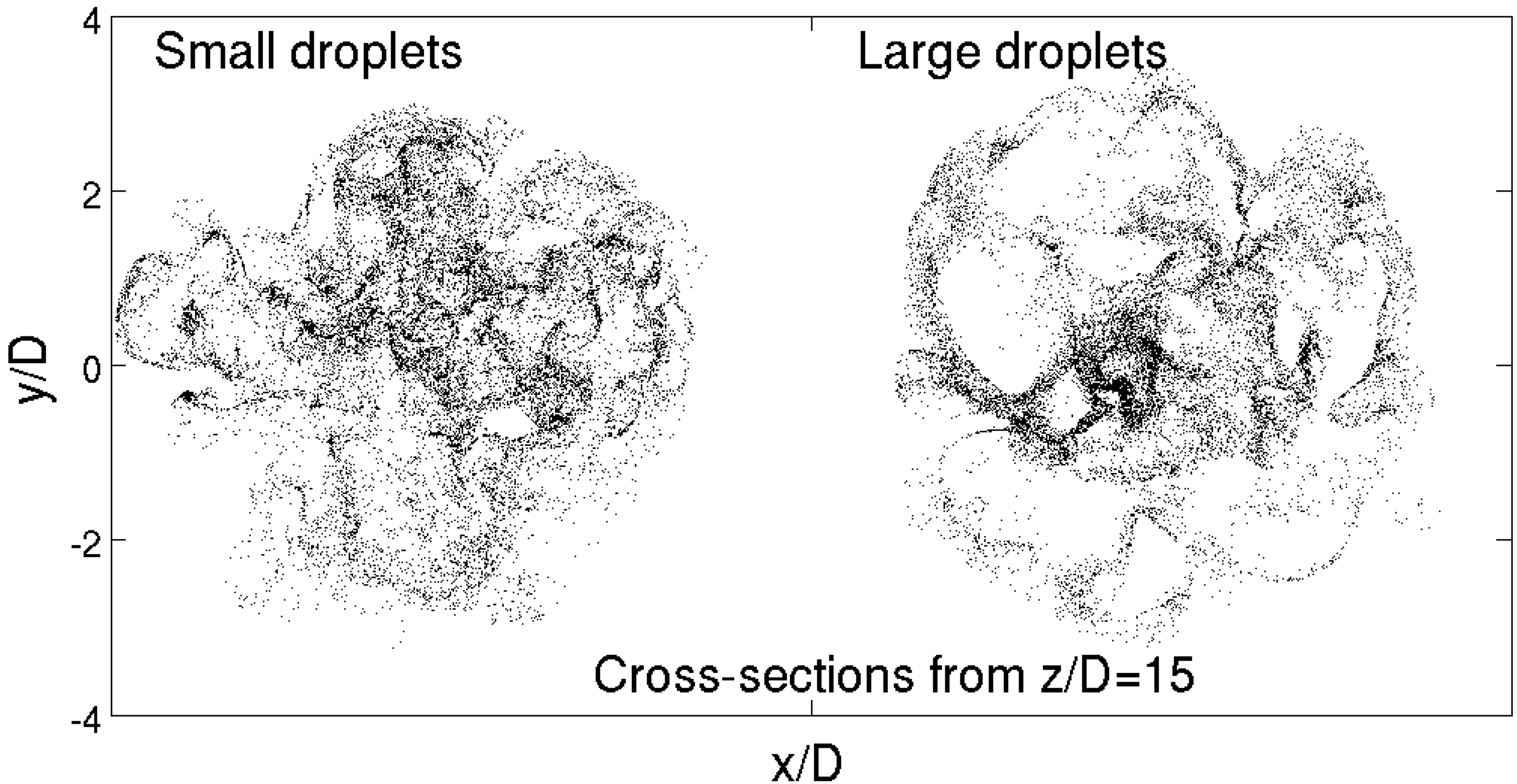


Analysis of Droplet Gas **Slip Velocity PDF's** is Consistent With the Observed Spray Shapes





Implications to Mixing and Spray Structure



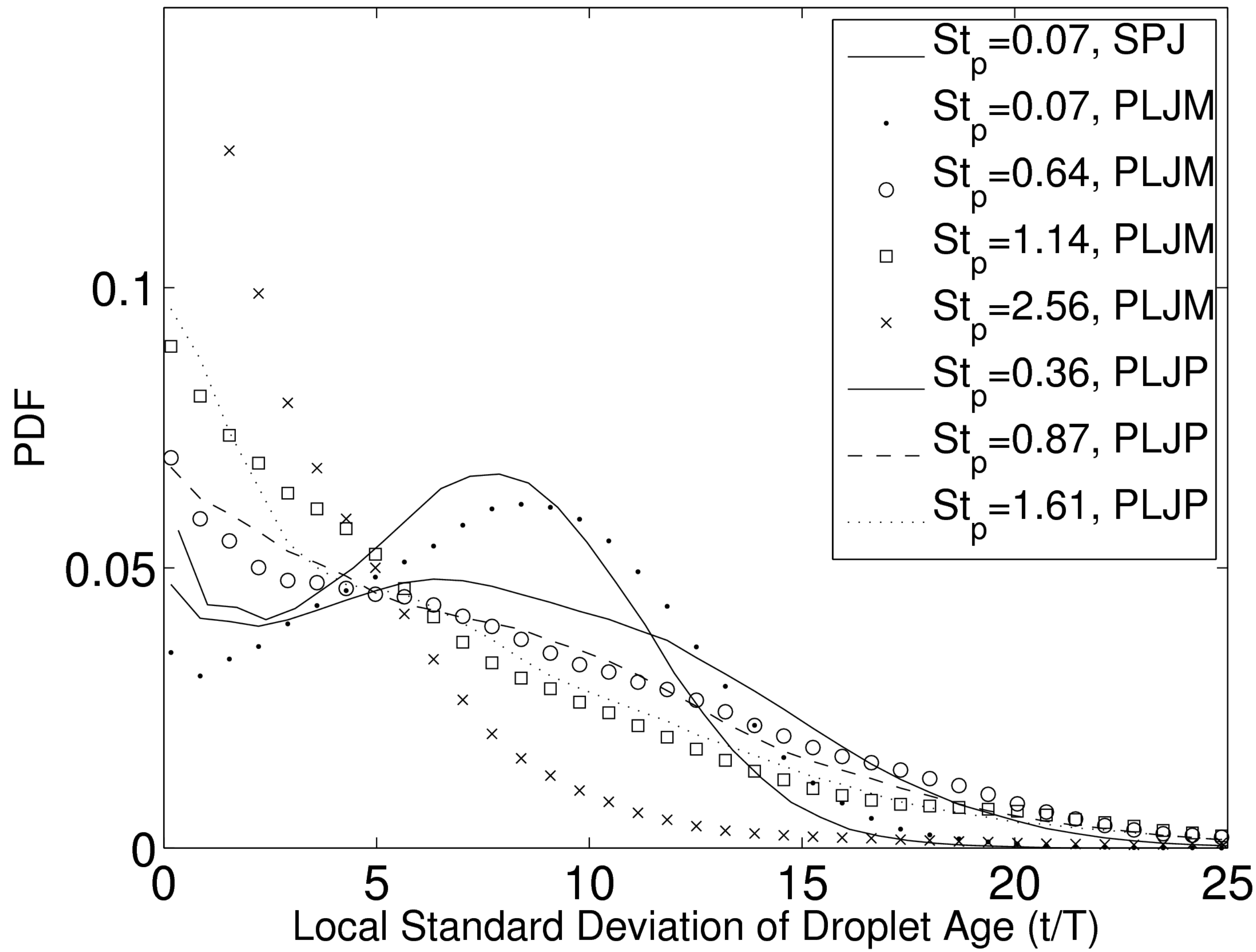
To Rigorously Quantify the Apparent Droplet Size Effects We Apply the "Lottery Analogy" of Mixing

Label All Droplets and Look at the Local Properties

Poor mixing -> nearby sphere numbers are correlated -> small standard deviation of droplet number.

Good mixing -> nearby sphere numbers are not correlated. -> large standard deviation of droplet number

The PDF of Local Droplet Number Standard Deviation Explains the Differences in Mixing



Conclusions

- Differences in spray shapes in droplet laden jets were studied and the situation is associated with spray formation process in diesel sprays (e.g. HCCI).
- Turbulent diffusivity quantifies the differences in spray shapes: implications to RANS droplet dispersion models.
- The PDF of standard deviation of droplet age explains the differences in mixing.
- Droplet size = > interaction with turbulence => the outcome determines the mixing.
- Here: small droplets mixed better than large droplets as the dissipation was not strong (not very high mass loading).

Fuel Spray Experiments and Large-Eddy Simulation of Droplet Size Effects on Spray Shape

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Large-Eddy Simulation (LES) and Lagrangian Particle Tracking (LPT) methods are used to show how droplet size influences spray shape and how realistic spray shapes, as seen in our experimental studies, can be produced with LES+LPT. As a model problem we study a round droplet laden gas jet at $Re = 10^4$ and $Ma = 0.3$. The initial slip velocity between the particulate and the carrier phases is $+0.25U_o$. Only monodisperse sprays are considered having Stokes numbers, $0.07 \leq St_p \leq 2.56$ translating to diameters between $2...12\mu m$. The droplet to gas stream mass loading ratio is 0.3 corresponding to the two-way momentum coupling regime. The results demonstrate that the mean Stokes number of the droplets has a significant role in the observed dynamics of the spray jet. The used simulation approach is able to reproduce a realistic spray shape as seen in the experiments.

I. Introduction

In diesel engines the structure and internal homogeneity of the fuel spray affects emissions. Here we demonstrate how droplet diameter may influence the spray shape and the internal spray structure. Understanding the connection between droplet size and mixing is essential to enable to predict accurately the formation of unwanted emissions. Motivated by these issues, it can be understood that the topic of droplet/particle size effects on turbulence production/dissipation and spray dispersion has gained a wide amount of interest in the literature.[1–4]

Here we briefly introduce our recent experimental studies on diesel sprays and present simulation results.[5–9] We apply the Large-Eddy Simulation method (accounting for the turbulence in the fluid phase) and Lagrangian Particle Tracking for the particle phase. What is especially interesting in our approach is the so called *implicit* LES approach in which *no turbulence* model is applied but, instead, a very fine computational grid is applied.

II. Fuel Spray Measurements

Our recent experimental activities regarding fuel spray studies have been published in the SAE Technical Paper Series.[5,6] The studies are related to spray formation at different injection pressures, injector nozzles and ambient gas densities using marine commonrail injectors. Figure (1) shows a typical set of images using backlight imaging: the camera and laser are pointed to each other from different sides of the measurement chamber. In measurements there was a short duration laser pulse and the width of the beam was expanded. This was done to get even and planar light to measurements. The measurements were controlled by computer which was also used for data acquisition. The original request to measure was sent to a trigger unit which synchronized the injector, timing of the laser, and the camera. Images were taken at different time after start of injection (ASOI) and thereby an additional delay was set to camera and laser. Imaging was performed with a 4 megapixel grayscale camera. The image is rectangular and the resolution of the camera is 12 bit. The double frame camera is capable of taking two consecutive images with a time interval of 200 ns. The light source is a double pulsed Nd:YAG laser which has a maximum pulse energy of 500 mJ (532 nm light). The pulse has a typical duration of 5 ns which is short enough to capture an instantaneous picture of a high velocity spray. Due to short pulse duration of the light source, high timing accuracy can be achieved. Very high resolution images were achieved because of short illumination time, high greyscale definition, and special back lightning. With double frame measurement system both diesel spray penetration and spray tip velocity was measured. It was found that the spray has separate acceleration and deceleration regions.[5,6]

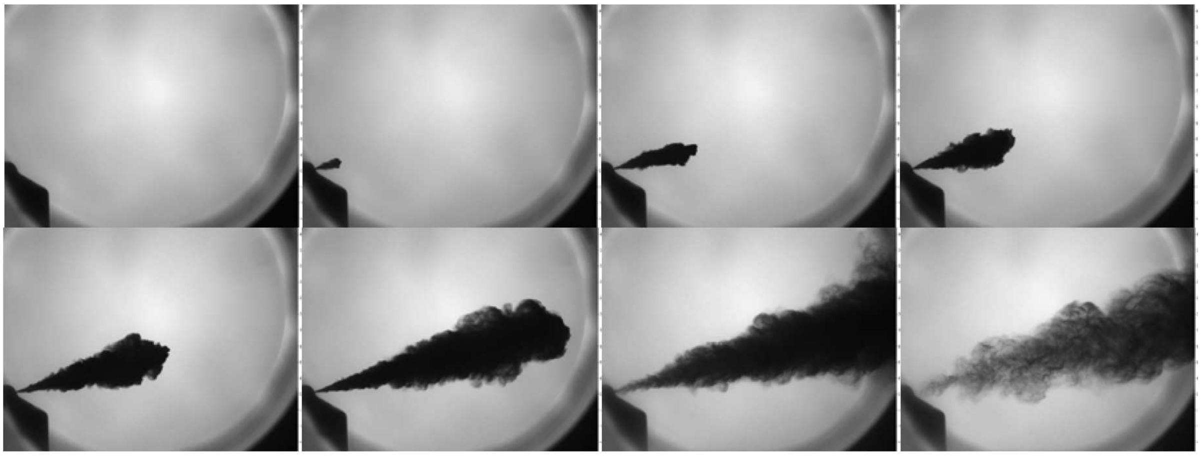

Figure 1. Snapshots of fuel spray evolution.

III. Problem Description

We have also carried out a number of studies regarding LES of fuel sprays which have in published in various forums.[7–9] Figure (2) shows an illustration of the computational setup where a round particle laden gas jet with diameter $D = 2mm$ enters a cylindrical chamber through a round orifice located in the wall of the cylinder. The chamber is enclosed by walls from the sides but has an open outflow boundary at the opposite end of the chamber so that fluid may leave the system. The vessel diameter is $8D$ and its length $35D$. The chamber is initially filled with nitrogen and there is a gas flow into the chamber. As the Mach number is low, $Ma = 0.3$, the density and the pressure will remain nearly constants in the chamber during the simulation. The inlet velocity profile is a top hat profile that is perturbed with uniformly distributed random noise. The mean gas exit velocity at the inlet is $U_o = 80m/s$ and the amplitude of the fluctuating component is 5% of the exit velocity. The inlet velocity boundary condition including the fluctuating component is non-vanishing only to the axial component of velocity and the other components of velocity are set to zero at the inlet. This corresponds to an average gas flow rate of $0.00154kg/s$ through the nozzle. The initial velocity of the particles is $U_p = 100m/s$ so that the slip velocity is $+0.25U_o$. The total injection time is $\tau_{inj} = 1.5ms$. The density of the gas is about $6.1kg/m^3$, the density of the droplets is $830kg/m^3$ and the measurements are performed at room temperature.

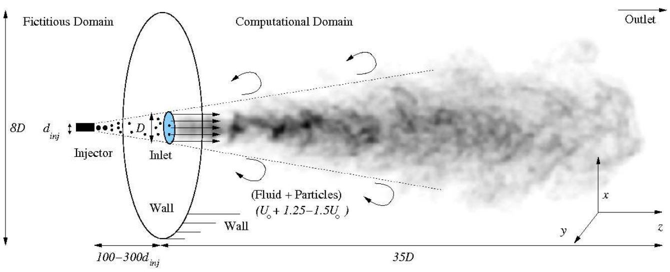

Figure 2. A schematic picture of the computational setup. Particles are injected randomly into the jet region at the orifice. The exit is located at $z = 35D$.

The grid resolution depends on the streamwise direction so that the grid spacing is gradually increasing in the downstream direction. The ratio between the thickest and the thinnest cell layer is 3 so that the mesh is very fine in the streamwise direction near the inlet and gradually becomes coarser. The mesh contains about

3.5 million cells. The number of cells in streamwise direction is 300. In general, to carry out an adequate LES of a spray one needs to capture a range of time and length scales providing a scale separation between the largest scales of turbulence and the smallest resolved ones. The smallest cells in the mesh are located in the jet axis and they are about $40 \times 40 \times 100\mu m$ in size. The Courant number is chosen so that its maximum in the computational domain was smaller or equal to about 0.12. This corresponds to a small timestep of $\Delta t_{max} = 0.6 \cdot 10^{-7}s$. The domain is decomposed in the streamwise direction onto domains (allocated to 32 processors).

IV. Simulation Results

IV.A. Spray Visualization Algorithm

It is important that the simulated sprays are visualized properly so that the post-processed spray images emulate the sprays that can be observed in reality. The algorithm that we use here is straightforward to implement and it is based simply on projecting droplet coordinates onto a two-dimensional grid. From this a line-of-sight mass intensity is observed which, when exponentially damped, gives a realistic luminosity (if exponential damping law for light intensity is assumed). Figure (3) shows three different spray visualizations of a cloud of tracer particles in a single phase gas jet.

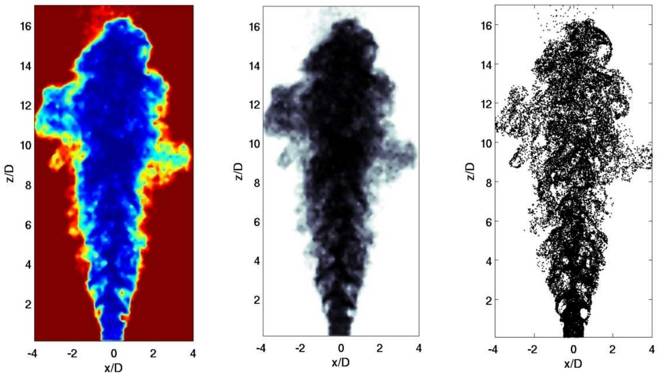

Figure 3. Three different spray visualizations. Left: Colorscale light intensity. Middle: Grayscale light intensity. Right: Visualization of tracer particles from a cutplane.

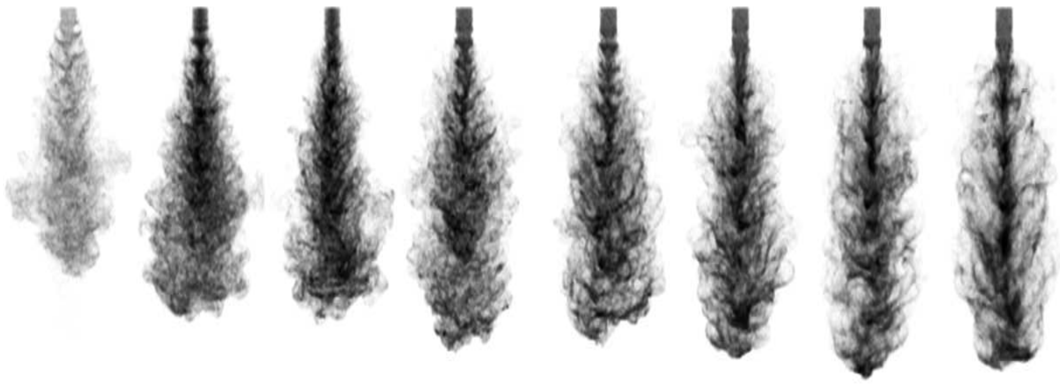

Figure 4. Simulated sprays. Left: Tracers in a single phase jet. Second from left: droplet laden jet with small droplets ($d = 2\mu m, St_p = 0.07$). Right: droplet laden jet with large droplets ($d = 2\mu m, St_p \approx 2$).

IV.B. Spray Shapes

The spray shapes are noted to depend strongly on droplet size. This is intuitive since, in general, e.g. a cloud of fine dust 'looks' different from a cloud of larger particles such as sand. In sprays (as well as in dust clouds) the physical explanation can be stated in terms of the ratio of droplet timescale (τ_p) and the integral timescale ($T = D/U_o$, where D is the jet diameter and $U_o = 80m/s$ i.e. the inlet gas velocity): if $\tau_p \gg T$ the droplets respond weakly to the motions of the large eddies, else if $\tau_p \ll T$ the droplets respond quickly to the motions of a size range of eddies. The apparent differences can be seen in Figure (4) which shows that the small droplets form a fog-like cloud whereas the large droplets stay more centered as they respond weakly to the small scale gas motions. The topic, including the effect of mass loading ratio, atomization and droplet size distribution on mixing, has been thorougly discussed in our recent studies.[7–9]

V. Summary

In this work a droplet laden jet has been studied using LES and LPT. The results show that spray shape depends on droplet size and that the present simulation method produces spray shapes that are very similar to experiments. The shape is associated with mixing of the jet. In fact, as explained in our recent papers, the mixing can be quantified in terms of droplet diffusivity that arises when droplet momentum relaxation timescales couple to the turbulent motions.[8,9]

Acknowledgments

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