TURBULENT DISPERSION OF HEAVY DROPLETS

Humberto Bocanegra Evans[1], Nico Dam [2] & Willem van de Water [1]
[1]*Applied Physics Faculty, Eindhoven University of Technology, Eindhoven, The Netherlands*
[2]*Mechanical Engineering Faculty, Eindhoven University of Technology, Eindhoven, The Netherlands*

Abstract The longstanding issue of turbulent dispersion of heavy droplets is revisited using a novel experimental technique. Within a cloud of phosphorescent droplets, thin cylindrical volumes are tagged and recorded in a high-speed fashion as they are advected by the flow. The widening of these volumes provides experimental evidence of dispersion which is faster than that of fluid parcels. We explore the effect of inertia in the dispersion of heavy droplets by experimenting with several droplet diameters.

We study the widening of a cloud of inertial droplets in a strongly turbulent flow. At $t = 0$ this cloud is a thin pencil–like line, whose width is $\Delta \cong 10\eta$, with η the Kolmogorov length (which is about 90 μm in our experiment). We create this initial cloud by laser–tagging droplets in a turbulent cloud chamber. The droplets are made out of a phosphorescent solution, and glow during a few Kolmogorov times τ_η, which allows us to follow them using a fast gated intensified camera.

A sketch of the experiment is shown in Figure 1. It consists of a chamber, where a strongly turbulent flow is driven by eight synthetic jets [2]. The flow is isotropic and homogeneous over our field of view; its characteristics are listed in Table 1. Droplets are created from a phosphorescent solution using a spinning disc aerosol generator. The phosphorescent solution has a lifetime $\tau_{ph} \approx 500$ μs comparable to the Kolmogorov timescale, which allows us to track the evolution of the droplet cloud for a few Kolmogorov times.

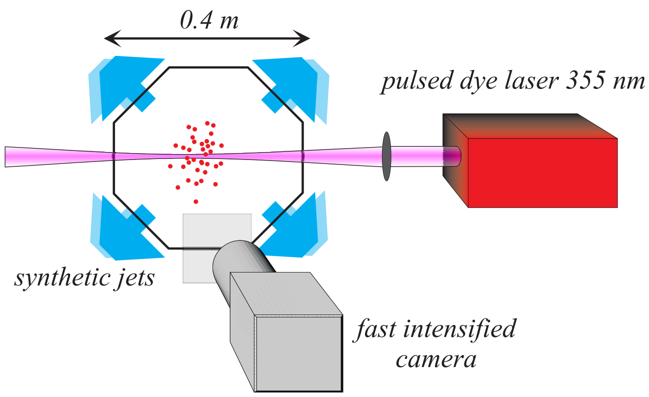

Figure 1. A schematic representation of the setup. We use a 355 nm pulsed laser to tag droplets within a turbulent cloud of inertial droplets. The turbulence, which is homogeneous and isotropic is stirred using eight synthetic jets. The droplets are made of a Europium-based solution and are produced using a spinning disk aerosol generator (not shown). After being tagged, they are recorded at 5 kHz for $t \approx 4\tau_\eta$.

The experimental measurements consist of series of sequences, with each sequence starting 0.5 μs after the tagging procedure. Once the volume has been tagged, a high speed camera is activated recording at a rate of 5000 FPS, equivalent to approximately two frames every Kolmogorov time. This procedure is repeated approximately 3200 times and statistics of the dispersion are obtained by phase averaging the recordings.

$u_{\rm rms}$ (m/s)	ε (m^2/s^3)	λ (mm)	Re_λ	τ_η (μs)	η (μm)
2.0	63.4	3.8	470	500	88

Table 1. Flow statistics with $u_{\rm rms}$ the turbulent velocity, ε the energy dissipation rate, λ the Taylor microscale, Re_λ the Taylor–Reynolds numberm, and τ_η and η the Kolmogorov time an length scales.

The droplet density is so small that droplet collisions can be neglected, as can the back reaction of the droplet motion on the flow. In summary, our technique allows us to follow a cloud of inertial particles that has been prepared in a non-intrusive way. The key question is how the spreading of this cloud should be compared to a cloud of passive tracers which faithfully follow the flow.

RESULTS

Our pencil–shaped clouds of inertial droplets have a Gaussian cross-section, $I(y) \sim \exp\left(y^2/\Delta^2\right)$. At short times, $t/\tau_\eta \lesssim 3$, the cloud expands ballistically, $\Delta^2(t) = \Delta^2(0) + 2v^2t^2$. For fluid tracers and times much smaller than the Lagrangian integral time, the velocity v should be the turbulent velocity u. We find that $v > u$, thus, clouds of inertial particles spread faster in turbulence than true fluid tracers. This remarkable observation agrees with [1], where the dispersion of diesel droplets in turbulent water is studied. The main differences between their experiment and ours is that our tagging technique is non-intrusive, thus avoiding complications due to the injection of particles in the turbulent flow; also, buoyancy produces a velocity comparable to the turbulent velocity fluctuations, whereas the droplets in our experiment have a terminal velocity over an order of magnitude smaller than the turbulent velocity fluctuations.

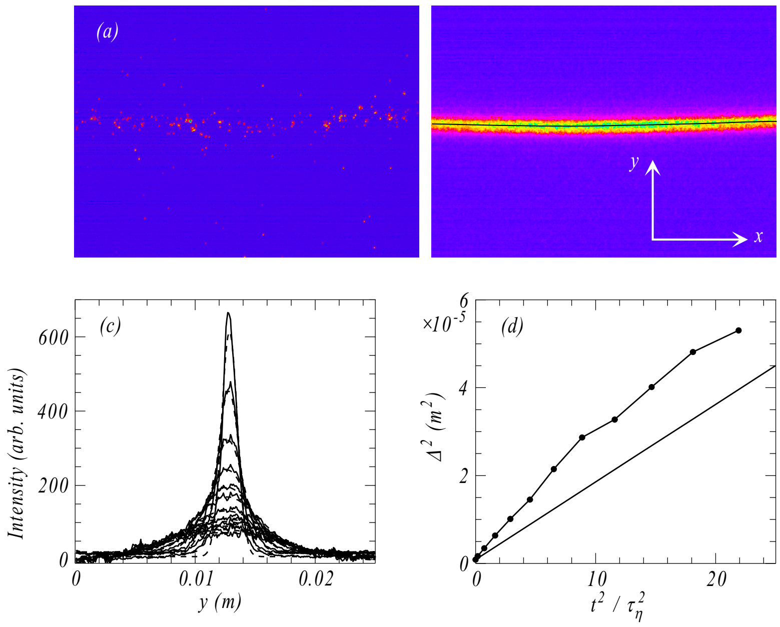

Figure 2. *a)* Snapshot of tagged droplets at $t = 1.2$ ms. *b)* averaged images taken at $t = 0.2$ms, the line indicates the backbone of the averaged image. The line is curved do to imaging nonlinearities. After straightening the images, they were summed horzontally. *c)* Full lines show the horizontally summed intensity $I(y,t)$, for time delays $t = 0.2 \ldots 2.4$ ms, dashed lines are Gaussian fits, $I(y,t) = \pi^{-1/2}\Delta^{-1}\exp(-(y-y_c)^2/\Delta^2)$. *d)* Dots show $\Delta(t)^2$ ($\Delta(0)/\eta = 11$), line indicates $\Delta(t)^2 = \Delta(0)^2 + 2\,u^2\,t$, with u the Eulerian fluid turbulent velocity.

CONCLUSION

We have developed an experimental diagnostic that allows us to tag and follow droplets suspended in a flow. This technique can aide in the study of particle-laden flows, and can help determine Lagrangian properties of the particles within these flows. We see a broad array of applications that include analysis of preferential concentration in dense clouds, and analysis of particle dispersion.

Tagging is a way to track entire clouds of droplets, focusing on the continuum dynamics of the droplet distribution. Due to the large number of droplets this would be much harder to achieve by tracking each droplet individually. An interesting approach is to combine both tagging and droplet tracking techniques, which would allow us to track a subset of droplets in clouds so dense that conventional tracking methods fail.

References

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[2] W. Hwang and J. K. Eaton. Creating homogeneous and isotropic turbulence without a mean flow. *Experiments in Fluids*, **36**(3):444–454, March 2004.