BREAKUP OF SMALL AGGREGATES IN BOUNDED AND UNBOUNDED TURBULENT FLOWS

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Abstract Breakup of small tracer-like aggregates is studied by means of numerical simulations in four different flows, namely homogeneous isotropic turbulence, smooth stochastic flow, turbulent channel flow, and developing boundary layer flow. Aggregate breakup occurs when the local hydrodynamic stress $\sigma \sim \varepsilon^{1/2}$, where ε is the local energy dissipation, overcomes a given threshold value $\sigma_{\rm cr}$ [or equivalently $\varepsilon_{\rm cr} \sim \sigma_{\rm cr}^2$] characteristic for a given type of aggregates. Following the aggregate trajectory upon release and detecting the first occurrence of local energy dissipation exceeding the predefined threshold allows for estimating the breakup rate as a function of $\varepsilon_{\rm cr}$. Results show that the breakup rate decreases with increasing threshold. For small values of the threshold, this decrease assumes consistent scaling among the different flows which is explained by universal small scale flow properties.

Small particles have a strong tendency to stick together and form clusters or aggregates that, depending on the type of particles, might undergo further transformations such as coalescences or sintering. Turbulence in the suspending fluid has a distinct influence on aggregate formation. It not only enhances the rate of aggregation due to more frequent collisions among particles, but also, viscous hydrodynamic stress generated by velocity gradients in the fluid flow cause aggregate restructuring and breakup. The interplay between aggregation and breakup crucially determines the dynamics of a suspension of aggregating particles which is of high relevance in many technological and natural systems.

While turbulent aggregation of small particles is a widely studied and relatively well understood phenomenon, aggregate breakup driven by turbulent fluid motions is less understood. Aggregate breakup occurs when forces acting to pull apart the aggregate overcome forces that hold the particles together. In a dilute suspension of small aggregates, the former are governed by velocity gradients in the fluid flow which are highly intermittent. This intermittency makes it difficult to predict the occurrence of a sufficiently high stress to cause breakup, and hence, to determine breakup dynamics.

In this work aggregate breakup in turbulence is studied by means of numerical simulations. The diluted aggregates are assumed to have negligible inertia and to be small with respect to the viscous length scale of the underlying turbulence. The aggregates thus behave like tracers when moving through the flow field. Breakup occurs when the local hydrodynamic stress $\sigma \sim \mu(\varepsilon/\nu)^{1/2}$ (μ is the dynamic viscosity, ν is the kinematic viscosity, and ε is the local energy dissipation) overcomes a threshold value $\sigma_{\rm cr}$ [or equivalently $\varepsilon_{\rm cr} \sim \nu(\sigma_{\rm cr}/\mu)^2$] that is characteristic for the type of aggregates considered. Typically, $\sigma_{\rm cr}$ is the larger the smaller the aggregate, i.e. a high stress is required to breakup a small aggregate.

In our simulations, breakup dynamics, i.e. the rate of breakup of aggregates of a given type, are determined by releasing a given number of aggregates in a certain region of the flow and following their trajectory until the local dissipation on the position of the aggregate overcomes for the first time the predefined threshold value. The timespan in between release and first occurrence of $\varepsilon_{\rm cr}$ defines an exit time. The inverse of the mean exit time gives the characteristic breakup rate for a given type of aggregates released in a given region of the flow [1].

In the present work, four different flows are considered, namely homogeneous isotropic turbulence (HIT), turbulent channel flow (CF), developing boundary layer flow (BLF), and a smooth stochastic flow (SSF) in an infinite domain. HIT was realized by large scale forcing of an incompressible fluid in a periodic box. A resolution of 2048^3 nodes allowed for resolving a turbulent Reynolds number of $R_\lambda \sim 450$, see [2] for details. CF was realized in a rectangular box bounded by solid walls on two sides and treating the other sides periodic. The studied flow had a shear Reynolds number of $R_\tau = 150$; the bulk Reynolds number was $R_b = 2100$ [3]. BLF was realized in a rectangular box with a solid wall on the long edge and flow parallel to it. Local forcing close to the inflow lead to a fully developed boundary layer evolving in streamwise direction. The studied flow reached a boundary layer thickness (characterized through the Reynolds number based on the momentum-loss thickness θ) of $R_\theta = 2500$, see [4] for details. SSF was realized in a periodic box by representing the fluid velocity as a Fourier series and evolving the modes by a Langevin process, see [5] for details. While in the first and last of these flows, the aggregates are released uniformly throughout the domain, in CF the aggregates are released along the centerplane of the channel. In BLF, the aggregates are released either inside or outside the boundary layer at the beginning of the computational domain.

Fig. 1 shows the breakup rate as a function of the critical dissipation required to break a certain type of aggregates

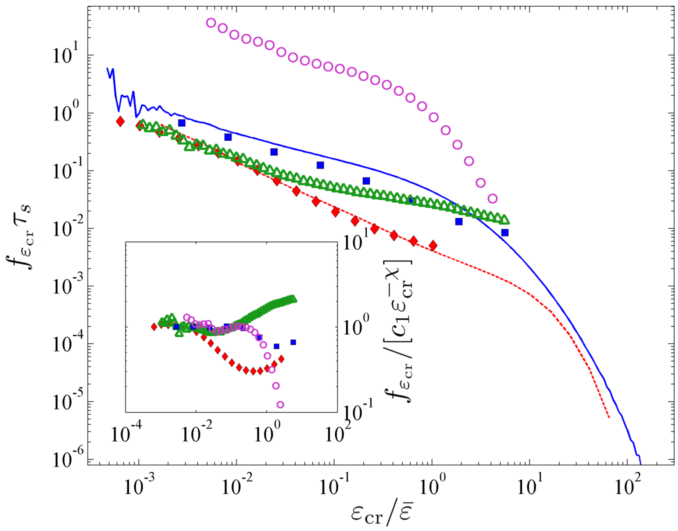

Figure 1. Breakup rate as a function of critical dissipation. Symbols refer to exit time measurements. Blue squares: homogeneous isotropic turbulence; the blue solid line shows a quasi-Eulerian proxy applicable for homogeneous flows [1]. Red diamonds: channel flow; the red dashed line shows an estimate from fitting the decaying umber of aggregates to an exponential. Green triangles: boundary layer flow where aggregates were released inside the boundary layer flow. Purple circles: smooth stochastic flow. **Inset.** Breakup rate compensated by the power law approximation $f_{\varepsilon_{\rm cr}} = c_1 \varepsilon_{\rm cr}^{-\chi}$, $\chi = 0.52$ valid for small $\varepsilon_{\rm cr}$ (the parameter c_1 is adjusted for the different flows).

(see caption for details). Axes in Fig. 1 are made dimensionless using a characteristic dissipation $\bar{\varepsilon}$ and a timescale $\tau_s = (\nu/\bar{\varepsilon})^{1/2}$ (for SSF, the correlation time of the Langevin evolution was used instead). For the homogeneous flows and the channel flow, $\bar{\varepsilon}$ corresponds to the mean, respectively the volume average dissipation, while for the boundary layer flow $\bar{\varepsilon}$ was taken as the mean dissipation in the region inside the BL where the aggregates were released.

We observe that with this normalization, the different sets in Fig. 1 are very close to each other. In particular, for small values of the critical dissipation the breakup rate $f_{\varepsilon_{\rm cr}}$ assumes power law scaling $f_{\varepsilon_{\rm cr}} \sim \varepsilon_{\rm cr}^{-\chi}$ with $\chi \approx 0.52$ consistent among the different sets. This is further illustrated in the inset in Fig. 1 that shows $f_{\varepsilon_{\rm cr}}$ compensated by the power law approximation which gives reasonable agreement.

The consistent behavior for small dissipation is explained as follows. Small values of $\varepsilon_{\rm cr}$ refer to weak aggregates. These aggregates breakup shortly after their release due to dissipation events brought up by local turbulent fluctuations. The properties of these local fluctuations, which represent small scale features of turbulence, for all flows resemble isotropic homogenous turbulence, thus giving raise to consistent breakup behavior for small $\varepsilon_{\rm cr}$ as observed in Fig. 1.

On the contrary, for large values of the critical dissipation a deviation of BL data from the other flows is observed. This is due to the streamwise and (strong) wall normal heterogeneity in this flow. An aggregate surviving the intense region at its release point at the beginning of the BL will flow to a calmer downstream region. There, it is only broken when drawn to the wall where it will experience high shear. Bringing the aggregate to the wall is driven by coherent fluid structures of scales larger than the viscous scales. This different mechanism explains the different breakup behavior for the heterogeneous flow.

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References

[1] M. U. Babler, L. Biferale, and A. S. Lanotte. Breakup of small aggregates driven by turbulent hydrodynamical stress. *Phys. Rev. E*, **85**:025301, 2012.

[2] J. Bec, L. Biferale, A. S. Lanotte, A. Scagliarini, and F. Toschi. Turbulent pair dispersion of inertial particles. *J. Fluid Mech.*, **645**:497–528, 2010.

[3] E. Pitton, C. Marchioli, V. Lavezzo, A. Soldati, and F. Toschi. Anisotropy in pair dispersion of inertial particles in turbulent channel flow. *Phys. Fluids*, **24**:073305, 2012.

[4] G. Sardina, P. Schlatter, F. Picano, C. M. Casciola, L. Brandt, and D. S. Henningson. Self-similar transport of inertial particles in a turbulent boundary layer. *J. Fluid Mech.*, **706**:584–596, 2012.

[5] J. C. Zahnow, J. Maerz, and U. Feudel. Particle-based modeling of aggregation and fragmentation processes: Fractal-like aggregates. *Physica D*, **240**:882–893, 2011.