DNS OF FULLY-RESOLVED DROPLET-LADEN ISOTROPIC TURBULENCE: A MASS-CONSERVING VOLUME OF FLUID METHOD

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Summary We developed a novel volume of fluid method for direct numerical simulation of droplet-laden turbulent flows. The method is globally and locally mass-conserving, robust, efficient and scalable. The method has been tested in several incompressible flows, and applied to droplet-laden decaying isotropic turbulence.

We developed a novel mass-conserving volume of fluid (VoF) method [5]. The VoF advection is performed with the Eulerian implicit - Eulerian algebraic - Lagrangian explicit (EI-EA-LE) algorithm originally proposed by Scardovelli *et al.* [3]. The original EI-EA-LE algorithm is globally mass-conserving but generates wisps and does not conserve the mass of the individual volumes tracked in the flow. We have improved this method with the addition of a redistribution and a wisps suppression algorithms, see Fig. 1 (left). Our method is wisps-free and thus conserves mass both globally and locally within each droplet. The method displays second-order spatial accuracy and almost second-order overall accuracy for typical values of the CFL number used in the simulations as shown in Fig. 2. A geometrical error smaller than 1% is obtained with a droplet resolution of 30 grid cells or more across the diameter.

In order to simulate droplets, the surface tension effects are treated with the continuum surface force (CSF) approach. The CSF approach leads to an algorithm where surface tension and pressure gradient across the interface balance exactly, therefore leading to minimal spurious currents determined only by errors in the numerical estimation of the interface curvature, that we compute accurately using a variable-stencil height-function technique [1]. The curvature computation algorithm is second-order accurate (Fig. 1, right) by enforcing the monotonicity of the local height function [4]. We tested the method for the viscous droplet-at-rest case. For that case with a droplet resolution of 32 cells across the diameter and $\Delta t/\Delta x = 0.01$, Table 1 reports the values of the maximum spurious currents averaged over 1000 time steps as a function of the non-dimensional surface tension coefficient σ.

In the case of non-zero Weber number, e.g. when a mean droplet velocity is present, the algorithm proves to be stable, and the spurious currents are negligible, as shown in Fig. 3 (left). In Fig. 3 (right), we present DNS results of fully-resolved droplet-laden incompressible decaying isotropic turbulence at an initial Reynolds number based on Taylor length-scale of turbulence $Re_\lambda = 75$ using a computational mesh of 1024^3 grid points and 7000 droplets. The droplet Weber number based on the r.m.s. velocity fluctuation of turbulence is $We = 0.5$, the initial droplet diameter is equal to the Taylor lenght-scale of turbulence, and the droplet volume fraction is $\phi = 0.1$. The curvature contours in Fig. 3 (right) show that the droplets curvature variations can reach and exceed 10% of the initial curvature (red and blue regions).

σ	cylinder $\|u\|_{max}$	sphere $\|u\|_{max}$
5	7.15e-4	2.46e-3
0.5	2.46e-4	1.02e-3
0.05	7.59e-5	3.30e-4

Table 1. Time-averaged maximum spurious currents for a viscous droplet at rest for different values of the non-dimensional surface tension coefficient σ.

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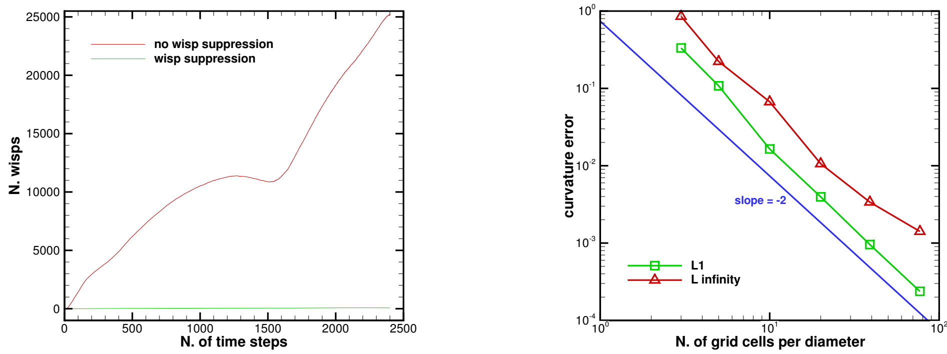

Figure 1. Total number of wisps vs number of time steps for a sphere of radius 0.15 advected in a time reversed single-vortex field [2] with period T=2 using a mesh of 128^3 grid points (left). Curvature error for a sphere as a function of grid resolution (right).

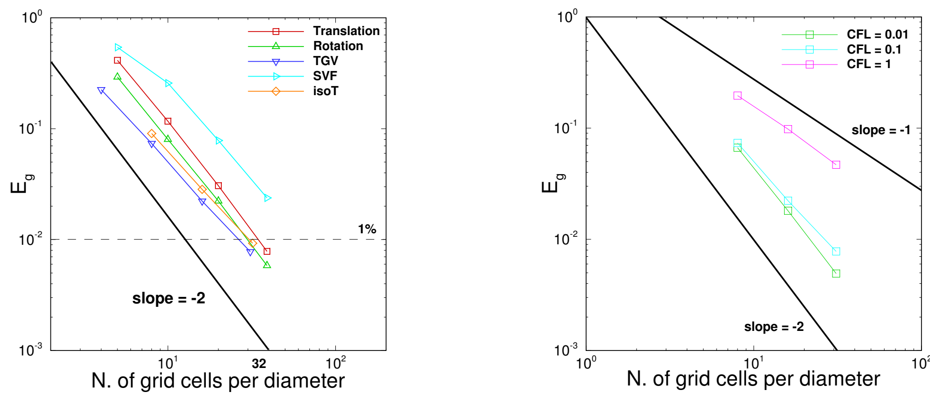

Figure 2. Geometrical error, E_g, of the advection and reconstruction algorithm for a sphere as a function of mesh resolution at CFL=0.1. Translation along the box diagonal, rotation and time-reversed single-vortex flow (SVF) with period T=2 for a sphere of radius 0.15. Time-reversed Taylor-Green vortex flow (TGV) with period T=2 for a sphere of radius 0.12. Time-reversed isotropic turbulence flow at $Re_{\lambda 0} = 75$ (isoT) with period T=1 (left). Sphere advection in Taylor-Green vortex flow: VoF geometrical error, E_g, versus number of grid points per diameter, as a function of CFL number (right).

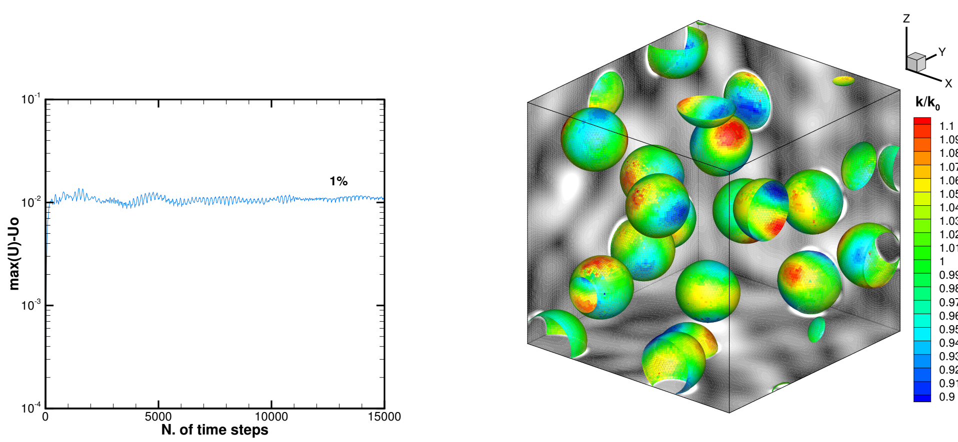

Figure 3. Velocity oscillations (spurious currents) for a translating sphere along the box diagonal, as a function of time (left). Fully coupled droplet-laden decaying isotropic turbulence, $Re_\lambda = 75$, laden with 7000 droplets. $C = 0.5$ iso-surface with normalized curvature color contours (k/k_0 where k_0 is the initial curvature of the spherical droplets) and vorticity magnitude contours (gray scale). The Weber number based on $r.m.s$ velocity and droplet diameter is 0.5, the volume fraction is $\phi = 0.1$, and the droplet resolution is 32 cells across the initial diameter. The plotted region is a 512^{th} of the entire cubic box simulated using a mesh of 1024^3 grid points (right).