EFFECTS OF VISCOSITY RATIO ON DROPLET-LADEN ISOTROPIC TURBULENCE

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Summary We performed direct numerical simulation (DNS) of droplet-laden isotropic turbulence. We released 3130 non-evaporating droplets of diameter approximately equal to the Taylor lengthscale (corresponding to 5% droplet volume fraction) in decaying isotropic turbulence at initial Taylor-scale Reynolds number $\mathrm{Re}_\lambda = 83$. We studied four cases: one single-phase case and three droplet-laden cases in which we varied the droplet- to carrier-fluid viscosity ratio ($1 \leq \mu_d/\mu_c \leq 100$). We first derived the turbulence kinetic energy (TKE) equations for the two-fluid, carrier-fluid and droplet-fluid flow. This allows us to explain the pathways for TKE exchange between the turbulent flow of the carrier fluid and the flow inside the droplet. Then, we analyze the effects of varying μ_d/μ_c on the turbulent kinetic energy budget of the carrier fluid, the droplet fluid and the two fluids, and, finally, we explain the underlying physical mechanisms for their modulation.

The interaction of dispersed droplets and turbulence is important in many natural and industrial processes, e.g. rain formation [1], liquid-liquid emulsion [2], spray cooling [3] and spray atomization in combustors [4, 5]. Often, e.g., during secondary atomization or the latter stages of rain formation, the droplets are larger than the Kolmogorov lengthscale, i.e., finite-size. The interaction of finite-size droplets and turbulence, in comparison to the interaction of finite-size particles and turbulence (e.g., in [6]), is expected to incorporate new physical mechanisms. These new mechanisms are a result of the droplet's ability to deform, develop internal circulation, break up and coalesce with other droplets. The first two processes are characterized by two additional non-dimensional parameters: the Weber number, We, and the viscosity ratio between the droplet fluid and carrier fluid $\gamma = \mu_d/\mu_c$. In [7], we have reported on the effects of varying We on droplet/turbulence interaction, and we now focus on the effects of varying γ on such interaction.

We have performed direct numerical simulation (DNS) of decaying isotropic turbulence laden with deformable droplets, whose diameter is approximately equal to the Taylor lengthscale at the time of droplet release in the flow field. We released 3130 non-evaporating droplets from rest in the isotropic turbulent flow at time $t = 1$. Figure 1 shows a snapshot of the computational domain after the droplets are released ($t = 1.5$). The non-dimensional parameters characterizing the two-fluid flow are the initial Taylor-scale Reynolds number at droplet release time, $\mathrm{Re}_\lambda = 83$, droplet Weber number based on the r.m.s. velocity at release time, $\mathrm{We}_{\mathrm{rms}} = 1$, the droplet- to carrier-fluid density ratio, $\rho_d/\rho_c = 10$, the droplet volume fraction, $\phi_v = 0.05$, and the droplet- to carrier-fluid viscosity ratio which is varied from 1 to 100 in the three droplet-laden cases studied. The initial droplet diameter is 1.1 Taylor lengthscales and 20 Kolmogorov lengthscales. The computational domain is a periodic cube, which is discretized using 1024^3 grid points, giving a droplet resolution of 32 grid points per diameter. The governing equations were solved numerically using a fast pressure-correction method [8] that has been verified and validated. To capture the droplet interface and to track the motion of the finite-size deforming droplets, we used a mass-conserving Volume-of-Fluid (VoF) method [9].

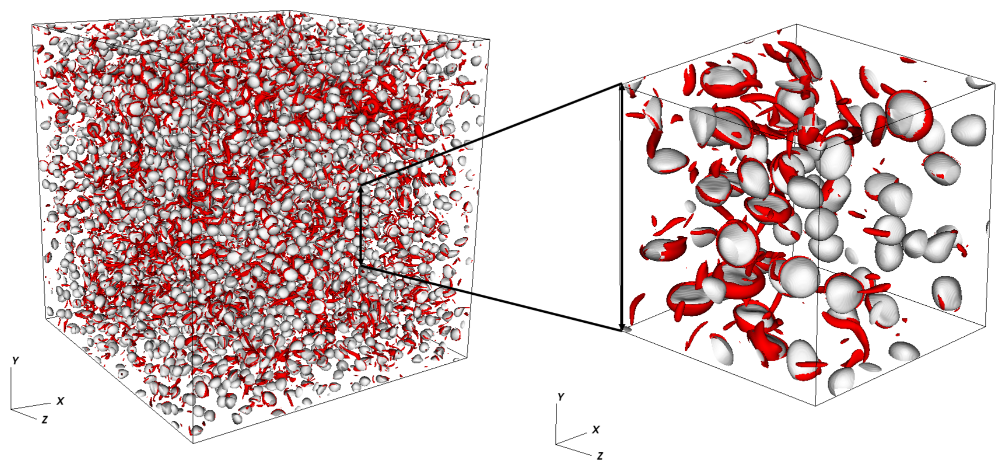

Figure 1: Instantaneous droplet interfaces in shaded white ($C = 0.5$ isosurface) and vortical structures in red ($\lambda_2 = -50$ isosurfaces) at $t = 1.5$. (Left) full domain ($1 \times 1 \times 1$); (right) sub-domain ($0.25 \times 0.25 \times 0.25$).

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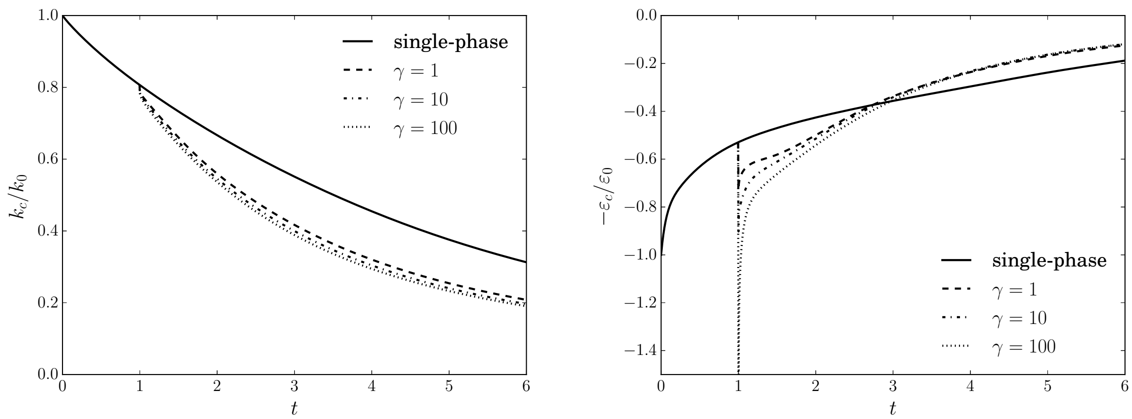
We simulate four cases: a single-phase case and three cases in which the viscosity ratio (γ) is increased from 1 to 10 to 100. Figure 2(a) shows the time evolution of the carrier-fluid turbulence kinetic energy (TKE) normalized by its initial value, $k_c(t)/k_0$, in the four cases. The presence of the droplets increases the decay rate of carrier-fluid TKE compared to the single-phase case. As the viscosity ratio (γ) increases from 1 to 100, the decay rate of $k_c(t)$ increases. By analyzing the evolution of the terms in the carrier-fluid TKE budget, the results show that as γ increases, the enhanced decay of $k_c(t)$ is due primarily to an increase in the dissipation rate of carrier-fluid TKE, $\varepsilon_c(t)$ (figure 2(b)). $\varepsilon_c(t)$ increases because as γ increases, the velocity gradient near the droplet interface increases in the carrier fluid and decreases in the droplet fluid (figure 3). Therefore, the carrier-fluid dissipation rate ($\varepsilon_c(t)$) increases, while the droplet fluid dissipation rate decreases.



(a) (b)

Figure 2: Temporal evolution of (a) the carrier-fluid turbulence kinetic energy, k_c, normalized by its initial value, k_0 and (b) the carrier-fluid dissipation rate of turbulence kinetic energy, ε_c, normalized by its initial value, k_0.

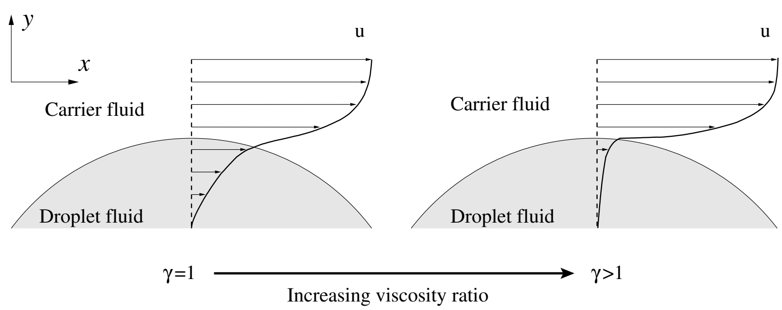


Figure 3: Illustration of the velocity profile, $u(y)$, at the interface of a droplet released from rest in uniform flow. The illustration depicts the effects of varying the viscosity ratio, γ. Unity viscosity ratio ($\gamma = 1$): at the interface, the velocity is continuous and the velocity gradient is continuous (left); viscosity ratio greater than unity ($\gamma > 1$): at the interface, the velocity is continuous and the velocity gradient is discontinuous (right).

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