Direct numerical simulation of droplet laden homogeneous shear turbulence: numerical method and flow physics

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Abstract: We have developed an explicit and direct pressure-correction method (FastRK3P*) to solve the incompressible Navier Stokes equations for two-fluid flows under shear-periodic boundary conditions. Using FastRK3P* coupled with the volume of fluid method (VoF), we have performed direct numerical simulations (DNS) of droplet-laden homogeneous shear turbulence (DLHST). The turbulent flow is at an initial Reynolds number based on Taylor microscale $Re_{\lambda_0} = 40$, and is initially laden with 1,258 droplets of diameter approximately equal to twice the Taylor length-scale of turbulence, resulting in a 5% droplet volume fraction. The droplet-to-fluid density and viscosity ratios are both equal to 10. In the present work, our objective is to determine the effects of varying the Weber number, We, and the shear number, Sh, on the budget of the turbulence kinetic energy (TKE). DNS results show the effects of the mean shear on droplet dynamics for different We, how this affects the terms of the TKE equation, and, thus, the evolution of TKE in DLHST.

Keywords: Direct Numerical Simulation, Turbulent Shear Flow, Shear-periodic Boundary Conditions, Droplet-Laden Flow, Multiphase Flow

1 Introduction

The combustion processes in electric power plants, jet engines, gasoline and diesel powered vehicles are the primary sources of carbon dioxide CO_2 emissions. Improving combustion efficiency is an effective method of decreasing these emissions. To achieve this goal, we must better understand the physical and chemical processes involved in the atomization, evaporation and combustion of liquid fuels. It is difficult to extract information about the turbulence kinetic energy (TKE) budget in multiphase flows from experiments, therefore, direct numerical simulation (DNS) is an effective tool for studying these flows. DNS has been used to study particle laden flows in isotropic turbulence [1] and in homogeneous shear turbulence (HST) [2]. DNS has also been used to study fully resolved droplet-laden isotropic turbulence [3]. In engineering applications, droplet breakup often occurs in regions with mean velocity gradients. DNS of HST can be used to study the effects of these velocity gradients on droplet deformation and breakup. In the current paper, we present DNS results of DLHST and study the effects of Sh and We on the budget of TKE in DLHST.

2 Numerical Method

There are numerical difficulties in simulating HST. The length of the largest turbulence scales grows in an unbounded manner, so simulations must be performed carefully to be physically meaningful [4]. In addition, the second order Adams-Bashforth temporal integration scheme is weakly unstable when simulating HST on fine grid resolutions [5]. In order to address this issue, we have developed a new numerical method called FastRK3P* for accurately simulating variable density two-phase incompressible flows (e.g., gas-liquid, liquid-liquid). FastRK3P* is stable, and it requires solving the Poisson equation for pressure only once per time step instead of three times as required by the iterative Crank-Nicholson scheme adopted in [5] or standard RK3 methodologies. FastRK3P* is the result of combining the methodologies developed in [6] and [7] with the VoF method of [8] and a newly developed mass-conserving algorithm for applying shear-periodic boundary conditions with the VoF method.

3 Results

First, we have verified FastRK3P* and applied it to perform DNS of DLHST for different values of shear number, Sh, and Weber number, We. For the DNS, the computational domain has $1200 \times 600 \times 600$ grid points, an initial number of 1,258 droplets of diameter approximately equal to twice the Taylor length-scale of turbulence (i.e., 5% droplet volume fraction), and droplet-to-fluid density and viscosity ratios both equal to 10. For the analysis of the DNS results, we have also derived the evolution equation of TKE for DLHST and we present the effects of varying Sh and We on the evolution of TKE by explaining the physical mechanisms that affect each term of the TKE evolution equation.

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