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DISPERSION OF FULLY RESOLVED LIQUID DROPLETS IN ISOTROPIC TURBULENT FLOW

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EXECUTIVE SUMMARY

The objective of our research is to enhance the understanding of the four-way coupling effects in droplet-laden isotropic turbulence. (Four-way coupling means there is a two-way coupling between the droplets and turbulence, in addition to a two-way coupling between the droplets themselves.) The deformable droplets are fully resolved in 3D space and time.

The droplet-laden turbulence is simulated by directly solving the Navier–Stokes equations via a variable-density projection method. Most of the computation time is spent in solving the variable-coefficient Poisson equation. In order to improve the computational performance, we have developed an efficient Message Passing Interface (MPI)-based multigrid solver, which is further accelerated with multiple graphics processing units (GPUs).

Further, we examine the kinetic energy transfer between the droplets and turbulence. We also compare the dispersion characteristics of deformable droplets and solid particles with identical diameters and density ratios in isotropic turbulence.

RESEARCH CHALLENGE

Liquid fuel combustion devices typically atomize fuel into sprays of fine droplets. The fuel droplets disperse in the surrounding turbulent air, vaporize, and mix with it. The resulting chemical reaction transforms the chemical bonding energy into thermal energy, followed by gas expansion, which provides the desired mechanical energy. Understanding the four-way coupling effects between droplets and carrier flow is a necessary prerequisite for the efficient optimization of the energy conversion process.

The method of direct numerical simulation (DNS) of the fully resolved droplet-laden turbulence should be highly efficient in order to allow for the use of the appropriate fine mesh and timestep resolutions on Blue Waters. Our multigrid (MG) solver is essential for the efficient solution of Navier–Stokes equations.

METHODS & CODES

Our numerical procedure solves the two-phase incompressible Navier–Stokes equation. The jump condition at the interface between the carrier phase and the dispersed phase (liquid droplets) is incorporated in the Navier–Stokes equation via the Ghost Fluid Method.

The interface is accurately resolved by a conservative Level Set Method that conserves the mass of the dispersed phase. The most time-consuming part of our algorithm is the solution of the variable-coefficient Poisson equation that is derived from the Navier–Stokes equation. In order to solve the Poisson equation efficiently, we have developed a V-cycle geometric multigrid solver that serves as a preconditioner to the Preconditioned Conjugate Gradient method. A comparison is made between the dispersion of finite-size solid particles and liquid droplets in isotropic turbulence. The dispersion of solid particles is studied using the Immersed Boundary Method under the same physical conditions as those of droplet-laden turbulence.

RESULTS & IMPACT

Using our recently developed multigrid solver with its linear strong scalability (as seen in Fig. 1), preliminary results show that the dispersion of finite-size liquid droplets in isotropic turbulence is larger than that of finite-size solid particles of the same diameter and density ratio. This is due to the reduced decay rate of turbulence kinetic energy caused by the four-way coupling between the droplets and carrier flow.

WHY BLUE WATERS

In order to accurately resolve the turbulence length- and timescales as well as the dynamical properties of the deformable droplets, the mesh size of our DNS should be 1024^3 ~ 2048^3. Accordingly, the required number of high-performance computing cores ranges from 33×10^3 to 260×10^3 to solve the problem efficiently. Blue Waters' XE6 nodes can accommodate this requirement. No other facility available to us can provide such a large computational resource.

Our recently developed multigrid solver has been efficiently parallelized as shown in Fig. 1. It has the potential to be accelerated with GPU technology. The XK7 GPUs can serve as a good platform for us to further develop our multigrid solver. Furthermore, the Blue Waters staff have always provided us with valuable assistance in postprocessing and profiling. This assistance is essential for our project.

PUBLICATIONS AND DATA SETS

Rosso, M., H. Wang, and S. Elghobashi, Dispersion of finite size droplets and solid particles in isotropic turbulence. *ICMF-2016—9th International Conference on Multiphase Flow*, Firenze, Italy, May 22–27, 2016.

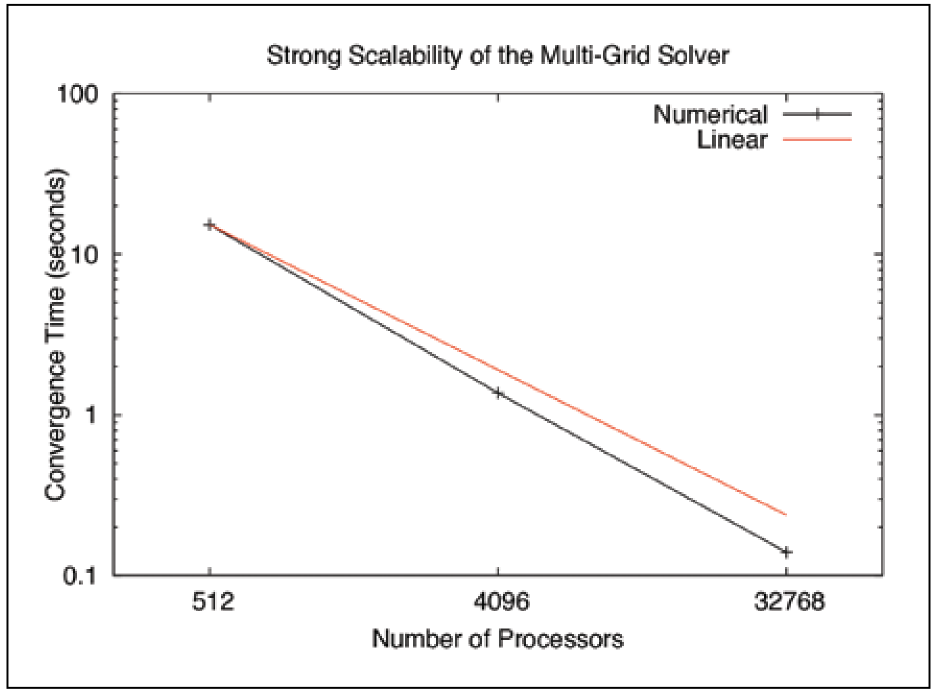

Figure 1: Scalability of our multigrid solver is indicated by the reduction of the time needed to solve a Poisson equation by increasing the number of Blue Waters processors. Our preconditioned conjugate gradient method uses a multigrid preconditioner. The mesh has 1024^3 grid points. The black line indicates the strong scalability of the solver and the red line shows a linear scalability as reference.

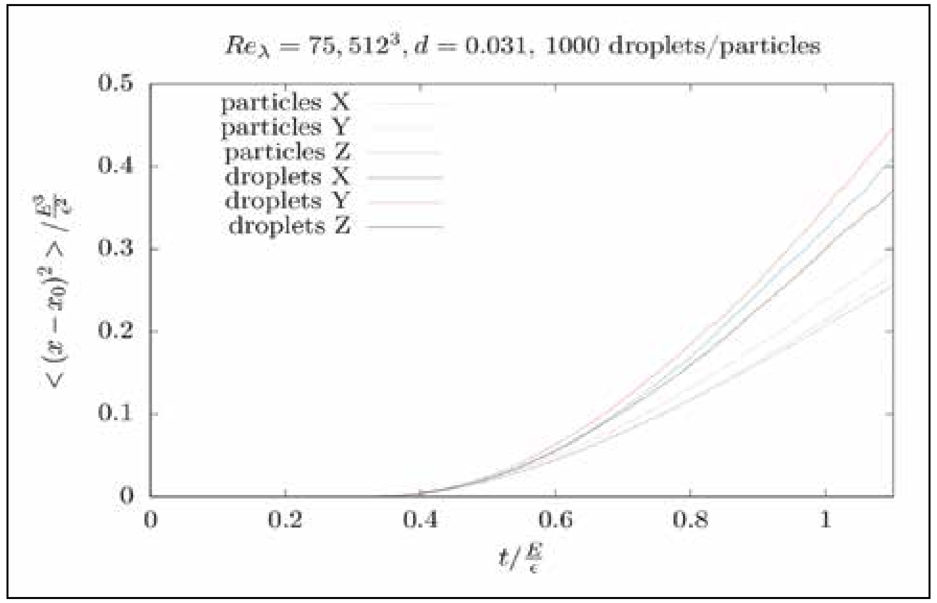

Figure 2: Comparison of the dispersion of liquid droplets and solid particles of the same diameter and density ratio in isotropic turbulence in the three coordinate directions. The dispersion is defined as the ensemble average of the square of the distance of a droplet/particle from its initial position. *E* is the turbulence kinetic energy. ε is the dissipation rate of *E*.