Abstract

Multiphase flows are a common phenomenon. Rains, sediment transport in rivers, snow and dust storms, mud slides and avalanches are examples of multiphase flows occurring in nature. Blood flow is an example of multiphase flow in the human body, which is of vital importance for survival. Multiphase flows occur widely in industrial applications from hydrocarbon extraction to fuel combustion in engines, from spray painting to spray drying, evaporators, pumps and pneumatic conveying. Predicting multiphase flows is of vital importance to understand natural phenomenon and to design and improve industrial processes. Separated flows and dispersed flows are two types of multiphase flows, which occur together in many industrial applications. Physical features of these two classes are different and the transition from one to another involves complex flow physics.

Experimental studies of multiphase flows are not easy, as most real world phenomenon cannot be scaled down to laboratory models. Even for those phenomenon that can be demonstrated at laboratory scale, rescaling to real world applications requires mathematical models. There are many challenges in experimental measurements of multiphase flows as well. Measurement techniques well suited for single phase flows have constraints when measuring multiphase phenomenon. Uncertainty in experimental measurements poses considerable difficulties in validating numerical models developed for predicting these flows. Owing to the computational effort required, direct simulation of multiphase flows, even for small scale real world applications is out of present scope. Numerical methods have been developed for dealing with each class of flow separately, that involves use of models for phenomenon that is computationally demanding.

Reynolds Averaged Navier-Stokes (RANS) methods for predicting multiphase flows place strong requirements on turbulence models, as information about fluctuating quantities in the field, that have significant effects on dispersed phase, is not available. Large Eddy Simulation (LES) gives better predictions than RANS as the instantaneous field data is available and large scale unsteadiness that effects the dispersed phase can be captured. Recent LES studies of multiphase flows showed that the sub-grid-scale (SGS) model used for the continuous phase has an effect on the evolution of the dispersed phase.

In this work, LES of multiphase flows is performed using Explicit Filtering Large Eddy Simulation method. In this method, spatial derivatives are computed using higher order compact schemes that have spectral-like resolution. SGS modeling is provided by the use of a filter with smoothly falling transfer function. This method is mathematically consistent and converges to a DNS as the grid is refined. It has been successfully applied to combustion and aero-acoustics and

this work is the first application of the method to multiphase flows. Study of dispersed multiphase flows was carried out in this work. Modeling of the dispersed phase is kept simple since the intention was to evaluate the capability of explicit filtering LES method in predicting multiphase flows.

Continuous phase is solved using a compressible formulation with explicit filtering method. Spatial derivatives are computed using fourth and sixth order compact schemes that use derivative splitting method proposed by Hixon & Turkel (2000*a*) and second order Runge-Kutta (RK2) time stepping. The grid is stretched as needed. Non-reflecting boundary conditions due to Poinsot & Lele (1992) are used to avoid acoustic reflections from boundaries. Buffer zones (Bogey & Bailly (2002)) are employed at outflow and lateral boundaries to damp vortical structures. The code developed for continuous phase is evaluated by studying round jets at $Re = 36,000$ and comparing with experimental measurements of Hussein *et al.* (1994) and Panchapakesan & Lumley (1993). Simulations showed excellent agreement with experimental results. Rate of decay of axial velocity and the evolution of turbulence intensities on the centerline matched very well with measurements. Radial profiles of mean and fluctuating components of velocities exhibit self-similarity. A set of studies were then performed using this code to assess the effect of numerical scheme, grid refinement & stretching and simulation times on the predictions. Results from these simulations showed good agreements with experiments and established the code for use in multiphase flows under various simulation conditions.

To assess the prediction of multiphase flows using this LES method, an evaporating spray experiment by Chen *et al.* (2006) was simulated. The experiment uses a nebuliser for generating a finely atomized spray of acetone, which avoids complex breakdown phenomenon associated with air blast atomizers and provides well defined boundary conditions for model evaluation. The nebuliser sits upstream in a pipe carrying air and droplets travel along with air for a distance of 10 diameters before exiting into a wind tunnel with co-flowing air. Droplet breakdown, if any, takes place inside the pipe and the spray is finely atomized by the time it reaches pipe exit. One of the experimental cases at $Re = 31,600$, with a mass loading of 1.1% and a jet velocity of 56 m/s is simulated. Particle size has a χ squared distribution with a Sauter mean diameter of 18μm. In the self-similar region, decay of centerline velocity and turbulence intensities matched well with experimental results. Continuous phase exhibits self-similar behavior. A series of simulations were then performed to match the initial region of the spray by altering the inflow conditions in the simulation. Simulation that matched the breakdown location of the experiment revealed the presence of a relaxation zone with a higher initial spreading rate, followed by a lower asymptotic spreading rate. Studies were performed to understand the effect of various phenomenon like evaporation and droplet size on this behavior.

A study of breakdown region of particle-laden jets was performed to understand the presence of relaxation zone post breakdown. Flow conditions were similar to evaporating spray experiment except that particles do not evaporate, mass loading is 2% and jet Reynolds number $Re = 2000$. A series of grid refinements were performed and on the largest grid, gird spacing $\Delta y = 7.5\eta$, where η is an estimate of the Kolmogorov length scale based on flow conditions. Decay of axial velocity on the centerline showed variations with grid refinement, tending to the experimentally measured value as the grid is refined. Variation of turbulence intensities along the centerline revealed a jump in axial velocity fluctuations at the breakdown location, while radial and azimuthal velocities showed a smooth increase to their asymptotic value. This jump was resolved on grid refinement and on fine grids axial velocity fluctuations followed the other two quantities closely in their rise to asymptotic state. Comparison of these quantities with a jet without particles revealed that the flow features are same for a jet with and without particles, and at the mass loading studied, particles have negligible effect on jet breakdown. Another study performed at a higher Reynolds number of $Re = 11,000$, under similar flow conditions showed similar behavior.

To assess the ability of predicting dispersed phase, simulations of particle-laden flows at low Stokes number were performed and compared against an experiment by Lau & Nathan (2014). The experiment studies variation of velocity and particle concentration along the centerline, and half widths of a jet velocity and concentration. Particles are injected into a pipe along with air, and the two phase flow is fully developed by the time it exits the pipe into a wind tunnel along with a co-flow. Particles are mono-disperse with a density of 1200 kg/m^3. Mass loading is 40% so that particles have a significant effect on the continuous phase. Two cases at particle Stokes number of 1.4, one with $Re = 10,000$, bulk velocity of 12 m/s and particle diameter of 20μm and another with $Re = 22,500$, bulk velocity of 36 m/s and particle diameter of 10μm were simulated. Simulations of both the cases showed good match with experimental measurements of centerline decay for the continuous phase. For the dispersed case, simulations with larger particles showed good match with experimental results, while smaller particles showed differences. This was understood to be the effect of lateral migration which is prominent in case of smaller particles, the models for which have not been used in the present simulation study.