LARGE EDDY SIMULATION OF PARTICLE LADEN FLOWS

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Abstract

Much attention has been paid to multiphase flow modelling in the last decades. The reason for such an interest is to be searched in the large variety of applications which such modelling can be applied to (e.g.: fluidized beds, gas turbine burners, coolant flows in nuclear plants). In most of these applications a key role is played by the turbulent mixing. Therefore, the contemporary use of multiphase flow simulation and refined turbulence modelling approaches such as Large Eddy Simulation (LES) can be seen as a powerful tool for gaining insight in complex processes. The present work focuses on dispersed multiphase flows and both aspects have been addressed: a classic two-fluid eulerian-eulerian model has been adopted and a proper numerical approach has been developed for the dispersed phase; a new turbulence closure model valid under high Reynolds number conditions has been developed and tested. Both the improvements have been implemented in a code for the numerical simulation of compressible reacting mixture and validated against experimental data measured on a particle laden flow configuration.

Mathematical model

When two-phase flows are considered, great attention must be paid to the assumptions under which the adopted model is developed, since these assumptions will affect the transport equations that govern the evolution of the two-phase system. The model developed in the present work is based on two main hypothesis: a) a condensed phase is dispersed in a continuous gaseous phase; b) dilute conditions are assumed. Under these hypothesis two way coupling between phases can be assumed, meaning that the equations governing each phase evolution present terms that account for the interaction with the other phase.

As to the complete set of filtered transport equations for the gas phase, that expresses the conservation of mass, momentum and energy, together with the thermodynamic state equation, the adopted equations are presented in [1].

The filtered balance equations coupled with SubGrid Scale models, may be numerically solved to simulate the unsteady behavior of the filtered variables.

The results that will be presented have been obtained neglecting the heat loss, the

kinetic energy dissipation during aerodynamic interaction between phases and the dissipation function. The latter are usually small at the resolved scales, when low Mach number conditions are considered.
A suitable turbulence model must be chosen in order to model the SubGrid Scale stress tensor τ^{SGS}. In the present work the Fractal Model (FM) [2,3,4,5] has been selected. The aim of FM in the absence of chemical reactions is to find an expression for μ_t. In the present work an important improvement has been made to the model: the Reynolds number Re_Δ at the filter cut off length scale Δ, that is the only input, is evaluated in a different way with respect to the original model [5]. In the old version this parameter was evaluated using the filtered gas velocity and density. In the present work it is evaluated using an estimate of the amplitude of the mode of lengthscale 2Δ of the signal (ρu), that will be addressed from now on as $(\rho u)_\Delta$, instead of the signal itself. In order to obtain $(\rho u)_\Delta$ it is necessary to apply some kind of high pass filter to the (ρu) field. In the present work a stencil of 5 or 4 points is used, depending on whether the variable (ρu) is collocated in the point where the estimate is to be calculated or not, respectively. Again, details on the implementation of the improved FM model and on the applied filter can be found in [1].
The model for the dispersed phase is based on the Mesoscopic Formalism that was first introduced by Février et al.[6] and takes advantage from the results of the Kinetic Theory for gases [7]. Details on the procedure to be followed in order to obtain the set of equations may be found in [6,8,9]. However, the uncorrelated motion of particles defined in these publications has been neglected in the present work. The model thus collapses on a classic two-fluid model. The complete set of equations consists of the conservation equations for the particle number density and for dispersed phase mass, momentum and enthalpy and can be found in [1]. It must be pointed out here that the choice has been made not to filter the transport equations for the dispersed phase. The particle inertia is assumed too high for scales smaller than Δ to develop in the particle motion, given the grid resolution necessary to solve the gas phase by LES technique.

Numerical approach

The system of equations that governs the evolution of the gas phase filtered variables is numerically solved by means of the HeaRT code developed in ENEA. The gas phase solver is based on a centered II order finite difference scheme on a staggered cylindrical non uniform grid. The idea is to define a different grid for each velocity component which is staggered in space by half grid width with respect to the scalar variables, ρ, p, T and Y_i. This discretization technique leads to a higher precision and to a more robust discretization of the time-dependent continuity equation, for which variable interpolations are not performed.
The equation system for the dispersed phase was numerically solved on the same computational grid used for the gas phase scalar variables, by means of a finite volume technique (or Godunov's method). This class of numerical methods is

made up of three stages: reconstruction, solution of discontinuities at the cell boundaries and time advancement.
In the present work a linear reconstruction around the averaged values of the conserved variables is taken, thus leading to a II order accurate method. The averaged values are considered to be equal to the local value at the cell center. In the case where the uncorrelated motion is neglected it can be shown that the system of equations for the dispersed phase has three coincident eigenvalues equal to the dispersed phase velocity. An upwind scheme has thus been selected for the reconstruction phase and a *minmod* slope limiter has been adopted. Specific Riemann solvers for the solution of the discontinuities at the cell boundaries have also been developed.
The advancement in time is performed for both phases by means of a III order Runge-Kutta scheme. The adopted numerical discretizations, the treatment of variables on the symmetry axis and the needed metric corrections are described in [1].

Model validation

The described model and numerical approach have been applied to the simulation of the Sommerfeld and Qiu [10] experiment, consisting in a particle laden flow obtained by injecting small (20−80 μm) glass particles in a confined swirled flow. In Figure 1 the computational domain is presented with a detail of the inlet ducts. Air and particles flow through the cylindrical duct to the test chamber while from the annular duct a swirled air flow is introduced in the test section. At the end of the latter an expansion chamber is present.
The structured computational grid in the test chamber is made up of 322*104*64 cells in the axial, radial and azimuthal direction respectively. The smallest cell dimension in both axial and radial direction is 0.5 mm, that occur at the inlet in the

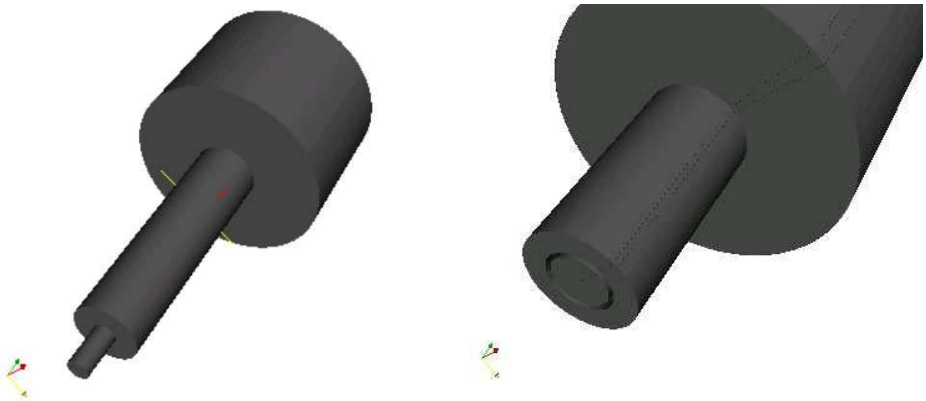

Figure 1. Computational domain (left) and a detail of the inlet (right).

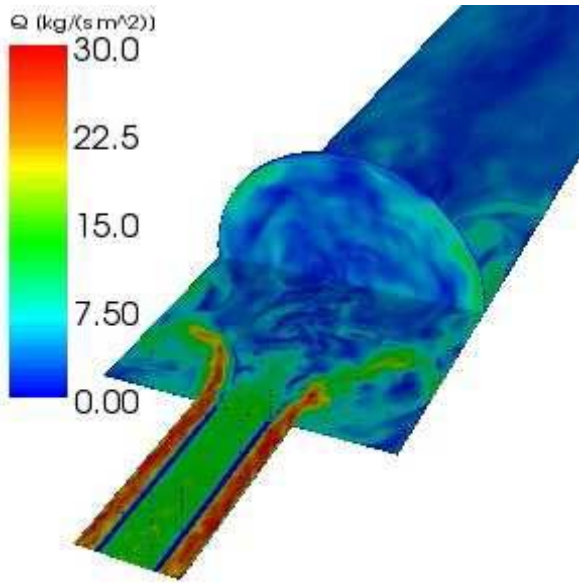

Figure 2. Instantaneous field of the momentum module $Q = \rho_f u_f$. The axial distance from the test chamber inlet of the plane normal to the axis is z = 150 mm.

test chamber and along the channel walls respectively. In the present validation a monodispersed class of particles with a 45 μm diameter is simulated.

In Figure 2 the field structure of the gas phase momentum is presented for a given instant, for the test section zone, on a radial plane and on a plane normal to the axis at z = 150 mm, where z is the distance from the plane where the injection ducts enter the test chamber. The momentum module $Q = | \rho_f u_f |$ of the gas phase is shown by means of contour levels. Since the gas density is almost constant, showing oscillations on the fourth significant digit around a mean value of ρ_f=1.165 kg/m^3, the contour plots of the momentum closely resemble those of the gas velocity.

The field structure is typical of swirled combustors. Two recirculating zones are present just aside from the injection zone, and extend up to z=0.085 m. A stagnation point is present at the center of the domain for z=0.09 m, after which a great toroidal recirculation zone extends for more than 20 cm in the axial direction. The instantaneous field shown in Figure 2 is characterized by a considerable asymmetry and by the presence of many small structures that only through a LES technique can be captured.

In Figure 5 the computed solution is compared to the experimental data for z=52mm. In the left part of Figure 5(a) it can be seen how both the mean and RMS axial gas velocities are very well reproduced by the HeaRT code. For both radial and tangential components, the RMS velocities are well predicted at all the radial

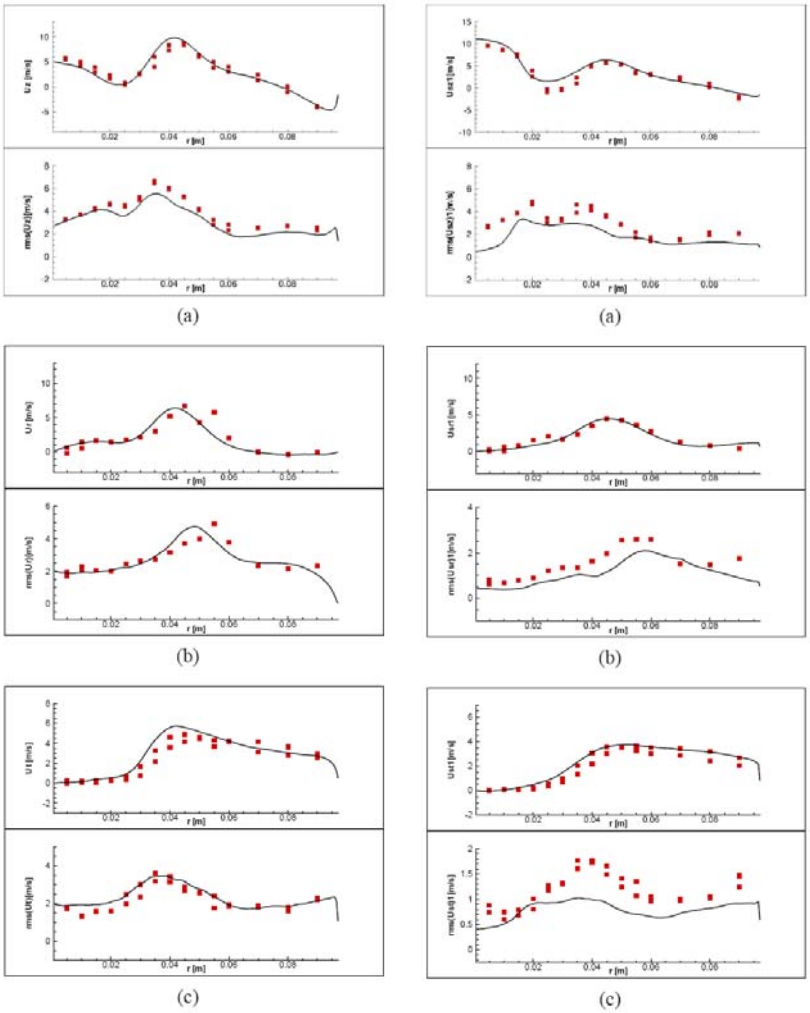

Figure 3. Mean (upper part) and RMS (lower part) axial (a), radial (b) and tangential (c) velocities for z = 52 mm. Left gas, right particles. Symbols are taken from experiments. Lines are computed.

positions with a slight overprediction for the tangential component. The mean velocity is very well reproduced. In the right part of Figure 5 the obtained results for the dispersed phase are presented. All the three components of the dispersed phase mean velocity are well reproduced while the RMS velocities are underpredicted. The reason for this underprediction may be searched in fact that the adopted Riemann solver does not conserve particles kinetic energy as it should. This induces a laminarization of the particle velocity field. The introduction of the uncorrelated motion is necessary in order to overcome this problem.

Conclusion

A Eulerian model for the numerical simulation of dispersed multiphase flows has been implemented in the HeaRT code for the Large Eddy Simulation of reacting mixtures. A finite volume approach has been adopted and customized limiters and Riemann solvers have been developed for the implementation of the dispersed phase equations. An improved turbulence model for the gas phase has also been implemented in the code. The latter has been validated against a particle laden flow well reproducing the mean flow for both phases. RMS velocity are well reproduced in the gas phase while they are underpredicted for the dispersed phase. The reason for this underestimation may be due to the fact that, being the uncorrelated motion neglected, the adopted Riemann solvers do not conserve the kinetic energy of the dispersed phase. An extension of the model is necessary in order to overcome this problem.

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