Chapter 6
Coupled Solvers for Gas–Solids Flows

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ABSTRACT

In recent years, the application of coupled solver techniques to solve the Navier-Stokes equations has become increasingly popular. The main reason for this, is the increased robustness originating from the implicit and global treatment of the pressure-velocity coupling. The drawback of a coupled solver are the increase in memory requirement and the increased complexity of implementation. However, fully coupled methods are reported to have an overall favorable computational cost when a suitable pre-conditioner and algorithm for solving the resulting set of linear equations are employed. In solving multi-phase flow problems, the coupled solver approach is even more advantageous than in single-phase, due to the presence of large source terms arising from the coupling of the phases. In this chapter, various strategies for the fully coupled approach are discussed. These strategies include employing artificial compressibility, applying physically consistent cell face interpolation, and applying momentum weighted cell face interpolation. The idea behind the strategies is outlined and their advantages and disadvantages are discussed. The treatment of source terms and volume fraction in coupled methods is also shown. Finally, a number of examples of implementations and calculations are presented.

1 INTRODUCTION

There is no dispute that on Cartesian grids, computation of incompressible gas-solids flows is best performed with the staggered scheme proposed by Harlow and Welch (1965). However when the grid is arbitrary, the use of collocated schemes is prevalent and more natural. One of the reasons for using collocated grids, is that the generalization from Cartesian to a general case grid with a collocated

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variable arrangement is, at least on paper, quite straightforward. The application of staggered grids to non-Cartesian meshes is much more complicated, as the nodes containing the scalars no longer lie on the line connecting the velocity neighbours. Staggered grids applied to non-Cartesian geometries often suffer from accuracy problems on non-uniform grids due to the use of Christoffel symbols (Aris, 1962) which are difficult to compute accurately on general grids (e.g. Wesseling et al., 1998). Although some researchers have proposed remedies to this, *e.g.*Perot (2000); Wenneker et al. (2003), the approach is still less natural than employing a collocated discretisation.

Although a collocated variable arrangement is more prevalent for non-Cartesian geometries, there are a number of drawbacks and potential pitfalls when employing collocated grids as well. A straightforward discretisation on a collocated grid results in severe pressure oscillations (Patankar, 1980), also referred to as pressure-velocity decoupling. To remedy this, the discretisation for the momentum convective velocity needs to differ from the continuity convection. Currently, there are two main approaches to solve this on a collocated grid: the pressure-weighted interpolation (Rhie and Chow, 1983; Zwart, 1999) and the physical consistent interpolation (Schneider and Raw, 1987; Deng et al., 1994). Moreover, applying source terms and body forces in the equation also introduces problems, as they cannot be precisely matched by the discretisation stencil of the pressure gradient stencil.

In the physical consistent interpolation, first proposed by Scheider and Raw (1987), the complete momentum equation is averaged to the cell faces. The resulting expression at the cell faces is then used to close the continuity equation. Although the method is very elegant, the major problem of the method is the interpolation of the viscous terms. Due to the size of the discretisation stencil of the viscous terms, their interpolated stencil becomes rather large (Deng et al., 1994) and may not perform well in near-wall regions. Moreover, the method is rather complex to code for a multiphase case, where care has to be taken with volume fractions and various kinds of source terms.

In pressure-weighted interpolation (Rhie and Chow, 1983; Zwart, 1999), the face velocity for the convective term in the continuity equation is determined by subtracting the difference between the pressure gradient and the interpolated pressure gradient from the linearly determined face fluxes. Mathematically, this can be seen as a filter for the velocity and pressure fields, forcing the local pressure profile to be linear, without affecting the accuracy of the continuity equation. The drawback of this approach becomes clear in the presence of source terms and gradients of density and volume fraction, as the physical pressure profile is no longer locally linear. This is one of the subjects of the current article.

Another benefit of collocated grids is that its discretisation enables to fully couple the velocity and pressure equations, as will be shown in this chapter. Although coupling the velocity and pressure equations lead to an increase in memory usage, the large advantage is increased robustness due to the implicit and global treatment of the pressure-velocity coupling. Moreover, fully coupled methods are reported to have an overal favourable computational cost when a suitable pre-conditioner and solver are employed (Ammara and Masson, 2004).

Almost all multiphase CFD solvers today are based upon standard decoupled approaches (*e.g.* SIMPLE, SIMPLER, PISO, fractional step, and other pressure projection methods, Ferziger and Peric, 2002) and most often employ a staggered variable arrangement. In these frameworks, the momentum equations are solved with a guessed pressure, and thereafter the pressure is corrected, so the velocity field satisfies the continuity equation. This procedure is repeated until the velocity field nearly satisfies the momentum equation as well. In multiphase flows, these approaches require an additional iteration, often called an outer iteration, updating the volume fraction of the phases.