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Liquid-Gas Interactions

20.1 Modeling

Liquid-gas interactions, e.g., the vaporization and subsequent combustion of liquid fuel droplets or the shock-induced mixing of liquids, are rather difficult problems in computational fluid dynamics. These problems address the interaction of liquid droplets with a compressible gas medium. There are three classical approaches to such problems: Both phases can be treated as compressible fluids (as we did in Chapter 15), both phases can be treated as incompressible fluids (as we did in Chapter 21), or the gas can be treated as a compressible fluid while the liquid is treated as an incompressible fluid. A completely incompressible treatment can be ruled out any time one is interested in shock waves or other compressible phenomena. A completely compressible treatment is not desirable, since a relatively high sound speed in the liquid phase can impose a restrictive (and inefficient) CFL condition. Moreover, a completely compressible approach is limited to liquids for which there are acceptable models for their compressible evolution. To overcome these difficulties, Caiden et al. [23] modeled the gas as a compressible fluid and the liquid as an incompressible fluid. They coupled a high-resolution shock-capturing scheme for the compressible gas flow to a standard incompressible flow solver for the liquid phase.
20.2 Treating the Interface

Since the interface is a contact discontinuity moving with the local fluid velocity, the Rankine-Hugoniot jump conditions imply that both the pressure and the normal velocity are continuous across the interface. An incompressible liquid can be thought of as the limiting case obtained by increasing the sound speed of a compressible liquid to infinity. In this sense, an incompressible fluid can be thought of as a very stiff compressible fluid, in fact, the stiffest. The interface separating the compressible flow from the incompressible flow is treated using the robust interpolation procedure outlined in Section 15.9. That is, the compressible gas is used to determine the interface pressure, while the incompressible liquid is used to determine the interface normal velocity.

Advancing the solution forward in time consists of four steps. First, the entire incompressible velocity field is extrapolated across the interface. The ghost cell values are used to find the intermediate incompressible velocity field $\tilde{V}^*$. Second, the entire compressible state vector is extrapolated across the interface, and the extrapolated tangential velocity is combined with the incompressible normal velocity to obtain a ghost cell velocity for the compressible fluid. Then the compressible gas is updated in time. Third, the level set function is advanced forward in time using the incompressible velocity field only, since the interface velocity is defined by the incompressible flow. The extrapolated ghost cell values of the incompressible velocity field are useful in this step. Fourth, the intermediate incompressible flow velocity $\tilde{V}^*$ is projected into a divergence-free state using the updated level set location and the updated values of the compressible pressure as Dirichlet boundary conditions at the interface. This last step accounts for the interface forces imposed by the pressure of the compressible fluid. Surface tension effects are easily included in this last step using Dirichlet pressure boundary conditions of $p = p_c + \sigma \kappa$, where $p_c$ is the compressible pressure, $\sigma$ is a constant, and $\kappa$ is the local interface curvature. This accounts for the jump in pressure due to surface tension forces, i.e., $[p] = \sigma \kappa$.

Figure 20.1 shows an incompressible liquid droplet moving from left to right in a compressible gas flow. Notice the lead shock in the compressible gas. Figure 20.2 shows a shock wave impinging on an incompressible liquid droplet. A reflected wave can be seen to the left, and a faint transmitted wave can be seen to the right.