Direct numerical simulation of compressible multi-phase flow with a pressure-based method

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Abstract: A pressure-based approach for the direct simulation of compressible multi-phase flow in conservative formulation is presented. The numerical method tracks the interface with a level set variable and treats the material interface as a contact discontinuity. The approach gives oscillation-free results in the vicinity of the material interface. The method has been implemented in 3D and first results of shock-droplet interactions are shown.

Keywords: Compressible multi-phase flow, DNS, pressure-based method, level set.

1 Introduction

Our motivation is the extension of an originally incompressible multi-phase flow solver to the compressible regime aiming at the simulation of droplets under extreme ambient conditions of high pressure and temperature where the compressibility effects inside the liquid phase can no longer be neglected. As a consequence, the flow equations require additional thermodynamic conditions given by an equation of state (EOS). This leads to stronger coupling effects at the material interface, which can cause spurious oscillations in the vicinity of the interface that have to be dealt with numerically by a special interface treatment. In order to stay as close as possible to the original incompressible numerical method we use a pressure-based algorithm for the compressible multiphase flow simulation.

2 The pressure-based approach

In a first step, we neglect viscosity and restrict ourselves to the compressible Euler equations. To circumvent their singular incompressible limit, the multiple pressure variables (MPV) scheme [1] for compressible and incompressible flows is used. It is based on an asymptotic expansion of the pressure in terms of a global flow Mach number parameter M

$$p(x,t) = p^{(0)}(t) + M^2 p^{(2)}(x,t). \tag{1}$$

The leading order pressure term $p^{(0)}$ satisfies the EOS in the incompressible limit case $M = 0$ while the pressure $p^{(2)}$ can be considered to be a hydrodynamic pressure.

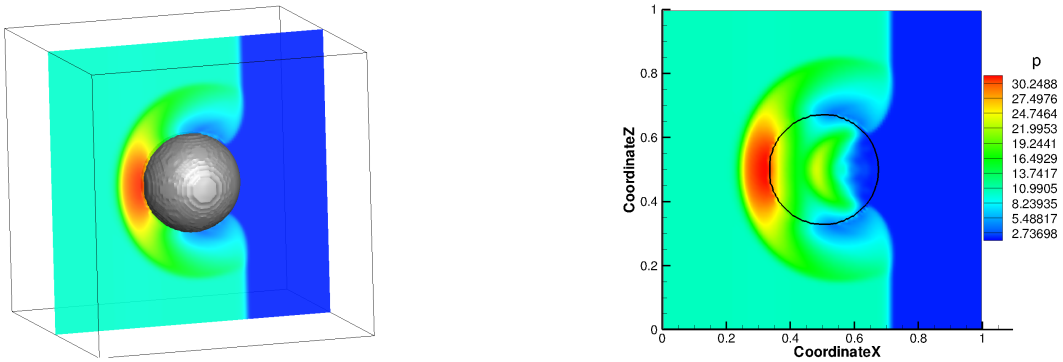

Figure 1: Shock impinging on 3D droplet. Plot of the pressure distribution in a plane around the droplet (left) and cut through the droplet center (right) (128^3 cells).

The method is used in a conservative formulation with the pressure as primary variable. The energy equation is reformulated in terms of pressure and kinetic energy using an appropriate EOS. The flow equations are discretized in a semi-implicit manner, similar to incompressible schemes. The spatial discretization is carried out on a Cartesian staggered grid.

In order to extend the scheme to multi-phase flows, the material interface has to be tracked, which is done with a level set approach. Moreover, distinct EOS are necessary to describe the thermodynamic behavior of the different materials, where the ideal gas EOS and the Tait EOS for liquids are used. It is well-known from the literature that density-based numerical schemes can suffer from unphysical spurious pressure and velocity oscillations at the interface location. Yet, it can be shown that our pressure-based scheme prevents this kind of oscillations due to the fact that pressure is used as primary variable in combination with an adequate spatial discretization [2]. The material interface can therefore be treated as a contact discontinuity, which avoids more complex interface treatments like the ghost fluid technique.

3 Conclusion and future work

The numerical scheme proves not only to give excellent results for one-dimensional multi-material shock tube test cases, but also for three-dimensional simulations. Fig. 3 shows the pressure distribution around and inside a 3D water droplet surrounded by air. A shock wave moves from left to right and impinges on the material interface. The results show typical wave structures, where the cut on the right e.g. shows a left moving shock wave inside the droplet that has been reflected at the water/air interface. The scope of the future and ongoing work is directed to further enhance the tracking and the resolution of the interface. At present, we are investigating the coupling of our pressure-based flow solver to a high-order discontinuous Galerkin approach for the level set transport. First results of this coupling are also shown and discussed.

References

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