SIMULATIONS OF AERODYNAMICS AND INTERFACIAL INSTABILITIES OF DROPLETS EXPOSED TO HIGH-SPEED GAS FLOWS

Chih-Hao Chang[* a)] , Xiaolong Deng[*,**] & Theo G. Theofanous[*]
[*]*Center for Risk Studies and Safety, University of California at Santa Barbara, California, 93117, USA*
[**]*Beijing Computational Science Research Center, Beijing, 100084, China*

Summary We developed a finite-volume based compressible Navier-Stokes solver with sharply defined interface, which is conservative and satisfies all jump conditions on interface, allowing us to resolve instabilities (R-T and K-H) on an immiscible interface with arbitrary density/viscosity ratios, subjected to large acceleration or velocity gradient. Its power is demonstrated by predicting the two types of known aerobreakup regimes: Rayleigh-Taylor piercing (RTP) and the K-H-aided, shear-induced entrainment (SIE).

INTRODUCTION

When a droplet is exposed to incident highspeed flow, it is subjected to rapid acceleration and deformation as the results of the aerodynamics surrounding the drop in the early stage. Subsequently, fluid instabilities (K-H or R-T depending on conditions) take over and, eventually, they lead to the breakup of the drop [1]. Such problems are rich in physics (compressibility, shock wave, flow separation, vortex dynamics, interfacial instabilities, etc.) and thus present a great challenge in numerical simulation. The key to successfully simulate the aerobreakup relies on the capability of a priori prediction of instabilities (K-H, R-T). However, even with the increasing efforts on developing free interface methods for compressible flows in the past decades [2, 3, 4], very little attention had been paid to resolved fluid instabilities with rigorous efforts towards validation. In addition, most of these works were done only for inviscid flows under mild conditions with moderate density ratios and low accelerations.

Here we report on a sharp interface method for compressible Navier-Stokes solver, which is based on finite-volume method with fluid interface being described by cut-faces. Interface velocities and pressures are considered as jump conditions within a Riemann problem, including fluid states, viscous stress and surface tension. The Riemann problem is solved exactly to provide pressures and normal velocity for computing inviscid fluxes on interface. The solver is further enhanced by using AMR and curved representation of interface. These result in a numerical method which is conservative and satisfies all jump conditions on interface.

NUMERICAL RESULTS AND DISCUSSION

As a principal test (Figure 1), we address the Rayleigh-Taylor instability problem. It shows that, even in the essentially-incompressible range, our method has very good agreement with the analytical solution [5].

Figure 2 shows the flow evolution for a glycerol drop in the RTP regime according to experiments [1] (*Oh*=1.82, *We*=523 and *M*=0.29). The simulation is run on a six-layer AMR grid with resolution equivalent to 200 meshes/diameter. We notice a main separation vortex is built up right after the shock wave passes the drop (t=50μs). The recirculating flow continuously pushes the interface inward and forms a bow-shape interface on the back. Meanwhile, the front interface is gradually flattened by the high stagnation pressure and the drop keeps expanding in the radial direction, which will contribute to the increase of drag force and eventually will lead to RTP as observed in the experiment (not shown here). In general, our method is able to capture the major features of the flow evolution and provide important details for understanding.

For the SIE regime we consider a TBP drop in supersonic flow (*Oh*=1.9, *We*=5,400 and *M*=1.3). The simulation is done on an AMR equivalent resolution of 200 meshes/diameter. In addition, a structured conformal mesh (SCM), which has a minimum grid size $\Delta y = 1/4000$, is used to resolve the boundary layer and ensure correct viscous stresses on interface. The numerical result at t=12μs is shown in Figure 3 together with an experimental picture. Compared to the previous case, the K-H instability develops significantly faster on the front interface. One interesting feature is the K-H waves, which develop into a large trough when near the sonic point. These effects can be attributed to the air compressibility, as we refer to the classic solution of compressible flow over a wavy wall [6]. For subsonic flow, the pressure is in-phase with the wave, thus it enhances the instability. On the other hand, for supersonic flow, the pressure is out-of-phase with the wave. Therefore, it stabilizes the interface. All these details are correctly captured in our simulation.

References

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a) Corresponding author. Email: chchang@engr.ucsb.edu.

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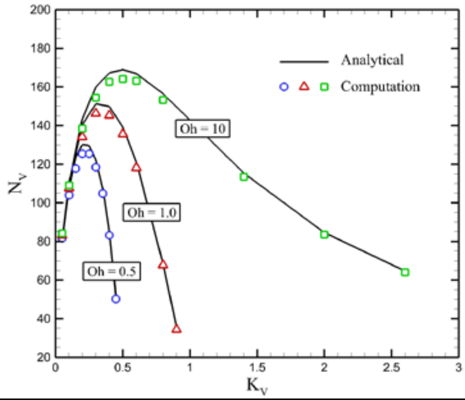

Figure 1. Comparison of numerical and analytical solutions for the Rayleigh-Taylor instability problem in the limit of Atwood number close to one. K_V and N_V are the wave number and growth factor normalized by characteristic viscous length and time scales, as defined in [1]. The sample space of Ohnesorge number encompasses the surface-tension-dominated (Oh=0.5) and the viscosity-dominated (Oh=10) regimes.

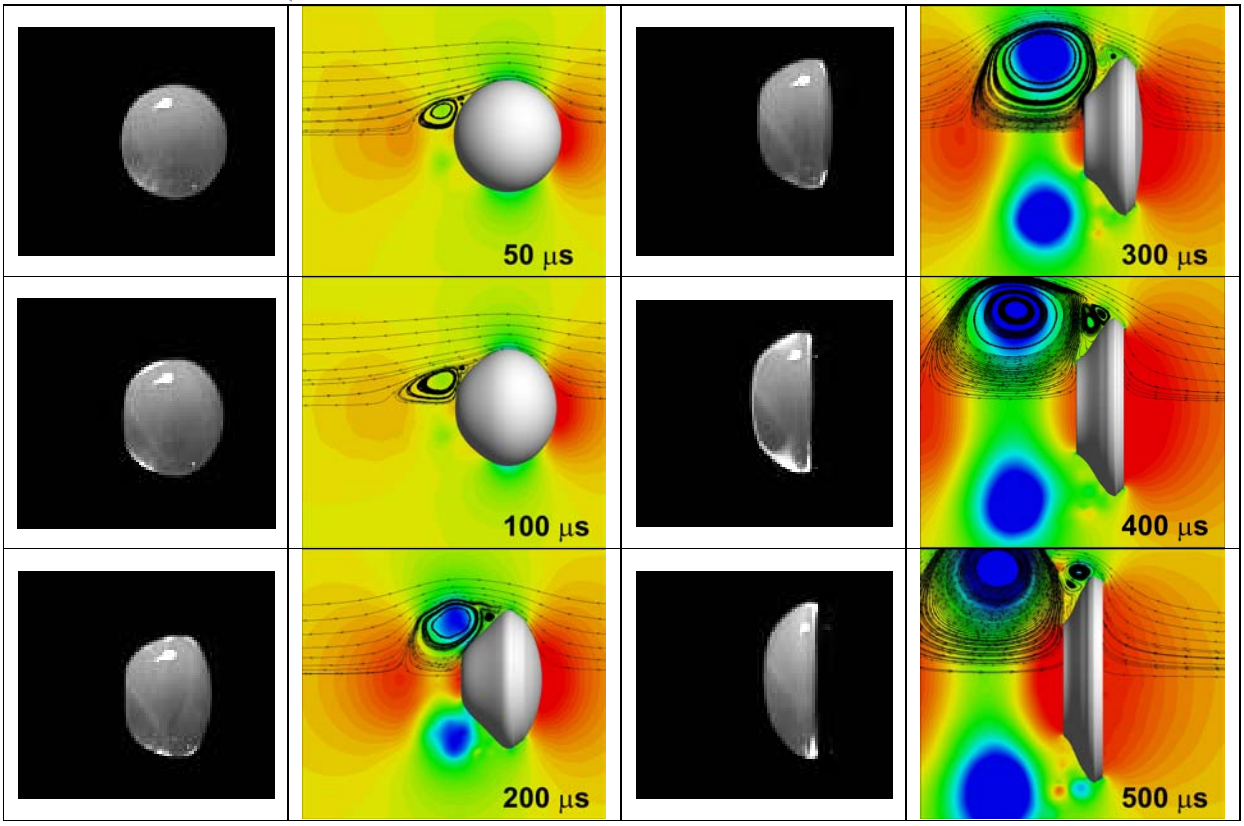

Figure 2. Evolution of a glycerol drop in subsonic flow (*Oh*=1.82, *We*=523 and *M*=0.29). Pressure contours and streamlines are shown in the simulation result plots. The details of separation control the exact shape of the back side, and on-going simulations at resolution of 800 meshes/diameter show a development much closer to the experiment.

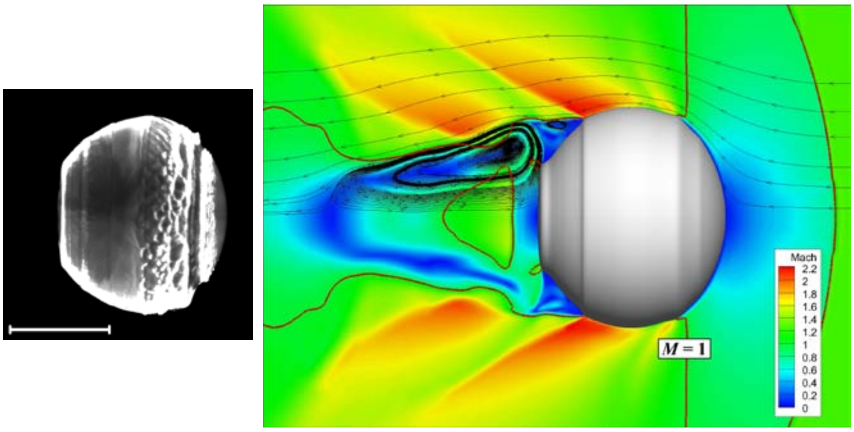

Figure 3. Snapshots of experiment and simulation results for a TBP drop in supersonic flow, t=12μs (*Oh*=1.9, *We*=5400, *M*=1.3).