EARLY-TIME INTERFACE INSTABILITIES IN HIGH INTENSITY AERO-BREAKUP OF LIQUID DROP

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Summary The early-time interface instabilities in high intensity (high Weber number and high Reynolds number) aero-breakup of liquid drop are investigated numerically. The results show that the instabilities, which originate from the upstream interface near the equator, are dominated by the KH (Kelvin-Helmholtz) instability. This is verified further with a specially modified simulation, which decreases the KH instability while keeps other flow properties unchanged, and the prediction from the linear-stability theory.

INTRODUCTION

The deformation and shattering of liquid drop after being suddenly exposed to uniform high speed gas flow (usually behind a shock wave) is called aerobreakup, which has a great variety of practical applications, such as internal combustion engines, nuclear fusion devices, agricultural and environmental sprays. Aerobreakup is the subsequence of physical instabilities. For high intensity (high Weber number and high Reynolds number) aerobreakup of a Newtonian liquid drop, the weak viscous dissipation and surface tension allow rapid growth of disturbances with large wavenumber. Due to the extremely high acoustic impedance mismatch at the interface, Richtmeyer-Meshkov (RM) instability is negligible. Therefore, the Kelvin-Helmholtz (KH) instability and the Rayleigh-Taylor (RT) instability are proposed as the main mechanisms. It was first postulated that the exponentially growing RT instability at the upstream front of the drop lead to a catastrophic shattering of the drop [2, 5]. Based on their experimental observations and simplistic estimations, Theofanous et al. [8, 7, 6] argued that the dominant mechanism is the shear-induced motion with a significant radial component and instabilities on the so-generated, stretched liquid sheet (more like the KH instability). In this work, we investigate the mechanisms at the early time of high intensity aerobreakup by numerical simulations.

GOVERNING EQUATION, NUMERICAL METHOD AND COMPUTATIONAL SETUP

The mathematical idealization of this problem is that of a two-dimensional, compressible Newtonian flow with vanishing surface tension and viscous dissipation. The governing equation can be written as a system of conservation laws, and is solved by the conservative sharp-interface method [4, 3]. We consider a typical case which is first proposed by Chang and Liou [1], in which a two-dimensional water drop in air is driven by a planar Mach 3 shock wave. With the dimensional references given by 1 atmosphere, 1 kg/m^3 and 1 cm, the drop has density of 1000 and diameter of 0.35, and the pre-shocked air has density 1.2 and undisturbed pressure 1. The computation has been carried out on equidistant grid with three resolutions, i.e. with $\Delta = 2.5 \times 10^{-3}$, 5×10^{-3} and 1×10^{-2}.

RESULTS AND DISCUSSION

Figure 1 shows the contours of pressure and flow speed computed with the highest resolution at times $t = 0.0635$, 0.253 and 0.76 after the impact of the shock, representing the three stages of the development of the instabilities. At the first stage, as shown in Fig. 1a, the shock diffracts around the drop just like around a solid cylinder, the transmitted shock wave in the drop is weak and travels faster than that in the air. While the pressure contours pass the air-water interface smoothly, a tangential velocity jump has been built up at the upstream interface away from the stagnation point, and its magnitude increases while towards the equator. At the second stage, as shown in Fig. 1b, while pressure contours pass the air-water interface smoothly near the upstream front, increasingly small disturbances can be found towards the equator. Beyond the equator the pressure contours become smooth again, though the magnitude of tangential velocity jump still increases until it reaches the flow separation region. At the third stage, as shown in Fig. 1c, the drop is deformed considerably and the flow separation region extends to the equator. While wrinkles and discrete small drops are produced at the positions where the pressure disturbances originate, the upstream front is relative smooth, and has only small magnitude corrugations. Note that the tangential velocity jump is smeared and turned into a shear layer with finite thickness above the wrinkles, which introduce tiny separation regions behind. In addition, it can be observed that small ripple-like sound waves bounce back and forth between the primary bow shock and the drop, and the sound waves within the drop produce a very complicated pattern. The obtained interface deformation and fluctuation are in quite good agreement with the experimental results of the early-time of aerobreakup [7, 6], where the upstream front is relative smooth and wrinkles and small drops are produced at the upstream interface near the equator. As shown in Fig. 1, the maximum growth rate of the RT instability is at the upstream front due to the maximum pressure gradient or acceleration. Since this region is also around the stagnation point, it has the minimum growth rate of the KH instability. For the interface towards the equator, the growth rate of the KH instability increases as the tangential velocity jump increases. The growth rate decreases again beyond the equator

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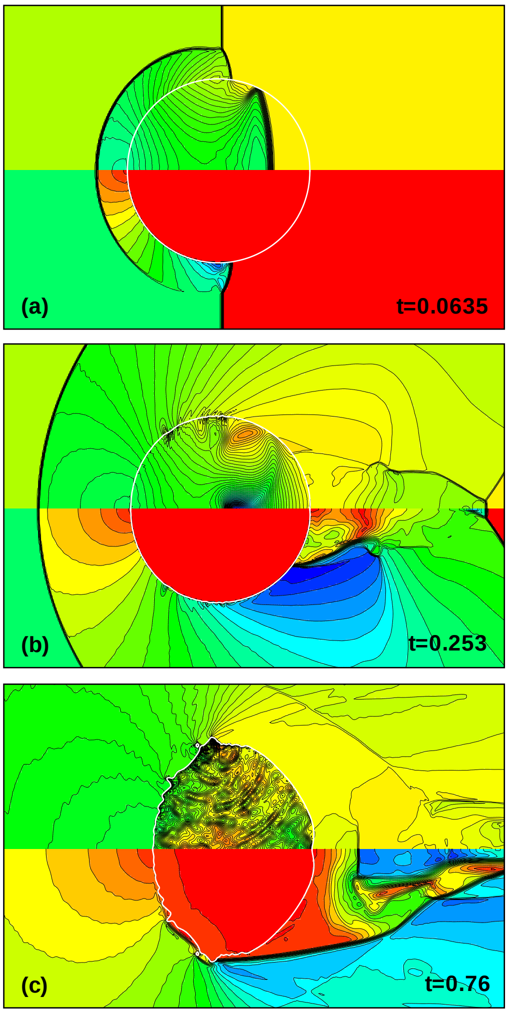

Figure 1. Shock interacting with a two-dimensional water drop at $t = 0.0635$, 0.253 and 0.76: (upper) 55 contours of pressure, from -20 to 70; (lower) 20 contours of pressure, from 0.1 to 4; the thick white solid line indicates the air-water interface.

due to the negligible tangential velocity jump connected to the flow separation region. These observations clearly suggest that the wrinkles and small drops are produced mainly due to the KH instability, which is in agreement with the arguments of Theofanous et al. [8, 7, 6].

References

[1] C.H. Chang and M.S. Liou. A robust and accurate approach to computing compressible multiphase flow: Stratified flow model and AUSM+-up scheme. *J. Comput. Phys.*, 225(1):840–873, 2007.

[2] EY Harper, GW Grube, I. Chang, et al. On the breakup of accelerating liquid drops. *J. Fluid Mech.*, 52(03):565–591, 1972.

[3] X Y Hu, N A Adams, and G Iaccarino. On the HLLC Riemann solver for interface interaction in compressible multi-fluid flow. *J. of Comput. Phys.*, 228:6572, 2009.

[4] X. Y. Hu, B. C. Khoo, N. A. Adams, and F. L. Huang. A conservative interface method for compressible flows. *J. Comput. Phys.*, 219:553, 2006.

[5] D.D. Joseph, J. Belanger, and GS Beavers. Breakup of a liquid drop suddenly exposed to a high-speed airstream. *Int. J. Multiphase Flow*, 25(6-7):1263–1303, 1999.

[6] TG Theofanous. Aerobreakup of newtonian and viscoelastic liquids. *Ann. Rev. Fluid Mech.*, 43:661–690, 2011.

[7] TG Theofanous and GJ Li. On the physics of aerobreakup. *Phy. Fluids*, 20:052103, 2008.

[8] TG Theofanous, GJ Li, and TN Dinh. Aerobreakup in rarefied supersonic gas flows. *J. Fluids Engn.*, 126(4):516–527, 2004.