Primary atomization under the simultaneous action of Rayleigh-Taylor and Kelvin-Helmholtz mechanisms

Vadivukkarasan M.[1], **and Mahesh V. Panchagnula**[1] †

[1]Department of Applied Mechanics, Indian Institute of Technology Madras, Chennai, 600036 India

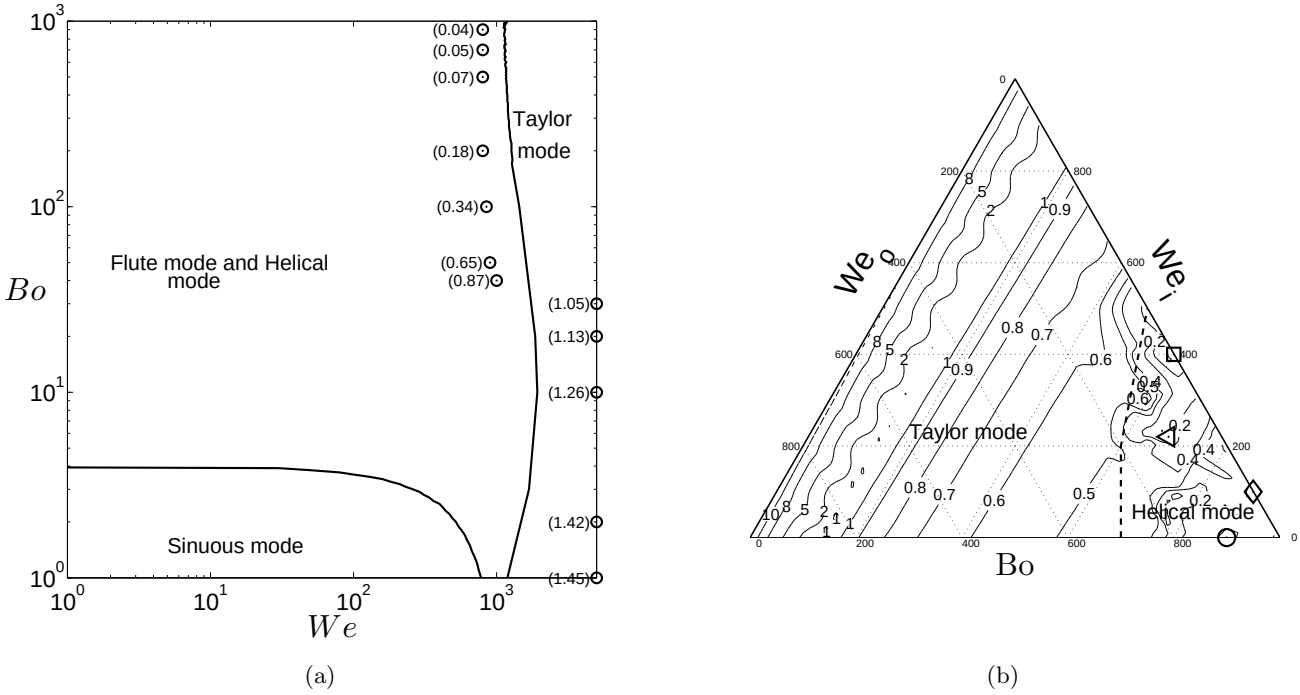
Abstract

The possibility of employing both Rayleigh-Taylor (R–T) (Mikaelian 2005) and Kelvin-Helmholtz (K–H) (Yang 1992; Panchagnula *et al.* 1996) mechanisms simultaneously as equal contributors to the primary destabilization process (Rehab *et al.* 1997; Lasheras *et al.* 1998) is discussed. A linear stability analysis is performed to develop an understanding of a primary atomization under this combined action. Three–dimensional disturbances are considered in order to predict the breakup structure (ligaments) observed in experiments (Santangelo & Sojka 1995). The fluids are assumed to be inviscid and incompressible. From the governing equations and the boundary conditions, a dispersion relation is derived and analyzed for a single as well as two interfaces. Four different regimes have been shown to be possible, based on the most unstable axial (k^*) and circumferential (m^*) wavenumbers. They are (i) Taylor mode ($k^* > 0, m^* = 0$). (ii) flute mode ($k^* > 0, m^* > 0$), (iii) sinuous mode ($k^* = 0, m^* = 1$) and (iv) helical mode ($k^* > 0, m^* > 0$). In order to represent the simultaneous action of k^* and m^*, a characteristic length scale ($\mathcal{L}^*$) is defined as $\mathcal{L}^* = \min\left(\frac{2\pi}{k^*}, \frac{2\pi}{m^*}, \frac{2\pi}{k^* m^*}\right)$, where $2\pi/k^*$ and $2\pi/m^*$ represent the two–dimensional length scales in the Taylor and flute modes respectively. The helical mode is represented by a scale given by $2\pi/k^* m^*$. This definition of $\mathcal{L}^*$ allows us to compare the deformation length scales in the three regimes, viz. Taylor, flute and helical mode using a single length scale measure. The dimensionless quantities relevant to this study are Bond number (Bo) representing the ratio of radial acceleration force to the surface tension force and Weber number (We) representing the ratio of the aerodynamic force due to the relative velocity to the surface tension force at each interface.

This study reveals that three-dimensional disturbances (helical modes) dominate the system behavior under certain parametric conditions, which is advantageous to interface distortion. In addition, this study also reveals that for a given energy, the length scale associated with destabilization due to radial acceleration (R–T mechanism) is significantly more efficient than the traditional way of destabilizing an interface using axial relative velocity (K–H mechanism, Lasheras & Hopfinger (2000)).

As can be seen, figure 1(a) represents the instability regime map in the Bond number (Bo) and Weber number (We) space (Villermaux & Clanet 2002; Clanet & Villermaux 2002). For $Bo < 40$, the value of $\mathcal{L}^*$ is found to be minimum when K–H mechanism is made dominant through high We. In contrast, for $Bo > 40$, the value of $\mathcal{L}^*$ is observed

† mvp@iitm.ac.in



(a) (b)

Figure 1: (a) Instability regime map in the Bond number (Bo) – Weber number (We) plane for a single interface. The continuous line separates the regimes showing different destabilization modes. The symbols indicate the location of We that yield the minimum value of $\mathcal{L}^*$ for a given Bo. The value of $\mathcal{L}^*$ is indicated in the parentheses next to symbol. (b) Instability regime map for an annular interface. A ternary phase diagram showing the effect of the three parameters. The three sides of the triangle of the regime map correspond to the Bond number (Bo), inner Weber number (We_i) and outer Weber number (We_o). $\zeta = Bo + We_i + We_o = 1000$ in this figure. The dashed line separates the regimes showing different destabilization modes. $\circ$ denotes the lowest characteristic length scale ($\mathcal{L}^* \approx 0.08$) obtained at ($Bo$,$We_i$,$We_o$) = $(900, 0, 100)$. The other symbols represent the $\mathcal{L}^* = 0.1$ at different flow conditions. $\square$ represents (600,400,0). $\triangleleft$ and $\diamond$ represents the (680,220,100) and (900,100,0) respectively.

to be minimum at some optimal We ($\sim 10^3$). This is because of the onset of short wavelength helical modes. Further, a continuous increase in We causes the instability mode to transition to the Taylor mode and yields higher $\mathcal{L}^*$. This implies that, for a given $Bo(> 40)$, any value of $We > 1200$ is counter-productive towards interface destabilization. Note that from figure 1(a) that $\mathcal{L}^*$ obtained for (Bo, We)=(30,5000) is 1.05 whereas (Bo, We)=(40,1000) yields 0.87. This signifies a slight increase in Bo will yield smaller $\mathcal{L}^*$ even at a lower We. Therefore, it is beneficial to operate at an optimal value of (Bo, We) as shown in figure 1(a) in the form of open circles.

The instability regime map and contours of $\mathcal{L}^*$ that correspond to the Bond number (Bo), inner Weber number (We_i) and outer Weber number (We_o) of an annular interface is shown in figure 1(b). Here, the minimum $\mathcal{L}^*$ is identified subject to the constraint of

constant total energy, ζ, causing the destabilization. For $\zeta = 1000$, the lowest value of $\mathcal{L}^*(\approx 0.08)$ occurs at (Bo,We_i,We_o)=(900,0,100). The relative proportion of Bo to We_o at this point suggests that 90% of ζ is used to induce radial acceleration, while the rest 10% is used to induce shear through the outer air stream which yields a minimum value of $\mathcal{L}^*$. It is worthwhile to note from figure that ζ can yield nearly the same minimum $\mathcal{L}^*$ at different flow conditions and such points are represented by symbols.

In conclusion, the results of our study open up new avenues for designing atomizers to destabilize a liquid sheet by radial motion instead of axial motion. In addition, the onset of transition from absolute instability to convective instability, in the (Bo-We) space is identified.

Acknowledgement

Initial discussion of M.V. Panchagnula with Prof. Emil J. Hopfinger were the foundations of this line of thinking. We would like to thank him for his time spent at IIT Madras as a visiting professor and for all the insightful discussions.

REFERENCES

Clanet, C. & Villermaux, E. 2002 Life of a smooth liquid sheet. *J. Fluid Mech.* **462**, 307–340.

Lasheras, J. C. & Hopfinger, E. J. 2000 Liquid jet instability and atomization in a coaxial gas stream. *Annu. Rev. Fluid Mech* **32**, 275–308.

Lasheras, J. C., Villermaux, E. & Hopfinger, E. J. 1998 Break-up and atomization of a round water jet by a high-speed annular air jet. *J. Fluid Mech.* **357**, 351–379.

Mikaelian, Karnig O. 2005 Rayleigh-Taylor and Richtmyer-Meshkov instabilities and mixing in stratified cylindrical shells. *Phys. Fluids* **17** (9), –.

Panchagnula, M.V., Sojka, P. E. & Santangelo, P. J 1996 On the three-dimensional instability of a swirling, annular, inviscid liquid sheet subject to unequal gas velocities. *Phys. Fluids* **8**, 3300–3312.

Rehab, H., Villermaux, E. & Hopfinger, E. J. 1997 Flow regimes of large-velocity-ratio coaxial jets. *J. Fluid Mech.* **345**, 357–381.

Santangelo, Philip J. & Sojka, Paul E. 1995 A holographic investigation of the near-nozzle structure of an effervescent atomizer-produced spray. *Atomiz. Sprays* **5**, 137–155.

Villermaux, E. & Clanet, C. 2002 Life of a flapping liquid sheet. *J. Fluid Mech.* **462**, 341–363.

Yang, H. Q. 1992 Asymmetric instability of a liquid jet. *Phys. Fluids* **4**, 681–689.