Vortices catapult droplets in atomization

J. John Soundar Jerome[1], S. Marty[2], J.-P. Matas[2], S. Zaleski[1] & J. Hoepffner[1]

[1] UPMC Univ Paris 06 & CNRS, UMR 7190, Institut Jean Le Rond d'Alembert, F-75005 Paris, France
[2] Laboratoire des Écoulements Géophysique et Industriels (LEGI), CNRS - Université Joseph Fourier, 38041 Grenoble Cedex 9, France
soundar@dalembert.upmc.fr

Résumé. Nous étudions un nouveau mécanisme d'éjection de gouttes dans des couches de mélange $2D$ diphasiques constitués d'un flux de gaz rapide et de liquide lent. Une perturbation sur l'interface du gaz et liquide se développe en onde de Kelvin-Helmholtz. Lorsque le rapport densité entre le gaz et le liquide est faible, l'onde croît dans la manière auto-similaire et la crête d'onde forme un filament qui oscille. Nous observons, dans les expériences et les simulations numériques, que la crête de l'onde est soumis à une rupture similaire d'un ≪ bag-breakup ≫ mais de dessous. L'angle d'éjection des gouttes résultantes de ce ≪ bag-breakup ≫, peut atteindre 50 degrés. Dans un écoulement où la plupart du quantité de mouvement est dans la direction horizontale, il est étonnant d'observer de telles si grandes angles d'éjection. Les visualisations de flux et les simulations numériques montrent que le sillage derrière l'onde grandit et devient instable. L'instabilité de sillage donc donne lieu au phénomène de lâcher tourbillonnaire, comme celui d'un sillage de cylindre. Le sillage gonfle d'en bas la langue liquide qui subit violemment un ≪ bag-breakup ≫. Alors, le lâcher tourbillonnaire, à son tours, catapulte finalement ces gouttelettes dans le flux de gaz.

Abstract. The mechanism of droplet ejection in $2D$ two-phase mixing layer consisting of a fast-moving gas flow and slow-moving liquid flow is studied via direct numerical simulations and experimental investigations. A disturbance on the gas-liquid interface grows into a Kelvin-Helmholtz wave and the wave crest forms a filament that oscillates as the wave grows downstream. Increasing the speed of the gas, it is observed, in both experiments and numerical simulations, that the wave crest undergoes a bag-breakup from below and the resulting droplets are thrown in to the gas stream at angles as large as 50 degrees. In a flow where most of the momentum is in the horizontal direction, it is very surprising to observe such acute droplet ejections. Flow visualizations techniques and direct computations point out that the recirculation region behind the wave grows and becomes unstable leading to vortex shedding similar to the wake behind a cylinder. During the process, the liquid filament of the wave crest swells up from below and undergoes bag breakup. The shed vortex eventually catapults these droplets in to the gas stream.

1 Introduction

Atomization is the process by which a liquid stream fragments or breaks up into droplets. It is a very common phenomenon in nature and also in many industrial applications [1,8]. One of the ways to make droplets or sprays is to form waves on the gas-liquid interface by a fast-moving gas on a liquid surface, for example, air-blast injectors systems. These waves grow by extracting the kinetic energy of the liquid and gas stream. If the kinetic energy is sufficiently large, thin liquid sheets and filaments are formed which break into droplets [4]. This step is called primary atomization. During the final and secondary atomization, these droplets form a fine spray via collision, stretching, etc. While the latter process determines the size and distribution of the droplets, the former plays an important role in determining the rate at which droplets are produced, the initial conditions for the extent of the dispersed two-phase flow, etc. The physical mechanisms of primary atomization are often complex, nonlinear and hence, are poorly understood. This is true not only for co-flowing gas-liquid mixing layers but also jets [5,7,9], planar sheets [3], etc. In this article, primary atomization process in a co-flowing gas-liquid mixing layer is illustrated, in particular, when the horizontal gas flow is fast. Consider for example figure 1a which shows such interactions in the presence of complex flow structures during the atomization process in a two-phase mixing layer experiment at LEGI. It is a snapshot taken by a high-speed camera (Photron SA1.1) in the

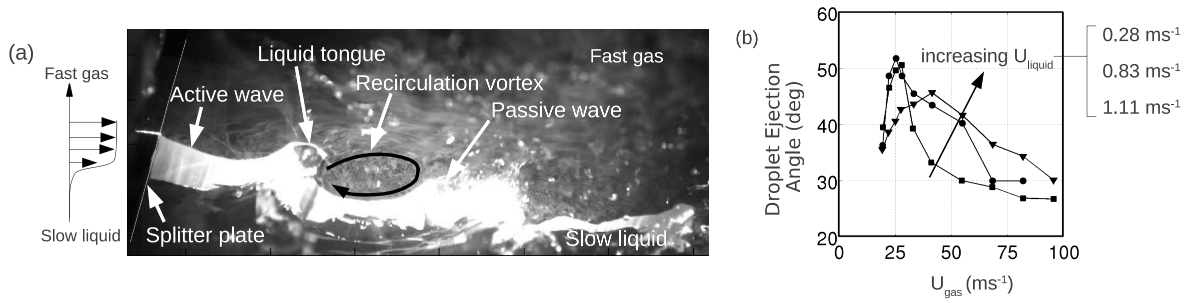

Figure 1. (a) Co-flowing air-water mixing layer visualized with a LASER sheet (LEGI) and smoke showing a liquid filament that breaks up into droplets on top of a recirculation vortex. (b) The variation of the droplet ejection angle α versus the gas speed (U_g) in two-phase mixing layer experiments by [14].

splitter plate experimental setup [10]. In figure 1a, an Argon LASER sheet illuminates the liquid surface showing two waves: the active wave which grows while remaining attached to the splitter plate and the passive wave (the previous active wave) that has left the plate. Between these waves, there is clearly a recirculation region and just above it, a liquid filament is observed. Experimental evidence shows that, as the liquid filament develops, it oscillates and eventually breaks up violently to from droplets via what looks like a "bag-break up" but from below. The measured values of angle of droplet ejection vary with the gas speed as shown in the same figure 3b. The angle increases steeply until about a critical value and then decreases monotonically, however slowly, with further increase in gas speed. Such a phenomena has already been observed in two-phase mixing layers by [14] and [2]. The physical mechanisms causing such a phenomena is, however, not clearly known. Note that these droplets are thrown into the air stream at angles as high as 50 degrees with respect to the horizontal axis. It is intriguing to find that, in a flow system with large horizontal momentum, droplets move in such oblique trajectories. The experimental results of [14] and [2] in figure 1 correspond to the case where the velocity of the air-flow (the lighter fluid) is much greater compared to that of water (the heavier fluid) with a air-flow recirculation region as identified in figure 1. The interaction of this zone with the wave crest and hence its influence on primary atomization processes have rarely been considered before. This is largely due to the fact that such events are complex and involve a large variety of scales. In this article, the phenomenon of vortex shedding in a $2D$ two-phase mixing layer is pointed out via experimental investigations. A droplet catapult mechanism via vortex shedding is then put forward to explain large angle of ejections observed by [14] and [2]. This mechanism is thoroughly studied via the evolution of a localized wave in $2D$ two-phase mixing layers using direct numerical simulations. Finally, supporting evidences are provided to show that vortices catapult droplets in atomization.

As observed in figure 1, the air-flow visualization of such vortices and related processes are, nonetheless, cumbersome and difficult because of the $3D$ nature of the two-phase mixing layer due to the influence of capillary waves and side walls which results in such violent events that are inhomogeneous in the transverse direction. This effect masks the visualization of the vortex behind the wave. Moreover, due to the presence of large number of droplets during the droplet catapult process, it is not easy to identify the air-water interface using the LASER sheet as it is reflected unequally by the droplets. However, these short-comings could be overcome by using a direct numerical simulation.

2 Localized self-similar wave

The evolution of a localized initial disturbance in an infinite $2D$ two-phase mixing layer is considered in this section. This is the simplest model that is pertinent to the phenomena introduced in the previous section. Under these conditions, only the dynamics of active wave and the effect of fast gas flow are investigated while the role of the passive wave, the splitter plate dimensions, the boundary layer thickness of the incoming flow, gravity, etc are neglected. An open source Navier-Stokes solver called GERRIS [13] is used in order to numerically solve this toy problem. An initial impulse disturbance in such flows eventually develops into a non-linear Kelvin-Helmholtz wave that grows and propagates downstream in a self-similar manner (for more details, [6] and [11]).

Our numerical investigation consists of an infinite $2D$ two-phase mixing layer with a fast-moving gas flow (density ρ_g) on top of a slow-moving heavier liquid flow (density ρ_l). Sufficiently far away from the gas-liquid interface, the gas flows at a speed $U_g = 1$ in the x-direction while the heavier liquid is at rest ($U_l = 0$). The viscosity of the two fluids is taken to be the same. Thus, the initial velocity field in the liquid and gas streams, is made up of error functions that satisfy the stress continuity at the interface. The non-dimensional parameters that characterize this analysis are, namely, the Reynolds number $\mathrm{Re} = U\delta/\nu$ where δ and ν are the mixing layer thickness and the dynamic viscosity, respectively, and the Weber number $\mathrm{We} = \rho_g U_g^2 \delta/\sigma$ where σ is the surface tension of the liquid. In the simulations, they are taken to be $\mathrm{Re} = 100$ and $\mathrm{We} = 1000$. They are large enough so that they do not play a deciding role on the droplet catapult phenomenon. The size of the simulation domain is $500\,\delta$ in length (x-direction) and 250δ in height (y-direction). These simulations are performed with periodic boundary conditions in the streamwise direction and symmetry boundary conditions at the top and bottom boundaries. The initial condition consists of a very small amplitude impulse disturbance on the component of velocity normal to the interface such that it disappears before a distance of δ units in the x-direction. Various spatial discretization levels were tried to validate the results and a spatial discretization of approximately 0.06δ units is chosen for which the error in the location of wave is found to be only $\leq 1\%$.

If one neglects, viscosity and capillarity effects, the only length scales in an infinite $2D$ two-phase mixing layer are $U_g t$ and δ. If vorticity field ω is considered as a function of x, y, t, U_g and δ, at sufficiently large time $t \gg \delta/U_g$, it can be shown that $\omega = U/\delta f\,(x/U_g t, y/U_g t, \rho_g/\rho_l)$ ([6]). Hence, in the self-similar coordinates $x^{'} = x/U_g t$ and $y^{'} = y/U_g t$, the shape, size and the dynamics of the wave depends only on a single parameter, namely, the density ratio $r = \rho_g/\rho_l$.

In figure 2, temporal evolution of a gas-liquid mixing layer subjected to a localized disturbance is presented for a density ratio, $r = 0.02$. The time axis is specified in δ/U units. Thick lines denote the gas-liquid interface whereas thin lines represent snapshots of the gas flow streamlines. Here, certain streamlines are left out for the sake of better visibility. Similar to the case of spatially evolving wave in the experiments shown before (figure 1a), the gas-liquid interface in figure 2b displays a liquid filament at the crest of the wave. A recirculation vortex is present at all times shown here. The interface is deformed by the incoming flow and the recirculation vortex, thus it oscillates and forms droplets at regular intervals. In figure 2a, the gas flow streamlines show the presence of periodic vortex shedding behind the wave; three such shedding events in the gas flow are displayed. Note that each shedding accompanies droplet formation from wave/gas-liquid interface. Thus, figure 2 already indicates that vortex shedding is connected to droplet ejection process.

This droplet ejection process is illustrated during one vortex shedding event in figure 2b. At this density ratio ($r = 0.02$), the wave moves much slower than the gas stream and hence, it acts as an obstacle in the gas flow. This implies that the gas flow past the wave is in a large manner similar to the flow past a backward facing step. Thus, the flow over the wave separates; and the separated flow reattaches after a small recirculation zone. Initially, the recirculation region is small as observed at $t = 107.5$ in figure 2(b). However, it grows and becomes unstable at subsequent times similar to the unstable recirculation region behind a backward facing step and this vortex is eventually shed. During this process of shedding, the liquid filament swells up until it breaks up into a blob of droplet. A droplet catapult mechanism is thus observed: (1) The incoming gas flow sees the slow-moving wave as an obstacle and thus, separates on the crest of the wave to form a small separation bubble as seen at $t = 107.5$. (2) As this recirculation region grows in to a vortex which swells up the liquid filament from below. At this stage (figure 2(b) for $t = 125$), the liquid filament resembles that in the initial stages of bag-breakup but from below. A bag breakup is analogous to bursting of soap bubbles blown from a soap film attached to a ring (see for example, [12,15]). While the incoming gas flow shears the liquid filament, the recirculation vortex is blowing it up from below. However, the wake has grown very large and is unstable. Hence, the vortex is shed as the liquid filament breaks-up from below and forms droplets. (3) During break-up the liquid

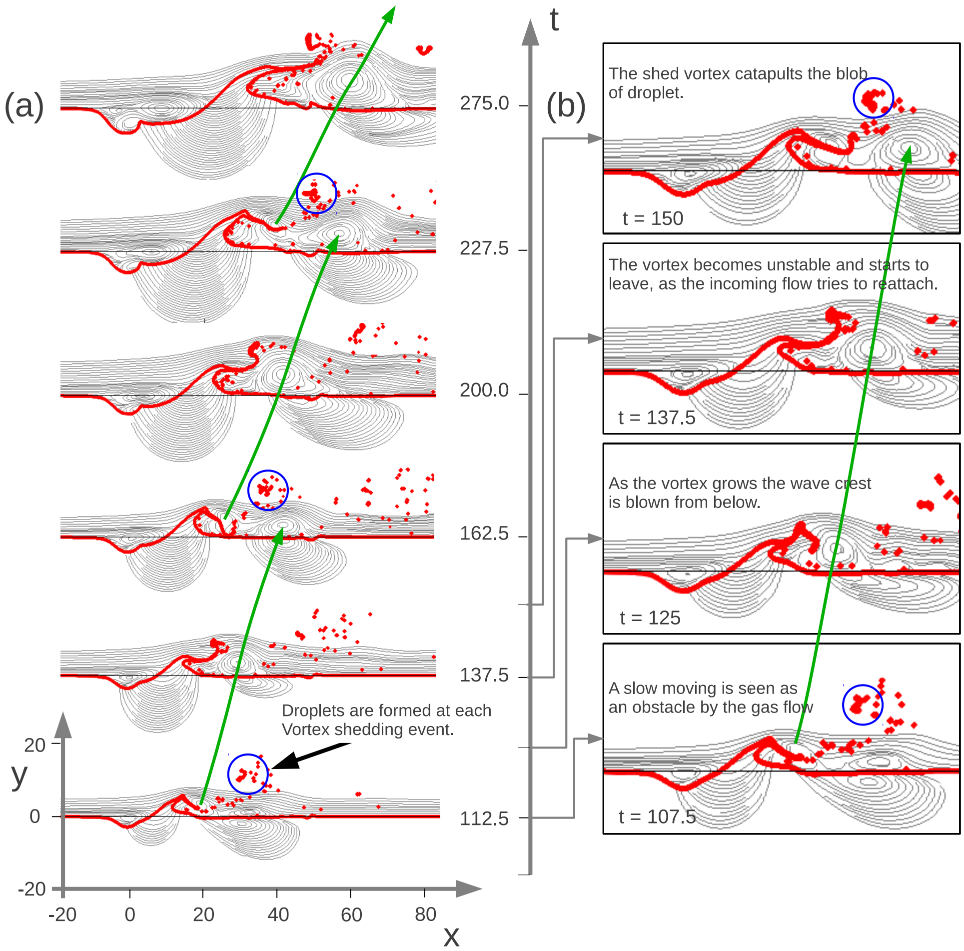

Figure 2. (a) Temporal evolution of gas-liquid interface (thick lines) and streamlines (thin lines) showing periodic vortex shedding and droplet ejection (circles) when the density ratio, $r = 0.02$. (b) Different stages during one such shedding-catapult process is displayed to illustrate the droplet catapult mechanism via vortex shedding.

filament is pushed downward by the incoming flow which momentarily remains attached while flowing past the crest of the ever-growing wave as seen at $t = 137.5$. (4) Such a gas flow is, however, unstable and so it eventually separates to form a tiny separation bubble on top of the liquid filament. At this stage, see figure 2(b): $t = 150$, the gas-liquid interface and the gas flow is the same as that at $t = 107.5$. Thus, a recirculation region is again formed behind the wave which further grows and leaves the wave while catapulting the liquid filament to result in break-up and hence, the droplet ejection. A quantitative measure of the effect of this change in gas flow morphology on the droplet dynamics can be deducted from the figure 3a. It displays the measured droplet angle of ejection over various density ratios. The error bars display the standard error over various measured angles at different times for a given density ratio. The angle of ejection α is computed by superposing snapshots of gas-liquid interface locations obtained from GERRIS for two consecutive time units. It is given by the angle that the superposed droplets make with the streamwise direction as shown in figure 3a for the cases $r = 0.08$, 0.025 and 0.01. As the density ratio r decreases, figure 3a shows that α remains almost constant but below zero until about $r = 0.04$. When the density ratio is decreased further, there is a steep increase in the angle of ejection α. Note that α as high as ≈ 40 degrees is observed.

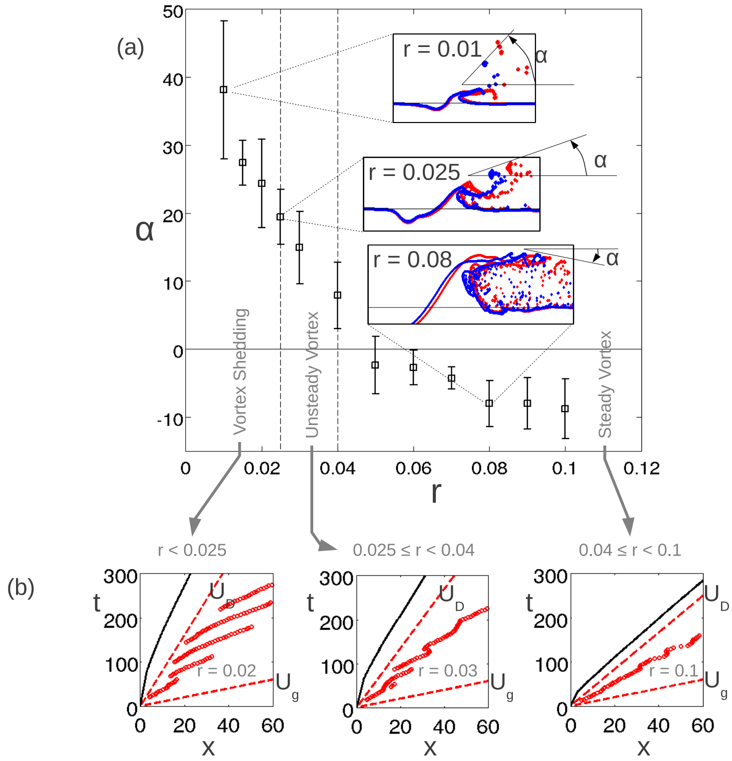

Figure 3. (a) Variation of droplet angle of ejection with density ratio, $r = \rho_g/\rho_l$. (b) Streamwise variation of the position of the wave centres and vortex centres at different times. Here, U_D represents the Dimotakis speed given by $\sqrt{(r)}/(1+\sqrt{r})$.

Figure 3b presents the spatio-temporal evolution of the wave and recirculation vortex for various density ratios by displaying their respective streamwise positions (thick lines and $\circ$ represent wave and vortex centres, respectively) with respect to time. For all the values of density ratios shown here, the position of wave monotonically increases with time. Thus, with respect to the gas flow, it moves at a constant horizontal speed which can be compared with the Dimotakis speed, $U_D = \sqrt{(r)}/(1+\sqrt{r})$ (plotted in dashed lines). It moves much slower than the gas flow ($\sim U/5$ to $U/15$) while its speed decreases with the density ratio, r. On the other hand, the streamwise of recirculation vortices vary non-monotonically with time over various values of r. For the cases when $0.04 \leq r < 0.1$, an approximately linear horizontal displacement of vortices with time is observed. Their horizontal speed nonetheless decreases with density ratio, however, much slower than that of the horizontal speed of the wave. This corresponds to the steady recirculation vortex that remains attached to the rear of the wave. When $0.025 \leq r < 0.04$, the vortex centres show large undulations in time while the centre of the wave moves at approximately steady speed U_D. Finally, for $r < 0.025$ regular vortex shedding is observed. Thus, three different gas flow configurations, namely, steady recirculation vortex, unsteady recirculation vortex and vortex shedding, can be identified from figure 3b over various decreasing values of density ratio. The vortex behind the wave moves downstream with approximately constant speed. As r decreases, this vortex shows strong unsteady motion in the streamwise direction. This flow configuration finally leads to vortex shedding as the density ratio r is further reduced. It is very clear from figure 3a and 3b that the onset of vortex shedding coincides exactly with the steep increase in droplet ejection angle. This is a direct evidence to the hypothesis that the dynamics of the recirculation region behind the wave is coupled to the phenomenon of droplet catapult. Thus, the vortex shedding can indeed eject droplets at large angles with respect to the gas flow via the droplet catapult mechanism.

3 Conclusions and Discussions

The process of droplet ejection in $2D$ two-phase mixing layer consisting of a fast-moving gas flow and slow-moving liquid flow is studied. A droplet catapult mechanism is thus identified and described: (1) A fast gas flow sees the slow-moving gas-liquid wave as an obstacle and thus, separates on the crest of the wave to form a small separation bubble. (2)The crest of the wave grows to form a liquid filament. At the same time, this recirculation region grows in to a vortex which swells up the liquid filament from below similar to bag-breakup but from below. However, the growing vortex becomes unstable and leaves the wake while the liquid filament breaks-up from below and forms droplets. (3) During break-up the liquid filament is pushed downward by the gas flow over it. The gas flow momentarily remains attached while flowing past the crest of the wave. (4) But such a flow situation is unstable and so it eventually separates to form a separation bubble on top of the liquid filament. Thus, a recirculation vortex is again formed behind the wave which further grows and leaves the wave while catapulting the liquid filament to result in break-up and hence, the droplet ejection.

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