Liquid jet breakup and subsequent droplet dynamics under normal gravity and in microgravity conditions

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We present an experimental study on the characteristics of liquid jets in different configurations. We consider jets injected perpendicular to gravity, jets injected parallel to gravity, and jets injected in a microgravity environment. We study the role played by gravity in the jet breakup length and in the dynamics of the droplets generated after breakup. We analyze droplets obtained in the dripping and jetting regimes, focusing the study on their size, trajectory, oscillation and rotation. The particularities of the considered injection configurations are analyzed. In normal gravity conditions, in the dripping and jetting regimes, the breakup length increases with the Weber number. The transition between these regimes occurs at $We_{cr} \approx 3.2$. Droplets are notably larger in the dripping regime than in the jetting one. In the latter case, droplet mean size decreases as the liquid flow rate is increased. In microgravity conditions, droplet trajectories form a conical shape due to droplet bouncing after collision. When a collision takes place, coalescence tends to occur at low modified Weber numbers ($We_m < 2$), while bouncing is observed at higher values ($We_m > 2$). The surface of a droplet oscillates after bouncing or coalescence events, following a damped oscillator behavior. The observed oscillation frequency agrees with theoretical predictions.

I. INTRODUCTION

The study of the different stages in the life of a liquid jet (formation, instability, breakup, droplet dispersion, atomization) is a key issue for applications in industries such as the pharmaceutical (drug delivery), electronics (PCB manufacturing), printing (ink-jet injection), car (diesel engines), or space (liquid rocket engines)^{1,2}. The development of high-speed photography and computer processing power allow the acquisition of new understanding of the physics involved in the phenomena associated with liquid jets.

The breakup of a falling jet, which gives rise to the subsequent formation of drops and spray, is determined by various parameters and can be classified into different regimes^{3,4}. Two main patterns controlled by different forces can be distinguished: large drop and fine spray. The instability that leads to the formation of drops with similar size to the jet diameter is known as the Rayleigh mode. On the other hand, the instability that leads to the formation of droplets much smaller than the jet diameter is known as the Taylor mode. In the first case, which corresponds to a regime of low jet velocity, the interaction between the liquid and the ambient gas triggers the breakup process with the growth of long-wavelength, small-amplitude disturbances on the liquid surface. The Rayleigh instability gives rise to the drop formation by means of capillary pinching. In the Taylor mode, corresponding to a high jet velocity regime, the breakup instability is associated with the growth of short-wavelength waves caused by the interfacial shear and pressure fluctuation which generates a spray.

Two different types of instabilities (convective and absolute) are considered in the Rayleigh mode assuming a reduced gravity environment. In the convective instability, a disturbance in a jet grows and propagates only in the downstream direction⁵. In the absolute instability, the disturbance propagates both downstream and upstream in the absence of gravity and ambient gas and for a Weber number (We) below a critical value depending on the Reynolds number of the jet⁶. Different authors carried out Rayleigh's linear stability analysis around the cylindrical base state of the jet, considering the effects of viscosity, outside gas, nozzle geometry or system dimensions^{2,6-9}. In normal gravity conditions, three mechanisms of liquid jet breakup in the laminar regime can be considered: periodic dripping, chaotic dripping, and jetting. The transition between the dripping and jetting regimes was found to occur at a critical Weber number We_{cr} ¹⁰. The dripping-jetting transition in a dripping faucet was studied in different fluids by Ambravaneswaran *et al.*¹¹. The authors

obtained phase diagrams showing transitions from simple and complex dripping to jetting. The variation with We of several quantitative measures of the dynamics for detecting the transition from dripping to jetting was also obtained.

Concerning the effects of gravity on the shape of liquid jets, Clarke¹² proposed a universal solution of a flow of a viscous jet under the influence of gravity. The proposed solution was a good predictor for the shape and size of viscous liquid jets. Gañán Calvo, Ferrera, and Montanero¹³, Montanero *et al.*¹⁴ found that the solution provides very accurate results for a wide range of Reynolds and Froude numbers.

Although the shape and instability of liquid jets have been extensively studied in normal gravity conditions, fewer studies have been carried out in microgravity. Under the action of gravity, the Navier Stokes equations lead to a universal solution with a monotonically decreasing jet radius¹², while the same equations admit a cylindrical shape in the absence of gravity. Indeed, one can find a universal scaling of the axial coordinate in terms of gravity, which becomes singular for $g = 0$ ¹⁴. The study of liquid jets in a microgravity environment allows one to investigate the competition between surface forces and inertial forces at low Weber numbers. As long as gravity is present, a certain volume of liquid is accelerated, and this often masks the effects of the surface forces. In addition, the study of liquid jet breakup in microgravity provides an ideal framework in which the characteristics and dynamics of the generated droplets can be examined for longer periods of time than in normal gravity conditions. This makes the microgravity environment very appropriate for the study of droplet collisions and oscillations. Moreover, the solution of a flow field of a liquid jet is often expressed under the hypothesis of axisymmetry. However, the only possible experimental condition in normal gravity in which axisymmetry is valid occurs when the jet is oriented parallel to gravity. The realization of experiments in microgravity conditions is the only possibility in which this gravitational term can be dismissed by maintaining axisymmetry.

Studies of jets in microgravity have mainly focused on the analysis of instabilities, jetting modes, and comparison with the behavior of vertically falling jets in normal gravity. Absolute and convective instabilities in liquid jets in reduced gravity were observed by Vihinen, Honohan, and Lin¹⁵ for Reynolds number $Re < 0.2$. O'Donnell, Chen, and Lin¹⁶ determined experimentally We_{cr} in the convective-absolute transition in liquid jets in microgravity for $50 < Re < 150$. The physics of vertically falling jets, their breakup, and subsequent drop

dynamics under normal and reduced gravity conditions and the effects of the two instabilities on these processes were studied in Edwards *et al.*¹⁷. Osborne and Steinberg¹⁸ determined experimentally the jetting modes and their corresponding breakup mechanisms as well as the transitions between jetting and chaotic dripping and between convective and absolute instabilities in microgravity conditions. In order of decreasing velocity, they observed: development of a long slender jet supporting a convective instability, producing drops with a little variation in size (jetting); a small to non-existent jet that produced drop sizes of great variability (chaotic dripping); and a large mass of fluid that accumulated at the nozzle and did not detach during the experiments (quasi-stable). The transition from jetting to chaotic dripping was consistent with the theoretical predictions of Clanet and Lasheras¹⁰. Recently, Amini, Ihme, and Dolatabadi¹⁹ studied the effect of gravity on the onset and growth rate of the Rayleigh instability in vertically falling viscous liquid jets. The transition between convective and absolute instability was characterized by the expression of a critical We as a function of capillary and Bond (Bo) numbers. The authors showed that the critical We decreases with increasing Bo , which explained the shift of the dripping/jetting transition to lower We when gravity is considered.

The characteristics and dynamics of the droplets generated in the jet breakup play an important role in different industrial applications, which has generated the interest of many researchers for several decades. Teng, Kinoshita, and Masutani²⁰ predicted the size of droplets formed during the breakup of cylindrical liquid jets from instability analysis. The size was found to depend on a modified Ohnesorge number. Cheong and Howes²¹ performed a numerical and experimental study of the capillary instability of jets injected parallel to gravity. Drop size in the jetting regime was found to decrease for increasing gravity level, as was later confirmed in Amini, Ihme, and Dolatabadi¹⁹. Oscillations in rotating and non-rotating glycerine/water and silicon oil drops in the microgravity environment provided by the Space shuttle were studied in Wang, Anilkumar, and Lee²². The oscillation of the drops was generated by two methods different from jet breakup. In one case, the drop started oscillating after turning off an acoustic field that kept it levitating. In the other case, the drop was gyro-stabilized through an imposed rotation along an axis, and oscillations were started by using an imposed field in that axis. The inviscid frequency shift of the damped oscillations due to nonlinearity was compared to theoretical predictions. Yamada and Sakai²³ studied the oscillation of micrometric droplets of water, ethylene glycol and 20

cSt silicon oil, generated by the coalescence of two droplets in normal gravity conditions. Suñol and González-Cinca²⁴ studied the collision between droplets created after jet breakup in a low gravity environment, showing that the conical shape of the jet is due to bouncing events between droplets.

Under normal gravity, if a liquid jet is injected perpendicular to the direction of gravity, the shape of the jet is no longer rectilinear but curved. Thus, the axisymmetry is broken and the problem becomes complex to solve analytically. Uddin and Decent²⁵ performed a theoretical study on the instability of liquid jets curved by gravity. The authors carried out a linear instability analysis to examine the behaviour of the most unstable wavenumber and the growth rate of instabilities. No experimental data have been found in the literature that could confirm the theoretical predictions.

In this paper we carry out an experimental analysis of the liquid jet breakup and subsequent droplet dynamics with the following configurations: jet injected perpendicular to gravity, jet injected parallel to gravity, and jet in microgravity conditions. We consider jets in both dripping and jetting regimes, analyzing the breakup length, droplet size and trajectories, as well as the droplet surface oscillations. This is the first analysis carried out comparing the three injection configurations. In addition, the analysis of the liquid jet from the breakup length of the liquid volume to the droplet collisions and oscillations gives a new complete view of the different phenomena taking place in an injected jet.

The paper is organized as follows: in Section II, the experimental setup is described. Experimental results and discussions are presented in Section III. Finally, the conclusions of the paper are presented in Section IV.

II. EXPERIMENTAL SETUP AND PROCEDURE

In order to study the liquid jet breakup and droplet dynamics in a microgravity environment, an experimental setup was designed and built to be used in the *Instituto Nacional de Técnica Aeroespacial* (INTA) Drop Tower (Torrejón de Ardoz, Spain). This facility provides 2.1 s of $10^{-3} \cdot g_0$, with $g_0 = 9.81 \text{ m/s}^2$.

The experimental setup consisted of systems for jet generation, data acquisition, control, and power supply. Fig. 1 shows a picture and a detailed sketch of the setup.

Distilled water (density $\rho = 998 \text{ kg/m}^3$, viscosity $\mu = 1 \cdot 10^{-3} \text{ Pa}\cdot\text{s}$, and surface tension

FIG. 1. Picture and sketch of the experimental setup. 1: Control unit, 2: LEDs, 3: Diffuser sheet, 4: Test tank, 5: Injectors, 6: High-speed Camera, 7: Residual bag, 8: Liquid reservoir, 9: DC/AC Inverter, 10: Liquid flow meter, 11: Liquid pump, 12: Filter, 13: NI PXI, 14: Batteries.

$\sigma = 7.28 \cdot 10^{-2}$ N/m) was used as working fluid. The liquid, initially contained in a flexible reservoir bag (EVA Nutribag 500 ml), was injected through a nozzle (internal diameter $d_c = 0.7$ mm) at controlled flow rates into a rectangular test tank (160 mm long, 200 mm wide, and 250 mm high). The liquid flow rate Q_L was varied from 5.00 ml/min up to 15.00 ml/min by means of a liquid pump (Ismatec MCP-Z Standard). We also used a liquid flow meter (Bronkhorst L30) to verify the flow rate in the line. The test tank was made of stainless steel with two methacrylate windows to allow the visualization of the tank interior. An empty flexible residual bag (EVA Nutribag 500 ml) was connected to the test tank to avoid any risk of overpressure.

The data acquisition system was composed of a high-speed camera and the illumination subsystem. The camera (RedLake MotionXtra HG-SE), which contained a built-in battery and an internal memory, was activated when a trigger signal was received just before the setup was released. The camera recorded the jets at rates between 500 and 1000 frames per second (recording images with 640×512 and 640×256 pixels, respectively), depending on the experimental run. The spatial resolution of the acquired images was 0.15 mm per pixel. The illumination subsystem consisted of a matrix of 280 ultra-bright LEDs and a diffuser sheet to homogenize the light.

The liquid pump and the data acquisition system were controlled wirelessly by LabView software.

The capsule containing the experimental setup was released six times (six drops), between which Q_L was the only parameter changed. Experiments were conducted at room temperature (approximately 20° C) and at ambient pressure.

III. RESULTS AND DISCUSSION

A. Jets in normal gravity

1. Jet breakup

In the experimental setup described in the previous section, a jet is created by injecting liquid at a fixed flow rate Q_L through a capillary tube oriented perpendicular to the gravity direction. With this arrangement, two different regimes have been observed under normal gravity by changing the liquid flow rate. When inertial forces are negligible compared to surface tension, a drop is formed at the nozzle outlet and grows continuously until it detaches from the nozzle. In this situation, the dripping regime, the nozzle leaks (see Figs. 2(a) and 2(b)). On the other hand, when inertial forces dominate surface forces, the jetting regime takes place (Figs. 2(c) to 2(e)). In this case, the jet emerging from the nozzle curves downwards due to the action of gravity. The liquid is contained in a curved cylinder with surface perturbations of growing amplitude. Once the amplitude equals the cylinder radius, the liquid bulk breaks forming droplets. Points in Fig. 3 show the steady-state trajectories for different values of the Froude number ($Fr = v/\sqrt{gd_c}$, where $v = 4Q_L/\pi d_c^2$ is fluid velocity and g is gravity). As expected, faster jets (large Fr) reach larger horizontal positions x for the same vertical position y .

In order to analyze the transition between the dripping and jetting regimes, the average breakup length $\langle L_b \rangle$ was obtained for different values of the liquid flow rate. L_b was measured over $N = 500$ frames for every Q_L , and an average value $\langle L_b \rangle = \frac{1}{N} \sum_{i=1}^N L_{bi}$ was calculated. The graphical definition of L_b in each regime is shown in Fig. 2 right for the case of injection perpendicular to gravity (an equivalent definition is used for jets parallel to gravity). In particular, in the jetting regime, L_b is given by the length of a circular arc from the center of the nozzle to the breakup position. Fig. 4 shows the variation of the normalized average

FIG. 2. Left: Snapshots of liquid patterns at different flow rates. (a) $Q_L = 5.00$ ml/min, (b) $Q_L = 10.00$ ml/min, (c) $Q_L = 13.15$ ml/min, (d) $Q_L = 13.50$ ml/min, (e) $Q_L = 15.00$ ml/min. Right: definition of the breakup length L_b .

FIG. 3. Steady-state trajectories for different Froude numbers and $We \in [3.0, 4.2]$.

breakup length $\langle L_b \rangle / d_c$, where d_c is the nozzle radius, with respect to We . Results for jets parallel ($\parallel$) and perpendicular ($\perp$) to gravity are presented in this plot. At low We and Bo numbers, the nature of the nozzle and thus the contact angle between the liquid and the nozzle play a crucial role in the determination of the volume of the drop. Therefore, the

results presented in Fig. 4 could change if a different nozzle were employed. Taking this into account, a comparison of the performance of a given nozzle in the different configurations can be carried out. Fig. 4 shows that in the dripping regime of the perpendicular jets, the breakup length increases linearly with We . This behavior differs from what is found when the injection is parallel to gravity, where the breakup length remains the same for any We in the dripping regime (as was also seen, for example, in Fig. 2 in Ambravaneswaran *et al.*¹¹). The transition between dripping and jetting takes place at $2 < We < 3$. In the jetting regime, the breakup length also grows linearly with We . It is interesting to note that $\langle L_b \rangle / d_c$ is significantly larger in the dripping regime at the highest We than in the jetting regime at the lowest We in the injection perpendicular to gravity. This behavior could depend on the nature of the nozzle and is characteristic of this configuration, since in the case of injection parallel to gravity the breakup length in the jetting regime is always larger than in the dripping regime (as was also seen in Ambravaneswaran *et al.*¹¹). A careful comparison of the snapshots in Figs. 2(b) and 2(c) confirms that in fact L_b is higher in the dripping regime (Fig. 2(b)) than in the jetting regime (Fig. 2(c)). This can be explained by the difference in the breakup process between the two regimes in the perpendicular jet configuration, which could also depend on the nozzle characteristics at low We . In the dripping mode, the forming droplet drags the liquid downwards, resulting in a neck that becomes thinner as the forming droplet grows. The breakup of the neck generates the droplet. In the jetting mode, droplets are generated by the Rayleigh instability in which the most unstable surface wave grows until the cylindrical shape is broken. This can occur at a very small distance from the nozzle, as can be observed in Fig. 2(c).

2. Droplet size distribution

Teng, Kinoshita, and Masutani²⁰ studied the size of the droplets generated after jet breakup in the jetting regime for Newtonian and non-Newtonian fluids, obtaining the following expression for the droplet mean diameter d_m :

$$\frac{d_m}{d_c} = \left(\frac{3\pi}{\sqrt{2}} \right)^{\frac{1}{3}} (1 + 3Oh)^{\frac{1}{6}}, \quad (1)$$

where $Oh = \mu / (\sqrt{\rho \sigma d_c})$ is the Ohnesorge number. At the range of parameters of our experiments, $Oh \ll 1$, which gives $d_m \approx 1.88d_c$.

FIG. 4. Variation of the normalized average breakup length with We for jets oriented perpendicular to gravity ($\perp$) and jets oriented parallel to gravity ($\parallel$).

If orifice effects are considered, Eq. 1 may be expressed more generally as²⁰ :

$$\frac{d_m}{d_c} = 1.88\alpha (1 + 3Oh)^{\frac{1}{6}}, \quad (2)$$

where α is an empirical parameter related to orifice effects, which is experimentally determined. Based on experimental data with $0.01 \leq 3Oh \leq 0.50$, Teng, Kinoshita, and Masutani²⁰ obtained the following expression for α :

$$\alpha = 1.1303 + 0.0236 \ln(3Oh), \quad (3)$$

205 which leads to a droplet mean diameter of $d_m \approx 2.12d_c$ in our case.

The size of the generated droplets was measured from the recorded images. Since droplets oscillate after jet breakup, an equivalent diameter d_e is defined as the diameter of a spherical droplet with a volume equal to that of the oscillating droplet. d_e measurements are carried out in two-dimensional images, thus the equivalent diameter is given by $d_e = 2\sqrt{A_m/\pi}$ 210 where A_m is the measured area of the oscillating droplet.

Fig. 5(a) and Fig. 5(b) show the droplet size distribution for three values of the liquid flow rate corresponding to the configuration with the jet oriented parallel and perpendicular to gravity, respectively. In both configurations, the case $Q_L = 10$ ml/min corresponds to the dripping regime, while in the other two cases a jetting regime is obtained. In the dripping

FIG. 5. Droplet size distribution for different liquid flow rates Q_L in normal gravity. (a) Jets oriented parallel to gravity. (b) Jets oriented perpendicular to gravity.

regime, droplets with $d_e \approx 4.5$ mm detach regularly from the nozzle. The distribution function is narrower in the parallel configuration, indicating a lower droplet size dispersion. At larger values of the liquid flow rate, already in the jetting regime, the droplet mean size is significantly smaller ($d_e \approx 2$ mm) than in the dripping regime, and decreases as Q_L is increased. The distribution function in the jetting regime is much wider than in the dripping regime, reflecting a higher size dispersion. The larger dispersion in the jetting regime can be explained because the distribution functions, despite containing data of droplets generated after coalescence events, are mainly obtained from the droplets directly generated by the jet breakup process. In the jetting regime, collisions between droplets after their generation occurs frequently, resulting in bouncing or coalescence events.

In the jetting regime, the droplet mean diameter obtained experimentally in both configurations is in good agreement with the prediction given by Eq. 2. The obtained d_e at $Q_L = 13.50$ ml/min in both configurations is slightly higher than the numerical values obtained in Cheong and Howes²¹ (in their Fig. 10, the parameter G is equivalent to $1/2\text{Fr}^2$). Cheong and Howes studied vertically falling jets with a similar setup to the one presented in this work. The diameter of their nozzles are 0.65, 0.90 and 1.40 mm, and, in addition to water, they used aqueous glycerol solutions. The discrepancy in the value of d_e can be explained by the fact of counting droplets after coalescence. However, in the case with $Q_L = 15.00$ ml/min the value of d_e is in good agreement with Cheong and Howes²¹ for both parallel and perpendicular jets.

FIG. 6. (a) x -coordinate (injection direction) and (b) y -coordinate (gravity direction) of the droplets center as a function of time for $Q_L = 15.00$ ml/min.

3. Droplet trajectories

After the jet breakup in the dripping regime, droplets fall vertically. In the jetting regime in the perpendicular configuration, the generated droplets follow a parabolic trajectory due to the action of gravity. An automatic method has been built to track the position of the center of the droplets along their trajectory. In Figs. 6(a) and 6(b), the x -coordinate (injection direction) and y -coordinate (gravity direction) of the droplets center are plotted as a function of time for $Q_L = 15.00$ ml/min. The region limited by $x \in [5, 10]$ mm and $y \in [-1, -2]$ mm corresponds to the breakup zone. At larger values of x and y , droplet dynamics show a linear and a quadratic behaviour, respectively, corresponding to a parabolic trajectory.

The trajectories of droplets injected at $Q_L = 15.00$ ml/min are shown in Fig. 7 left, where the dashed lines correspond to the normal gravity case. The mean of the droplet trajectories is given by the curve at $Fr = 7.8$ in Fig. 3. A droplet path reaching larger distances than the rest ($x = 28$ mm) can be observed in Fig. 7 left. The origin of this abnormal behaviour is an irregularity in the jet breakup mechanism as observed in the recorded videos. They show the generated droplet colliding with a bigger droplet and bouncing, which significantly deviates its trajectory. Fig. 7 right shows a sketch of the collision process between two droplets of a similar size. Droplets can collide if they are at t_1 on a converging path or in parallel trajectories with $v_i > v_j$ and $0 < b < r_i + r_j$.

FIG. 7. Left: Droplet trajectories for $Q_L = 15.00$ ml/min (dashed lines: normal gravity, solid lines: microgravity). Right: sketch of the collision process between two droplets.

B. Jets in microgravity

1. Jet breakup

When a liquid jet emerges from a nozzle in microgravity conditions, it quickly loses its cylindrical shape due to the action of inertial and surface tension forces. The cylindrical jet is perturbed by the competition between cohesive and disruptive forces giving rise to surface oscillations. Under certain conditions, the oscillations can be amplified and the liquid body disintegrates into drops at a distance L_b from the nozzle outlet (Rayleigh instability).

Fig. 8 shows the liquid patterns obtained when a liquid jet is injected at different flow rates into the test cell in microgravity. At low flow rates, $0 < Q_L < 10.00$ ml/min, inertial forces are negligible compared to surface tension and a nearly-spherical droplet is formed, growing without detaching from the nozzle (quasi-stable growth in Fig. 8(a)). At $Q_L = 10.00$ ml/min, the generated droplet remains attached to the nozzle but loses its spherical shape due to the action of liquid inertia (Fig. 8(b)). At $Q_L = 13.15$ ml/min, inertial forces are strong enough to create a small liquid jet. In this case, jet breaks at a small length and droplets of different size are generated (chaotic dripping in Fig. 8(c)). At higher liquid flow rates, $Q_L \geq 13.50$ ml/min, the breakup length increases and the droplet size, with little variation for a given Q_L , decreases with the flow rate (jetting in Figs. 8(d) and 8(e)).

FIG. 8. Snapshots of liquid patterns at different flow rates. (a) $Q_L = 5.00$ ml/min. (b) $Q_L = 10.00$ ml/min. (c) $Q_L = 13.15$ ml/min. (d) $Q_L = 13.50$ ml/min. (e) $Q_L = 15.00$ ml/min.

These observations are consistent with previous works (e.g. Clanet and Lasheras¹⁰, Osborne and Steinberg¹⁸). Our observations manifest in addition that a liquid injected at a given Q_L adopting a jetting regime under normal gravity will show the same regime or chaotic dripping in microgravity. Moreover, at the flow rates in which a dripping regime is observed in normal gravity, a quasi-stable growth without breakup is obtained in weightlessness.

Clanet and Lasheras¹⁰ studied the dripping to jetting transition, obtaining an expression for the critical We at which the transition occurs:

$$We_{cr} = 4 \frac{Bo_o}{Bo} \left[1 + KBo_oBo - \left((1 + KBo_oBo)^2 - 1 \right)^{1/2} \right]^2, \quad (4)$$

where Bo and Bo_o are the Bond numbers ($Bo = \sqrt{\rho g d_c^2 / (2\sigma)}$), based on the inside and outside diameter of the tube, respectively, and $K = 0.37$ for the case of water injected in air.

Considering the sharp-edged nozzle geometry used in the experiments ($Bo_0 \approx Bo$), Eq. 4 becomes:

$$We_{cr} = 4 \left[1 + KBo^2 - \left((1 + KBo^2)^2 - 1 \right)^{1/2} \right]^2, \quad (5)$$

with $Bo = 0.18$. Fig. 9 shows We as a function of the Reynolds number ($Re = \rho v d_c / \mu$) for the six cases considered. Dripping and jetting regimes are distinguished. The transition

FIG. 9. Weber number as a function of the Reynolds number.

between dripping and jetting regimes occurs at $We_{cr} \approx 3.2$, a slightly lower value than the one predicted by Eq. 5 in our experimental conditions.

In order to study the effects of the Weber number on the breakup length L_b , we follow the procedure detailed in Lefebvre¹. The maximum growth rate of an axisymmetric disturbance in the injection direction of a jet is given by $q_{max} = 0.34\sqrt{\sigma/\rho r_0^3}$ at $kr_0 = 0.697$, where k is the wavenumber and r_0 is the radius of the undisturbed jet. Taking this into account, an expression for the breakup length of a liquid jet subjected only to inertial and surface tension forces as a function of the Weber number can be obtained:

$$\frac{L_b}{d_c} = 1.03\sqrt{We} \ln \left(\frac{d_c}{2\delta_0} \right), \quad (6)$$

where δ_0 is the amplitude of the initial disturbance and $d_c = 2r_0$. When effects of viscosity are considered, Eq. 6 is replaced by:

$$\frac{L_b}{d_c} = \sqrt{We} (1 + 3Oh) \ln \left(\frac{d_c}{2\delta_0} \right) \quad (7)$$

The initial disturbance δ_0 depends on the nozzle geometry and liquid flow rate and can not be determined. However, Grant and Middleman²⁶ obtained the following empirical correlation of data in the laminar region:

$$\frac{L_b}{d_c} = A \left(\sqrt{We} (1 + 3Oh) \right)^B, \quad (8)$$

FIG. 10. Normalized average breakup length. Solid line: fit of the points in the jetting regime of the perpendicular configuration with $A = 0.18$ and $B = 5.95$.

with $A = 19.5$ and $B = 0.85$.

In Fig. 10, the normalized average breakup length $\langle L_b \rangle$ is plotted as a function of the Weber number. Data shown correspond to both normal gravity and microgravity conditions.

Each point has been obtained from the average of the values of L_b measured over 500 frames.

In the jetting regime, L_b in the case of injection perpendicular to gravity does not show any dependence on the gravity level. In the case of the parallel configuration, L_b slightly decreases

when gravity is considered, as was observed in experiments in Edwards *et al.*¹⁷, Cheong and Howes²¹ and numerical results in Amini, Ihme, and Dolatabadi¹⁹. Therefore we can

conclude that the effects of gravity in the determination of L_b are more important in the parallel configuration than in the case of injection perpendicular to gravity. In fact, in this

latter case the effects of gravity on L_b are negligible in the range considered. Thus, while gravity plays a fundamental role in the path deflection of jets perpendicular to g , the role

played by gravity on L_b turns out to be more important in jets parallel to g . This non-intuitive observation is due to the fact that when the jet is oriented parallel to the gravity

force, it is accelerated in the direction of injection which results in a droplet generation closer to the nozzle since the instability grows faster as the Bond number increases. This result

is in agreement with other experiments^{17,21} showing that the breakup length is reduced by gravity, resulting in the formation of smaller droplets.

FIG. 11. Droplet size distribution in microgravity for different liquid flow rates Q_L .

The experimental points in the jetting regime of the perpendicular configuration are fitted to Eq. 8 in Fig. 10 with $A = 0.18$ and $B = 5.95$. The discrepancy in the fitting parameters with respect to Grant and Middleman²⁶ is presumably due to the fact that our experiments were carried out in a regime of much lower flow rates close to the dripping-jetting transition.

In microgravity conditions, the interaction of the jet with the environment could play an important role, in particular at low We ²⁷. Therefore, the chaotic dynamics occurring around the dripping-jetting regime and right after the jetting regime is established in the absence of gravity is of different nature than the one reported in normal gravity conditions in previous works of Clanet and Lasheras¹⁰, Ambravaneswaran *et al.*¹¹. Thus, the discrepancies found in the dripping-jetting analysis in microgravity compared to normal gravity could also be due to the different nature of the chaotic regime.

2. Droplet size distribution

The size of the droplets created after jet breakup in microgravity conditions has been measured. Since the majority of the droplets oscillate, the introduction of the equivalent diameter d_e becomes necessary.

Fig. 11 shows the droplet size distribution for different values of the liquid flow rate. For $Q_L = 13.15$ ml/min, the dispersion of the droplet size is significantly wider than in the cases

FIG. 12. Droplet size distribution in normal gravity and microgravity for: (a) $Q_L = 13.50$ ml/min; (b) $Q_L = 15.00$ ml/min.

corresponding to $Q_L = 13.50$ ml/min and $Q_L = 15.00$ ml/min. This is due to the fact that $Q_L = 13.15$ ml/min corresponds to the chaotic dripping regime, in which the jet breaks up randomly generating droplets of different size.

As stated before, the maximum growth rate of the jet perturbation takes place at $kr_0 = 0.697$, which gives a wavelength of the fastest growing disturbance of $\lambda = 4.51d_c$. After breakup, a cylinder of length $4.51d_c$ becomes a spherical droplet. Thus, $(4.51d_c)(\pi d_c^2/4) = \pi d_e^3/6$, which gives an equivalent diameter $d_e = 1.89d_c$. However, the experimental data reveal that $2d_c \lesssim d_e \lesssim 3d_c$. In all cases, the mean value of the droplet size obtained experimentally is higher than the theoretical prediction. The disagreement is mainly due to droplet coalescence events taking place just after breakup, which can be observed in the recorded high-speed videos. Coalescence is largely promoted by the oscillation of droplets after breakup. Even if the distance between droplets is kept constant, the amplitude of the oscillation can be sufficiently large to allow droplets to collide and, consequently, bounce or coalesce.

Fig. 12 shows the droplet size distribution for $Q_L = 13.50$ ml/min and $Q_L = 15.00$ ml/min for the perpendicular jet configuration in normal gravity and microgravity conditions. In the case of $Q_L = 13.50$ ml/min, the droplet size mean value is $\langle d_e \rangle_{1g} = 2.22$ mm and $\langle d_e \rangle_{0g} = 2.13$ mm for normal gravity and microgravity, respectively. In the case of $Q_L = 15.00$ ml/min, the mean values are $\langle d_e \rangle_{1g} = 1.85$ mm and $\langle d_e \rangle_{0g} = 1.76$ mm. Therefore, no significant dependence on the gravity level can be observed. As it happens with the behaviour of

FIG. 13. x -coordinate of the droplets center as a function of time for $Q_L = 15.00$ ml/min.

the breakup length, this is a characteristics of the injection configuration perpendicular to gravity.

3. *Droplet trajectories*

Fig. 13 shows the x -coordinate (being x the direction of injection) of the droplets center as a function of time for $Q_L = 15.00$ ml/min. The white band without data points between $x = 5$ mm and $x = 10$ mm corresponds to the jet breakup zone. Data have been obtained by the same tracking method used in the normal gravity case. Although the method encountered some difficulties to distinguish surfaces when topological changes (due to breakup or coalescence) took place, and thus a small number of points are misplaced, some information can still be extracted from the plot. The alignment of points reveals a small velocity dispersion of the droplets generated after breakup. In addition, droplet velocity turns out to be very similar to the velocity of the jet from which the droplet is generated. On the other hand, the droplet generation frequency f_g can be obtained from the time interval between two consecutive lines of points. The droplet generation is very regular, with $f_g \approx 80$ drops/s. The case of $Q_L = 13.15$ ml/min (chaotic dripping) showed an irregular droplet generation for which no clear value of f_g could be obtained.

Fig. 7 left shows the droplet trajectories for $Q_L = 15$ ml/min in microgravity in solid

lines. Droplets created after jet breakup keep an initial rectilinear trajectory in the direction
of injection. The deflection is explained by the collision of two droplets after breakup. Thus,
the cone-shape created by the trajectories is due to droplet collisions near the breakup point.
The collision process is illustrated in Fig. 7 right, where droplet i is approaching droplet j
since $|\vec{v}_i| > |\vec{v}_j|$ with impact parameter $b \neq 0$. Although velocities at time t_1 are horizontal,
velocities after the collision (t_3) have a non-zero component perpendicular to the direction
of injection.

When two droplets collide, they can either bounce or coalesce. The result of the collision
depends on the droplets size, the relative velocity between droplets, and the impact
parameter of the collision. In order to determine the role played by these parameters in the
final result of a collision, we introduce a modified Weber number We_m as a function of the
relative velocity $v_{\text{rel}} = v_i - v_j$ between droplets i and j , $We_m = \rho v_{\text{rel}}^2 d^* / \sigma$, where $d^* = \sqrt{d_i d_j}$,
being d_i and d_j the equivalent diameter of droplet i and j , respectively.

The normalized impact parameter as a function of the modified Weber number is pre-
sented in Fig. 14. The bouncing and coalescence events for the parameter values considered
are indicated. Since the spatial resolution of the images is low compared to the droplet
mean size (approximately 10 pixels per droplet diameter), only four values of b/d^* could be
considered (which correspond to 0, 1, 2 and 3 pixels). Coalescence tends to take place at low
modified Weber numbers ($We_m < 2$), while bouncing occurs at higher values ($We_m > 2$).
This is in agreement with the fact that coalescence is more likely to occur at low relative
velocity between droplets. It is worth mentioning that all droplets were oscillating before
the collision, which influences the behaviour (bouncing or coalescence) after it.

C. Droplet oscillations

Droplet surface oscillations can be generated after jet breakup, coalescence, or even after
droplet bouncing. Although gravity is not expected to play an important role in the droplet
oscillations observed in our experiments, analyzing them in a microgravity environment is
advantageous in terms of localization and duration of the phenomenon.

Two parameters characterizing the droplet oscillation have been measured: diameter d_x
in the direction of injection x , and angle ϕ between the major axis of the droplet and the
 y direction. The damping coefficient and the frequency of oscillation are derived from the

FIG. 14. Normalized impact parameter b/d as a function of the modified Weber number.

FIG. 15. Left: schematic definition of the angle ϕ and the diameter d_x in the direction of injection. Right: time variation of ϕ . (a) $d_e = 2.47$ mm, (b) $d_e = 2.16$ mm.

diameter measurements. Fig. 15 left shows a schematic definition of ϕ and d_x .

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The angle ϕ provides information about the dominant mode of vibration and the rotation of the droplet with respect to its geometrical center. Fig. 15 right shows the variation of ϕ as a function of time. It can be observed that ϕ oscillates between two values separated by approximately 90° , which indicates that the second mode of oscillation, $n = 2$, is the

FIG. 16. Droplet diameter d_x as a function of time. Smooth lines are fits using the damped oscillator model. (a) $d_e = 2.01$ mm. (b) $d_e = 2.16$ mm.

dominant one. The first mode corresponds to volume oscillations, while the third and fourth
 405 modes would lead to differences in ϕ of 60° and 45° , respectively. The average value of ϕ in
 Fig. 15(a) and 15(b) tend to increase and decrease, respectively. This behaviour indicates a
 rotation of both droplets around their center of mass. The rotation appears to be slightly
 faster in the larger droplet.

Fig. 16 shows the evolution of the droplet diameter d_x as a function of time for droplets
 410 with equivalent diameter $d_e = 2.01$ mm and $d_e = 2.16$ mm. Damping coefficient and oscil-
 lation frequency can be obtained by fitting the experimental data to the damped oscillator
 model:

$$d_x(t) = d_e + A_2 e^{-\gamma_2 t} \cos(\omega_2 t + \varphi), \quad (9)$$

where A_2 , γ_2 and $\omega_2 = 2\pi f_2$ are the amplitude, the damping coefficient and the frequency
 of vibration of the second mode, respectively.

415 The oscillation frequency can be written as a function of the surface tension, the density
 and the size of the droplet as²⁸:

$$f_n^2 = \frac{2\sigma n(n-1)(n+2)}{\pi^2 \rho d_e^3}, \quad (10)$$

Thus, the frequency of the second mode is given by:

$$f_2 \approx \frac{4}{\pi d_e} \sqrt{\frac{\sigma}{\rho d_e}} \quad (11)$$

FIG. 17. Oscillation frequency (second mode, $n = 2$) of the droplets as a function of their equivalent diameter. Points: experimental data. Line: theoretical prediction.

Fig. 17 shows the oscillation frequency measured for different equivalent diameters and the prediction given by Eq. 11. The measurement of frequency is remarkably more accurate than that of the damping coefficient, even if the resolution of the images is the same, because frequency is measured from the temporal axis. Since droplet size in our experiments is considerably larger than in the experiments by Yamada and Sakai²³, the frequency of oscillation is consistently lower than in their work. The good agreement between our experimental results and the theoretical prediction indicates that the damped oscillator model is a good approximation, confirming that gravity does not play any role in the frequency of oscillation of the considered droplets.

IV. CONCLUSIONS

We have presented experimental results obtained under normal gravity and microgravity conditions which provide new insight into the characteristics of liquid jets and the dynamics of the droplets generated after their breakup. The main insight gained by our results is related to the behaviour of jets injected perpendicular to gravity in the dripping and jetting regimes as well as the role played by gravity in the observed phenomena. We focused our investigation on the jet breakup and the characteristics of the generated droplets, namely, size, trajectory, oscillation and rotation.

In the normal gravity case, two different regimes (dripping and jetting) were observed

at the considered flow rates in jets injected perpendicular to gravity. The variation of a normalized average breakup length with We was obtained. In the dripping regime the breakup length increases with We . This behaviour differs from what is found when the injection is parallel to gravity, in which the breakup length remains the same for any We . In the jetting regime the breakup length grows linearly with We . The breakup length is larger at the highest We value in the dripping regime than at the lowest We value in the jetting regime. This is a characteristic of the injection configuration perpendicular to gravity.

The analysis of jets in microgravity revealed that the injection of a liquid with $We > 3.2$ that gives rise to a jetting regime under normal gravity will give rise to a jetting or a chaotic regime in microgravity. Similarly, in the cases $We < 3.2$ in which a dripping regime was observed in normal gravity, a quasi-stable growth without breakup was obtained in weightlessness. The transition between dripping and jetting regimes occurs at $We_{cr} \approx 3.2$, a slightly lower value than the one predicted by theory. In the jetting regime the influence of gravity on the breakup length in the perpendicular configuration is negligible.

The analysis of the droplet size distribution in normal gravity showed droplets being significantly larger in the dripping regime than in the jetting regime. Size dispersion was larger in the jetting case, probably because some coalescences just after breakup were considered in the measurements in this regime. In the two levels of gravity considered, the droplet mean size decreases as the liquid flow rate is increased. In the jetting regime of the perpendicular configuration, droplet size did not show any significant dependence on the considered levels of gravity.

In normal gravity conditions, although droplets in the jetting regime of jets perpendicular to gravity follow an expected parabolic trajectory, collisions of droplets after jet breakup can deviate them to describe much longer paths. In microgravity, droplet trajectories form a conical shape due to droplet bouncing after collision. When a collision takes place, coalescence tends to occur at low modified Weber numbers ($We_m < 2$), while bouncing is observed at higher values ($We_m > 2$).

We observed the rotation of droplets around their center of mass when their surface oscillates following a damped oscillator model. The obtained oscillation frequency agrees with theoretical predictions.

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