



Drop impact into a deep pool: vortex shedding and jet formation

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One of the simplest splashing scenarios results from the impact of a single drop on a deep pool. The traditional understanding of this process is that the impact generates an axisymmetric sheet-like jet that later breaks up into secondary droplets. Recently it was shown that even this simplest of scenarios is more complicated than expected because multiple jets can be generated from a single impact event and there are transitions in the multiplicity of jets as the experimental parameters are varied. Here, we use experiments and numerical simulations of a single drop impacting on a deep pool to examine the transition from impacts that produce a single jet to those that produce two jets. Using high-speed X-ray imaging methods we show that vortex separation within the drop leads to the formation of a second jet long after the formation of the ejecta sheet. Using numerical simulations we develop a phase diagram for this transition and show that the capillary number is the most appropriate order parameter for the transition.

Key words: breakup/coalescence, drops, drops and bubbles

1. Introduction

Drop impact phenomena are omnipresent in nature and industrial applications. Despite well over a hundred years of study, many fundamental questions – regarding, for example, splash morphology, droplet size distribution, merger process of the drop and liquid substrate – remain unsettled (Yarin 2006; Deegan, Brunet & Eggers 2008).

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An ongoing renaissance of the subject driven by new experimental (Thoroddsen, Etoh & Takehara 2003; Xu, Zhang & Nagel 2005; Fezzaa & Wang 2008; Kolinski *et al.* 2012) and computational techniques (Oguz & Prosperetti 1989; Josserand & Zaleski 2003; Popinet 2003; Howison *et al.* 2005; Popinet 2009; Tryggvason, Scardovelli & Zaleski 2011) has revealed previously unsuspected effects and structures. One such structure is the ejecta sheet.

From Worthington's pioneering studies (Worthington 1882) onward, the standard picture of splashing from drop impact with a liquid layer consisted of the formation, growth and disintegration of a single sheet-like jet, herein called the lamella. However, Weiss & Yarin (1999), using inviscid irrotational numerical computations, found evidence of an earlier jet but did not follow its evolution through the entire lifetime of the splash, because of a very strong stretching of the Lagrangian frame they used. This jet was first observed experimentally by Thoroddsen (2002), who called it the ejecta sheet, although his experiments revealed that the ejecta sheet evolved into the leading edge of the lamella. More recent experiments showed that at high Reynolds numbers the ejecta and lamella are truly distinct jets, but coalesce into a single jet below a threshold in the Reynolds number (Zhang *et al.* 2012a). At even higher Reynolds numbers, multiple generations of ejecta sheets are possible (Zhang *et al.* 2012b). The dynamics of the ejecta sheet was also studied by Thoroddsen *et al.* (2011) and Thoraval *et al.* (2012), who reproduced numerically the complex evolution of the ejecta shapes.

Here, we report the results of our investigation of the bifurcation from one to two jets using experiments and numerical simulations. We report two different types of experiments. In the first set, the use of different fluids in the drop and the pool allows for the direct observation of the interface between the liquid in the pool and the drop. These experiments reveal that a second jet is formed by a vortex ring separating from the free surface and later resurfacing. In the second set, the fluid is the same in the drop and the pool. While the vortex is not experimentally observable in these experiments, the similar shape of the air-liquid interface in both the two-fluid experiments and the single-fluid experiments (compare figures 1g and 2e) strongly suggests that the same vortex shedding observed directly in the two-fluid system is also occurring in the single-fluid system. This is confirmed by our numerical simulations of the single-fluid system. We observe in simulations a vortex that either remains attached to the surface or separates from the surface depending on the system parameters. When the vortex remains attached, a single jet is produced; when it detaches, two jets are produced. While we were unable to identify the mechanism causing the transition, we find that the capillary number is the best order parameter for characterizing it.

2. Experiments

In the experiments of Zhang *et al.* (2012a,b) the impact of a drop onto a deep pool of the same liquid was studied using X-ray high-speed phase contrast imaging. These experiments showed the existence of two distinct sheet-like jets, each capable of producing secondary droplets, that at low Reynolds numbers merged into a single jet (see figure 1). The earlier emerging of these jets has the usual characteristics of a jet generated by the collision of fluid bodies. We call this jet the ejecta since it most resembles the ejecta sheet identified by Weiss & Yarin (1999) and Thoroddsen (2002). The later emerging jet begins curled up and unwinds with time, an evolution so patently different from that of the ejecta that it strongly hints at a different genesis.

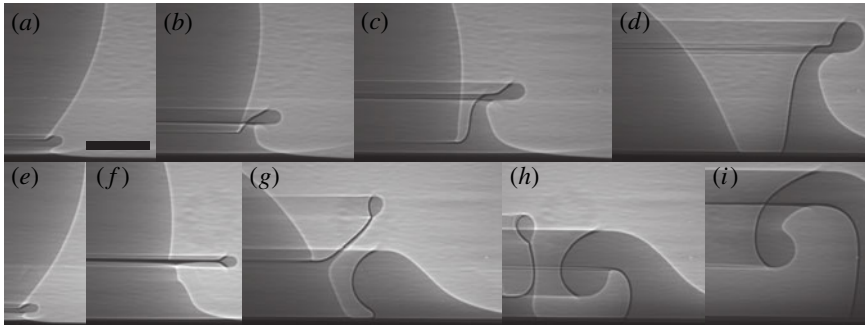


FIGURE 1. Phase contrast X-ray images showing the evolution of the lamella (*a–d*) at $We = 268$ and $Re = 1978$ and an ejecta sheet and roll jet (*e–i*) at $We = 292$ and $Re = 2042$. At later times (not shown), the tip of the roll jet overtakes the base, and the jet curves away from the centre, rather than as shown in (*g–i*), where it curves towards the centre. The scale bar corresponds to 0.25 mm. Time increases from left to right.

Here, we call this structure the roll jet. At low Reynolds numbers, only one jet is generated and it can be interpreted as a merger of the ejecta and the roll jet into a single jet. Here, we call this single jet the lamella because it most resembles the structure traditionally identified as the jet that produces a crown (or corona) splash (e.g. figure 1 of Zhang *et al.* (2010)).

Thoraval *et al.* (2012) showed that the base of the ejecta sheet can rise on the side of the drop, shedding vortices along the way. To investigate whether such a vortex is present in conditions similar to those where two jets form, we repeated the experiments described in Zhang *et al.* (2012*a*), except that the fluids in the pool and the drop were slightly different. The fluid in the drop was a silicone oil with density $\rho = 0.759 \text{ g cm}^{-3}$, viscosity $\mu = 0.49 \text{ cP}$ and surface tension $\sigma = 15.7 \text{ dyn cm}^{-1}$; the fluid in the pool was also a silicone oil with $\rho = 0.813 \text{ g cm}^{-3}$, $\mu = 0.82 \text{ cP}$ and $\sigma = 17.2 \text{ dyn cm}^{-1}$. These two fluids are miscible, and as such the interfacial tension between them is negligible. Since X-ray phase contrast imaging is sensitive to density gradients, these experiments reveal the evolution of the fluid–fluid interface between the drop and the pool. A typical sequence illustrating the formation of a rolled up vortex sheet, which we call a roll jet, is shown in figure 2 (see the supplementary movies available at <http://dx.doi.org/10.1017/jfm.2014.723> for a video of the same sequence). In figure 2(*a*), the presence of two vortices is shown inside the two bumps on the side of the drop. The first jet emerges (2*b*) at the location of the higher vortex. Despite its early emergence, its characteristically curled shape indicates that it is not an ejecta sheet, but rather a roll jet. The second vortex separates from the free surface and forms a second roll jet further from the centre (see 2*d–f*).

3. Numerical simulations

The similar morphology of the jets in the two-fluid system to that in the single-fluid system (drop and pool composed of same fluid) suggests that the same vortex dynamics is occurring in a single-fluid system. Since the motion of the drop–pool interface is invisible to the X-ray technique when the fluids are the same, we instead used numerical simulations. These reproduce with high fidelity all the features and evolution of the free surface observed experimentally. Moreover, the simulations provide data on the flow everywhere in the fluid and access a greater swath of the parameter space than is accessible experimentally.

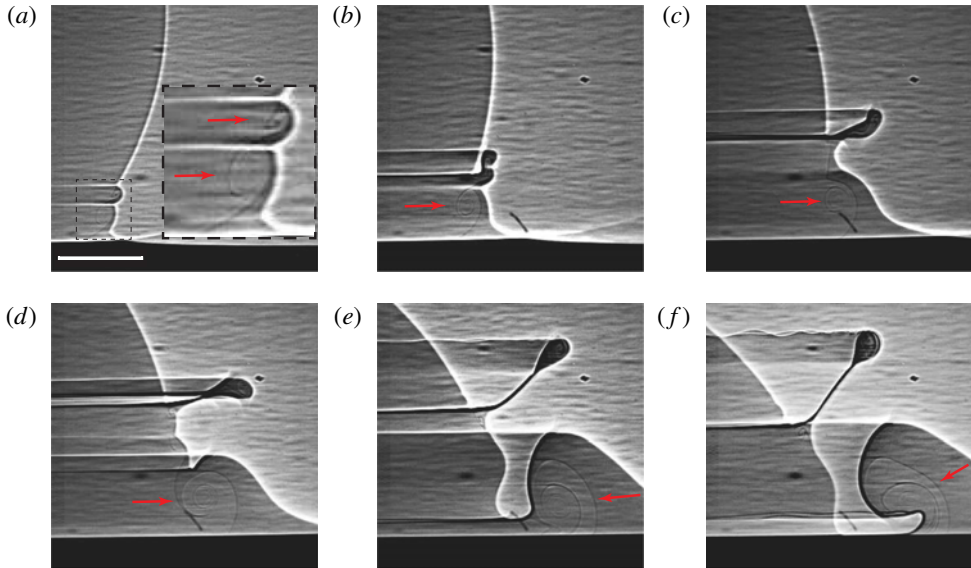


FIGURE 2. Phase contrast X-ray images showing the formation of two roll jets. A vortex forms on the interface near the nascent ejecta (*a,b*), separates (*c*) and reconnects with the interface to form the roll jet (*d–f*). The impact speed $U = 220 \text{ cm s}^{-1}$ and the drop diameter $D = 0.16 \text{ cm}$. The scale bar corresponds to 0.2 mm . The fluids in the pool and the drop were slightly different (see text). Since our technique is sensitive to density differences, the vortex is rendered visible by the contrast between the entwined fluids. The red arrows point to the centre of the vortex.

3.1. Numerical method

We simulate a gas–liquid system with respective densities ρ_g and ρ_l and viscosities μ_g and μ_l using the Navier–Stokes equations:

$$\rho(\partial_t \mathbf{u} + \mathbf{u} \cdot \nabla \mathbf{u}) = -\nabla p + \nabla \cdot (2\mu \mathbf{D}) + \gamma \kappa \delta_s \mathbf{n} + \rho g z, \quad (3.1)$$

$$\nabla \cdot \mathbf{u} = 0, \quad (3.2)$$

where \mathbf{u} is the fluid velocity, $\rho \equiv \rho(\mathbf{x}, t)$ is the density, $\mu \equiv \mu(\mathbf{x}, t)$ is the viscosity and \mathbf{D} is the deformation tensor. The Dirac distribution function δ_s expresses the fact that the surface tension term is concentrated at the interface, κ and \mathbf{n} being the curvature and the normal of the interface respectively. We use the Gerris code, a quad/octree-based multilevel solver described in detail in Popinet (2003). The interface is tracked by a volume-of-fluid method described in Popinet (2009) and Tryggvason *et al.* (2011). The accuracy of the code has been validated for a number of multiphase flow problems (Fuster *et al.* 2009; Popinet 2009; Agbaglah *et al.* 2011), including splashing (see e.g. Thoraval *et al.* 2012, 2013; Agbaglah & Deegan 2014).

3.2. Numerical simulations

We model a drop with diameter D and speed U falling vertically through an initially quiescent gas and impacting on a deep pool of the same liquid with depth $H = 5D$. The simulation is characterized by five dimensionless parameters: the viscosity and density ratios (μ_l/μ_g and ρ_l/ρ_g), the liquid Reynolds number $Re = \rho_l U D / \mu_l$, the

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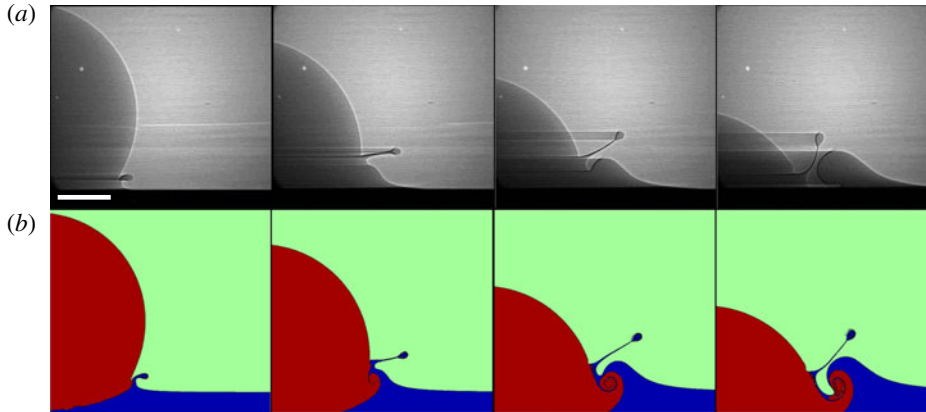


FIGURE 3. Comparison of X-ray phase contrast images from experiments (a) with simulation (b) for $We = 292$ and $Re = 2042$ at $\tilde{t} = tU/D = 0.161, 0.261, 0.46, 0.811$ (left to right). The experimental configuration and conditions are given in Zhang *et al.* (2012a) for the SO₃ fluid listed therein; the scale bar corresponds to 0.2 mm. The colours in the simulation indicate the fluid from the drop (red) and the pool (blue), and the ambient gas (green).

Weber number $We = \rho_l U^2 D / \sigma$ and the Froude number $U^2 / (gD)$. In our initial simulations we could discern no effect due to gravity, and thus it was omitted from subsequent simulations. We use the axisymmetric formulation of the Navier–Stokes equations to exploit the symmetry of the experimental features studied here. The computational domain is $5D \times 10D$ and is discretized with an adaptive mesh up to a maximum number 2^{14} of grid points along each dimension, corresponding to a minimum mesh size $\Delta x = D/3277$. The mesh is adapted based on four criteria: distance to the interface, curvature of the interface, vorticity and velocity magnitude.

Figure 3 compares simulation results with the equivalent experimental profiles obtained by high-speed X-ray imaging. The experimental profiles were obtained in the same data runs as reported in Zhang *et al.* (2012a). Briefly, the fluid was silicone oil with $D = 0.2$ cm, $\mu_l = 1.3$ cP, $\rho_l = 0.851$ g cm⁻³, $\sigma = 17.6$ dyne cm⁻¹ and $U = 156$ cm s⁻¹, incidence was normal to the pool, the surrounding gas was air, and the pool depth was 5 cm. The excellent agreement between the experiments and simulations demonstrates the accuracy with which our simulations capture the dynamics.

We ran simulations in the parameter range $Re \leq 5000$ and $We \leq 900$ with air as the surrounding gas ($\mu_g = 1.94 \times 10^{-2}$ cP and $\rho_g = 1.2 \times 10^{-3}$ g cm⁻³). We fixed $\rho_l / \rho_g = 709$, $U = 156$ cm s⁻¹ and $D = 0.2$ cm, and varied μ_l and σ to select Re and We . We observed the four distinct behaviours shown in figure 4. At high Re where two jets emerge, the simulation results in figure 4(c) show a vortex ring driving the growth of the roll jet. This vortex ring originates at the corner where the ejecta and the drop meet, it detaches from the free surface along the downward direction, travels horizontal below the pool level, and resurfaces to form the roll jet. Figure 5 illustrates the flow field around the vortex-shedding event and shows that after the vortex sheds all the fluid entering the ejecta comes from the pool.

Irrespective of Re , at early times there is always a large patch of vorticity near the point where the upper side of the jet and the drop meet. The large outward mean flow

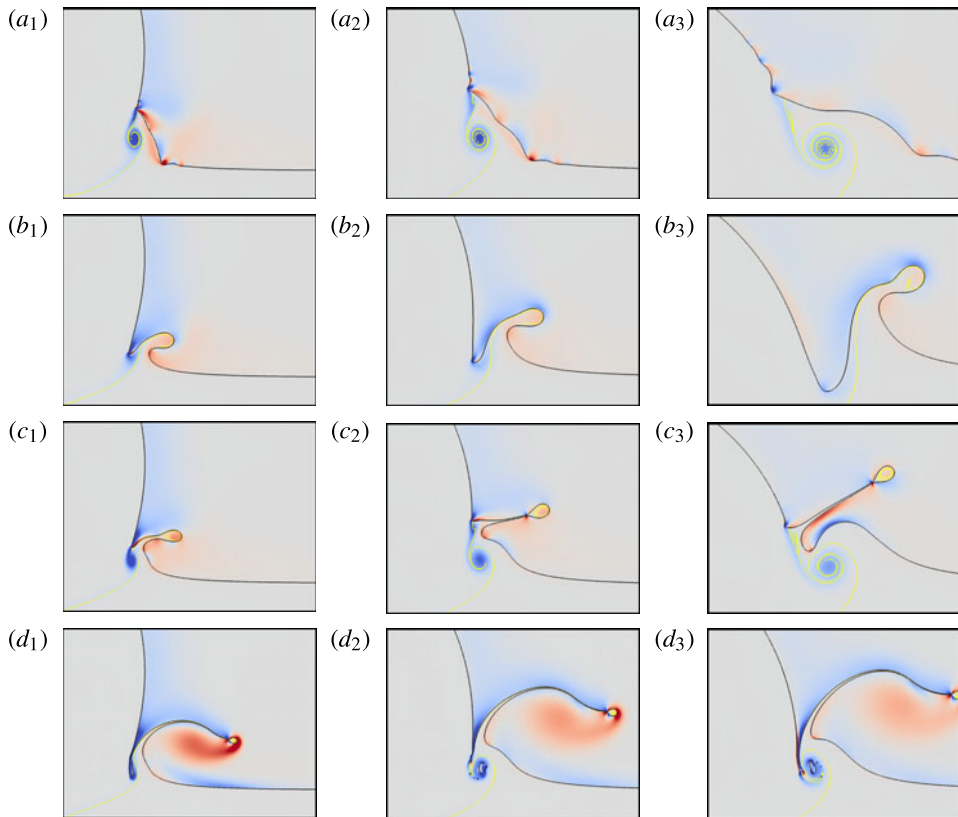


FIGURE 4. Qualitatively different flows observed in simulations: (a) vortex separation forming a roll jet without a preceding ejecta ($We = 100$, $Re = 2500$); (b) ejecta without vortex shedding leading to a lamella ($We = 292$, $Re = 1000$); (c) ejecta plus vortex separation leading to separate roll jet ($We = 292$, $Re = 2042$); (d) collision of the ejecta with the drop plus vortex shedding leading to a separate roll jet ($We = 700$, $Re = 3000$). The columns correspond to equal times $\tilde{t} = 0.211, 0.311, 0.511$ (from left to right) except for (d_3) which corresponds to $\tilde{t} = 0.372$. The colour indicates vorticity, with blue/red representing counterclockwise/clockwise rotation. The thin yellow line within the drop indicates the boundary between the fluid from the drop and the pool.

hides the fact that this vorticity patch is a vortex attached to the free surface (see, for example, figure 5). Below some critical Re (see figure 4b), we observe that the vortex ring remains attached to the interface at all times, becoming progressively larger but weaker, and eventually merges with the base of the ejecta to form the lamella. Thus, our simulations show that the transition from one jet (the lamella) to two jets (an ejecta and a roll jet) observed in experiments (Zhang *et al.* 2012a) is dictated by whether the vortex remains attached to the free surface.

At the highest Re and We in our range of study the ejecta reconnects with the drop surface, capturing a bubble. This process leads to air entrainment and vortex separation, as shown in figure 4(d), and is the same as the ‘bumping’ regime described in Thoraval *et al.* (2012). At high Re and low We we observe vortex shedding and the formation of a lamella but no ejecta.

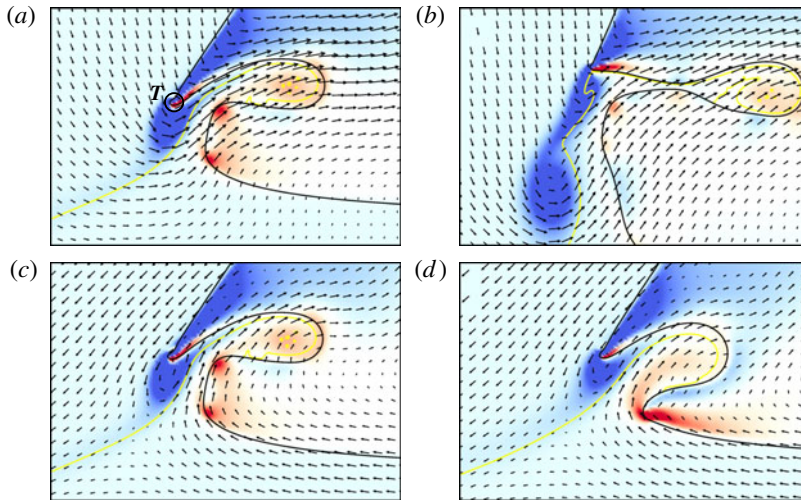


FIGURE 5. Flow field and vorticity at the base of the jet in the laboratory frame (*a,b*) and in the reference frame comoving with the point *T* (*c,d*). (*a–c*) Vortex-shedding splash at $We = 292$ and $Re = 3000$ for $\tilde{t} = 0.141$ (*a,c*) and $\tilde{t} = 0.236$ (*b*). Note that in (*b*) the liquid entering the jet originates almost exclusively from the pool. (*d*) Non-shedding splash at $We = 292$ and $Re = 1500$ for $\tilde{t} = 0.141$. The flow field of non-shedding splashes at other parameter values at all times looks similar to (*a*) in the laboratory frame or (*c* or *d*) in the comoving frame.

The parametric dependence of the four regimes depicted in figure 4 as found in simulations is given by the phase diagram in figure 6. Each simulation point in figure 6 took two weeks of computation on seven cores using the MPI library combined with dynamic load balancing as described in Agbaglah *et al.* (2011). For reference, the equivalent experimental observations from Zhang *et al.* (2012a) are also shown. The two datasets show strong agreement. The boundary between shedding and no shedding is reasonably captured by the relation $Re = 5We$, or equivalently $Ca \equiv \eta U / \sigma = 0.2$.

3.3. Characterizing the vortex shedding

In order to investigate the mechanism for vortex shedding, we measured various characteristics of the flow. Since the shedding event occurs in the vicinity where the jet emerges from the drop, our measurements focused on this zone and particularly on *T*, the point within this zone of maximum curvature of the air–liquid interface (see figure 5*a*). We found that there are no simple characteristics that herald a shedding event. For example, as shown in figure 7, the time dependence and magnitude of the curvature κ_T at *T* right up until the shedding event begins are indistinguishable from those of the non-shedding cases. In other words, we find no way to predict which configurations will shed a vortex. The same is true of the vorticity (see figure 8), the velocity (see the remark in the caption to figure 5), the local Reynolds number $Re_L = \rho_l u \kappa_T^{-1} / \mu_l$ (see figure 9*a*), where u is the maximum speed tangential to the interface around *T*, and the local Weber number $\rho_l u^2 \kappa_T^{-1} / \sigma$.

Nonetheless, the initiation of shedding is clearly signalled by the vorticity and the curvature. Figure 7(*b*) shows that a subset of the simulations exhibit a minima in the

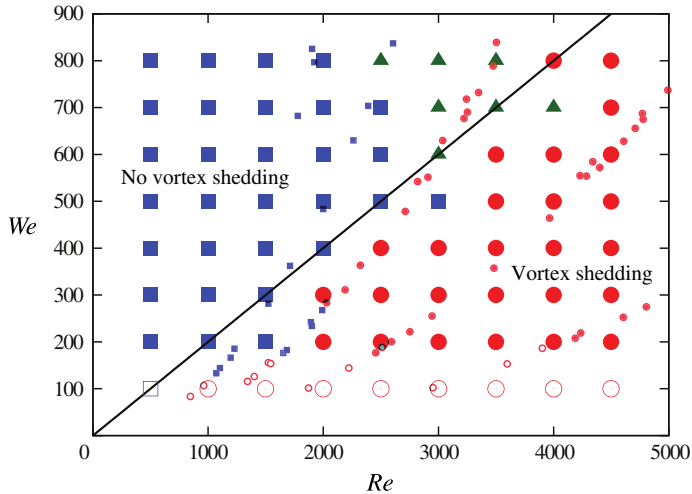


FIGURE 6. Phase diagram for vortex shedding. Simulations (shown with large symbols) that exhibit vortex shedding are represented with circles, no vortex shedding with squares and bumping with triangles. Filled symbols indicate the presence of ejecta while open symbols have no ejecta. The experimental results reported in Zhang *et al.* (2012a) are plotted with small symbols using the same convention as for the simulations; the bumping regime was not distinguished in these experiments. The solid dark line represents the approximate limit of the vorticity-shedding regime: $Ca = 0.2$.

curvature. All shedding cases exhibit such a minimum, and the minimum occurs prior to a visually discernible separation of the vortex. Thus, we take this minimum as a signal that the vortex separation process has started. Rescaling of the time by the visco-capillary time $t_{\mu\sigma} = \mu_l D / \sigma$ as in figure 7(b) shows that the initiation of shedding occurs at a remarkably uniform time $t \approx 1.05 t_{\mu\sigma}$. These results hint at the importance of the capillary number $Ca = \mu_l U / \sigma$, because $t_{\mu\sigma}$ in dimensionless units D/U is Ca . Indeed, the local capillary number $Ca_L = u \mu_l / \sigma$ for vortex-shedding splashes is lower at all times than for non-shedding splashes (see figure 9b). Moreover, taking the time averaging threshold value of Ca indicated in figure 9(b) yields a value of 0.2. Plotting this value on the phase diagram (figure 6) fairly accurately captures the transition. Therefore, our data indicate that an understanding of the interplay between viscous and capillary forces in the vicinity of T is the most important ingredient for understanding the transition between one and two jets.

4. Discussion and conclusion

We used experiments and numerical simulations to observe the transition from one jet to two jets in splashing from impact of a drop on a deep pool of the same liquid as a function of Re and We . We found that the mechanism driving this transition is the separation of a ring vortex from the air–liquid interface where the first jet emerges from the drop. The separated vortex eventually resurfaces and forms a second jet. The character of this second jet is quite distinct from that of the first jet. The first jet is formed through collision: two bodies of fluid collide and their linear momentum is focused into an outward-bound stream. In contrast, the second jet emerges tightly wound, uncoiling as it evolves, whipping the fluid at its tip outward.

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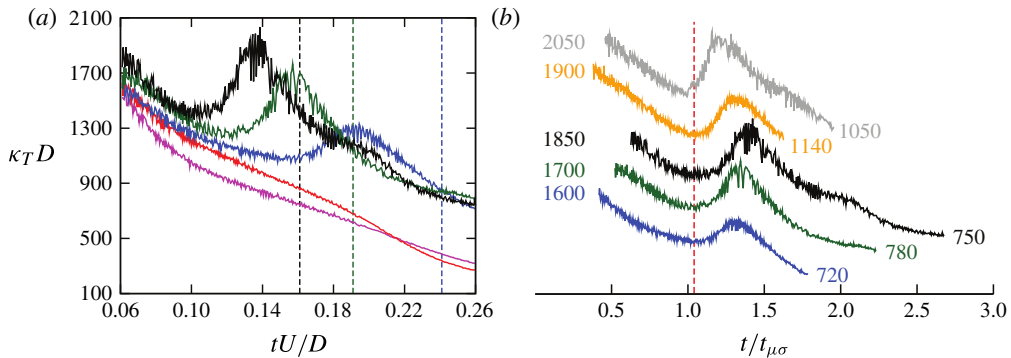


FIGURE 7. (a) Mean curvature at T versus time for $We = 300$ and $Re = 1000$ (magenta), 1500 (red), 2000 (blue), 2500 (dark green) and 3000 (black). The vertical dashed lines indicate the time of the vortex separation chosen by eye when the material line defined by the pool–drop interface exhibits strong swirling such as in figure 4(c_2). The peak in the data indicates vortex shedding; conversely, its absence indicates that the vortex remains attached to the interface. (b) Mean curvature at T with time in units of the visco-capillary time ($t_{\mu\sigma} = \mu_l D/\sigma$) for $We = 300$ and $Re = 2000$ (blue), 2500 (dark green), 3000 (black); $We = 400$ and $Re = 2500$ (orange), 3000 (dark grey). The curves have been vertically shifted in order to avoid overlapping and clearly show the positions of the minima; their starting and ending values are listed with the same colour as the data.

In our experiments we focused on a deep pool because a shallower pool introduces another parameter, the depth, and the additional complexity that entails (Yarin & Weiss 1995; Cossali, Coghe & Marengo 1997; Wang & Chen 2000; Rioboo *et al.* 2003). Nonetheless, the limited depth-wise penetration of the flow observed in simulations (see figure 4) suggests that depths as shallow as D are sufficient for the manifestation of two jets. The observation of vortex shedding at the pool–drop interface (Castrejón-Pita, Castrejón-Pita & Hutchings 2012) for $\tilde{t} < 1$ and in shallower pool depths (Thoraval *et al.* 2013) suggests that similar phenomena may occur in yet shallower depths at high Re .

Our simulations show that the transition is best characterized by the capillary number. Nonetheless, the separation process sufficiently resembles separation from a free surface observed in other configurations to warrant investigation of whether the criteria established in these other flows can be usefully applied to splashing. Batchelor (1967) argues on general grounds that separation can only occur at large curvatures. This qualitative statement was examined recently by Moore *et al.* (2014), who looked at the high- Re perturbations to steady two-dimension Helmholtz flows relevant for the flow in the jet root of Wagner’s theory for droplet impact (Howison *et al.* 2005). They showed in this situation that vortex shedding is possible only if the Re_L is of order unity. This is consistent with figure 9(a), although unsteady effects could play a role here. Figure 7 shows that the curvatures of shedding and non-shedding splashes are comparable, and furthermore the curvature at the instant of shedding is always lower than the values at early times in non-shedding splashes. Hence, the curvature by itself cannot be the sole criterion for shedding.

Leal (1989) investigated separation from a bubble and found that separation occurs when the surface vorticity reaches a critical value and Re is large. As with the curvature, we observe higher surface vorticities in non-shedding splashes than we do

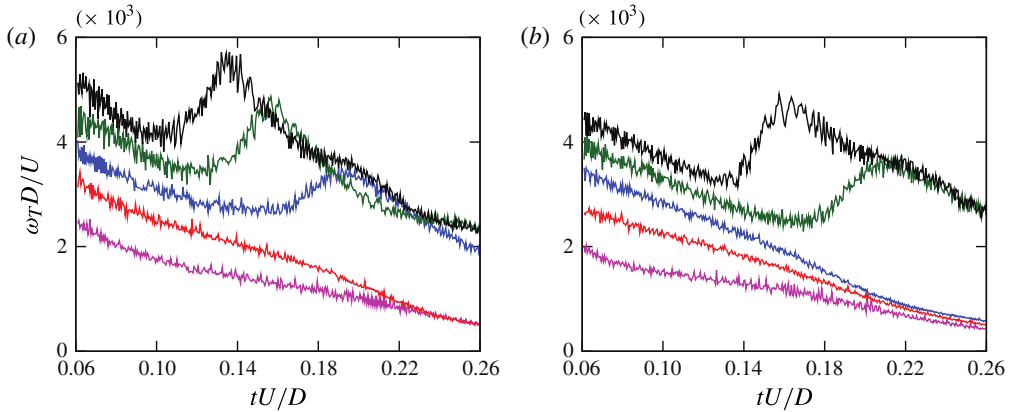


FIGURE 8. Maximum absolute value of the vorticity ω_T on the interface near T (equivalent to the deepest blue in figure 5) for (a) $We = 300$ and (b) $We = 400$ at $Re = 1000$ (magenta), 1500 (red), 2000 (blue), 2500 (green), 3000 (black).

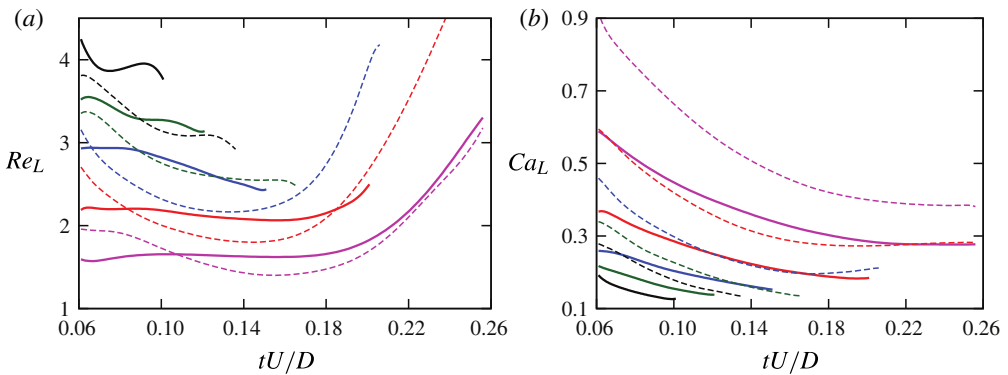


FIGURE 9. (a) Local Reynolds number Re_L and (b) local capillary number Ca_L around T for $We = 300$ (solid) and $We = 400$ (dashed), and $Re = 1000$ (magenta), 1500 (red), 2000 (blue), 2500 (dark green) and 3000 (black).

at the instant of separation in shedding splashes. Hence, surface vorticity is not a good criterion for vortex shedding in drop impact.

Finally, we note that the flow at T resembles the classic problem of a jet plunging into a pool. In the latter, the jet drags the interface downward and for sufficiently fast flows can cause opposing sides of the interface to meet, pinch off and entrain bubbles. The transition to air entrainment is known to be governed by the local capillary number at low viscosities (Kiger & Duncan 2012). The similar kinematics and the same dependence on the capillary number suggest that the physics of the plunging jet may be fruitfully applied to the jet problem considered here.

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Supplementary movies

Supplementary movies are available at <http://dx.doi.org/10.1017/jfm.2014.723>.

References

- AGBAGLAH, G. & DEEGAN, R. D. 2014 Growth and instability of the liquid rim in the crown splash regime. *J. Fluid Mech.* **752**, 485–496.
- AGBAGLAH, G., DELAUX, S., FUSTER, D., HOEPFFNER, J., JOSSERAND, C., POPINET, S., RAY, P., SCARDOVELLI, R. & ZALESKI, S. 2011 Parallel simulation of multiphase flows using octree adaptivity and the volume-of-fluid method. *C. R. Méc.* **339**, 194–207.
- BATCHELOR, G. K. 1967 *An Introduction to Fluid Dynamics*. Cambridge University Press.
- CASTREJÓN-PITA, A., CASTREJÓN-PITA, J. & HUTCHINGS, I. 2012 Experimental observation of von Kármán vortices during drop impact. *Phys. Rev. E* **86**, 045301.
- COSSALI, G. E., COGHE, A. & MARENGO, M. 1997 Impact of a single drop on a wetted solid surface. *Exp. Fluids* **22** (6), 463–472.
- DEEGAN, R. D., BRUNET, P. & EGGERS, J. 2008 Complexities of splashing. *Nonlinearity* **21** (1), C1–C11.
- FEZZAA, K. & WANG, Y. J. 2008 Ultrafast x-ray phase-contrast imaging of the initial coalescence phase of two water droplets. *Phys. Rev. Lett.* **100** (10), 104501.
- FUSTER, D., AGBAGLAH, G., JOSSERAND, C., POPINET, S. & ZALESKI, S. 2009 Numerical simulation of droplets, bubbles and waves: state of the art. *Fluid Dyn. Res.* **41** (6), 065001.
- HOWISON, S. D., OCKENDON, J. R., OLIVER, J. M., PURVIS, R. & SMITH, F. T. 2005 Droplet impact on a thin fluid layer. *J. Fluid Mech.* **542**, 1–23.
- JOSSERAND, C. & ZALESKI, S. 2003 Droplet splashing on a thin liquid film. *Phys. Fluids* **15** (6), 1650–1657.
- KIGER, K. T. & DUNCAN, J. H. 2012 Air-entrainment mechanisms in plunging jets and breaking waves. *Annu. Rev. Fluid Mech.* **44**, 563–596.
- KOLINSKI, J. M., RUBINSTEIN, S. M., MANDRE, S., BRENNER, M. P., WEITZ, D. A. & MAHADEVAN, L. 2012 Skating on a film of air: drops impacting on a surface. *Phys. Rev. Lett.* **108**, 074503.
- LEAL, L. G. 1989 Vorticity transport and wake structure for bluff bodies at finite Reynolds number. *Phys. Fluids* **A1**, 124–131.
- MOORE, M. R., OCKENDON, H., OCKENDON, J. R. & OLIVER, J. M. 2014 Capillary and viscous perturbations to Helmholtz flows. *J. Fluid Mech.* **742**, R1. doi:10.1017/jfm.2014.39.
- OGUZ, H. N. & PROSPERETTI, A. 1989 Surface-tension effects in the contact of liquid surfaces. *J. Fluid Mech.* **203**, 149–171.
- POPINET, S. 2003 Gerris: a tree-based adaptive solver for the incompressible Euler equations in complex geometries. *J. Comput. Phys.* **190** (2), 572–600.
- POPINET, S. 2009 An accurate adaptive solver for surface-tension-driven interfacial flows. *J. Comput. Phys.* **228** (16), 5838–5866.
- RIOBOO, R., BAUTHIER, C., CONTI, J., VOUE, M. & DE CONINCK, J. 2003 Experimental investigation of splash and crown formation during single drop impact on wetted surfaces. *Exp. Fluids* **35** (6), 648–652.
- THORAVAL, M.-J., TAKEHARA, K., ETOH, T. G., POPINET, S., RAY, P., JOSSERAND, C., ZALESKI, S. & THORODDSSEN, S. T. 2012 von Karman vortex street within an impacting drop. *Phys. Rev. Lett.* **108** (26), 264506.
- THORAVAL, M.-J., TAKEHARA, K., ETOH, T. G. & THORODDSSEN, S. T. 2013 Drop impact entrapment of bubble rings. *J. Fluid Mech.* **724**, 234–258.
- THORODDSSEN, S. T. 2002 The ejecta sheet generated by the impact of a drop. *J. Fluid Mech.* **451**, 373–381.

- THORODDSEN, S. T., ETOH, T. G. & TAKEHARA, K. 2003 Air entrapment under an impacting drop. *J. Fluid Mech.* **478**, 125–134.
- THORODDSEN, S. T., THORAVAL, M. J., TAKEHARA, K. & ETOH, T. G. 2011 Droplet splashing by a slingshot mechanism. *Phys. Rev. Lett.* **106** (3), 034501.
- TRYGGVASON, G., SCARDOVELLI, R. & ZALESKI, S. 2011 *Direct Numerical Simulations of Gas–Liquid Multiphase Flows*. Cambridge University Press.
- WANG, A. B. & CHEN, C. C. 2000 Splashing impact of a single drop onto very thin liquid films. *Phys. Fluids* **12** (9), 2155–2158.
- WEISS, D. A. & YARIN, A. L. 1999 Single drop impact onto liquid films: neck distortion, jetting, tiny bubble entrainment, and crown formation. *J. Fluid Mech.* **385**, 229–254.
- WORTHINGTON, A. M. 1882 On impact with a liquid surface. *Proc. Phys. Soc. Lond.* **34**, 217–230.
- XU, L., ZHANG, W. W. & NAGEL, S. R. 2005 Drop splashing on a dry smooth surface. *Phys. Rev. Lett.* **94**, 184505.
- YARIN, A. L. 2006 Drop impact dynamics: splashing, spreading, receding, bouncing. *Annu. Rev. Fluid Mech.* **38**, 159–192.
- YARIN, A. L. & WEISS, D. A. 1995 Impact of drops on solid-surfaces—self-similar capillary waves, and splashing as a new-type of kinematic discontinuity. *J. Fluid Mech.* **283**, 141–173.
- ZHANG, L. V., BRUNET, P., EGGERS, J. & DEEGAN, R. D. 2010 Wavelength selection in the crown splash. *Phys. Fluids* **22** (12), 122105.
- ZHANG, L. V., TOOLE, J., FEZZAA, K. & DEEGAN, R. D. 2012a Evolution of the ejecta sheet from the impact of a drop with a deep pool. *J. Fluid Mech.* **690**, 5–15.
- ZHANG, L. V., TOOLE, J., FEZZAA, K. & DEEGAN, R. D. 2012b Splashing from drop impact into a deep pool: multiplicity of jets and the failure of conventional scaling. *J. Fluid Mech.* **703**, 402–413.