Effects of Fluid Viscosity on Drop-on-Demand Ink-Jet Break-Off

Stephen D. Hoath*, Graham D. Martin and Ian M. Hutchings; University of Cambridge, Department of Engineering, Institute for Manufacturing, Alan Reece Building, 17 Charles Babbage Road, Cambridge CB3 0FS, UK

Abstract

Simulations of the jetting of Newtonian fluids from drop-on-demand print heads show that the radial jet pinch-off region, which may lie inside the nozzle, is strongly affected by the fluid viscosity over the range of values that are commonly used. Jet profiles beyond the nozzle exit predicted in these simulations match previously published high resolution images very well and validate the code used. The simulations show that the radial velocity at the minimum radius in the pinch-off region falls exponentially soon after neck formation but then approaches a speed near that predicted theoretically for filament rupture.

The overall jet length is primarily controlled by the slow speed of radial pinch-off. Towards the final break-off time, competition between the original radial minimum and a developing second radial minimum can alter the flow conditions towards symmetry. The simulations also explain why visible jets are shaped like truncated cones. Pinch-off occurs typically within one nozzle radius of the nozzle exit, and while it may be located within the nozzle region, another radial minimum also forms outside the nozzle, close to the exit for low viscosity fluids but well beyond it for higher viscosity fluid. The radial collapse follows a power law with time, with the power-law index n varying between the value of n=2/3 expected for an inviscid fluid and n=1 law expected for a viscous fluid. The transition in behavior occurs at a viscosity of ~20 mPa s, which is within the range of ~10–40 mPa s typical of most DoD inks formulations.

Introduction

This paper discusses the processes involved in the thinning of the ligaments of Newtonian liquids formed in drop-on-demand (DoD) ink-jet printing, just before and including the final pinch-off. In particular the roles of the viscosity η and surface tension σ are examined. Through the pressure associated with the free surface curvature, the surface tension provides the key driver for the rupture of the liquid ligament. Viscous forces, on the other hand, dissipate energy and so mitigate the action of the surface tension. The ratio (σ/η) has the dimensions of a speed, with a magnitude of ~ 0.5–5.0 m/s for typical DoD inks, being lower for higher viscosity fluids. The ratio (σ/η) should therefore be very relevant to fluid motion, and in particular to the dynamics of the rupture of thin fluid filaments such as those ejected from the printhead in DoD printing, since these deliver liquid drops at speeds which are similar to the ratio (σ/η). Break-off times are related to the ratio (η/σ).

A numerical model for the simulation of free-surface fluid motion associated with flow from continuous inkjet (CIJ) and DoD nozzles have been developed by Harlen and Morrison [1,2] as part of a recently-completed project [3]. The model assumes axisymmetric jetting of either Newtonian or viscoelastic fluids from short nozzles with a simplified geometry based on real commercial inkjet print heads, and its predictions generally match the experimental observations well. The model has also been applied to other nozzle shapes including long cones and cylinders in studies of fluid properties such as dynamic surface tension, as reported elsewhere in this conference [4].

Predictions from this model for viscous Newtonian fluids in DoD mode are shown in Figure 1 and shed light on an important aspect of the experimental observations shown in Figure 2 [5]. At the time of detachment from the nozzle, the ink jet typically has a conical rather than a cylindrical shape, and is so wide at the nozzle exit that naïve extrapolation of the jet shape back into the nozzle suggests that the detachment point (i.e. the apex of the cone) should lie a long distance behind the nozzle inlet. This seems physically unrealistic, and thus poses problems of interpretation.

The model predictions shown in Figure 1 indicate the presence of an ‘inner’ pinch-off region, which forms (asymmetrically) between the fluid meniscus inside the nozzle (to the left hand side of the diagram) and the ‘outer’ region (outside the nozzle, to the right hand side). As the inner portion of the ligament shrinks radially, there is almost no disturbance of the meniscus or the outer portion of the jet. It is possible that this collapse within the nozzle may result in a cascade of threads of diminishing diameter [6]. The small size, less than the nozzle radius, of this ‘inner’ pinch-off region allows the jet to break off within the nozzle depth while retaining an ‘outer’ waist radius of ~ 3 μm as found experimentally and shown in Figure 2 [5].

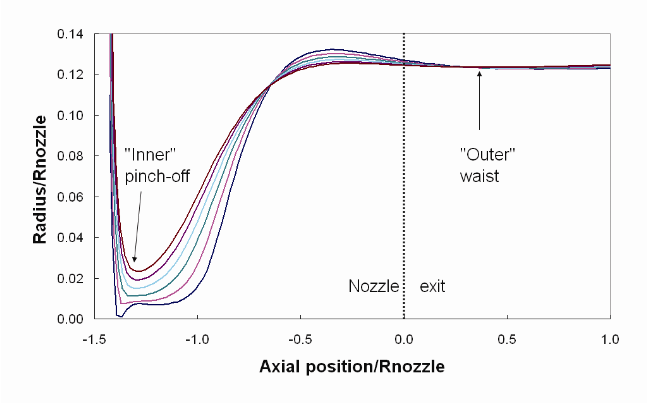

***Figure 1**: Simulation results at different short times before final break-off, for the fluid ligament within and close to the nozzle, for fluid with a viscosity of 0.01 Pa s and surface tension 0.025 N/m² producing ~6 m/s drops. Profiles, scaled by the nozzle radius (Rnozzle = 25 μm), are shown magnified in the radial direction by factor of ~10. The nozzle exit is shown by the dotted vertical line while the nozzle inlet would lie at an axial position of -2.0. The predicted conical shape of the ligament extending to the right is not visible.*

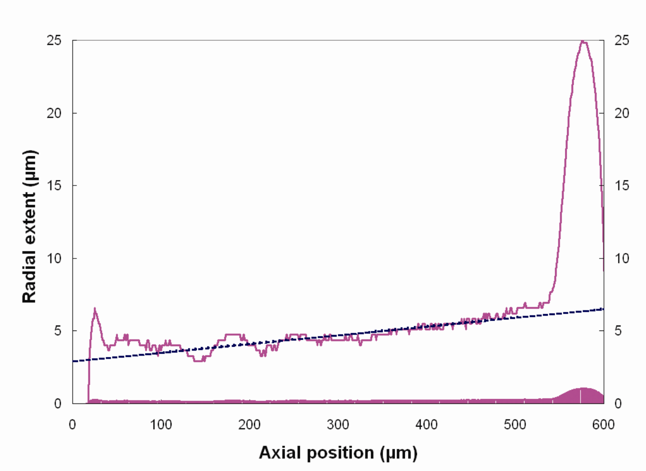

***Figure 2**: Radial profile along a jet of fluid with viscosity 0.01 Pa s (with 6 m/s final drop velocity) just after it has detached from the nozzle [5]. The upper trace is magnified to show the detail and the conical shape of the ligament. The zero of axial position corresponds to the location of the nozzle exit (radius 25 μm). Extrapolation along the broken line suggests that break-off occurs ~500 μm (~20 x nozzle radius) behind the nozzle. The ligament has a radius ~3 μm (~0.12 x nozzle radius) near the break-off point.*

There is also value in comparing the numerical results for the collapse of DoD jets with theoretical predictions [e.g. 7-10] and observations [11] for the radial pinch-off of ligaments in filament stretching tests, since this behavior is often compared with the collapse of a DoD inkjet, although it occurs at a slower rate. Examples of this method are presented by Vadillo et al. [11], and are proving increasingly useful for viscoelastic fluid characterization. A thread of fluid is stretched rapidly between two pistons ~1 mm in diameter, and then shrinks radially (symmetrically) exhibiting minimum width at its mid-point. However, subsequent fluid motion may not be symmetric and final pinch-off may occur at one or both ends.

During the final stages of ligament thinning, where radial distance scales are no longer related to the boundary conditions e.g. the radius of the piston, nozzle or jet head, Eggers has argued [7] that viscous fluid motion must exhibit a universal, self-similar behavior. His results imply that the ligament radius r at the 'inner' pinch-off varies as a power law τ^n, with $\tau = t_b - t$, the remaining time before break-off, and $n = 1$. The pinching speed V is given by:

$$V = - \mathrm{d}r/\mathrm{d}t = 0.0304\ (\sigma/\eta) \qquad (1)$$

The predicted shape of the ligament profile, near the pinch-off, is asymmetric, rather like that seen in CIJ or in break-off from a massive fluid body. Equation (1) is derived from the length scale determined from the viscous length $l_v = (\eta^2/\sigma\rho)$ and the time scale determined from the viscous time $t_v = (\eta^3/\sigma^2\rho)$ where ρ is the fluid density [7]. For typical DoD inks the length and time scales are ~ 4 to 40 µm and ~ 2 to 40 µs respectively, while the radial collapse speed from equation (1) is ~ 0.025-0.075 m/s, much less than the axial speed of ~ 6 m/s.

Another theory for ligament pinch-off has been proposed by Papageorgiou [8], for 1-D Stokes flow, which produces a symmetrical ligament profile and a faster but still linear ($n = 1$) radial thinning speed:

$$V = 0.0709\ (\sigma/\eta) \qquad (2)$$

This result may be more relevant for the rupture in the mid-region of the ligament, with equation (1) being more applicable to the asymmetric collapse close to the meniscus or head of the ligament.

Radial necking during the constant extension of a Newtonian fluid filament has a linear dependence on elapsed time t [9]

$$r = r_0 - (1/6)\times(\sigma/\eta)\ t \qquad (3)$$

Differentiation of equation (4) gives stretching filament necking at

$$V = 0.1667\ (\sigma/\eta) \qquad (4)$$

Equations (3) and (4) imply finite break-off times and pinching speeds of ~ 40-160 µs and ~ 0.1-0.4 m/s for typical DoD fluid jets.

Inviscid fluid flow, which may be relevant when the length scale is not too small, has been studied by Day, Hinch and Lister [10]. The radial (or axial) distance involved scales as $\tau^{2/3}(\sigma/\rho)^{1/3}$. In this case the radius r does not fall linearly with elapsed time t, as predicted by equations (1-3), but follows a power law with $n = 2/3$. The pinch-off speed V rises very rapidly just before the break-off:

$$V = (2/3)\times(\sigma/\rho)^{1/3}\ \tau^{-1/3} \qquad (5)$$

Figure 3 shows predictions for the minimum radius and the radial pinching speed for the fluid that was profiled in Figure 1. Stretching filament speed equation (4) does not apply to inkjets. The simulation speed results show an initial exponential decay that appears to limit near to "Eggers" value, equation (1), for a significant period before rising to exceed the "Papageorgiou" value, equation (2), immediately prior to a final, unseen, pinch-off. The Speed-Equation (1) curve slope was found to be linear in fluid ratio (σ/η); this dependence is just like that of equations (1) and (2): so the break-off time scale essentially scales with (η/σ). Simulated dynamics of DoD pinch-off are only similar, rather than identical, to the dynamics for filament stretching theories [7-10].

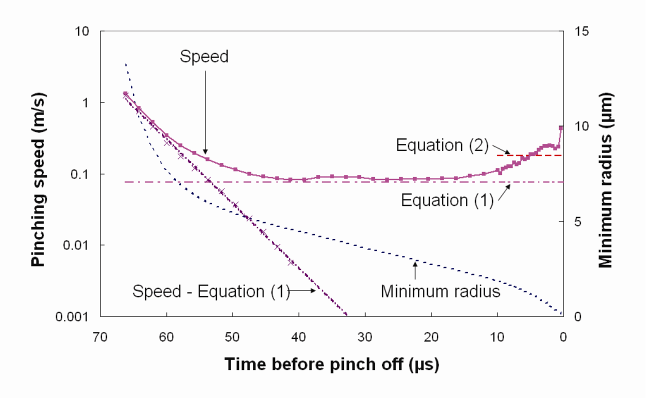

***Figure 3**: Results for radial pinching speed and minimum radius of the "inner" region extracted from the computational model as a function of the deduced time before pinch off. The nozzle (radius 25 μm) was driven to produce ~ 6 m/s drops of fluid with η = 0.01 Pa s and σ = 0.025 N/m. Various limits are shown.*

Computational modeling of ligament pinch-off

We have used the computational model developed by Harlen and Morrison [1,2] to study the effect of fluid viscosity on the pinch-off of thin jets for typical drop-on-demand printing conditions. Theories for radial collapse that ignore the viscosity of the surrounding air will eventually fail when the ligament becomes extremely thin because the interaction between the air and the liquid then becomes significant. The 'Eggers' regime [7] must therefore then give way to the behavior expected for a viscous thread within a viscous fluid [12]. However in the present work we justify modeling the jet collapse with no external fluid, because the final behavior at which air viscosity would be important occurs below the minimum scale for the computational grid, and on timescales that are negligibly small.

The model allows a choice of ligament radius below which the fluid bodies are assumed to become separated, and will thereby slightly underestimate the true break-off time. However, the choice of this critical radius makes negligible difference to the predicted final drop volumes and speeds.

We have characterized the predictions of fluid ligament collapse in terms of a power law variation of minimum radius with time, for which, as discussed above, we would expect $n = 2/3$ for inviscid behavior and $n = 1$ for viscous behavior. Figure 4 shows a transition in the pinching behavior near a viscosity of ~0.020 Pa s (~ 20 cP), which is within the range typical of DoD inkjet fluids.

As shown above, the simulations also predict the 'outer' jet profile, which is accessible to observation and measurement. Interesting predictions include the minimum radial width (or waist) of the 'outer' profile near the break-off time and, although the break-off location shows some dependence on the assumed critical radius, the axial location of this 'outer' waist. We investigated the effects of viscosity on the 'outer' region as the ligament radius moves towards the 'inner' scales. Figures 5 and 6 both show that viscosity would be expected to have a marked effect for DoD inkjets, especially for fluids with viscosities above ~ 0.016 Pa s.

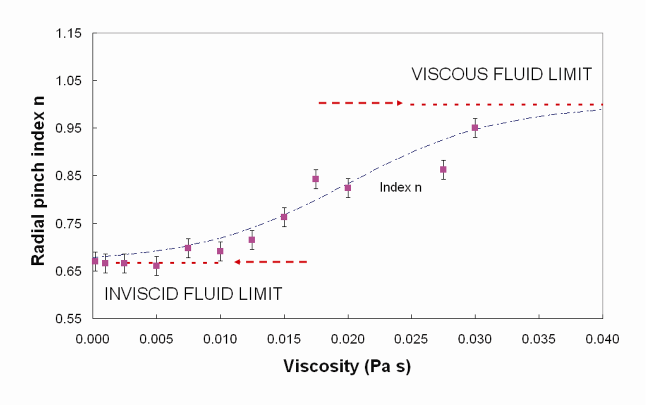

***Figure 4**: Power law index n deduced from the DoD simulation for fluids with Newtonian viscosity between 0.001 and 0.030 Pa s (0-30 cP). Simulated fluid had the surface tension of 0.025 N/m^2 although the power law index n results were quite similar for other realistic choices of surface tension values. These simulations were for a 50 μm diameter DoD nozzle driven for drops at ~ 6 m/s. The "inner" fluid behavior changes from inviscid limit n=2/3 towards viscous limit n = 1 as the viscosity is increased through a transition value η ~ 0.02 Pa s. Dashed curve "Index n" is shown merely as a smooth guide over the transition.*

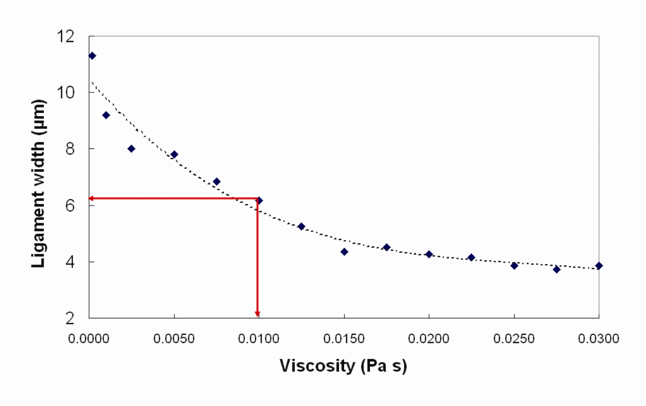

***Figure 5**: Predictions of the minimum width of the 'outer' ligament at the time when the jet detaches (i.e. at the 'inner' break-off time) for a final drop speed of ~ 6 m/s. The prediction matches accurately the observed value derived from Figure 2 [5] as indicated by the solid lines.*

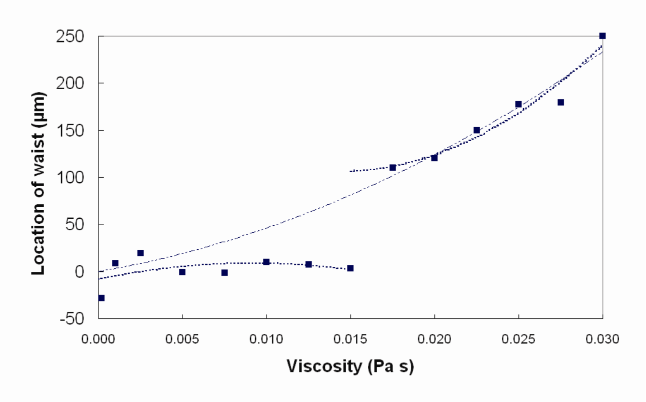

***Figure 6**: Predictions of the axial location of the waist for the conditions used for Figure 5. There is a marked shift in the location of the waist for viscosities above ~0.016 Pa s. Lower viscosities give a waist close to the nozzle exit, while for higher viscosities the waist is shifted downstream from the exit.*

Discussion

The good agreement between the radial pinching speed magnitudes and trends in the power law index n with viscosity in the simulation and the simple models, together with the experimental validation of the 'outer' waist size as predicted by the simulation, provide confidence in the simulation method.

In practice the location of jet pinch-off may be influenced by the printhead drive waveform and the nozzle firing rate and the resulting meniscus position and shape, quite apart from variations in these produced by changes to the fluid due to its external environment. In the present simulations we assumed the same drive waveform for all values of viscosity, altering its amplitude only to achieve a final drop speed of ~ 6 m/s.

The location of the 'inner' collapse point is found to shift quite rapidly in the axial direction in these simulations, especially in the final stages where multiple necks form as seen in the formation of falling water droplets from an outlet [6]. This, and other work [11], implies that the break-off of DoD jets may also depend rather strongly on viscosity and not conform to models which predict stable pinching locations, such as those discussed above [7–10].

The early stage pinching predicted for Newtonian fluids does not follow the linear theoretical predictions [e.g. 9] for a constantly stretching filament where elasticity is absent. Even when the strain is modified to reflect the measured variation of the inkjet tip speed, the range of pinching speeds predicted is only a factor of 2-3 rather than the factor of > ~10, as seen in Figure 3 before the 'plateau'. This might be taken in support of the divorce between 'inner' and 'outer' regions due to independent radial pinching relationships.

Studies of filament stretching of viscoelastic fluids [13] suggest that the viscosity will also become important for DoD jetting of such non-Newtonian liquids. Here, we have restricted our attention to Newtonian fluids, without the added complication of the viscoelasticity which is present in most real DoD inks.

Conclusions

There appears to be a transition between inviscid and viscous behavior, which influences the location at which DoD jets break-off from the nozzle. Ligaments formed from viscous inks may rupture far from the nozzle exit, with adverse consequences for the reliability of the printing process. The transition in behavior occurs at a viscosity of ~0.020 Pa s, which is within the range of ~0.010–0.040 Pa s typical of most DoD inks formulations.

Simulations show similarity between DoD break-off and ligament rupture in filament stretching experiments, although they are not identical.

The timescale of DoD break-off is controlled by the ratio (η/σ) in both the early and main stages of radial collapse. The simulation results explain the observed ligament width and the location of an 'outer' waist for solvent fluids at the break-off time. This waist is close to the nozzle exit, and relatively wide, for lower viscosity fluids, whereas it moves away and systematically becomes thinner for higher viscosity fluids.

The simulation model developed by Harlen and Morrison [1,2] has proved to be successful in predicting several key observations and will be used more extensively in future.

Acknowledgements

This work was supported by the UK Engineering and Physical Sciences Research Council. We thank Oliver Harlen and Neil Morrison for development of the simulation code used, John Hinch for insightful comments on the 'outer' shape, and Damien Vadillo for comments on viscoelastic fluid stretching experiments.

References

[1] Harlen, O., N. Morrison, et al. (2009). Jet break-up of polymeric fluids in inkjet printing (presentation). Institute for Mathematics and its Applications Annual Program Year Workshop on Flowing Complex Fluids: Fluid Mechanics-Interaction of Microstructure and Flow. University of Minnesota;

[2] Morrison, N.F. and O.G. Harlen, (2010), "Viscoelasticity in Inkjet Printing", Rheologica Acta **49**(6), 619-632

[3] http://www.ifm.eng.cam.ac.uk/pp/inkjet/NextGenInkTec.html

[4] Hoath, S.D., W-K. Hsiao, et al (2010), 26th Int. Conf on Non-impact printing NIP26, Austin, TX, Society for Imaging Science and Technology, Austin, Texas, September 2010 , Volume 26, p….. "Continuous Ink-Jet Diameters and The Velocity Profile Across The Nozzle Exit"

[5] Hutchings, I. M., G. D. Martin, et al. (2007). "High speed imaging and analysis of jet and drop formation." Journal of Imaging Science and Technology **51**(5): 438-444.

[6] Shi, X.D., M.P. Brenner and S.R. Nagel (1994), Science **265**, 219-222, "A Cascade of Structure in a Drop Falling from a Faucet"

[7] Eggers, J. (1993). "Universal Pinching of 3d Axisymmetrical Free-Surface Flow", Physical Review Letters **71**(21): 3458-3460.

[8] Papageorgiou, D. T. (1995). "On the Breakup of Viscous-Liquid Threads", Physics of Fluids **7**(7): 1529-1544.

[9] Entov, V.M. and E.J. Hinch (1997) Journal of Non-Newtonian Fluid Mechanics **72**, 31 "Effect of a spectrum of relaxation times on the capillary thinning of a filament of elastic liquid"

[10] Day, R. F., E. J. Hinch, et al. (1998). "Self-similar capillary pinchoff of an inviscid fluid", Physical Review Letters **80**(4): 704-707

[11] Vadillo, D. C., T. R. Tuladhar, et al. (2010). "Evaluation of ink jet fluids performance using the "Cambridge Trimaster" filament stretch and break-up device", Journal of Rheology **54**(2), 261-282

[12] Lister, J.R. and H.A. Stone (1998), "Capillary break up of a viscous thread surrounded by another viscous fluid", Physics of Fluids **10**(11), 2758-2764

[13] Vadillo, D., private communication.

Author Biography

Stephen Hoath received his BA in physics (1972) and then his DPhil in nuclear physics (1977) from the University of Oxford, UK. Lecturer in Physics at the University of Birmingham, UK (1979), he then worked for BOC Edwards High Vacuum (1986) and smaller companies(1997, 2001) before joining the University of Cambridge, UK, Inkjet Research Centre (2005). His inkjet work has focused on jetting. An IS&T and IOP member, he is a Teaching Associate at Gonville & Caius College, Cambridge, UK.