Dynamics of Jetted Liquid Filaments

Pascal Pierron[1], Sandrine Allaman[1] and Arthur Soucemarianadin[2]*
[1]ARDEJE, Valence, France
[2]Université Joseph Fourier, Grenoble, France

Abstract

The formation of liquid filaments is a topic of great interest because of its frequent occurrence in a wide variety of engineering applications such as coating, spraying and ink-jet printing technologies. Given the rapid evolution of the latter technology and the ever-increasing demand for enhanced resolution, good to excellent printer performances under different operating conditions are deemed necessary. The required performances could be in terms of drop sizes, optical density, color gamut and uniformity and so on. It is well known that critical issues in print quality are imperfections related to the manufacturing of print heads, the uneven spreading of ink on the print media and certainly above all the ability of the inks to be ejected from the print-heads and the evolution in time of the jetted liquid filaments. This last topic is the one which is considered in detail in this paper.

More and more markets are opening towards drop on demand ink-jet printing, ranging from the packaging industry to printing on electronic components. At the same time, there is need to cut down drastically the costs related to numerous and time consuming experiments. For this purpose, we have developed an automated print quality optimization apparatus, which allows us to follow the drop from the exit of the nozzle to drop impact. This device will be briefly discussed and used to follow the full ejection process and to detail the drop formation from pinch-off to the recoiling with eventual secondary break-up.

In this paper, we also focus on the design of the electronic control of jetting by means of a specific wave form generator for ink-jet print-heads. This computer controlled device has a versatile architecture and can be used to drive different print-heads. It proved to be invaluable notably in generating different forms of satellite drops with a given print-head.

Finally, the different measurements which have been performed using the above two devices allow to better quantify the various non-linear hydrodynamic phenomena for the free surface flow under consideration. We show that the framework of dynamic singularities which has been largely used elsewhere to construct similarity solutions for hydrodynamic problems can prove to be helpful in the analysis of the pinch-off phenomenon in DOD ink-jet printing.

Introduction

Liquid drop formation is a topic of interest in many engineering applications. Indeed, technologies for producing streams of small more or less uniformly sized droplets have been developed for a number of applications such as aerosol calibration standards,[1,2] spray and combustion studies[3-6] and ink-jet printing.[7-10] Different ways may be envisaged in order to analyze the formation of drops.

On one hand, there exists a large body of literature[11-17] on what happens when liquid drips from a faucet. Indeed, as it falls, the physical quantities describing the liquid filament become discontinuous in a finite time which are then amenable to self-similarity solutions. On the other hand, experimental evidence and industrial practice show that the behavior of a jetted filament is very similar in nature to that of a dripping drop. We will examine in this paper how close these two situations are.

For doing this, we will rely on the results obtained using quite heavily the waveform generator and the print quality optimization apparatus. The former device helps to drive commercially available print-heads with a large spectrum in terms of signal waveforms, thus it possible to form drops with and without satellites. The latter one is indispensable in measuring many of the characteristics of the print-head as well as the transient ones of the filament. The phase-locking system embedded in the print quality optimization apparatus helps to use the pseudo-cinematography technique and to follow versus time the various types of non-linear effects. Our work differs in at least the following aspects from others usually found in the literature on drop formation in DOD print-heads:

1. We provide results on the continuous evolution of the free surface from nozzle exit to filament pinch-off. Other works are essentially limited to the measurement of global parameters such as break-up lengths or drop sizes.
2. We pinpoint here some of the interactions which develop and lead to drop pinch-off with slow or fast satellites in the case of multiple drop sized technology.
3. We analyze the different results within the framework of dynamic singularities and we show its ability to predict the thinning dynamics of the radius as well as the time of pinch-off under different

experimental conditions. These results are reported for the first time.

Experimental

In this section, we present the waveform generator, the print quality optimization apparatus and two different drop forming devices. The drop forming devices have been chosen such as to have very different working frequencies and very different pinch-off times so as to show that the analysis which is performed is independent of the drop forming capabilities of the print-head.

Waveform Generator

The design of this electronic system allows to drive some of the commercially available piezoelectric ink jet with a large spectrum in terms of signal waveforms. As described in detail elsewhere18, the system includes a PC running under Windows tm environment, a specific power supply, an electronic rack and the analog outputs for the print-head (Figure 1).

The power supply delivers two voltages, +240V DC and –50V DC for a positive shape, +50V DC and –200V DC for a negative one. This device is able to produce a signal having any shape either positive between -30V and +200V or negative between +30V and –200V. The power amplifier component has the capability to deliver an high amperage current for each piezoelectric element (2A max).

The waveform is defined by the user using a specific proprietary software. A practical problem which is solved here in the fabrication of the waveform are the excellent characteristics in terms of slew rate, amplitude of the signal, dwell or holding time. These characteristics are especially useful for creating main drops and satellites of different forms. The results obtained are to be compared with those mentioned on drop size modulation in office printers.19,20

Print Quality Optimization Apparatus

There is need in identifying and rejecting correctly heads or inks having printing problems. The required performances[21] for the print-heads could be in terms of drop sizes, for the inks in terms of optical density, color gamut and uniformity and so on. It is well known in the existing literature that critical issues in print quality are the coalescence of ink on the print media[22,23] and/or imperfections related to the manufacturing of print heads.[24] The overall expected performance[25] is to precisely determine the relationships between ink and print head, and ink and print media. In the same time, the range of possible markets for drop on demand ink-jet printing is growing with applications in a number of areas. The fluids used are very different from one another and the challenge is to define a precise link between print quality and the entire drop ejection and impact process.

For this purpose, we have developed an automated print quality optimization apparatus,[26] which allows us to follow the drop from the exit of the nozzle to drop impact. This system has a comprehensive set of built-in electronics, optical and mechanical hardware which allows taking very high magnification computer controlled photographs at different times and at different locations. Figure 1 shows a global view of the print quality optimization apparatus fitted with one commercially available print-head and the picture on the screen represents the drop ejection process in DOD printing as seen on the video display unit.

To perform a control of the entire head, the first requirement is to precisely move the print head from one nozzle to another in front of the static image acquisition system. This requires a very high precision mechanical support for the head. Microstep motors combined with encoders have been chosen. The motion control is possible using the software.

Depending on the configuration, the print quality optimization apparatus uses one, two or three CCD cameras. Standard speed (25 images/sec) and enhanced speed (larger than 300 images/sec) cameras are available with a frame grabber. For the time being only standard speed images have been examined. The frame grabber acquires images with adjustable magnification, according to the target object.

The electronic stroboscopic illumination control includes two types of illumination sources, laser diode and high luminosity LED. The laser diode allows longer distance of work between the object and the illumination source, and furthermore, for shadowgraphy images a higher power diffused light. Our electronic device allows us to deliver regularly spaced flashes of 100 ns. The apparatus is also capable of providing pseudo-cinematography movies of the entire drop formation. This is specially useful for rheological and instability studies.[26]

Drop Ejection Devices

In this sub-section, we describe briefly the two drop forming devices which have been used in our experiments. The first one is the single nozzle (printhead #1) Lee Micro-Dispense Valve [tm] based on a moving solenoid with an operating frequency of upto 1,200 Hz and working pressures of 700 mbars. The jetting velocity depends on the inlet pressure and could be varied. The nozzle diameter in our application is 75 µm. The response time of the device is of the order of 0.25 ms.

The second drop generating device is a multi-nozzle Spectra [tm] (printhead #2) designed for a wide range of industrial and commercial printing applications. It operates under back pressure to frequencies of upto 24 kHz and temperatures of 90°C. The head is fitted with a nozzle plate having 256 orifices with a radius of about 32 µm. A high voltage fire pulse with controlled slew rates is necessary to actuate the piezoelectric transducer for each channel. Both drop forming devices are controlled accurately using the waveform generator which has been described above.

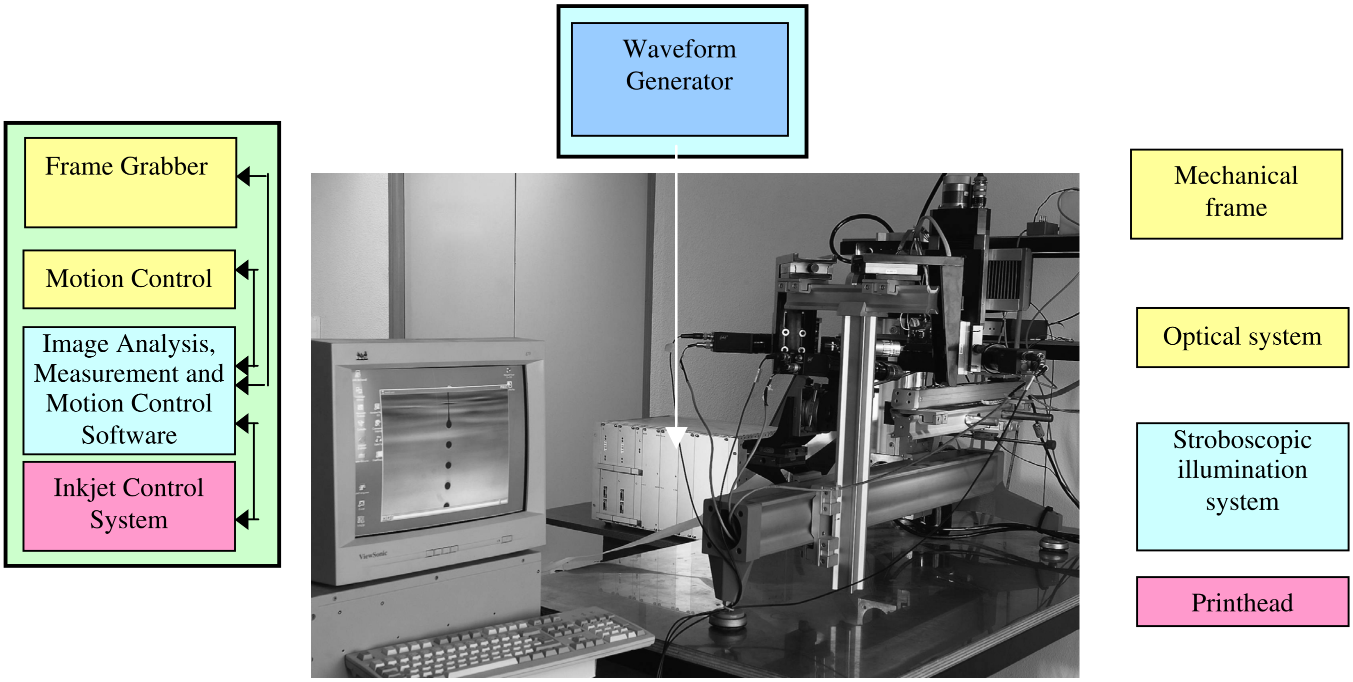

Figure 1. Print Quality Optimization Apparatus and Waveform Generator

Results and Discussion

This section is focused on the analysis of the jetting process for the above described drop forming devices. It is essential to recall here that because of the very different physical processes involved in the ejection of the drop for the two devices, the time scales involved cover several orders of magnitude.

Drop Formation

The entire history of drop deformation[13] is illustrated in figure 2 for a drop ejection from a Spectra printhead working at a frequency of 10 kHz. It shows the variation of the dimensionless drop elongation with time measured backward with To being the time at the instant of drop pinch-off. It is interesting to note that the behavior is similar to that of a drop dripping from a faucet. Indeed in the first stages of drop formation, the changes are slow say from about 100 to 10 µs before drop pinch-off and very suddenly everything accelerates leading to drastic changes in the final form of the drop.

The feature which is considered in general for a rupturing drop within the framework of dynamic singularities is the evolution of the minimum fluid thickness Hmin versus time. We represent that variable below in figure 3 in the case of a typical drop formation process with printhead #2. The arrows indicate the location of minimum neck thickness. We can notice that there are typically three zones for the evolution of the fluid neck. The first one extends from the beginning to about 10 µs, the second one from thereafter upto 40 µs and the final zone covers the pinch-off régime. The fluid filament happens to stay almost cylindrical during all the thinning process as shown on the photographs which are inserted on the figure.

Further information on the drop formation behavior can be gained by plotting Hmin versus To-t where To is the pinch-off time as shown in figure 4. This representation has the advantage of emphasizing the power law behaviors. We can thus notice that there is at least three zones with very different slopes ranging from 0.34 to 0.15 and passing through a plateau where the minimum neck thickness does not change much. This is discrepancy to the overall behavior which can be observed when a Newtonian fluid detaches as a drop from a capillary. This may be an effect of the important initial velocity of ejection as found in the DOD process.

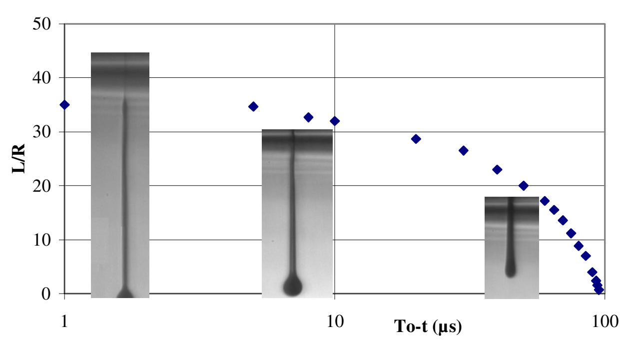

Figure 2. Transient evolution of the dimensionless length of drops

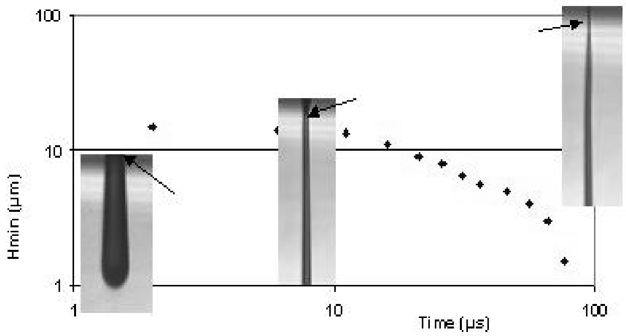

Figure 3. Evolution in time of the minimum neck thickness

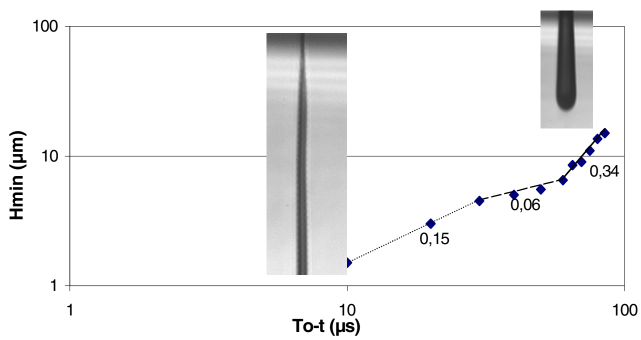

Figure 4. Power law behavior of the minimum neck thickness

Drop Pinch-Off

Inviscid pinch-off has been considered recently16 to study both the ejection of an ink drop and its possible breakage during flight. Using dimensional analysis and assuming that the initial conditions are not important near pinch-off the above authors suggest the possible variation of the radius versus time.

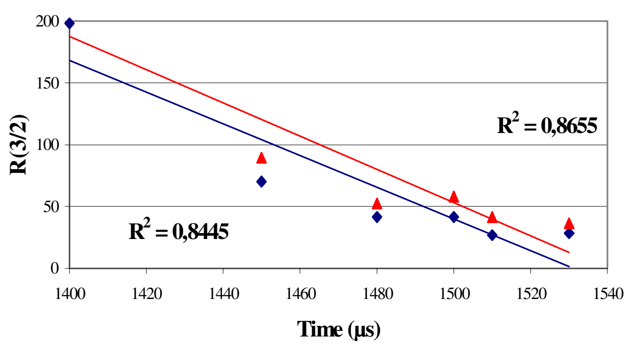

Figure 5. Evolution of the radius near pinch-off for print-head #1

We follow that analysis closely and we plot the variation of R3/2 against actual time t for two distinct points during the formation and pinch-off of a drop in the case of print-head #1 working at frequency of several hundred hertz. We chose to follow the evolution of the radius at two different given locations from the nozzle exit instead of the minimum neck thickness because of the geometry of the print-head which prevents taking measurements close to nozzle exit. Figure 5 shows that the data are consistent. The coefficient of correlation obtained for the straight line is of the order of 0.85 which is fair. Moreover the intersection of the straight line with the horizontal axis predicts quite accurately the experimental pinch-off time.

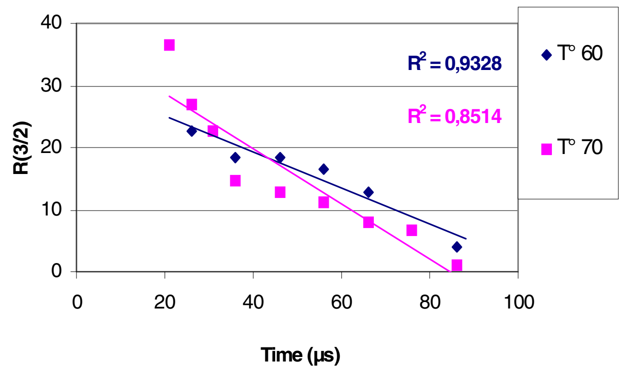

Figure 6. Evolution of the minimum neck thickness versus time near pinch-off for print-head #2

We have done the same analysis for print-head #2, working at a frequency of 10 kHz, plotting this time the evolution of Hmin raised to power 3/2 against actual time. The results are shown in figure 6. Once again the data are consistent especially in the case of the lowest temperature where the viscosity is higher. In the case of the highest temperature, the correlation is only fair and this may be attributed to the lower accuracy in the measurements. Further work is ongoing to compare quantitatively DOD pinch-off and drop break-up occurring in continuous ink-jets.[27]

Conclusion

In this paper, we have first presented specific tools for initiating drop formation with different print-heads and for following closely the topological changes of the free surface. The measurements have been performed from the exit of the fluid from the nozzle upto drop pinch-off both from a spatial and a temporal point of view with resolutions close respectively to micrometers and microseconds.

We have then performed an analysis of the non-linear dynamics within the framework of dynamic singularities where we show that the DOD pinch-off process is very much akin to that found for a drop dripping from a capillary. Another remarkable feature, is that the results do not seem to depend on the initial conditions. Indeed, we have been able to demonstrate the validity of the analysis, for print-heads which work on different principles and at different time scales. This gives confidence to extend this analysis further, say, to thermal inkjet print-heads

Some of the work presently carried on is focused on the following items and will be reported in the near future:

- Effects during pinch-off related to the characteristics of the fluid (viscosity, density) and of the print-head (frequency, velocity of the jetted filament).
- Evolution versus time of the jetted filament ongoing contraction under the action of surface tension forces.

References

1. R.N. Berglund and B.Y.H. Liu, *Environ. Sci. Technol.,* **7**, 147 (1973).
2. J.L. Dressler and G.O. Kraemer, Standard Technical Publication 1083*, American Society of Testing Materials,* 30 (1990).
3. R.B. Peterson, *Rev. Sci. Instrum*., **59**, 960 (1988).
4. G.J. Green, F. Takahashi, D.E. Walsh, and F.L. Dryer, *Rev. Sci. Instrum*., **60**, 646 (1989).
5. J.D. Dressler, *Proc. of the Vth International Conf. On Liquid Atomization and Spray Systems*, 397 (1991).
6. G. Chen and A. Gomez, *Proc. XXIVth International Symposium on Combustion*, 1531 (1992).
7. W.G. Cross and L. Cheng., *Rev. Sci. Instrum*., **46**, 263 (1975).
8. H.C. Lee, *IBM J. Res. Dev.* **18**, 364 (1974).
9. W.T. Pimbley and H.C. Lee, *IBM J. Res. Dev.* **21**, 21 (1977).
10. P.A. Torpey, *Phys Fluids A*, **1**, 661 (1989).
11. D.H. Peregrine et al*., J. Fluid Mech*. **212**, 25 (1990).
12. X.D Shi et al., *Science*, **265**, 219, (1994).
13. X. Zhang and O.A. Basaran, *Phys. Fluids*, **7**, No. 6, (1995).
14. J. Eggers, *Rev. Mod. Phys*., **69**, 865 (1997).
15. M.P. Brenner et al., *Phys. Fluids* **9**, 1573, (1997).
16. R.F. Day et al., *Phys. Rev. Letters*, **80**, 704, (1998).
17. B. Ambravaneswaran et al., *Phys. Rev. Letters*, **85**, 5332, (2000).
18. P. Pierron et al*, Proc. IS&T, NIP 16*, 56, (2000).
19. T. Mimura and S. Sakai, *Proc. IS&T, DPP2001*, 230, (2001).
20. S. Korol and C. Greb*, Proc. IS&T, NIP 16*, 61, (2000).
21. Lars Janson, *Printer Technologies*, 199, (1987).
22. Nathan Jones et al., *Proc. IS&T, NIP 14*, 161, (1998).
23. Ming-Kai Tse and Alice H. Klein, *Proc. IS&T, NIP 14*, 167, (1998).
24. David J. Forrest et al., *Proc. IS&T, NIP 14*, 590. (1998).
25. Peter A. Torpey, *Proc. IS&T, NIP 10*, 464, (1994).
26. P. Pierron and C. Schlemer*, Proc. IS&T, DPP2001*, 203, (2001).
27. B. Lopez et al., *Proc. IS&T, NIP 16*, 50, (2000).

Acknowledgments

The authors extend their appreciation to the **EEC** for partially funding this work through a project grant. Moreover Arthur Soucemarianadin is especially grateful to **EGIDE** (Ministère des Affaires Etrangères et Ministère de l'Education Nationale, de la Recherche et de la Technologie) for making available a funding through the PROCOPE program.

Biographies

Pascal Pierron is project leader at Ardeje a company highly specialized in the electronic and computer architecture of non impact printing processes. He is responsible for the analysis of drop on demand printing processes.

Sandrine Allaman is R&D engineer at Ardeje working on drop formation and impact.

Arthur Soucemarianadin is Professor at the University Joseph Fourier in Grenoble, France. He is a member of various international scientific societies and European Editor of the Journal of Imaging Science and Technology. E-mail: souce@ujf-grenoble.fr