Transient Phenomena During Drop Formation In DOD Printing

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Abstract

Given the rapid evolution of ink jet technology and the ever-increasing demand for enhanced resolution, excellent printer performances under different industrial operating conditions are deemed necessary. The performance of an ink jet printer depends not only on the head assembly, but also on the coupling between the ink rheological behavior and the waveform signal applied to produce the droplet. In order to better follow and understand the phenomenon of filament pinch-off we have developed different techniques which are detailed here.

In this paper, we will first focus on the dynamics of filament break-up. The development of finite time singularities i.e. the evolution versus time of quantities such as the minimum radius of the filament is given. It is also shown here that the thinning of the neck during droplet snap off displays behaviors which are quite different depending on the inks used. These new results complement some of our earlier measurements of the drop formation phenomenon.

The other results reported in the paper concern the transient contraction of the filament being swallowed in the drop following break-off. This is the first time that such short lived filaments are captured and examined in detail. These results shed more light on the interaction between the fluid and the flow particularly when different waveform signals are used.

Finally, we show that the framework of dynamic singularities which can be used 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. Indeed, they allow to better quantify under the form of scaling laws the various non-linear hydrodynamic phenomena from drop snap off to filament retraction and give a unified picture of the drop formation phenomenon.

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] In these various areas, different ways may be envisaged in order to form and analyze the occurrence 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 from a print-head is similar in nature to that of a dripping drop. We will examine in this paper how close these two situations are taking into account different types of drop ejection devices and different fluids.

For doing this, we will rely on the results obtained using the waveform generator and the print quality optimization apparatus. The former device is computer controlled device one with a versatile architecture and can be used to drive different print-heads. It helps to drive commercially available print-heads with a large spectrum in terms of signal waveforms, thus it is possible to form drops with and without satellites.

The latter device is indispensable in measuring many of the characteristics of the print-head as well as the transient ones of the filament. Indeed 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. It allows i.e. to characterize the performance of print-heads 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. 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. This enables to optimize the ability of the inks to be ejected from the print-heads and the evolution in time of the jetted liquid filaments forming main and satellite drops. This last topic is the one which is considered in detail in this paper.

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 consider different types of jetting devices and provide data on drop formation which enable to compare them on the same basis.
3. We test fluids largely different in terms of viscosities and show the effects in terms of drop formation.
4. 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.
5. 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. We also give the characteristics of the fluids used in this study. They differ mainly through their viscosities.

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 elsewhere[18], 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 using this specific waveform generator compare favorably 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 which may present 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 apparatus26, 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 high precision mechanical support for the head. Microstep motors combined with encoders have been chosen. The motion control is possible using the embedded 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 silhouette imaging a higher power diffused light. Our electronic device allows us to deliver regularly spaced flashes of 100 ns. We have noticed that an appropriate illumination type is around 300 ns. This allows to capture images which do not present too much blur. The apparatus is also capable of providing pseudo-cinematography movies of the entire drop formation thanks to the fact that the phase locking is accurately controlled by computer. This is specially useful for rheological and instability studies.[26]

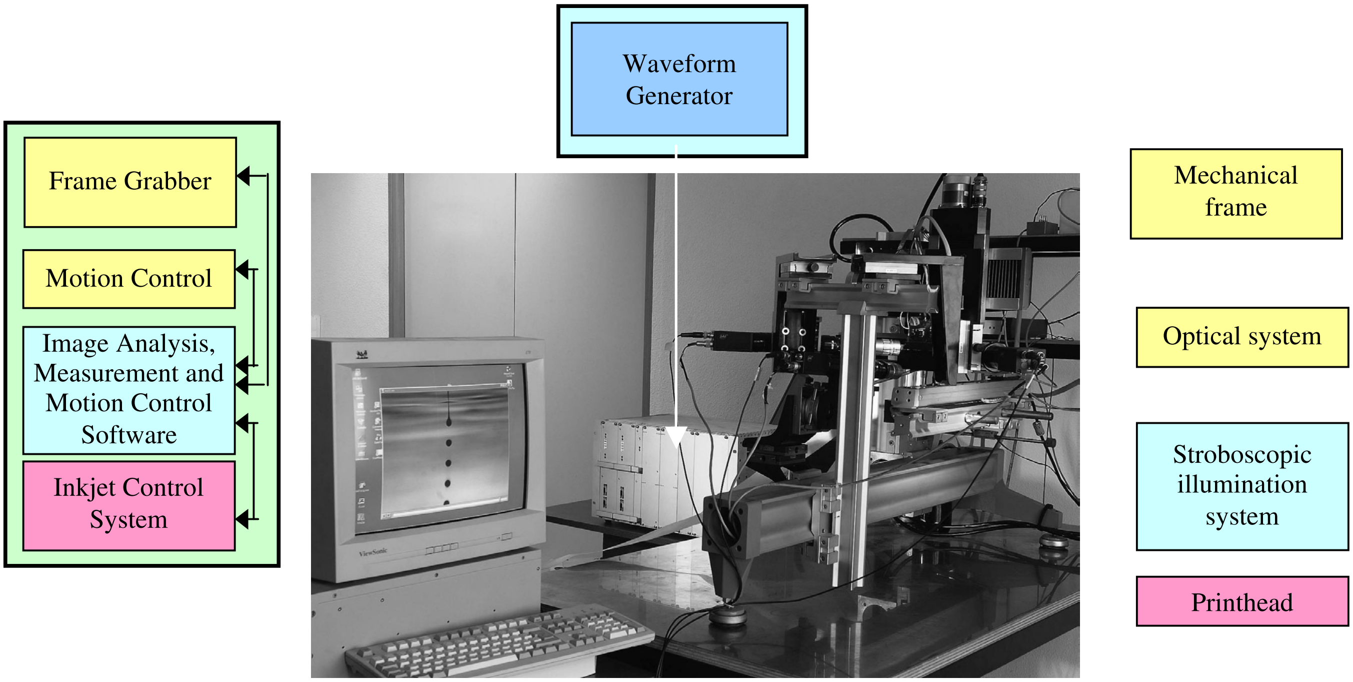

Figure 1. Print Quality Optimization Apparatus and Waveform Generator

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 a multi-nozzle IJT^{tm} (printhead #1) designed for a wide range of industrial and commercial printing applications. This printhead is designed on a shear mode technology and comprises 64 nozzles with dimensions of 60*60 µm. Built-in heating elements allow to work at a maximum temperature of 40°C. A high voltage fire pulse with controlled slew rates is necessary to actuate the piezoelectric transducer for each channel which may operate at a maximum frequency of 6 kHz using the waveform generator which has been described above.

The second drop generating device is a multi-nozzle Xaar^{tm} (printhead #2) designed on the shared wall mode It operates under back pressure to frequencies of upto 8 kHz. There are different types of Xaar^{tm} printheads, the one we have used comprises 128 orifices with a radius of about 32 µm. The firing voltage is lower than for the former IJT device (about 35 Volts) and this printhead only functions at ambient temperature. Specific electronic equipment has been built for the accurate control of this printhead and is detailed elsewhere.[27]

Results and Discussion

This section is focused on the analysis of the jetting process for the above described drop forming devices. The experimental observations and analysis procedures have been designed to obtain both qualitative and quantitative information on the transient shapes of the ejection of the liquid filament which then forms a drop. It is essential to recall here that because of the very different physical processes involved in the ejection of the filament and the retraction into a drop, the time scales which are involved in these processes cover several orders of magnitude.

Filament Ejection

Once the drop ejection device is primed in order to remove all air from the chamber, it is usually advisable to start working with fluids which wet the surface in order to get rid of the very small bubbles which may still remain caught in the small capillaries.

We show in figure 2 the latest stages of the process of filament ejection and drop formation for a given ink. Once the pressure pulse is initiated on the generator the filament ejection process takes about 200 µs to be completed for this specific case The first picture shows the thinning of the filament 15 µs before ejection from the nozzle which is the second photograph and the third one corresponds to the retraction stage shows the thickening of the filament 15 µs after the ejection has taken place. The sequence shows that the drop formation takes place without a satellite drop. These low resolution pictures not only allow a rapid qualitative evaluation of drop formation but are also helpful for calculating an average velocity of the drop.

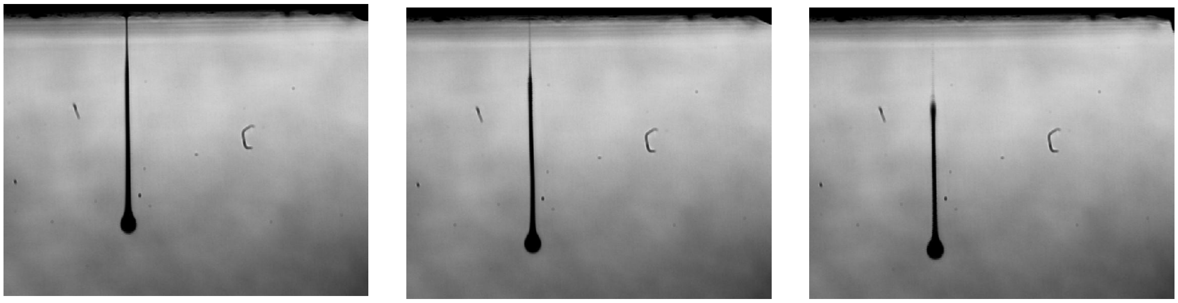

Figure 2. Filament ejection and drop formation

It is important to note that these photographs and others which are displayed in the different figures of this paper have all been obtained using the pseudo-cinematography technique and thus represent an average of many hundreds of pictures taken at well defined strobe delays.

Transient Shapes of Drops

On one hand, the pinch-off of pendant drops of viscous fluids that fall from an orifice under the action of gravity has been widely investigated both experimentally and theoretically.[11,13,15,28] On the other hand, very little has been done to compare the formation of a jetted drop with that of a drop dripping from a liquid faucet although these two flows share interesting similarities as already noted elsewhere[29] despite the fact that in the case of DOD printing the rupture of the filament happens at its forefront in contrast to what is found for the liquid faucet. In this paper, we provide additional information in a form useful for direct comparison with results reported in the literature on the transient behavior of the pendant drop.

Figure 3 shows the evolution of the liquid filament up to the time of ejection of the filament. The entire history of drop deformation is thus illustrated for a given fluid of viscosity 3 mPa.s (noted fluid #B hereinafter) at ambient temperature. The experiments have been performed at the same operating conditions using the two printheads described in the above section.

The figure shows the variation of the dimensionless drop elongation with time measured backward with To being the time at the instant of drop pinch-off. In this figure, L represents the length of the filament whilst R is the radius of the orifice. The behavior is similar in some aspects to that of a drop dripping from a faucet as shown in the inserts both far and near pinch-off. 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 there is strong acceleration in the process which leads to drastic changes in the final form of the drop.

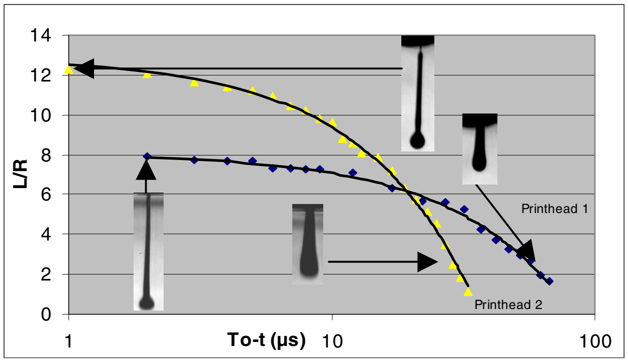

Figure 3. Transient evolution of the drops for two printheads

As one can also note from the above figure, the ratio L/R is higher than 8 in the case of both printheads although they are very much different in terms of radius. This seems to indicate that some given value of L/R perhaps needs to be reached before filament ejection can occur. Further experiments are being performed to confirm this assumption. Because our parameters are not the same as for drop dripping experiments a direct comparison is not possible. Nevertheless it should be noted that the value of L/R at drop pinch-off is very close to that found for a pendant drop[28] with a fluid having the same value of surface tension as ours.

In figure 4, we report the results obtained with printhead #1 for two fluids which differ in terms of viscosities. Thanks to the built-in heating capabilities of this printhead we have been able to conduct our experiments at a temperature of 40°C and at this temperature, fluid #A has a viscosity of 15 mPa.s which is five times more viscous than what is found for fluid #B at ambient.

One can note that although the time for filament ejection in the case of the more viscous fluid is more than two times larger than for the less viscous, the increase in the value of the ratio L/R is only about 25% fold so the filament does not really extend much more. This is consistent with our previous assumption that some threshold value of L/R needs to be attained before drop ejection can occur.

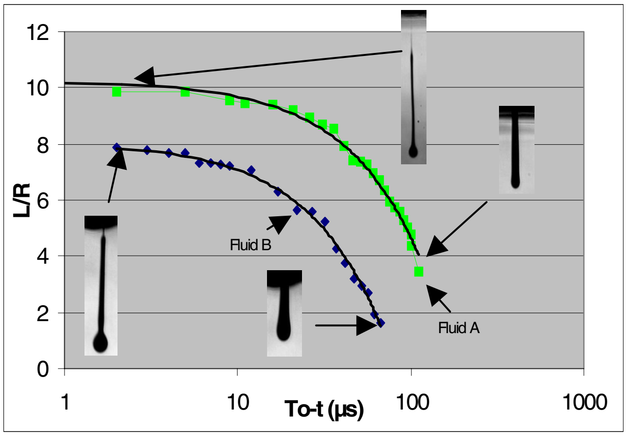

Figure 4. Transient evolution of the drops for two different fluids

Thinning Dynamics of the Filament

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 Rmin as noted hereinafter versus time. This value is found by an automatic search on the database. The evolution of the minimum radius can be described by a power law of the following form:

$$R_{min} = k\,(T_0 - t)^m \qquad (1)$$

where k is some constant, T_0 is the time for which Rmin vanishes and m is some scaling exponent. The value for m reported in the literature for the thinning dynamics of low viscosity fluids in the case of a pendant drop is 2/3.

We have checked this value in the case for the above two fluids using again printhead #1 and the results are shown in figure 5. The points are experimental (triangles for fluid #B) and the full curves are plotted after doing a linear regression. The value of the exponent m which is obtained is 0.52 for both fluids. This value is sufficiently different from that found for the dripping drop to hypothesize that the thinning dynamics of the jetted filament although close to that of the pendant drop are not exactly the same.

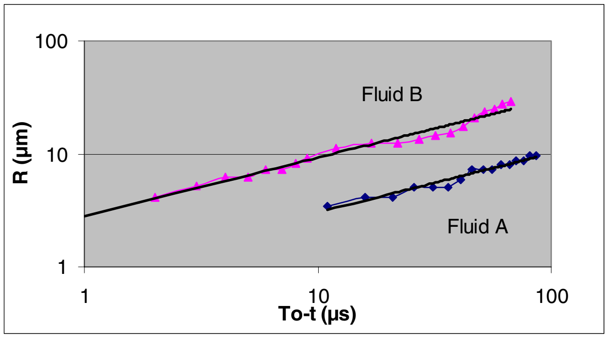

Figure 5. Evolution of the minimum neck radius versus time

We now compare our results with reported in the literature concerning the breakage of an inviscid fluid under the action of surface tension. Inviscid pinch-off has been considered recently[16] 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 one possible variation of the minimum necking radius versus time.

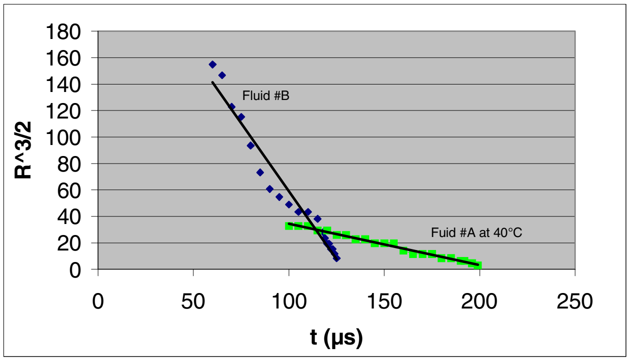

Figure 6. Scaling of the minimum neck radius versus time

We follow closely the above analysis[16] and we plot the variation of $R^{3/2}$ against actual time t where R is the minimum neck radius. The scaling for R comes from the only dimensionless grouping which is found for inviscid fluids involving the time t. In figure 6, we show the results obtained for both fluids using printhead #1 working at several kilohertz. The experimental points represent the behavior from the early stages of the formation of the filament up to the pinch-off of a drop. The straight lines are obtained performing a regression analysis once again. The coefficient of correlation is of the order of 0.95 for both fluids and the intersection of the straight lines with the horizontal axis predicts very accurately the experimental pinch-off times which differ by a factor of two between the fluids. This seems to indicate that an inviscid approximation is valid for low viscosity fluids and that quite interestingly self-similarity may extend quite far from pinch-off.

Conclusion

In this paper, we have first presented specific tools for initiating filament ejection with different DOD printheads and for following closely the topological changes of the free surface upto drop formation under different operating conditions. We have shown that this has led to several original developments mainly in terms of specific electronic equipment.

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. This has allowed to determine accurately the scaling exponents for the case of jetted fluids. It is useful to recall that such experiments have not been performed before.

The analysis of the transient non-linear dynamics within the framework of dynamic singularities shows that the DOD pinch-off process is in some aspects very much akin to that found for a drop dripping from a capillary under the effect of gravity. Another remarkable feature of the flow, is that the results do not seem to depend neither on the initial conditions nor on the characteristics of the fluid. Indeed, we have been able to show the validity of the analysis for two sorts of print-heads and for various fluids which involve quite different time scales.

That results of the analysis show differences between the jetted filament and the dripping drop. Thus, one has to be cautious and not use the results out of their context since the scaling laws appear to be different. Moreover our experiments only span a variation of less than an order of magnitude in terms of viscosities and need further confirmation. However, it should be noticed that many of the commercial printheads are limited in terms of jetting to fluid viscosities of about 20 to 30 mPa.s This gives confidence to extend this analysis further say to thermal inkjet print-heads

We have essentially considered until now the effect of different parameters during development of the filament and pinch-off. We are focusing presently on the evolution versus time of the jetted filament ongoing contraction under the action of surface tension forces and the similarities which may exist with drop formation in continuous ink-jet printing.[30]

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Biography

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