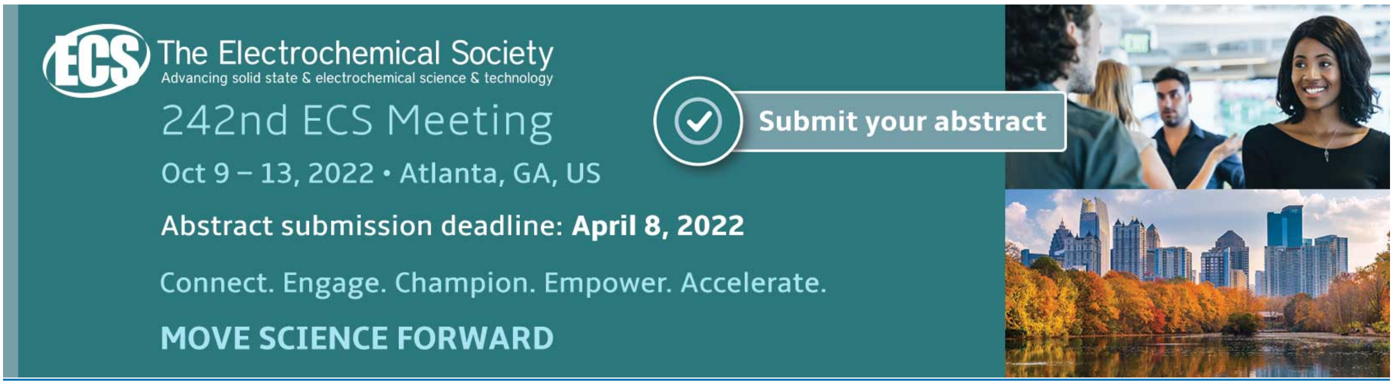
Journal of Physics: Conference Series

Inkjet printing - the physics of manipulating liquid jets and drops

To cite this article: G D Martin *et al* 2008 *J. Phys.: Conf. Ser.* **105** 012001



Engineering and Physics—Synergy for Success IOP Publishing
Journal of Physics: Conference Series **105** (2008) 012001 doi:10.1088/1742-6596/105/1/012001

Inkjet printing - the physics of manipulating liquid jets and drops

Graham D Martin, Stephen D Hoath and Ian M Hutchings

Inkjet Research Centre, Institute for Manufacturing, University of Cambridge, Mill Lane, Cambridge CB2 1RX, UK

E-mail: gdm31@cam.ac.uk

Abstract. Over the last 30 years inkjet printing technology has been developed for many applications including: product date codes, mailing shots, desktop printing, large-area graphics and, most recently, the direct writing of materials to form electronic, biological, polymeric and metallic devices. The new non-graphical applications require higher print rates, better resolution and higher reliability while printing more complex, non-Newtonian and heavily solids-loaded liquids. This makes the understanding of the physics involved in the precise manipulation of liquid jets and drops ever more important. The proper understanding and control of jet formation and subsequent motion of the jetted materials requires physical studies into material properties at very high shear rates, acoustic modes in print heads, instabilities of jets, drop formation, drop motion, stretching of fluid ligaments, the role of polymers in jet break up, electrical charging of drops and the aerodynamic and electrostatic interaction of jets and drops in flight. Techniques for observation, measurement and analysis are evolving to assist these studies. This paper presents some examples of the application of physics to understanding and implementing inkjet printing, including recent work at the Cambridge Inkjet Research Centre.

1. Introduction

Most people today are familiar with desktop inkjet printers which have transformed our ability to print text, create colourful business graphics, print web pages and reproduce photographs of very high quality. The core of these devices is the inkjet print head which generates and places millions of tiny coloured ink drops (volume ~10 pL) in a matrix pattern to give the impression of sharply-defined text or a subtly-graded full-colour image. The ability to do this is the culmination of many years development effort. To make an inkjet printer work reliably requires contributions from many engineering disciplines and a good knowledge of the physical principles that lie behind them. The engineers and physicists who develop inkjet systems need to understand fluid mechanics, acoustics, electrostatics, optics, imaging, colour, ink chemistry, fluid-surface interactions, micro-engineering, materials, electronics, software and, of course, plumbing. Some of the problems in inkjet printing particularly relating to physics will be considered in more detail in this paper.

The generation and manipulation of liquid drops has fascinated scientists for many years. Early experiments by Jean-Antoine Nollet in 1749 demonstrated the effects of static electricity on a stream of drops. In the 19th Century Lord Rayleigh conducted many experiments observing the creation of drops from jets, as well as interactions between drops [1, 2]. Worthington, in the early 20th Century, studied the phenomena of jets emerging from drops falling into liquid surfaces [3].

2. Applications

Home and office printing is a major application for inkjet. Almost everyone who has used a PC will at some time have printed their work with an inkjet printer. Predictions of the 'paperless' office have proved unfounded as the combination of personal computer and high-quality colour printing has encouraged more rather than less personal printing. However, the industrial application of inkjet printing began before the office inkjet and continues today. Inkjet systems are used to print information such as sell-by dates on to products and to address magazines and junk mail. Inkjet arrays are used in place of conventional printing technology to produce short run colour graphics on paper, plastics and board. These exploit the great advantage of inkjet printing that images are electronically stored so that the costly, and time consuming, plate-making and change-over processes are not needed to print new images. In more recent industrial applications, instead of printing images onto paper or other substrates, inkjets are being used as part of the product fabrication process to print structural or functional materials.

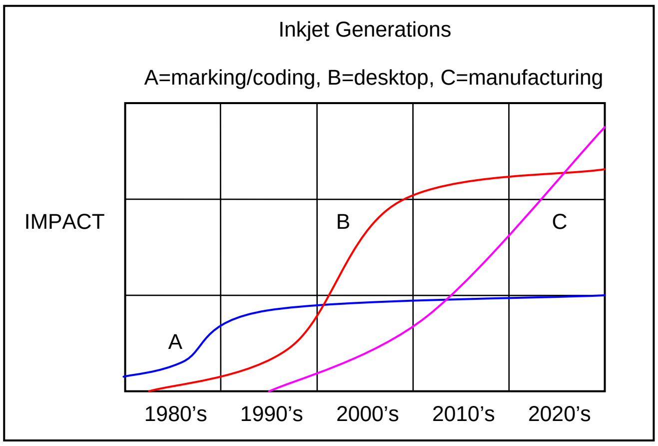


Figure 1. Evolution of inkjet applications.

Figure 1 shows how inkjet applications have developed, and continue to develop, with time. The first commercial applications were for marking and coding. The establishment of inkjet as a home/office printing tool represents the second generation. The third generation, taking off now, involves the industrial application of inkjet for both printing and manufacturing. Items such as mobile phones and electric razors are beginning to appear which incorporate displays fabricated by inkjet printing. As part of their production process, light emitting polymers are inkjet-printed into each of the many thousands of individual pixels which form the display. The use of this technology for much larger flat-panel displays has been demonstrated, and a number of companies and research groups are exploring the printing of active and passive electronic devices. Printed electronics can be placed directly on to, and integrated with, the associated substrate (for example, the casing of a mobile phone, an RFID tag on a product or as part of the packaging which interacts with the consumer). 3-D objects can be built up by overlaying successive solid printed 'images'. This technique is already successfully used for rapid prototyping but can also be used to make functional parts; the process can in principle be used to deposit a range of different materials in precise locations to form a complex, composite structure. This is encouraged by the development of more robust print heads and the increasing range of printable fluids and suspensions.

Some of these applications put extreme demands on the precise functioning and reliability of the inkjet systems. A misplaced drop in an address on an envelope is usually acceptable; a blank pixel in a display is not. Hence there is continued interest in understanding how inkjets work and in facing the challenges posed by a wide range of sometimes complex inks and substrates.

3. Inkjet Technologies

The principles of inkjet printing split into two major and a few minor categories. The major division is between the continuous and drop-on-demand processes.

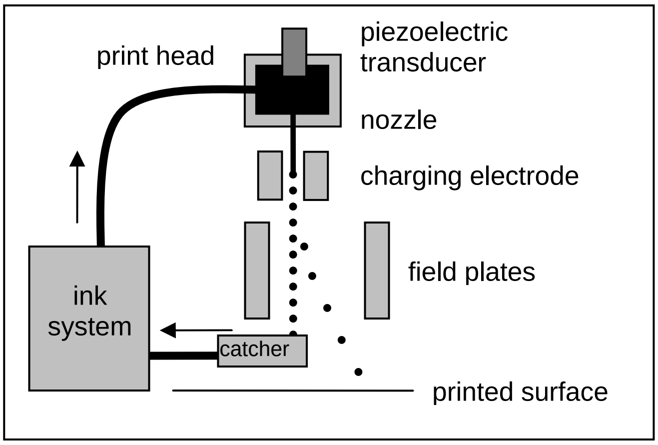


Figure 2. Schematic diagram of a continuous inkjet printer.

As the name implies, the continuous inkjet process starts by forming drops from a continuously flowing jet of ink which is forced out of a nozzle under pressure. Figure 2 illustrates a single-jet system. As discussed below, disturbances at a particular wavelength along the jet will grow and eventually cause the jet to break up into drops. By imposing a regular disturbance at the correct frequency (for example with a piezoelectric transducer) this break-up can be controlled and a very uniform stream of drops produced. Certain drops from this stream are then selected individually for printing. A common means of selection is to use electrically-conducting ink, and to charge the drop inductively as it is forming by having an electrode nearby held at an appropriate potential. When the drop breaks from the stream the induced charge cannot flow along the liquid column and is retained on the drop; the electrode can then be switched to a different voltage to charge the next drop being formed. The drops then pass through a fixed electric field which deflects the charged drops by an amount which depends on their charge. Uncharged drops are captured and the ink reused, while charged drops are directed onto the substrate, and the level of charge controls the position at which they strike it. A single jet can, in this way, print a line of characters by charging drops to various levels to form a line, say, 7 or 15 drops high. The characters are built up by moving the substrate and printing successive lines. In a more complex system, four or more arrays of continuous jets, each array printing a primary colour and each jet addressing one row of pixels along the substrate, can be used to print full-colour images very rapidly.

When a stream of drops is created in this way it is common to find that, as well as the principal drop, smaller, satellite drops are created from the ligament as it parts. These satellite drops will, depending on the details of the applied disturbance and the ink characteristics, either recombine with the main drop or be deflected to unwanted places and cause poor printing and printer failure. There have been some attempts to create small satellite drops deliberately and use them for high-resolution printing.

The second major inkjet technology is termed ‘drop-on-demand’. Drop-on-demand print heads usually have an array of nozzles, each of which ejects ink drops only when required to form the image. Figure 3 shows schematically how each nozzle works. An actuator of some kind creates a rapid change in the cavity volume and imparts some momentum to the ejected drop. This is a dynamic process, in which wave propagation in the ink and the geometry of the cavity behind the nozzle have significant effects. Although other methods have been explored, the two most common means to trigger the ejection are the creation of a vapour bubble within the ink using a heater pad ('bubble jet') or the distortion of a piezoelectric ceramic element. As the droplet of ink is ejected it first emerges as a jet, followed by a ligament or tail which is still connected to the ink in the nozzle (Figure 4).

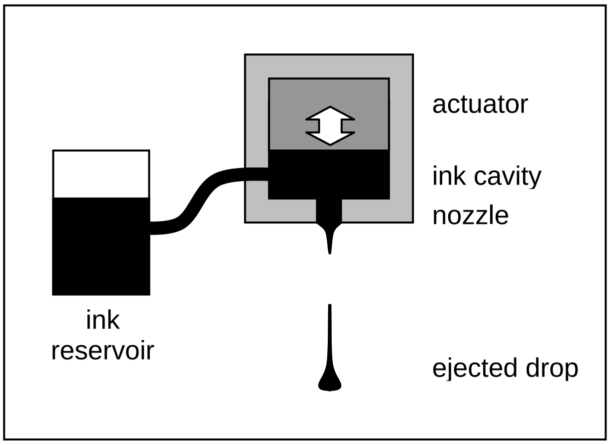


Figure 3. Schematic diagram of a drop-on-demand print head.

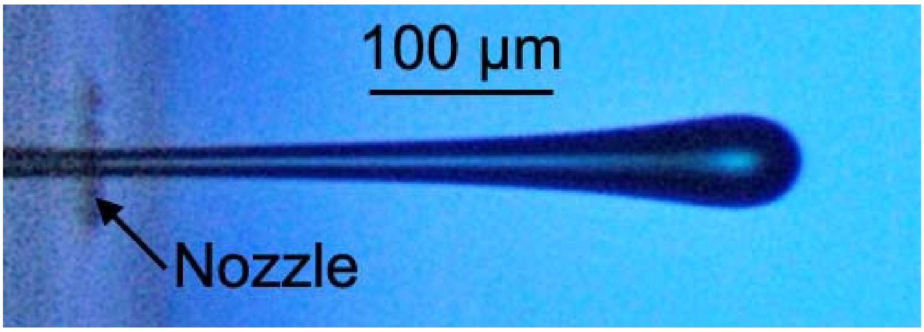


Figure 4. High-speed photograph showing a jet of ink emerging from a drop-on-demand nozzle. The jet is typically travelling at 5-10 m s^{-1}.

At a later stage the ligament parts: some ink returns to the nozzle and the rest of the tail joins the drop, or possibly breaks up into smaller satellite drops (figure 5). Before another drop can be ejected the cavity must refill and any acoustic disturbance must have attenuated enough not to affect the formation of the next drop.

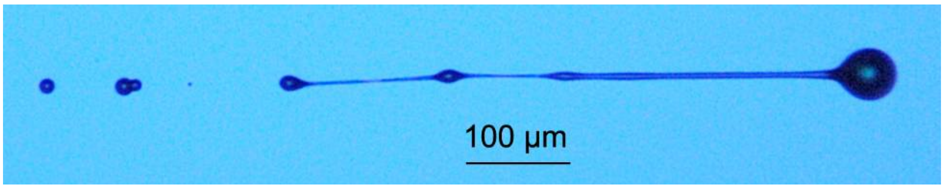


Figure 5. High-speed photograph showing a jet in flight after it has become detached from the nozzle. The ligament is breaking up to form satellites.

Drop-on-demand technology is in some ways simpler than continuous as it does not require the external drop selection and recovery system; however the techniques needed to make the print head, particularly with many fine nozzles, are very demanding. One issue confronting any drop-on-demand system is the need for the ink to dry or solidify on the printed surface, but not to dry in or clog the nozzle. This can be addressed at the print head, by appropriate cleaning and capping for example, and at the substrate by using low volatility inks and absorbing substrates, heaters, dryers or UV-curable inks.

Inkjet images are normally formed by printing drops at discrete locations in a matrix on the substrate. The spacings of these drops determine the resolution of the printer. To create the illusion of different grey levels or continuous colour very small drops are printed at an appropriate density on a fine matrix (i.e. at high resolution) which are then integrated by the eye to produce a impression of the required shade or colour. Some drop-on-demand print heads, instead of producing one drop, are able to produce a rapid sequence of small drops which are then all delivered to one pixel position. The relative velocities for the drops in these packets may be arranged so that they merge together before reaching the substrate. Hence the grey level or colour can be changed by varying the number of drops in the packet, and hence the total volume of ink which constitutes the pixel.

One further inkjet process worth mentioning is the electrostatic technique (Figure 6) in which electric fields are used to create liquid streams and drops. When a sufficiently high potential difference is applied between a liquid in a nozzle and a nearby plate, a conical surface is formed (Taylor cone) and liquid can jet from its tip. Several groups have used this phenomenon as the basis for a printing process.

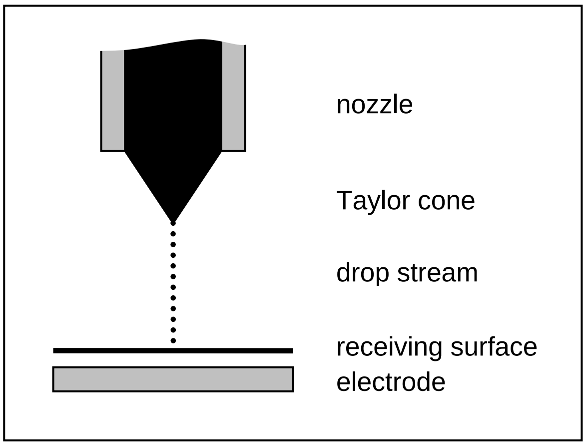


Figure 6. The phenomenon of electrostatic jetting.

4. Observation of jets and drops

The observation of inkjet jets and drops on the very small length scales and short times involved poses particular experimental problems. Figure 7 shows one method. A camera is used to observe drops emerging from a nozzle illuminated from behind by a suitable light source. There will be electronics to control the print head and trigger print events and, depending on the exact configuration, this may be linked to the control of the illumination and the camera. As much of the jetting process is repeatable, multiple-flash stroboscopic techniques can be used to make useful observations. In this technique the illumination is flashed many times per image frame in synchronisation with drop generation. Hence each frame recorded represents the superimposed images of many similar events. This technique can be used to study the evolution of drop formation over time, by changing the phase of the illumination relative to the drop ejection event. For stroboscopic imaging the flash duration is typically ≈ 1 μs. As ink drops and satellites are typically 1 to 100 μm in size with velocities between 5 and 20 m s^{-1}, significant movement can take place during the exposure which will blur the image. Any events which are not repeatable in position and timing will also result in additional blurring.

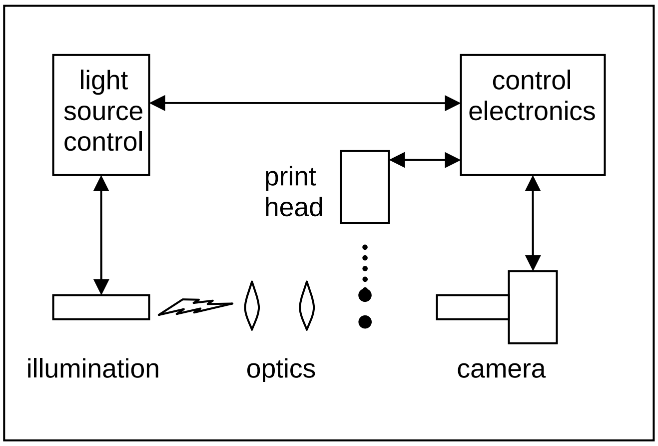


Figure 7. Typical apparatus for jet and drop visualisation.

Alternatively, a high-speed framing camera can be used, with either continuous illumination or synchronised flash, to observe single events as they occur. To capture a drop formation event the framing rate of the camera needs to be around 1 MHz. Although cameras with this capability are available the pixel resolution tends to be poor and often only a small number of consecutive frames can be captured.

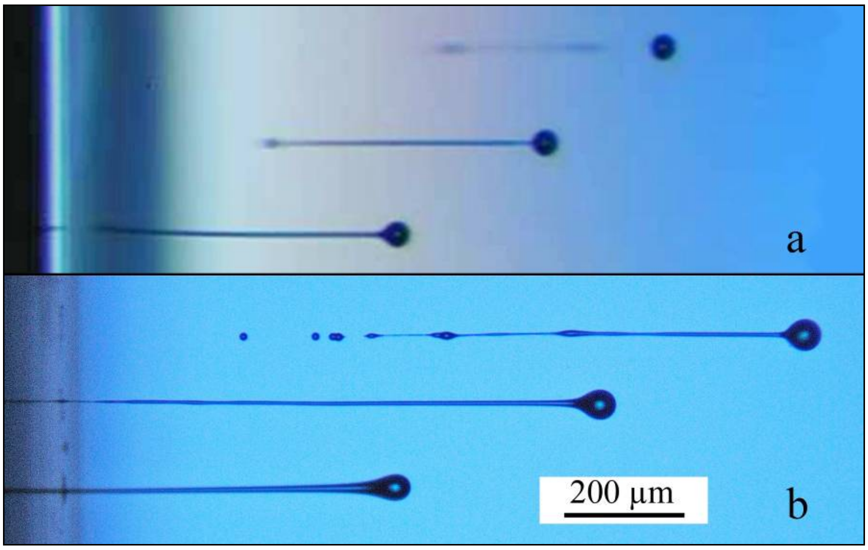


Figure 8. Comparison of strobed (a) and single-flash (b) images.

With a flash of sufficiently short duration and high intensity, single events can be captured by opening the camera shutter, timing the flash to coincide with the event, and then closing the shutter. This allows the use of a camera with high optical resolution so that images with both high temporal and high spatial resolution can be obtained. Figure 8 compares the results for both stroboscopic and single-flash illumination, with otherwise similar equipment. A 20 ns duration light source at the Inkjet Research Centre was used to capture this and other images in this paper. By taking successive images and incrementing the delay time, a pseudo-sequence can be built up which shows the evolution of these highly repeatable events.

Images obtained in this way contain a great deal of information, and techniques have been developed to analyse the images automatically, to locate the jets and drops and to retrieve and analyse the data. For example, Figure 9 shows measurements of jet tip profiles just as a drop is emerging from a nozzle [4].

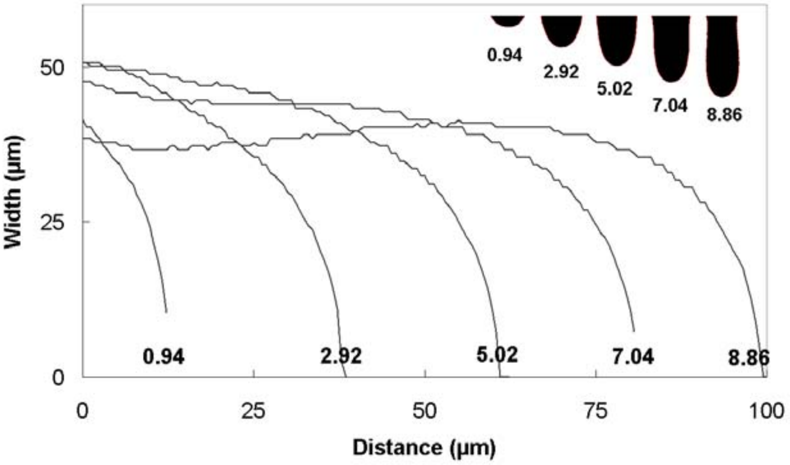


Figure 9. Jet tip profiles for ink drops emerging from a 50 μm nozzle at various times (μs) following emergence [4].

5. The formation of jets and drops

An extended cylinder of liquid, such as a jet issuing from a nozzle, is in an unstable state. Small disturbances will grow and cause it eventually to collapse into more energetically favourable spherical drops. In the early 19th century, Savart was the first to study perturbations growing on a jet of water [5]. In 1849 Plateau [6] showed that, on an infinite cylinder of fluid with radius r, disturbances with wavelength, $\lambda > 2\pi r$ will reduce surface energy and hence tend to grow. In 1879 Lord Rayleigh realised that the growth of the disturbance, driven by surface tension, competed with inertia and was able to show that the most rapid growth happens when $\lambda \approx 9r$. For a liquid of low viscosity, this therefore tends to be the value around which the drop size distribution is centred if a jet is left to break up spontaneously. In a continuous inkjet printer a disturbance is imposed on the jet, usually using a vibrating piezoelectric element, so that the jet is forced to break up at close to this optimum wavelength. The frequency of this disturbance is therefore λv where v is the jet velocity and $\lambda \approx 9r$. Geometry dictates that the radius of the resulting drops is approximately $2r$.

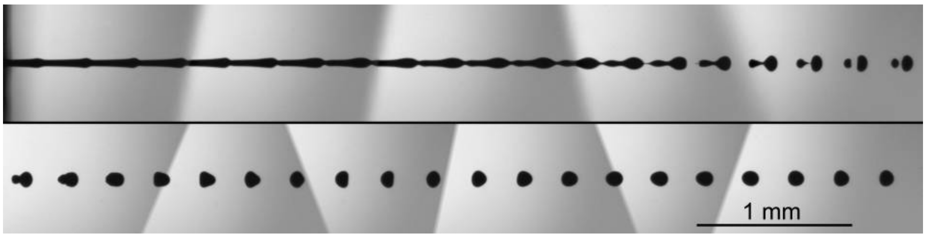


Figure 10. Composite stroboscopic image showing the break-up of a continuous jet travelling from left to right.

Figure 10 shows a continuous ink jet which is being stimulated to break up into regular drops, the lower image being a continuation of the upper image. These drops follow the approximate rules for spacing and size outlined above. However, in addition to the main drop a smaller satellite drop is created slightly later which, in this case, recombines with the main drop in front of it after a few periods. Satellite creation is very common in inkjets although, by judicious selection of parameters, it can be minimised or eliminated altogether. Various regimes of satellite creation can be observed [7]. Satellites can be forward-merging, as illustrated here, backward-merging or the satellite may travel at the same velocity as the main drops without merging (so-called 'infinite' satellites). The linear analysis of Rayleigh does not predict the formation of satellites at all. Subsequent theories have predicted satellites but do not explain their detailed behaviour. Pimbley et. al. [8], for example, consider a jet emerging from a nozzle with an imposed sinusoidal velocity disturbance by using a one-dimensional non-linear model solved to second order. By changing the disturbance amplitude, they show a qualitative agreement with observation predicting forward-merging, backward-merging or 'infinite' satellites. Unlike linear analysis, this predicts that, depending on various parameters including disturbance amplitude, break-up will tend to occur at one end or other of the ligament joining the forming drop to the jet. In the image shown in Figure 11 the ligament is about to break at the end closest to the rest of the jet and then will break later at the other end. During the time that the ligament and drop are still connected (the satellite interaction time) they are drawn towards each other by surface tension forces and so, after separation, the drop and the satellite which forms from the ligament will be moving towards each other and will later merge. Similarly, when the ligament breaks first at the drop end, the resulting satellite is backward-merging. The 'infinite satellite' case arises when the ligament breaks at both ends simultaneously.

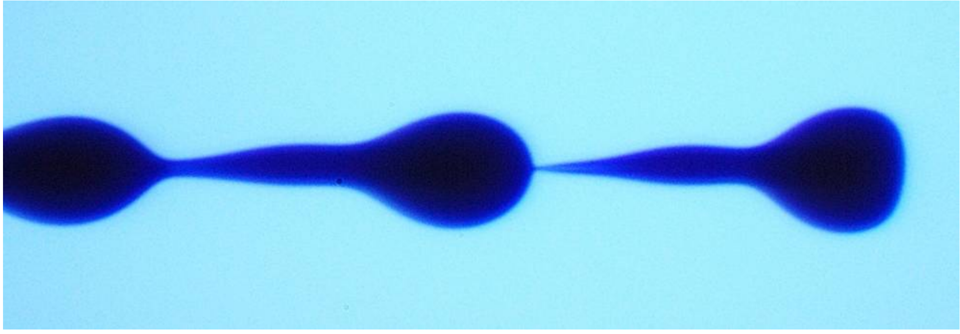


Figure 11. Image of break-up in a continuous jet, showing the ligament breaking at the end nearest the rest of the jet.

In some circumstances the satellite interaction time can be long enough to frustrate the formation of the satellite and the ligament then merges with the drop before a satellite can form.

For inkjet printers using continuous jets, satellite formation must be controlled to avoid disruption of the printing process. If satellites are generated then it is preferable that they forward-merge before entering the electrostatic deflection field. Once they have entered the field, the higher charge-to-mass ratio of satellites means that they are more strongly deflected and may, for example, hit the field plates; ink will then build up and cause electrical breakdown and printer failure. For a given ink, satellite formation is normally controlled pragmatically by changing the amplitude of the driving disturbance. This amplitude will change the satellite behaviour and also changes the distance over which the jet forms into drops, the break-up length, in a way which is not predicted by theories based on effectively stationary liquid columns or jets with a uniform velocity profile. Figure 12 show typical behaviour in which, as the disturbance is increased, the break-up length reduces to a minimum and then increases again, followed perhaps by further oscillations.

Work by Luxford [9] and Lopez et. al. [10] suggests that this behaviour can be explained by considering how the jet velocity profile (and the way it changes after leaving the nozzle) affects the growth of the disturbance on the jet and hence influences both satellite formation and break-up length.

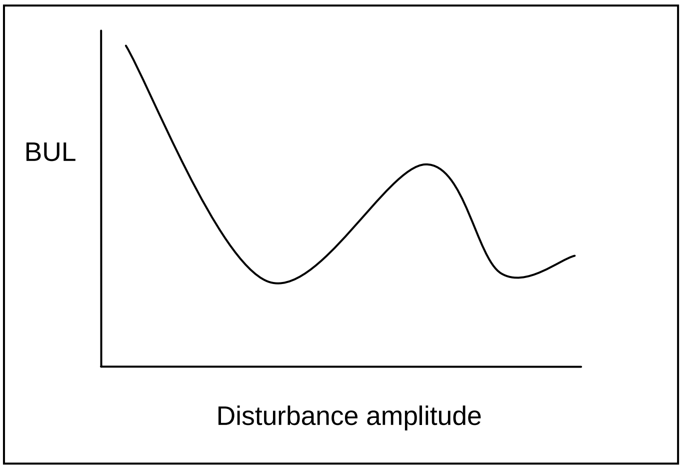


Figure 12. Typical behaviour of a continuous inkjet, showing how the break-up length (BUL) varies with the amplitude of the imposed disturbance.

In Figure 10 it can be seen that once the satellite has merged with the main drop, then the drop oscillates for a while before eventually the oscillation decays. Rayleigh [1] showed that for a drop radius r, surface tension σ and density ρ the resonant oscillation frequency ω is given by:

$$\omega = \sqrt{\frac{8\sigma}{\rho r^3}} \tag{1}$$

It can also be shown that, for a liquid of viscosity η, the oscillation will decay with a time constant [11]:

$$\tau = \frac{\rho r^2}{5\eta} \tag{2}$$

Figure 13 shows experimental measurements of drop elongation (E = vertical diameter / horizontal diameter), derived from images similar to those in Figure 10. Also plotted for comparison is the expression:

$$E = 1 + F\sin(\omega t + \phi)\exp\left(-\frac{t}{\tau}\right) \tag{3}$$

This function has been fitted to the data by adjusting the amplitude factor (F), the phase (ϕ), the frequency (ω) and the time constant (τ). Except at early times this provides a good fit to the data and allows estimates of the liquid's surface tension and viscosity to be made. At early times higher order modes of oscillation are present which complicate the behaviour.

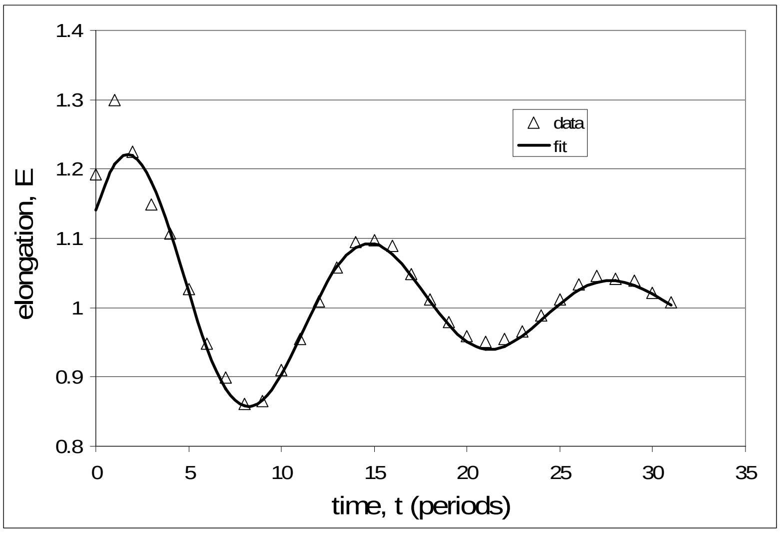


Figure 13. Comparison of experimental measurements of drop oscillation, in a continuous inkjet system, with a simple model of a decaying harmonic motion.

In a drop-on-demand printer a 'jet' is formed as the ink emerges from the nozzle. The actuator is driven by an electrical waveform with a shape experimentally determined to suit the structure of the print head and the properties of the ink. This waveform produces either movement in the piezoelectric actuator or heats a resistive pad to create a vapour bubble. This is in turn transformed, via the acoustic response of the ink, the ink jet cavity and nozzle assembly, into a pressure variation in the liquid at the nozzle entrance. This will cause ink to be ejected. Normally the time for which the drive waveform is applied is significantly shorter than the time needed for the jet to emerge and the drop(s) then to form from the jet. The drop initially emerges from the nozzle at relatively high speed. Once the drive impulse has diminished the drop continues to move, still joined to the ink in the nozzle through a stretching ligament (Figure 4, above). As this ligament stretches the drop will decelerate, in part through dissipative energy loss from viscous forces, partly through the energy required to create new liquid surface as the ligament stretches, and also (although this is a minor contribution) through the effects of air drag.

At some point the ligament breaks, and then surface tension drives the newly-formed drop towards a spherical shape. If the ligament is long it may well break into one or more satellites (as seen in Figure 5 above) as well. The formation of satellite drops from the ligament is clearly a similar process to the formation of drops from a continuous jet.

The dominant forces which control the behaviour of jets and drops of Newtonian liquids arise from viscosity and surface tension. In comparing and analysing jetting and break-up phenomena, it is useful to describe the conditions in terms of appropriate dimensionless groups. The Reynolds number Re, defined by Re = $\rho DV/\eta$, describes the ratio between inertial and viscous forces in a fluid with dynamic viscosity η and density ρ, at a velocity V and a characteristic length D, here taken to be the jet or drop diameter. The Weber number We, where We = $\rho DV^2/\sigma$ and σ is the surface tension, describes the ratio between kinetic energy and surface energy. It is sometimes more useful to consider the value of the Ohnesorge number Oh to describe the relative importance of viscous and surface forces, where Oh = $\mathrm{We}^{1/2}/\mathrm{Re}$. For non-Newtonian fluids which are of increasing interest as applications of inkjet printing become wider, still other dimensionless groups can be used to incorporate the effects of viscoelasticity, such as the Weissenberg number Wi = $\lambda V/D$ where λ is the characteristic relaxation time of the fluid [12].

One common performance measure for a drop-on-demand print-head is the velocity of the drops. This can be used to compare the uniformity across the whole array and also to determine the variation of performance with drop frequency. Ideally the rate at which drops are printed should not affect either their volume or their velocity. In practice there is an upper limit on the rate of drop firing after which the printer will fail, for example, by not being able to replenish the ink in the nozzle chamber quickly enough. Before this ultimate limit is reached there is likely to be variation in drop volumes and velocities because there is insufficient time for the nozzle to reach an equilibrium state before the next drop is fired. The details of this behaviour will depend on the design of the printer. The need to pack nozzles closely together to increase the printing resolution means that there is often cross-talk between adjacent nozzles. In some print-head designs, adjacent nozzles share actuators (for example, in a common wall) and hence the sequence of firing has to be constrained to accommodate this.

6. Charge and deflection

In a continuous inkjet system the most common method by which drops are selected for printing is by electrostatic charging by induction from a nearby electrode. The conductive jet, the forming drop and the charging electrode form an R-C circuit in which the resistance and the capacitance both change with time. The resistance increases as the drop ligament diameter diminishes, becoming infinite at the point of drop break-off. To ensure that the charge on the drop is sufficient and well-controlled, it is important that the forming drop begins to charge soon after the previous drop has parted. Figure 14 illustrates how the charge on a capacitor increases with time (for a constant RC). It is preferable that the break-off occurs in the 'plateau' region B rather than the slope region A where the charge will be less and the level of charge is more sensitive to small changes in timing. This timing or 'phasing' is usually achieved by detecting the charge on the drops as they move past a separate detection electrode (placed, for example, just below the charging electrode). Clearly the time constant of the R-C circuit must be such that the plateau region is reached well within the period of drop formation. The conductivity of the ink must be high enough to ensure this.

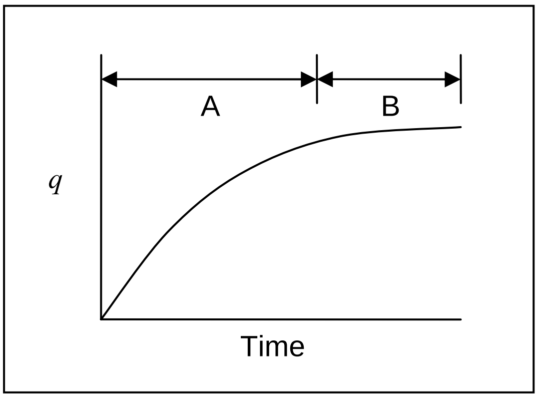


Figure 14. Evolution of charge on drop (q) with time.

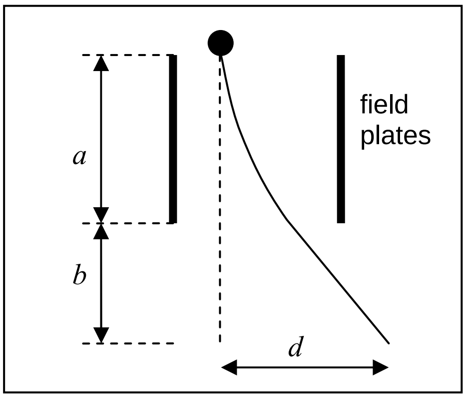


Figure 15. Deflection of a moving charged drop in an electric field.

The chemistry of the ink can disrupt drop formation and charging. For example, the incorporation of long-chain polymers tends to inhibit drop break-off, leading to very thin and hence high-resistance ligaments. Once charged, the drops move through a constant electric field and are deflected. The deflection, *d* for the geometry shown in Figure 15 can be estimated from:

$$d = \frac{qEa}{mv^2}\left(\frac{a}{2}+b\right) \tag{4}$$

where q is the charge on the drop, m is its mass, E is the electric field and v the velocity of the drop (assumed to be constant) in the vertical direction. This will give an under-estimate of the true deflection as aerodynamic retardation will slow the drop in flight, and field-fringing will provide forces beyond the top and bottom edges of the field plates.

Conditions are usually more complex than this simple model assumes, as several drops are in flight at once. These drops will interact aerodynamically and will also repel each other electrostatically. While equation (4) suggests that the deflection is proportional to the charge on the drop, if other drops are nearby then they also influence the deflection and it may even be impossible to achieve a particular deflection because of these interactions. The charging sequence needed to print a specific pattern is normally found by initial estimate or calculation, followed by experimental iteration until sufficient drop placement accuracy has been achieved.

7. Vibrations and acoustics

The vibrational and acoustic behaviour of inkjet print-heads and inks play an important role in the performance of these devices. This behaviour can be analysed in various ways. Antohe et. al. [13] considered the application of a simple trapezoidal drive waveform to a drop-on-demand print-head with long channels in which the side walls flex. The side walls are made from a piezoelectric ceramic (PZT) constructed and poled to achieve the required flexing movement. Figure 16 shows the arrangement schematically. The rising front of the drive waveform increases the volume of the cavity and creates a negative pressure in the channel. This is followed by a positive pressure wave moving from the refill end of the channel. The rear of the drive waveform then causes a positive pressure wave in the cavity. By adjusting the duration of the drive pulse these waves can be timed to interfere constructively at the nozzle end and hence boost the resultant drop velocity. More complex waveforms are used to further adjust and improve the drop ejection. In a design producing multiple drops per pixel, the waveform for the whole drop packet is developed to optimise ejection of the complete stream of droplets.

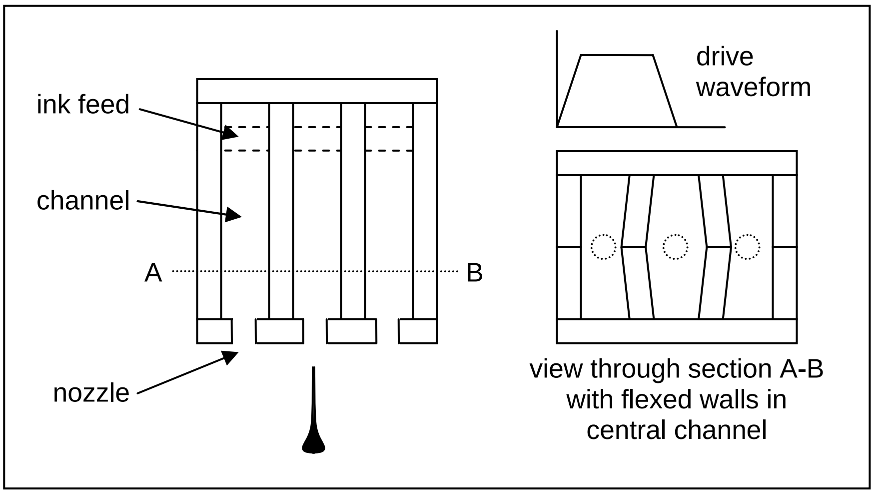


Figure 16. Schematic diagram showing three channels from a larger print head.

Some researchers [14, 15] have used equivalent circuit models for various parts of the system, expressed in terms of the acoustic impedance of each component such as the nozzle, pressure chamber and actuator. These can then be used to evaluate and optimise the way in which each component in the system influences the behaviour of the whole. Finally, much can be learned by using numerical modelling techniques such as finite element analysis and computational fluid dynamics to study vibrations, acoustics and flows within inkjet systems.

8. Drop-surface interactions

All applications of inkjets involve deposition of liquid on to a surface: these surfaces can be treated to enhance certain qualities of the final print. The application requirements within different markets vary considerably. In graphics printing either the substrate or the print head array is moved to exploit interactions between placement of successive drops to help evenly spread or cover areas, at least to the extent that the visual impression in the final product is satisfactory. However, for deposition of functional materials, as in displays and printed electronics, the precision of subsequent drop placement in a location may be enhanced by exploiting the 'coffee stain' patterns by which solid-loaded drops dry, and capillary flow forces can be used to help define track widths and thickness.

Jetting, spreading and drying of the deposited material also depend on the type of fluid used: this may be aqueous or solvent-based, may be chemically reactive or UV-curable, and may contain polymers, or ceramic or biological particles, with a range of possible sizes. Dyes and surfactants, anti-clogging agents and stabilisers also play their part in these potentially very complex 'inks'.

Since inkjet applications generally require controlled drop placement and the elimination of spurious effects, the conditions for drop-surface interactions must be controlled to avoid splashing. Surface features, such as ridges, on otherwise flat substrates have a crucial role in controlling the lateral flow of liquid after the impact of a drop. Areas that are pre-wetted, for example if they have been previously printed, also show different behaviour from a dry surface. Substrates that are porous by nature or allow diffusion of the liquid into the bulk provide rather different types of drying behaviour than impervious surfaces on which the ink is held. The control and timing of substrate drying after inkjet printing plays an important role in industrial applications.

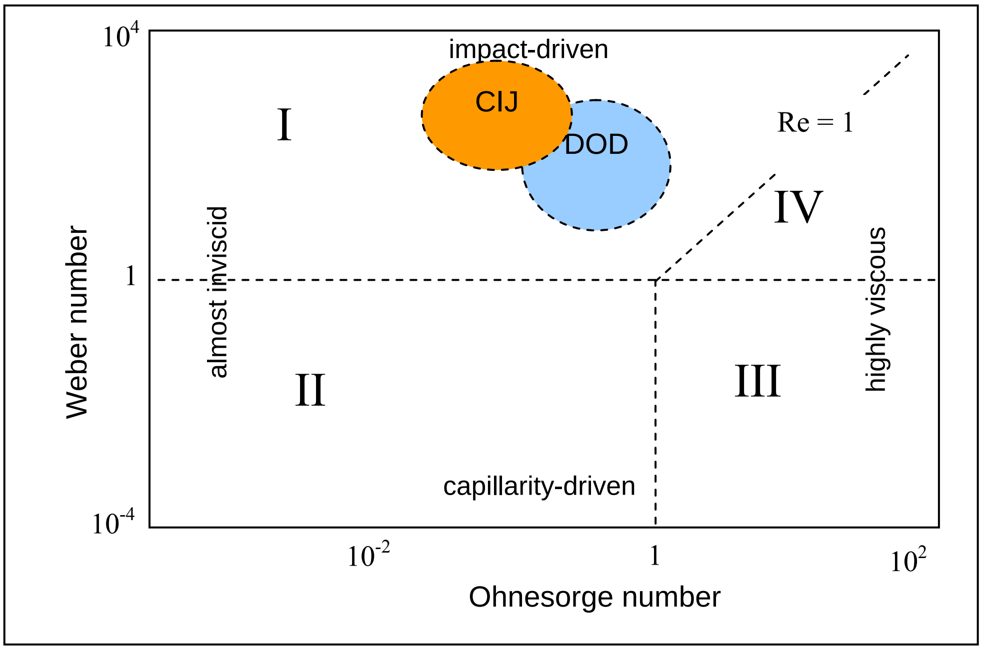


Figure 17. Schematic diagram adapted from Schiaffino and Sonin [18] showing four regimes of behaviour for a liquid drop on impact, based on the values of Weber and Ohnesorge numbers. Typical values for drop-on-demand (DOD) and continuous (CIJ) inkjets are shown.

The rich range of phenomena which occur on the impact of a droplet against a solid surface is the subject of active research [16]. A simple description can be based on the values of the Weber and Ohnesorge numbers, as shown in Figure 17. Conditions in inkjet printing lie predominantly in regime

I [17], where the initial spreading of the drop occurs rapidly, resisted primarily by fluid inertia. Viscous effects may play a role later in the process as the speed of spreading falls.

9. Conclusions

Classical physics has an important role to play in many aspects of inkjet printing. The proper understanding and control of jet formation and subsequent motion of the jetted materials requires physical studies into liquid properties at very high shear rates, acoustic modes in print heads, instabilities of jets, drop formation, drop motion, stretching of fluid ligaments, the role of polymers in jet break up, electrical charging of drops and the aerodynamic and electrostatic interaction of jets and drops in flight. Techniques for observation, measurement and analysis are evolving to assist these studies.

Acknowledgements

The work carried out at the Inkjet Research Centre at Cambridge was supported by the UK Engineering and Physical Sciences Research Council.

References

[1] Lord Rayleigh 1879 On the Capillary Phenomena of Jets *Proceedings of the Royal Society of London* **29** 71-97

[2] Lord Rayleigh 1882 Further Observations of Liquid Jets *Proceedings of the Royal Society of London* **34** 130-45

[3] Worthington A M 1908 *A Study of Splashes* (Longmans, Green and Co., London)

[4] Hutchings I M, Martin G D, Hoath S D and Morgan R H 2006 High Speed Imaging and Analysis of Jet and Drop Formation Proc. *IS&T, NIP* **22**

[5] Savart F 1833 *Annal. Chim.* **53** 337

[6] Plateau J 1849 *Acad. Sci. Bruxelles Me´m.* **23** 5

[7] Vassallo P and Ashgriz N 1991 Satellite Formation and Merging in Liquid Jet Breakup *Proceedings: Mathematical and Physical Sciences* **433** 269-86

[8] Pimbley W T, Lee H C, 1977 Satellite droplet formation in a liquid jet *IBM J. Res. Dev* **21** 21-30

[9] Luxford G 1999 Momentum Fluctuations in and Break-up of an Ink-Jet *Proc. IS&T, NIP* **15** 26-30

[10] Lopez B, Kalaaji A, Soucemarianadin A, Attané P 2000 Mechanisms of Drop Formation in Continuous Ink-Jets *Proc. IS&T, NIP* **16** 50-55

[11] Rhim W, Ohsaka K, Paradis P and Spjut R E 1999 Noncontact technique for measuring surface tension and viscosity of molten materials using high temperature electrostatic levitation *Review of Scientific Instruments* **70(6)** 2796-801

[12] McKinley G H 2005 Dimensionless groups for understanding free surface flows of complex fluids *Society of Rheology, Rheology Bulletin* **74**(2) 6-9

[13] Antohe B V, and Wallace D B 2001 Acoustic Phenomena in a Demand-Mode Piezoelectric Ink-Jet Printer *Proc. IS&T, NIP* **17** 885-9

[14] Sakai S 2000 Dynamics of Piezoelectric Inkjet Printing Systems *Proc. IS&T, NIP* **16** 15-20

[15] Deshpande N V 1996 Significance of Inertance and Resistance in Fluidics of Thermal Ink-Jet Transducers *The Journal of Imaging Science and Technology* **40** 396-400

[16] Yarin A L 2006 Drop impact dynamics: splashing, spreading, receding, bouncing..... *Ann. Rev. Fluid Mech.* **38** 159-192

[17] van Dam D B and Le Clerc C 2004 Experimental study of the impact of an ink-jet printed droplet on a solid substrate *Phys. Fluids* **16** 3402-3414

[18] Schiaffino S and Sonin A A 1997 Molten drop deposition and solidification at low Weber numbers *Phys. Fluids* **9** 3172-3187