1 Introductory Remarks

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1.1 Introduction

From newspapers to food packaging, from magazines to junk mail and roadside advertising, we live in a world of printed materials. The process of printing involves the reproduction of a pattern on a substrate, usually in order to represent text or images or, in many cases, both. Conventional printing methods, including, for example, lithography, flexography, gravure, and screen printing, have evolved over several centuries and can now achieve remarkable levels of quality at very low cost. All these processes share a common feature: the pattern to be printed is embodied in a physical form such as on a roll, plate, or screen and transferred from this template during the act of printing through direct or indirect contact with the substrate. The pattern of ink that forms the printed text or image on the substrate thus originates in a pattern that is defined before the printing machine starts to run. Changes to the printed product can be achieved only by changing the master pattern, which involves making physical changes to the template within the printing machine.

Inkjet printing, in contrast, employs a fundamentally different principle. Rather than the printed pattern being created by transfer of ink from a pre-existing master pattern, it is progressively built up directly on to the substrate by the deposition of a large number of individual, tiny drops of ink. Each small droplet, typically 10–100 μm in diameter, is created and deposited under digital control, so that each pattern printed in a sequence by the same machine can just as readily be different from all the others as it can be the same.

Today's printing industry represents a major area of economic activity, currently accounting for some US $900 billion per annum globally and likely to exceed US $1000 billion by 2020. Over the past 20 years, a small but increasing fraction of this activity has been based on inkjet technology, and this proportion is forecast to grow significantly. There are several reasons for this. Because the patterns to be printed by inkjet are defined digitally and thus represented by digital data files and never as physical master templates, they can very easily be changed, and the setup costs and times for inkjet printing are, therefore, low. As a digital printing

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process, inkjet is thus ideally suited for short print runs for which profit margins can be high, and as the process has increased in reliability and robustness, the run lengths at which inkjet competes with more conventional processes in terms of cost have also increased. High resolution and image quality, once the sole preserve of conventional printing, can be more readily attained by inkjet methods. Inkjet printing is very well established for printing variable information such as use-by dates and batch codes on to products in a manufacturing environment, and as inkjet print quality increases, more opportunities become available for printing bespoke, personalized products. Table 1.1 summarizes the very wide range of applications in which printing is used and shows how inkjet technology is progressively encroaching into major areas. Already ubiquitous in the small office and home environment, inkjet printing is likely to take an increasingly important share of the commercial printing market soon and to become more widely used for decorative products, packaging, general industrial applications, and textile printing as well [1].

The principles of inkjet printing were first developed commercially during the 1970s and 1980s and first applied practically to marking products with dates and codes and addressing mail. As indicated in Figure 1.1, the technology used for these purposes, which demand high operating speeds but can tolerate quite low resolution in the printed text, is now fully mature. These printers, which use "continuous inkjet" (CIJ) technology, are widely used as standard equipment in factories worldwide. The next development, from the 1990s onward, involved "drop-on-demand" (DOD) printing, which is capable of achieving much higher resolution than these early coders and achieving digital reproduction of text and images at low cost in the domestic and small office environment. More recently, applications of inkjet printing in the commercial world, and for other uses listed in Table 1.1, have been developing rapidly, and these applications also predominantly use the DOD technology. The principles by which small drops of ink are formed and manipulated, in both CIJ and DOD modes, are described in the next section.

1.2
Drop Formation: Continuous Inkjet and Drop-on-Demand

In both the CIJ and DOD methods, the liquid ink flows through a small hole (usually called a *nozzle*). The essential difference between the two methods lies in the nature of the flow through the nozzle. In CIJ, as the name implies, the flow is continuous, while in DOD, it is impulsive.

A CIJ system produces a continuous stream of drops, from which those to be printed on to the substrate are selected as required, whereas in DOD printing, the ink is emitted through the nozzle to form a short jet, which then condenses into a drop, only when that drop is needed.

A continuous stream of liquid emerging from a nozzle is inherently unstable and will eventually break up into a stream of droplets under the influence of surface tension forces, as shown, for example, in Figure 1.2a. This process was first studied

Table 1.1 Range of applications for which printing is currently used, showing market penetration of inkjet-based processes.

	Small office and home	Commercial print	Decorative products	Packaging	General industrial	Textiles
Already widely used	Home printers, local office printers/copiers	Billing and ticketing, graphic displays, point-of-purchase	Signage, banners, stickers, ceramic tiles		Coding and marking	T-shirts
Starting to be used		Books, brochures, flyers, newspapers, magazines	Wallpaper	Labels: self-adhesive, shrink, and so on	Displays, dashboards, plastic cards, 3D printing	“Designer” fabrics, ties, scarves
Medium-term target			Flooring, décor (e.g., melamine)	Corrugated board, cartons, cans, glass bottles	Printed circuit boards, electronic devices	Soft furnishings, other clothing
Not a current target		Banknotes, security printing		Flexible packaging, molded tubs, bottles	Toys, other durables	Carpets, rugs

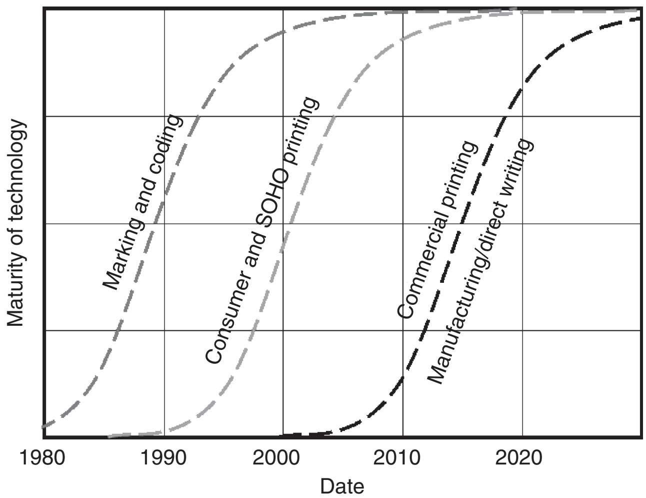

Figure 1.1 The applications of inkjet technology have developed in three waves: initially for marking and coding, followed by desktop printing of text and graphics in the home and small office environment, and currently, increasing use in commercial printing and manufacturing [2].

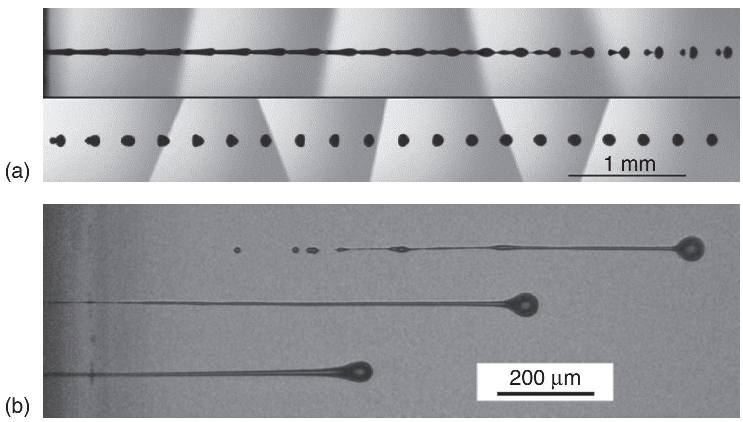

Figure 1.2 Images of liquid jets, moving from left to right, showing (a) breakup of a continuous jet to form drops (the lower image is a continuation of the upper image) and (b) jet and drop formation in drop-on-demand mode from three nozzles situated toward the left of the frame. (from Martin and Hutchings [3].)

as long ago as 1833 by Savart [4] and analyzed quantitatively by Rayleigh in 1879, who showed that the wavelength of the most rapidly growing disturbance in the jet (and, thus, the distance between the centers of the resulting drops) was about 4.5 times the diameter of jet (see also Chapter 7). This phenomenon, often called *Rayleigh breakup*, was first employed as the basis for a CIJ printer (for recording oscillograph traces) by Sweet at Stanford University in the early 1960s. Sweet's design introduced the key concepts of stimulating jet breakup by modulating it at an appropriate frequency and using electrostatic forces to deflect the drops [5]. In the stream shown in Figure 1.2a, the breakup was stimulated by vibration applied to the fluid upstream of the nozzle, but an unstimulated jet will also break up in a similar way, although after traveling a longer distance.

In modern CIJ printing, the drops to be printed on to the substrate are usually steered electrostatically. As each drop detaches from the end of the continuous stream, an electric charge is induced on it so that, when it subsequently passes through a fixed electric field, it is deflected by the correct amount to land at the right place on the substrate. Drops that carry no charge, in contrast, are arranged to land in a gutter from which the surplus ink can be recovered and recycled back to the nozzle. In this way, a stream of drops from a single nozzle, in combination with a moving substrate, can be used to print a swathe of text or image. CIJ is also used in multi-nozzle configurations, with each jet addressing one pixel position across the printed swathe. The printed pattern is created by switching drops from individual jets either into a gutter or on to a substrate by deflection in an electric field, as described above, or by other means.

Figure 1.2b shows images of jets ejected from three nozzles in DOD mode and traveling to the right. The main droplet, which forms the head of the jet, is followed by a long ligament of liquid, which eventually detaches from the nozzle (at the left-hand edge of the picture) and is pulled toward the head of the jet, while, at the same time, becoming thinner and, in this case, forming a series of "satellite" drops. The final form of the jet may be a single spherical drop (the ideal case) or, quite commonly, a main drop followed by one or more, smaller, "satellite" drops. In DOD printing, the drops are not "steered"; many nozzles (from hundreds to thousands) are arranged in an array in each printhead, and the position at which each drop lands on the substrate is controlled by the relative motion between the drop and the substrate and by the timing of the drop ejection, as well as by the selection of the appropriate nozzle from the array.

Most current DOD printers use one of two different methods to generate the pressure pulse needed to eject an ink drop. Many printheads use the deformation of a piezoelectric ceramic element for this purpose, while in other types (thermal inkjet, sometimes called *bubble jet*), the pressure pulse which ejects the drop is generated from the expansion of a small bubble of vapor produced by the action of a small electric heating element on the liquid. There are advantages and disadvantages of both types of actuation. Piezoelectric printheads can handle a wider range of liquids than thermal printheads (which are restricted to inks which satisfactorily vaporize), while the latter can be simpler and cheaper to fabricate. Piezoelectric DOD printheads were first devised in the 1970s, with thermal DOD being developed a little later [3, 5].

The drop diameters used in inkjet printing, typically from 10 to 100 μm, correspond to drop volumes from 0.5 to 500 pl. Drop speeds, at the point where the drops strike the substrate, are typically $5-8\,\mathrm{m\,s^{-1}}$ for DOD printing and $10-30\,\mathrm{m\,s^{-1}}$ for CIJ.

1.3
Surface Tension and Viscosity

Two physical properties dominate the behavior of the liquid jets and drops involved in inkjet printing: *surface tension* and *viscosity.* We shall remind ourselves briefly of their definitions, following the discussion by Martin and Hutchings [3].

The surface tension of a liquid reflects the fact that atoms or molecules at a free surface have a higher energy than those in the bulk. There is a cost in terms of energy in creating new surface area. For a free droplet of liquid, the shape with the lowest surface area, and therefore the lowest surface energy, is a sphere, and in the absence of other influences such as electrostatic, gravitational, or aerodynamic forces, that is the shape a free drop will adopt. If the liquid is in contact with a solid surface, for example after it has been printed on to a substrate, then we need to consider not only the energy of its free surface (which is usually in contact with air or solvent vapor) but also the energy of the interface between the liquid and the solid substrate. In that case (and where, as in inkjet printing, the effect of gravity is negligible), the equilibrium shape of the drop becomes a spherical cap, as discussed in Chapters 8 and 9.

The surface tension in a liquid causes a force to act in the plane of the free surface perpendicularly to a free edge in that surface, which can be measured directly by various experimental arrangements. The force is proportional to the length of the edge, and the surface tension γ can therefore be defined as the force per unit length. Since by moving the edge in the direction of the force we will increase the area of the surface and also do work on the system against the surface tension, we can also treat the force per unit length as a *surface energy*: the work done in creating unit area of new surface. The two are equivalent, as are the SI units of $N\,m^{-1}$ and $J\,m^{-2}$. Most liquids of practical interest for inkjet printing have surface tensions, γ, of the order of tens of $mN\,m^{-1}$ (or $mJ\,m^{-2}$). For pure water at 20 °C, $\gamma = 72.5\,mN\,m^{-1}$, while for many organic liquids (which have smaller intermolecular energies than water), γ lies in the range from 20 to 40 $mN\,m^{-1}$.

The tendency of a liquid to form the shape with the lowest total energy, which in the case of a free drop causes it to become a sphere, is responsible for the breakup of the stream in CIJ printing and for the formation of the main drop and any satellite drops in DOD printing.

The forces that resist the contraction of a liquid jet through the action of surface tension have two origins: the inertia of the liquid and its viscosity. Inertial forces are those associated with a change in a body's momentum: in the case of a moving liquid, they are proportional to its density and the rate of change of velocity. Viscous forces arise from the interactions between molecules of the liquid and act between regions of liquid moving relative to each other. A simple example, which forms the basis for the definition of viscosity, is given by a shear flow as shown in Figure 1.3a.

A region of liquid is defined by two parallel surfaces a distance d apart. The lower surface is stationary, and the upper surface moves relative to it at a constant

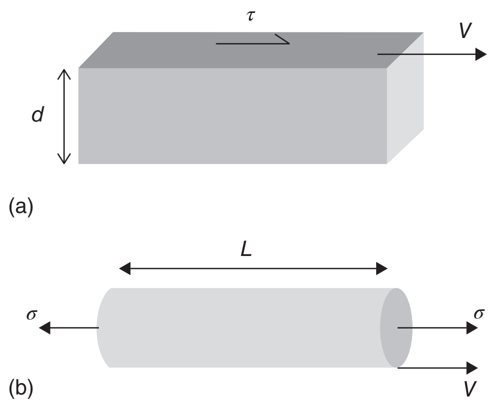

Figure 1.3 Geometry used to define: (a) shear flow and (b) extensional flow [3].

velocity v. We assume that this generates a linear gradient of velocity through the liquid, normal to the upper and lower surfaces. The shear strain rate $\dot{\gamma}$ is given by:

$$\dot{\gamma} = V/d$$

and for many liquids, the shear stress τ acting on the upper and lower surfaces is proportional to $\dot{\gamma}$:

$$\tau = \eta\dot{\gamma}$$

The constant η is the *dynamic viscosity* of the liquid, and if η is independent of $\dot{\gamma}$, then this behavior is termed *linear* or *Newtonian*. The simple term "viscosity," without further qualification, usually means the dynamic viscosity as defined for a shear flow. The SI unit for dynamic viscosity is the pascal second (Pa s). The older (c.g.s.) unit of viscosity, the poise (symbol P), or more commonly centipoise (cP), is still in widespread use and conversion is straightforward: 1 mPa s = 1 cP. Water has a viscosity of almost exactly 1 mPa s at 20 °C, while fluids used in inkjet printing typically have viscosities in the range from ~2 to ~50 mPa s. The viscosity of most liquids falls rapidly with increasing temperature, and this is often exploited in inkjet printing: by varying the temperature of the printhead, it is possible to optimize the viscosity of the ink for drop generation.

The shear flow shown in Figure 1.3a represents a particular pattern of liquid flow, but it does not represent well the flow that occurs in the formation or collapse of a jet. We may also need to consider the extensional or elongational flow, which is shown in idealized form in Figure 1.3b. If a cylindrical column of liquid of length L is stretched along its axis at a velocity V, the uniaxial strain rate $\dot{\varepsilon}$ is given by:

$$\dot{\varepsilon} = V/L$$

and the axial stress σ is linearly proportional to the strain rate:

$$\sigma = \eta_{\mathrm{T}}\dot{\varepsilon}$$

The constant of proportionality η_T is called the *extensional viscosity*, and for a Newtonian liquid, η_T is three times the shear viscosity η. The ratio η_T/η is called the *Trouton ratio* and can be significantly greater than 3 for non-Newtonian liquids that are viscoelastic. Viscoelastic liquids exhibit a time-dependent elastic response as well as viscosity due, for example, to the presence of polymer molecules in solution. Organic solvents are usually Newtonian, as is water, but practical inkjet inks often exhibit some degree of viscoelasticity (also see Chapters 5, 6, and 13).

1.4
Dimensionless Groups in Inkjet Printing

Surface tension, inertia, and viscosity play key roles in the formation and behavior of liquid jets and drops. Two dimensionless numbers can be used to characterize the relative importance of these: the Reynolds and Weber numbers. The Reynolds number Re represents the ratio between inertial and viscous forces in a moving fluid and is defined by Eq. (1.1):

$$Re = \frac{\rho V d}{\eta} \tag{1.1}$$

where ρ is the density of the fluid, V is its velocity, η is its viscosity, and d is a characteristic length: typically, the diameter of the jet, nozzle, or drop.

The Weber number We depends on the ratio between inertia and surface tension:

$$We = \frac{\rho V^2 d}{\gamma} \tag{1.2}$$

where γ is the surface tension. For a spherical drop traveling at velocity V, the ratio between its kinetic energy and the energy of its free surface is $We/6$.

The influence of velocity in these two dimensionless groups can be removed by forming a further group, the Ohnesorge number Oh defined by:

$$Oh = \frac{\sqrt{We}}{Re} = \frac{\eta}{\sqrt{\gamma \rho d}} \tag{1.3}$$

The value of the Ohnesorge number, which reflects only the physical properties of the liquid and the size scale of the jet or drop, but is independent of the driving conditions (which control the velocity), turns out to be closely related to the behavior of a jet emerging from a nozzle and, thus, to the conditions in DOD printing. If the Ohnesorge number is too high ($Oh > \sim 1$), then viscous forces will prevent the separation of a drop, while if it is too low ($Oh < \sim 0.1$), the jet will form a large number of satellite droplets. Satisfactory performance of a fluid in DOD inkjet printing thus requires an appropriate combination of physical properties, which will also depend on the droplet size and velocity (through the value of the Reynolds or Weber number) as shown in Figure 1.4 [6]. Some authors use the symbol Z for the inverse of the Ohnesorge number ($Z = 1/Oh$). The range over which

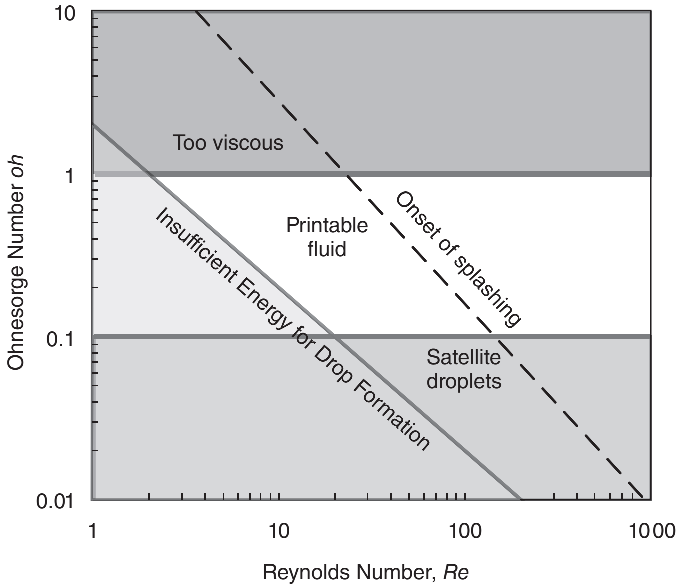

Figure 1.4 Schematic diagram showing the operating regime for stable operation of drop-on-demand inkjet printing, in terms of the Ohnesorge and Reynolds numbers. (Reproduced with permission from McKinley and Renardy [6]. Copyright (2011) American Institute of Physics.)

liquids can be printed is often quoted as $10 > Z > 1$ (e.g., [7]), although other work has suggested that $14 < Z < 4$ may be more appropriate [8].

These ranges of Ohnesorge number provide some bounds to the "printability" of the liquid, but other factors must also be considered: the jet must possess enough kinetic energy to be ejected from the nozzle (leading to the solid diagonal line in Figure 1.4 corresponding to $Re = 2/Oh$), and it is also desirable to avoid splashing of the drop on impact with the substrate (which leads to the broken diagonal line for which $OhRe^{5/4} = 50$) [9].

1.5 Length and Time Scales in Inkjet Printing

It is useful to review the wide range of length and time scales involved in inkjet printing, because these pose challenges for the scientific study and optimization of the various processes involved. Figure 1.5 shows that the length scales concerned extend from nanometers to meters.

At the smallest length scales, atomic and molecular diameters provide a fundamental limit to any treatment of fluids as homogeneous continua, while inks often contain colloidal pigments and other small particles 10–100 nm in diameter. The liquid drops, jets, and ligaments formed from the printhead range in dimensions

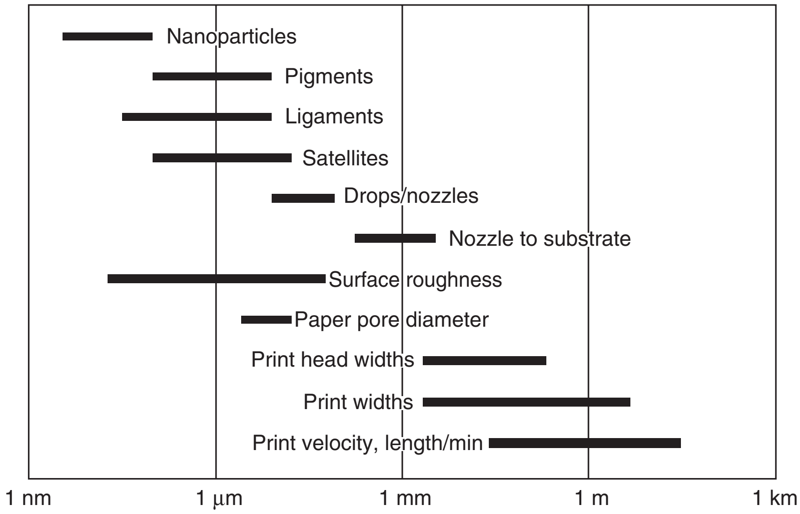

Figure 1.5 Length scales involved in inkjet printing.

from far below 1 µm (for thinning ligaments) to tens of micrometers (for main drop diameters) and hundreds of micrometers (for ligament lengths). The main drops are usually of size similar to the diameters of the nozzles (10–100 µm), while the standoff distance over which the drop travels from the printhead to the substrate may range from less than 1 mm (for typical DOD systems) to several tens of mm (for CIJ printing). Shorter standoff distances will generally give more precise drop placement but demand greater accuracy of substrate movement

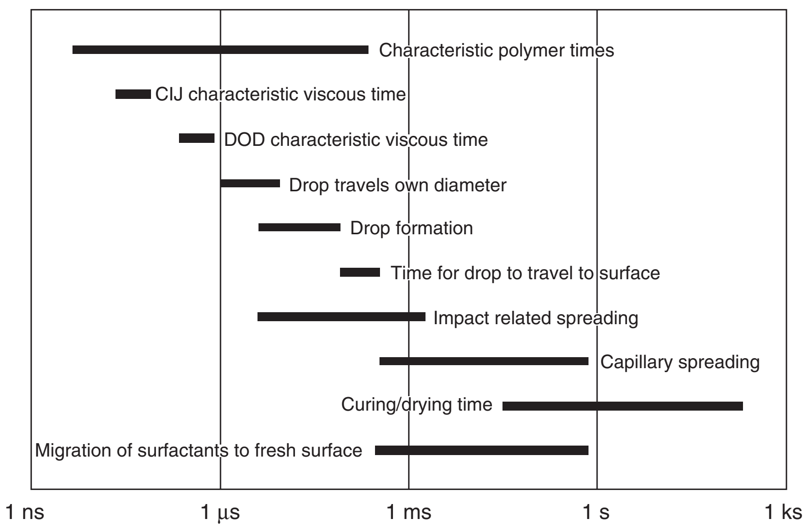

Figure 1.6 Time scales involved in inkjet printing.

and a smoother, flatter surface. The substrates for many applications have surface roughness below 100 nm (0.1 μm), but porous media such as paper have significant inhomogeneity due their inherent fibrous structure, producing pores on the surface through which liquid and pigment particles can penetrate. Lower limits to printed line widths, for example, for printed electronics, are about 10 μm; the width of the printed substrate may in contrast extend to several meters, for advertising banners and vehicle wraps.

The time scales shown in Figure 1.6 exhibit a similarly wide range. Some characteristic times are intrinsic to the fluid and independent of the diameter and speed of the jet or drop, while others are independent of the fluid but linked via length and speed. Impact of the drop on to a substrate is fundamental to inkjet printing; capillary spreading and the curing/drying timescale provide the basis for controlling the extent of the deposit on the substrate. As surfactants and other additives may be required for the functionality of the inkjet applications, it is important to understand that they are generally slow-acting for jetting but not for the deposition.

1.6 The Structure of This Book

This textbook is structured with chapters discussing the behavior of liquid as it is jetted from within an inkjet printhead through the air and then impacts on to and spreads on a substrate to form a deposit. Fluid mechanics relevant to inkjet printing and the principles underlying the jetting action of printheads are introduced. The nature of complex fluids is shown to have significant influence on fluid behavior under inkjet printing conditions. Numerical simulations explore the jetting, free flying, and spreading behavior of such liquids, with serious discussion about validation of the correspondence between computed and observed behavior in each phase. Experimental techniques for visualization and measurement of jets and droplets and the characterization of fluids and surfaces are described. Some inkjet applications and a forward look to the near future of inkjet technology complete the story told by "The Science of Inkjet and Droplets." Needless to say, the scientific story continues to unfold with new discoveries and insights gained through research and applications. There are undoubtedly some omissions from the story and some particular topics which are only mentioned in passing, although this textbook aims to remain a standard reference.

1.7 Symbols Used

In view of the breadth of science covered by the many contributors, and in the references cited, variable symbols are defined within each chapter quite independently, to reflect their usage in the particular scientific fields, so that the user can recognize them in context. This also means that some of the key parameter definitions are repeated in slightly different forms across the textbook.

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