Part I

Printer/print head

3
Ink jet printing technology (CIJ/DOD)

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3.1 Introduction

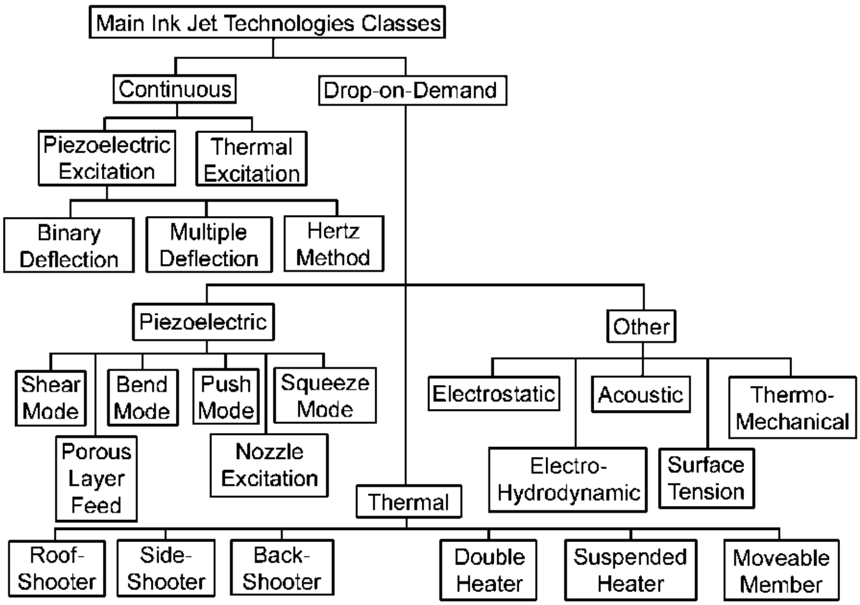
Ink jet is a technology that enables the delivery of liquid ink to a medium whereby only the ink drops make contact with the medium. It is therefore a non-impact printing method. Much of the fundamental theory behind the ink jet technology was developed at the end of the nineteenth century by Lord Rayleigh (Rayleigh, 1878) but the development of the technology itself did not start until the late 1950s and 1960s.

Ink jet has three basic components, all of which need to work well in order to produce an acceptable output. These pieces are the print head, the ink, and the medium. The objective of this chapter is to review the ink jet state of the art from the print head standpoint. We start in the next section by describing the ink jet technology classes and explaining the advantages and disadvantages of two of the most prevalent technologies. In Section 3.3 we discuss aspects to consider when selecting a print head technology. Section 3.4 provides a list of the companies that presently have active print head development programs. Finally, in Section 3.5, we speculate on what developments one might expect to see in the near future.

3.2 Ink jet technologies

Ink jet technologies are typically classified in two large classes: Continuous Ink Jet (CIJ) and Drop-on-Demand Ink Jet (DOD). In CIJ, ink is squirted through nozzles at a constant speed by applying a constant pressure. The jet of ink is naturally unstable and breaks up into droplets shortly after leaving the nozzle. The drops are left to go to the medium or deflected to a gutter for recirculation depending on the image being printed. The deflection is usually achieved by electrically charging the drops and applying an electric field to control the trajectory. The name 'continuous' originates in the fact that drops are ejected at all times.

In DOD ink jet, drops are ejected only when needed to form the image. The two main drop ejector mechanisms used to generate drops are piezoelectric ink



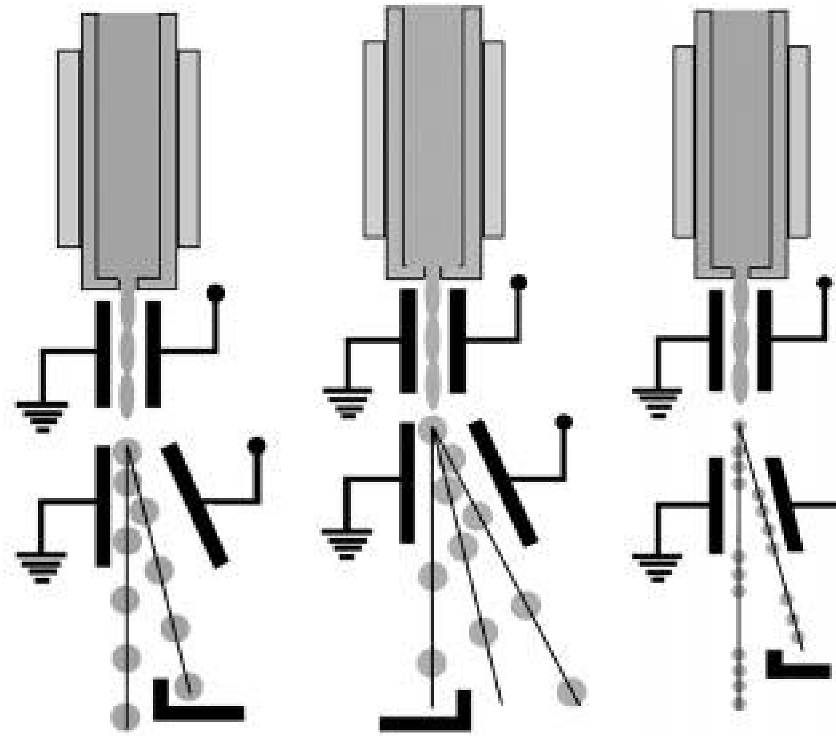
3.1 Main classes of ink jet technologies.

jet (PIJ) and thermal ink jet (TIJ). In PIJ, the volume of an ink chamber inside the nozzle is quickly reduced by means of a piezoelectric actuator, which squeezes the ink droplet out of the nozzle. In TIJ, an electrical heater located inside each nozzle is used to raise the temperature of the ink to the point of bubble nucleation. The explosive expansion of the vapor bubble propels the ink outside the nozzle. Other less common drop generator technologies disclosed in the patent literature will be briefly described below but most of our focus will be on CIJ, PIJ and TIJ. Figure 3.1 shows the classification of the various ink jet technologies.

3.2.1 Continuous ink jet

In CIJ the jet of ink generated by each nozzle breaks up into droplets shortly after exiting the nozzle. Without any other intervention, the breakup would occur randomly and would result in droplets of variable sizes. This is usually corrected by providing a periodic excitation to the nozzle in the time domain that translates into a spatial perturbation in the jet of fluid. The combination of the jet velocity and frequency of the excitation determines the droplet size, which can be controlled to very high accuracy.

In the traditional CIJ approach, a piezoelectric transducer is coupled to the print head to provide the periodic excitation. The oscillations are therefore mechanical in nature. After leaving the nozzle, the drops are electrically charged by an amount that depends on the image to be printed. The drops then pass

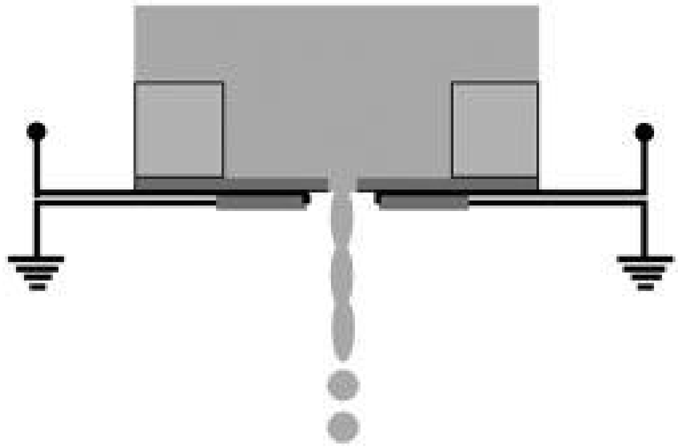


3.2 (left) Continuous ink jet – binary deflection.
3.3 (middle) Continuous ink jet – multiple deflection.
3.4 (right) Continuous ink jet – Hertz method.

through an electric field to cause them to deflect. There are two ways of deflecting the drops in piezoelectric-driven CIJ. In the binary deflection method the droplets are directed either to a single pixel location in the medium or to the recirculating gutter. In the multiple-deflection method the deflection is variable so the drops can address several pixels. These two concepts are illustrated in Figs 3.2 and 3.3.

There is a variant of CIJ called the Hertz method after Dr Carl H. Hertz of Sweden who invented it (Hertz *et al.*, 1986). In the Hertz method the amount of ink deposited per pixel is variable. This is achieved by generating very small drops (of the order of 3 pL) at speeds of about 40 m/s with excitation frequencies of over 1 MHz (see Fig. 3.4). The drops not intended to reach the medium are charged and deflected to a gutter. The printing drops are given a smaller charge to prevent them from merging in flight. Iris Graphics has successfully commercialized this technology on digital color proofers. The company is now part of Kodak.

Kodak has recently disclosed a CIJ system in which thermal pulses are used to uniformly break up the jet of ink (Hawkins, 2003; Anagnostopoulos *et al.*,



3.5 Continuous ink jet – thermal excitation.

2001). In this version of the technology, each nozzle has an annular electrical heater that is pulsed at a certain frequency. The heat generated raises the temperature of the ink jet in the vicinity of the nozzle and locally lowers the viscosity of the ink. Because the heating pulse is periodic in time and the jet velocity is constant, the resulting jet breaks up into equally sized drops in a reproducible way. This type of drop ejector is illustrated in Fig. 3.5.

The thermal CIJ technology lends itself to several deflection mechanisms. One could certainly charge the drops and use the standard electric field-driven method to achieve the deflection. Another option disclosed by Kodak is air deflection in combination with modulation of the drop size by the heating pulse so that when no drops are needed their size is reduced and an air current deflects them to a gutter. A third approach is based on dividing the annular heater that controls the drop breakup into two independently controlled heaters placed on diametrically opposite sides of the nozzle. By applying different energy to each heater, the direction of the jet can be steered at will.

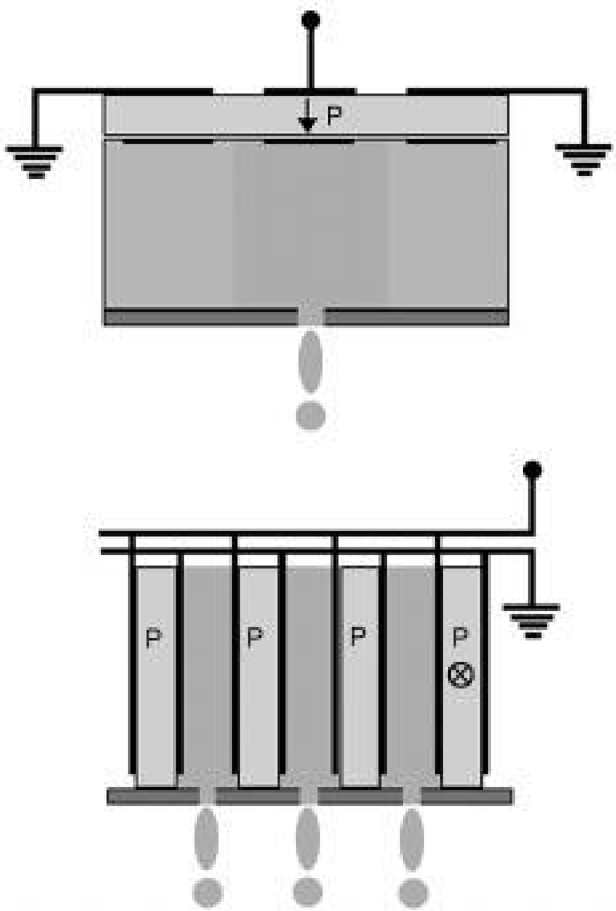
Because of the complexities associated with conventional CIJ (charge and deflection, ink recirculation, pressurization) such print heads tend to be costly. On the other hand, because the nozzles are actively refilled by the positive pressure operation, the operating frequencies of these devices are typically at least an order of magnitude higher than in DOD systems. For these reasons, CIJ systems are generally used in industrial applications.

3.2.2 Drop-on-demand piezoelectric ink jet

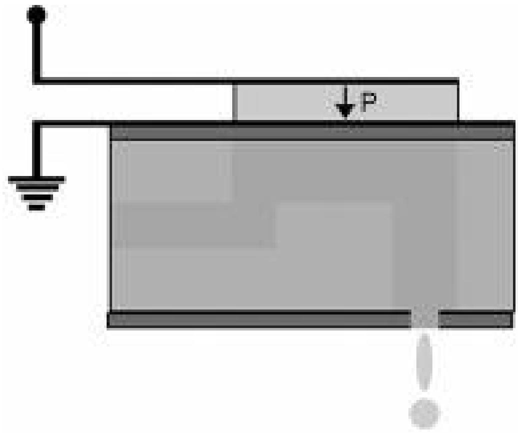
In piezoelectric ink jet, the mechanism used to generate the droplets is a piezoelectric element, typically made of lead zirconate titanate (PZT). Depending on the architecture of the head, the piezoelectric transducer could be attached to a membrane that forms an ink chamber wall or could actually constitute the chamber itself. In either case, when a voltage is applied to the electrodes of the piezoelectric element the volume of the chamber is typically reduced, which results in a droplet of ink being squirted out of the nozzle.

PIJ print heads are sometimes subdivided in different classes according to the geometry of the drop ejector and/or how the piezoelectric element operates. The classes, shown in Fig. 3.1, are 'shear mode', 'bend mode', 'push mode', 'squeeze mode', 'nozzle excitation', and 'porous layer feed',

A common configuration used, for example, by Spectra (Fishbeck *et al.*, 1989) is the shear mode. In shear mode ink jet, the electric field is perpendicular to the poling direction of the piezoelectric material (see Fig. 3.6). The application of this field produces a shear motion in the piezoelectric material that makes the membrane move like an oil can. Xaar's drop ejectors (Temple *et*



3.6 Drop-on-demand piezoelectric ink jet – shear mode.



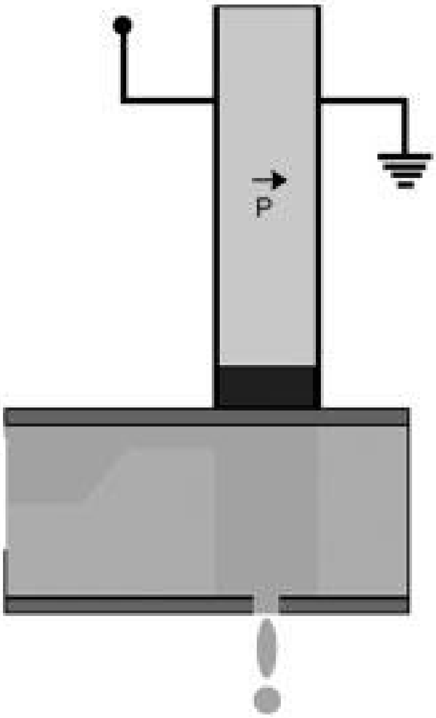
3.7 Drop-on-demand piezoelectric ink jet – bend mode.

al., 1995) also operate in the shear mode (i.e., the electric field is perpendicular to the poling direction), but in their version the firing chambers are grooves diced into the piezoelectric material and the electrodes are placed inside the chambers. For that reason, this configuration is also referred to as 'shared wall'. Unlike Spectra's version of the technology, the walls approaching each other cause the volume reduction in the chambers during firing.

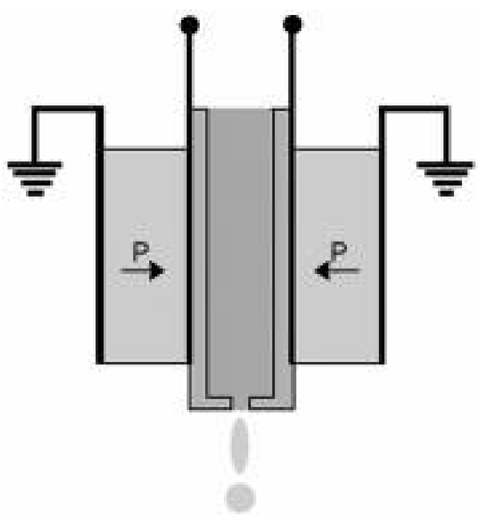
In bend mode piezoelectric ink jet, the electric field and poling directions are parallel. The piezoelectric material is placed on the membrane and the membrane moves like an oil can. This configuration is illustrated in Fig. 3.7. Print heads made by companies such as PicoJet and Xerox (Tektronix) as well as some of Epson's print heads operate in this mode. In the push mode piezoelectric ink jet used by Trident, the electric field and polarization vectors are also parallel but the membrane is placed in the expanding direction of the piezoelectric material (see Fig. 3.8). In the squeeze mode the drop ejector is a hollow tube of piezoelectric material. Upon the application of an electric field, the inside volume of the tube (firing chamber) decreases its radius and ejects the ink in the direction of its axis (Fig. 3.9).

A novel way of configuring a piezoelectric drop ejector has been disclosed by The Technology Partnership (Arnott *et al.*, 2002) and, independently, by HP (Haluzak *et al.*, 2004). In this configuration the piezoelectric elements are mounted on the nozzle plate (see Fig. 3.10). The simplicity of the fluid path achieved in this concept should result in significant cost advantages as well as robustness against the presence of air bubbles in the ink path. To our knowledge, this concept has not yet been commercialized.

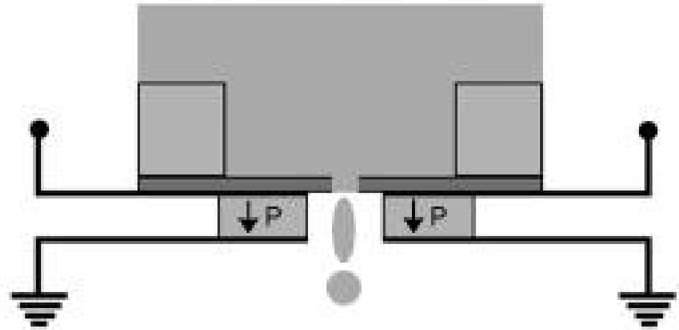
In the piezoelectric print head designed by Aprion, the actuator chamber is made out of a porous metal layer (e.g., sintered stainless steel) and the ink is fed to the chamber through this porous material. The concept is illustrated in Fig. 3.11.



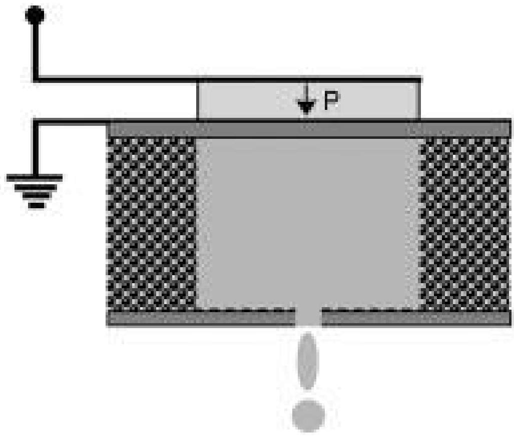
3.8 Drop-on-demand piezoelectric ink jet – push mode.



3.9 Drop-on-demand piezoelectric ink jet – squeeze mode.



3.10 Drop-on-demand piezoelectric ink jet – nozzle excitation.



3.11 Drop-on-demand piezoelectric ink jet – porous layer.

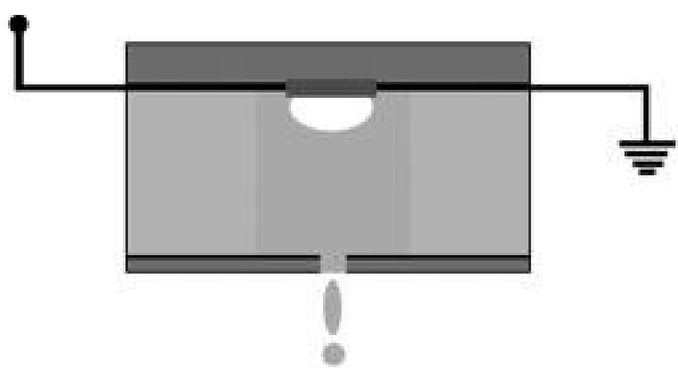
In piezoelectric ink jet, waveforms with various levels of complexity can be used to control the whole ejection process (Lubinsky *et al.*, 2002). Pre-pulses can be timed to get the nozzle meniscus to bulge out or in, thereby increasing or reducing the ink present in the front channel. This results in larger or smaller droplets, respectively. More complex waveforms are also used to effectively increase or decrease the drop volume by pumping small droplets that merge into a single (larger) drop shortly after leaving the nozzle. In principle, all of these techniques are capable of adjusting the drop volume over an order of magnitude, though this is not very common in commercial products.

3.2.3 Drop-on-demand thermal ink jet

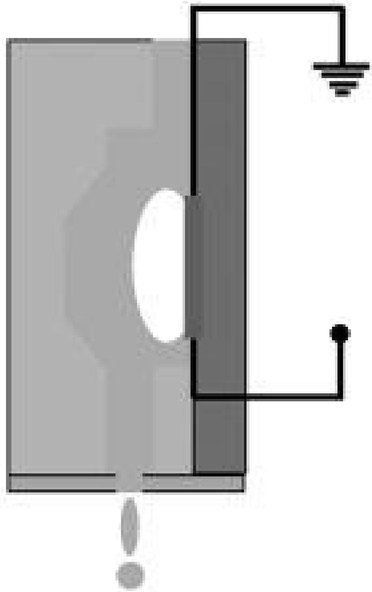
In TIJ an electric heater is typically built inside the nozzle, usually by microelectronic device fabrication techniques. A current pulse is allowed to flow through the heater to quickly raise the temperature of the ink in its vicinity to over 300ºC. This causes a vapor bubble to violently nucleate and expand, ejecting an ink droplet through the nozzle orifice. Water tends to cause more explosive bubble growth than other solvents. For this reason, TIJ favors water-based inks.

The TIJ process resembles an explosion. Once the bubble nucleates and starts expanding, there is no point in continuing to provide power to the heater because the bubble is a poor thermal conductor. Thus, the pulse is usually tailored to stop shortly after bubble nucleation. As the bubble expands it cools and its pressure (which starts at over 70 atmospheres in water based inks) drops quickly. The bubble reaches its maximum size and then, just as violently, it collapses, retracting the meniscus to a region inside the channel. After the bubble collapses, capillary action drives the refill process, which continues until the channel is full again, ready to fire. Because of its explosive nature, there is little control over the process beyond the pulse length and power applied. Techniques of providing a short pre-pulse (or train of pre-pulses) to pre-warm the ink in the vicinity of the heater are sometimes used. With these techniques, one can control or modify in a limited way the total ejected ink volume.

There are several configurations of TIJ drop ejectors, the most common being the 'roof-shooter' and 'side-shooter' types. In the 'roof-shooter' type shown in Fig. 3.12, the plane where the heater resides is parallel to the nozzle plane. In the 'side-shooter' type, the nozzle plane is perpendicular to the heater plane. This configuration is illustrated in Fig. 3.13. There are also 'back-shooter' drop generator designs (Lee *et al.*, 2004) where the heater is located on the back side of the nozzle plate, as shown in Fig. 3.14. Canon introduced in 1997 a side-shooter version with multiple heaters that enables drop modulation. A top view of this design is shown in Fig. 3.15. Sony has developed a roof-shooter type drop ejector (Eguchi *et al.*, 2004) that has two independently-driven side-by-side heaters (see Fig. 3.16). This feature can be used to control the directionality of the ejected drop. Energy-efficient configurations with suspended heaters have also been proposed (Kubby, 1998; Hideyuki *et al.*, 2004). In these configurations

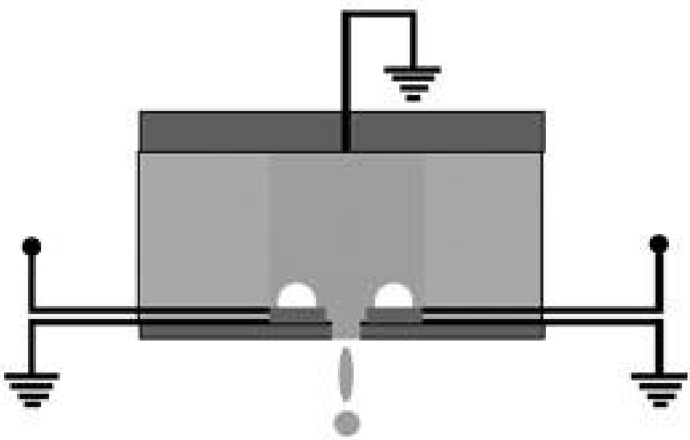


3.12 Drop-on-demand thermal ink jet – roof shooter.

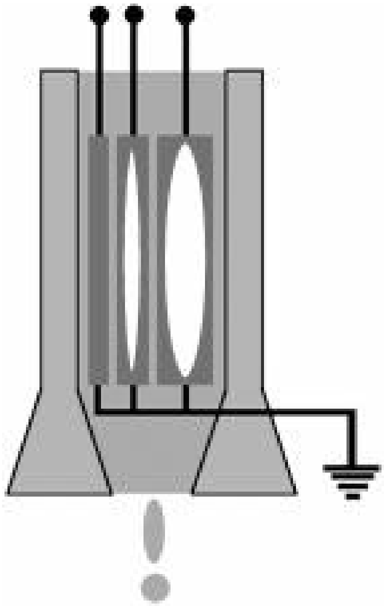


3.13 Drop-on-demand thermal ink jet – side shooter.

(shown in Fig. 3.17), because the heater is embedded in the ink, a larger portion of the total heat generated during the fire is transferred to the ink, resulting in higher energy efficiency than in the configurations where the heater is in a substrate. Finally, Canon has disclosed in a series of patents (see, for example, Kudo *et al.*, 1998) a drop ejector design with a moveable member that, pushed during the vapor bubble expansion, prevents the ink from flowing into the ink



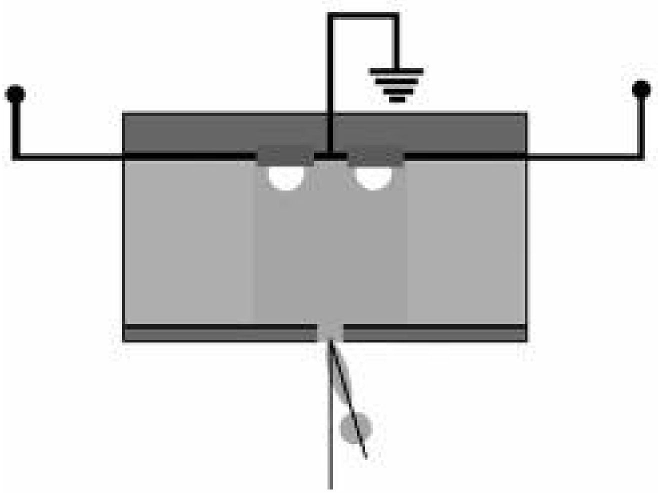
3.14 Drop-on-demand thermal ink jet – back shooter.



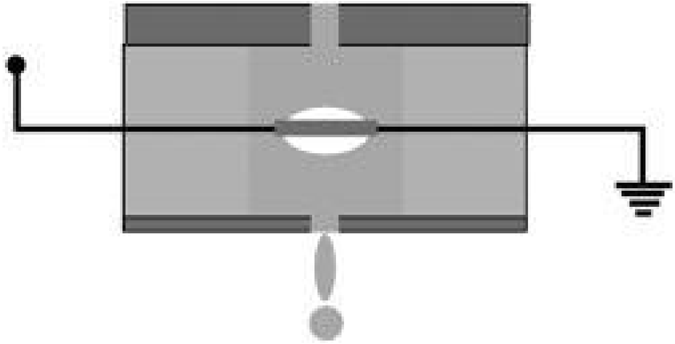
3.15 Drop-on-demand thermal ink jet – multi heater.

reservoir through the rear channel region. This feature would be expected to enhance the energy efficiency of the drop ejector (see Fig. 3.18).

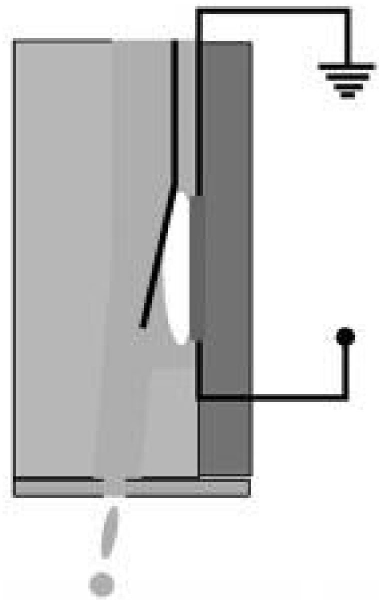
The fabrication methods used to make TIJ print heads are typically those that are used by the semiconductor industry. This enables the possibility of building a substantial amount of the drive and control electronics into the print head. As a



3.16 Drop-on-demand thermal ink jet – double heater.



3.17 Drop-on-demand thermal ink jet – suspended heater.

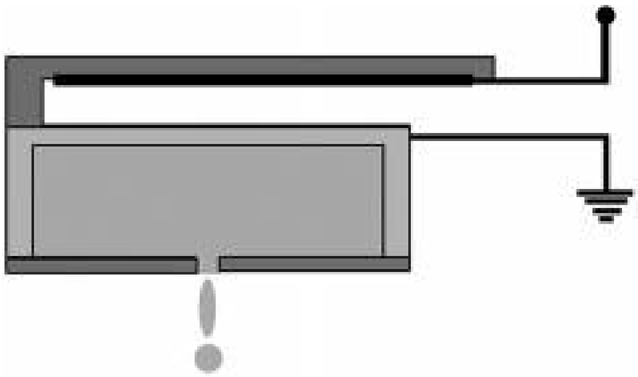


3.18 Drop-on-demand thermal ink jet – moveable member.

result of this integration, a typical commercial TIJ print head can have hundreds of nozzles but only tens of leads. This, coupled with the batch processing economies of IC fabrication techniques, results in low cost, multi-nozzle print head arrays.

3.2.4 Other drop-on-demand ink jet technologies

Though the most widely used DOD technologies are PIJ and TIJ, there are other DOD technologies at various stages of development that can potentially succeed

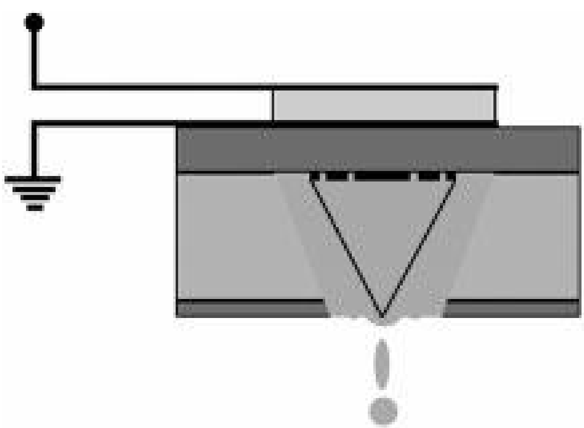


3.19 Drop-on-demand electrostatic ink jet.

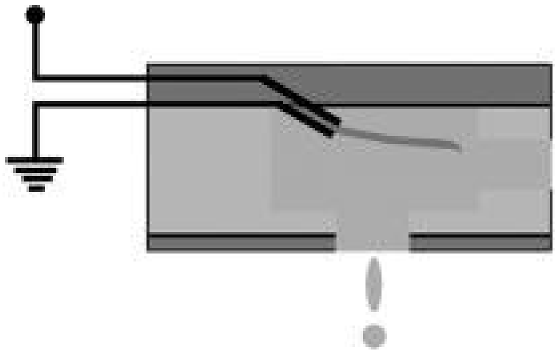
in addressing the customer needs of some markets. In this section we give a sampling of this wide range of ideas by describing five of them. A more detailed description can be found in the book by Stephen F. Pond (Pond, 2000).

Similar to a piezoelectric transducer, an electric field can be used directly to move the membrane of an ink chamber and thus produce drop ejection. This technology is enabled by MEMS (Micro Electro Mechanical System) fabrication techniques. This is the principle of operation of an electrostatic ink jet drop ejector shown in Fig. 3.19. Epson has the only commercial product (a point-of-sale printer) based on this technology, though other companies have some level of R&D focused on it.

Xerox has developed an ink jet technology in which an acoustic excitation is focused on the free surface of the ink in order to eject a drop (Quate *et al.*, 1991) (see Fig. 3.20). One advantage of this technology is that, in principle, no nozzle structure is needed. On the other hand, the ink level has to be tightly controlled



3.20 Drop-on-demand acoustic ink jet.

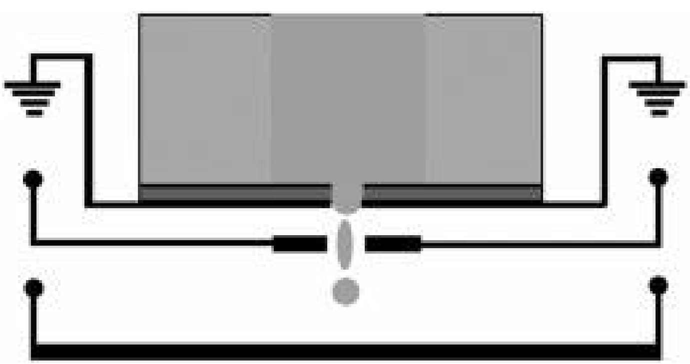


3.21 Drop-on-demand thermo-mechanical ink jet.

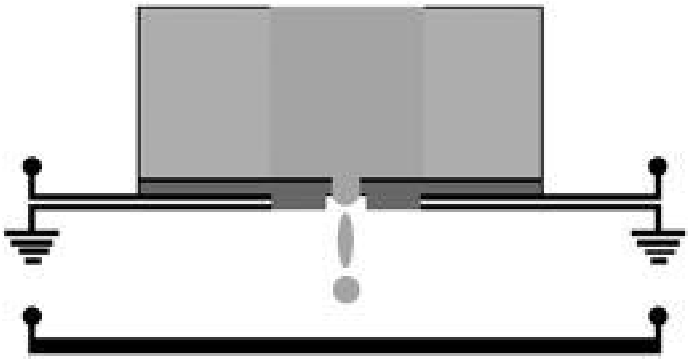
and patent literature shows (Hadimioglu *et al.*, 1993) that nozzles can be used to control the ink level quite effectively. The technology has been demonstrated, but to our knowledge no product has been commercialized to date.

The thermo-mechanical ink jet technology disclosed is another example of drop on demand ink jet (Silverbrook, 2001; Trauernicht *et al.*, 2002). The principle of operation is based on the sudden motion of a composite structure caused by differing coefficients of thermal expansion induced by the heating of an electric resistor. Many embodiments have been disclosed for this concept. In one embodiment the motion of a paddle immersed in the ink behind the nozzle initiates the drop ejection process (see Fig. 3.21). In another, the nozzle structure itself is made to move inward thereby generating a drop. To our knowledge this method is not yet commercial.

A mechanism sometimes referred to as 'Electro-hydrodynamic Extraction' has been also used to generate ink drops (see, for example, Newcombe *et al.*, 1999). The concept is illustrated in Fig. 3.22. Equilibrium is achieved in the non-printing state between a negative pressure provided at the ink supply and a standby electric field generated by an extraction electrode located in front of the



3.22 Drop-on-demand electro-hydrodynamic extraction ink jet.



3.23 Drop-on-demand surface tension driven ink jet.

nozzle. When a drop is needed, a higher potential is applied to the extraction electrode, causing the drop ejection. A collection electrode behind the medium is also required to guide the drop to the medium. Casio commercialized this technology in the early seventies but, to our knowledge, no product is being sold at the present time.

Silverbrook has disclosed in a series of patents assigned to Kodak (Silverbrook, 1999) the concept we refer to in Fig. 3.1 as ‘Surface Tension Driven Ink Jet’. The concept, also called ‘Liquid Ink Fault Tolerant’ (LIFT) ink jet, consists of establishing equilibrium in the nozzle between a positive driving force and surface tension. This driving force can be a positive head pressure or a high voltage differential, both of which would cause the ejection of drops if the ink surface tension were lowered. When an electrical heating element is positioned at the nozzle is activated, the ink temperature increases, lowering the surface tension of the ink and inducing the ejection of a drop. We are not aware of any commercial product that utilizes this technology. The concept is illustrated in Fig. 3.23.

3.2.5 Strengths and weaknesses of the various technologies

The technologies described in the previous sections have advantages and disadvantages depending on the application for which they are intended. In this subsection we illustrate this point by comparing the two main DOD technologies: PIJ versus TIJ.

The displacement that can be achieved with a piezoelectric material sets a limit to the packing density of nozzles in PIJ. Current techniques and operating voltages typically produce displacements on the order of 0.1 μm. Thus to generate a volume change of 30 pL (i.e., 3000 μm^3), a 30,000 μm^2 area per firing chamber is necessary. This should be compared to a heater area of about 1300 μm^2 of a comparable TIJ drop ejector. In reality, the situation is worse because the change in chamber volume required to eject a drop of a given size is on the order of twice the drop volume. For this reason the native resolution (i.e., the number of nozzles per inch in the direction of the nozzle array) of commercial TIJ heads is significantly higher than for PIJ heads. Of course this problem can be dealt with by laying out extensive two-dimensional arrays of nozzles but at a cost of substantially more real estate.

Another advantage of TIJ (mentioned previously) is that semiconductor fabrication techniques are used to manufacture these types of heads. It is therefore possible to integrate the electronics necessary to drive the heaters into the print head. This has been difficult to achieve with PIJ print heads and, to our knowledge, no such devices have yet been commercialized.

For the two reasons stated above, TIJ print heads tend to be more compact and less costly than their PIJ counterparts.

A problem intrinsic to ink jet technology is the detrimental effect on jetting of the presence of trapped air bubbles in the ink system. A bubble is a compliant element in the system and can absorb a substantial portion of the driving pressure pulse, rendering it totally or partially ineffective.

There are many possible sources of air bubbles in ink jet devices. Air dissolved in the ink can nucleate at rough surfaces and sharp edges. Particulates suspended in the ink can also lead to air bubble nucleation. Another source of trapped bubbles is the presence of corners in the ink delivery system that can be difficult to fill in the priming process. PIJ waveforms typically tend to create areas of low pressure in the ink in portions of the firing cycle which tend to ex-solve air through a process called rectified diffusion. Rectified diffusion occurs because the rate of diffusion of a gas toward the liquid during the compression portion of the cycle is smaller than the rate at which the gas leaves the liquid in the low pressure portion, causing the bubble to grow. Finally, the heating of the ink during the firing pulse in TIJ devices also causes air ex-solution.

Air management is another area where the state of the art TIJ is superior to PIJ. The main reason for this is that TIJ devices have the drop generator energy source very close to the nozzle, which tends to flush air bubbles away from the critical regions more effectively. The ink path from the firing chamber to the nozzle tends to be more complex in commercial PIJ devices and in most cases degassed ink is used.

An advantage of piezoelectric ink jet relative to thermal ink jet is ink latitude. Because the vapor pressure of water at the nucleation temperature is abnormally high, water is a very good ‘propellant’. Though examples of drop ejection of non-aqueous fluids from thermal ink jet devices have been disclosed, all commercially available TIJ print heads fire aqueous inks. Piezoelectric heads, on the other hand, can easily fire any fluid, within a given range of operating viscosity and surface tension. For this reason, most industrial non-conventional applications of ink jet use piezoelectric technology. UV inks, phase-change inks and solvent-based inks, for example, are jetted with PIJ devices.

As discussed in Section 3.2.2, another PIJ advantage relative to TIJ is the ability to control the volume of the drop through the shape of the waveform. Pre-pulsing techniques can be used in thermal ink jet to affect the volume of the drop (Becerra *et al.*, 2004) but the effect produced is fairly modest compared to PIJ, where up to an order of magnitude of drop volume variation is possible.

The management of the waste heat is an important issue in thermal ink jet. In TIJ devices only a small fraction of the heat generated by the heater is ejected with the drop in one cycle. Therefore, unless measures are taken to control this problem, the temperature of the head increases with use and duty cycle. As the temperature increases, the ink viscosity decreases and the thermal energy stored in the superheated layer of ink at the time of bubble nucleation increases (Freire, 1997). The end result of these effects is that the drop volume drifts upward, causing print quality issues. Heat sinks and/or fluid paths that enable self-cooling are typically used to manage this heat in combination with pre-warming algorithms. In contrast, for piezoelectric devices, most of the energy dissipation occurs in the driver electronics that are typically thermally disconnected from the actual print head. Thus, the operation of piezoelectric devices is naturally more isothermal.

Drop ejector lifetime is another aspect where PIJ is generally considered to be more robust than TIJ. Two failure modes unique to TIJ contribute to this difference. The accumulation of ink-related deposits on the surface of the heater, called ‘kogation’, is one of them. These deposits tend to thermally insulate the heater, causing non-uniform nucleation. Over time, drop ejection failure occurs. Bubble collapse is another cause of drop ejector failure in TIJ. This process is very violent and can erode the heater surface through a phenomenon called cavitation damage. Ink formulation and coating the heater surface with highly durable materials are common practices that bring the drop ejector lifetime up to acceptable levels for TIJ applications.

3.3 Aspects to consider and metrics to use in the print head selection process

The decision as to which technology and version to use for a given application has to take into account a variety of factors. These factors can be loosely grouped in four categories: image quality, cost, printer productivity (or throughput), and ink latitude. In this section we discuss these topics and, in some cases, introduce metrics that can help in the technology selection process.

3.3.1 Image quality

The key image quality parameter to be considered in making a print head decision is the drop volume. In general, the lower the drop volume, the finer are the details that can be imaged. This is because, given the ink and medium, the drop volume determines the size of the printed dot. As expected, the drop volumes ejected by commercial print heads have come down significantly over time. The first drop-on-demand thermal ink jet print heads for desktop applications produced drop volumes in excess of 100 pL. Nowadays photo printers use TIJ or PIJ print heads capable of delivering drop volumes as low as 1.5 to 2 pL.

When addressing print quality, drop volume should not be confused with resolution. Resolution refers to the scale of the grid over which the dots are placed and it is customary to measure it in 'dots per inch' or dpi. Often the addressable points are located in a rectangular grid. In such cases, two resolutions are quoted, one for each of the orthogonal directions. For example, a printer that uses a reciprocating carriage could print at a resolution of 2400 × 1200 dpi. This means that the dots are placed at a 2400 dpi spacing (i.e., 10.6 μm apart) in the direction of the motion of the carriage and at a 1200 dpi spacing (i.e., 21 μm) in the perpendicular direction. It follows that increasing the resolution improves print quality but only up to a point. If the resolution is increased to the point that the dot diameter is much larger than the resolution, the print quality improvement is insignificant (and other problems related to drying time and speed could be generated). Moreover, the resolution is essentially a feature of the system. Virtually any resolution can be achieved with a given print head using multi-pass printing and/or adjusting the print head effective resolution by rotation. The drop volume, on the other hand, is a parameter intrinsic to the ink–head combination.

Gray scale (i.e., the ability to generate drops of variable sizes from the same print head) is another print head characteristic that is usually considered under image quality. We believe, however, that drop volume (in this case the smallest achievable one) is still the appropriate metric to describe image quality even in print heads with gray scale capabilities. This is because the ability to eject larger drop volumes does not impact image quality but, rather, *productivity* in solid tones and regions of high area coverage.

3.3.2 Cost

The cost of the print heads obviously impacts the cost of the machine. Given the ink and media, the productivity of the printer is determined by the operating frequency and the total number of nozzles in the printer. For this reason, a metric frequently used to normalize cost is the cost per nozzle.

The cost of ownership or running cost is obviously impacted by the price of the ink and media, but the print head lifetime is also a factor in this cost because it determines how often the print head needs to be replaced. It is common for print head manufacturers to test their print heads to failure with a recommended ink and use Weibull statistics to determine a minimum life. Many factors can affect print head lifetime. They can range from contamination in the ink delivery system to loss of hydrophobicity of the print head nozzle plate. At the center of the problem is the ink–print head interaction. Therefore, unless the manufacturer's recommended ink is used, the quoted minimum life cannot be taken for granted and reliability tests will be needed.

Another print head related cost that needs to be considered in the total running cost is ink royalty. Some head manufacturers would add a royalty cost that is usually computed as a percent of ink sales per print head.

3.3.3 Productivity

The fastest way of printing at full area coverage is to have all nozzles fire at the maximum allowable frequency. The required amount of ink per unit area for full area coverage printing is a function of the ink and medium. It follows that the productivity of a print head is given by the amount of ink it can deliver per unit time. Thus,

$$P_H = n \times f \times V$$

where P_H is the productivity, n is the number of nozzles in the head, f is the operating frequency and V is the drop volume. Note that if the desired printing resolution is not equal to the print head native resolution, more passes will be needed (or the print head would have to be placed so that the array direction is not perpendicular to the printing direction) but the productivity definition stated above still limits the maximum throughput.

The productivity metric P_H introduced above is clearly a print head centric metric. The more primitive nozzle productivity can sometimes be used ($P_N = f \times V$). From a performance standpoint this is probably the main discriminator between CIJ and DOD ink jet. This is because the maximum operating frequency in state of the art DOD ink jet is in the tens of kilohertz whereas CIJ typically operates at hundreds of kilohertz.

Some of the metrics introduced above can be combined to address other questions. For example, one can define the print head productivity cost as the ratio between the head cost and its productivity. The print head productivity cost therefore measures the dollar cost of 1 liter per hour of productivity. Similarly, one can compute the productivity cost per nozzle, i.e., the dollar cost of 1 liter per hour of productivity *per nozzle*. For example, the cost of CIJ print heads is high. On the other hand, they tend to be very productive because of the high frequencies at which they operate. The productivity cost per nozzle of some CIJ systems is actually quite competitive, making them suitable for high-speed applications.

3.3.4 Ink latitude

Another key factor in the technology decision is ink latitude. As discussed in the previous section, commercial TIJ print heads are typically effective for low viscosity (i.e., less than about 4 cps) water-based inks. Therefore, PIJ print heads are generally used for industrial applications that require operating outside this region. We do not have a good metric to address ink latitude other than the manufacturer recommended range for the viscosity and surface tension of the fluid to be ejected. Within PIJ heads there are certain limitations regarding the ink vehicle. Some print heads are manufactured with materials (typically adhesives) that are affected by the presence of water. Those heads cannot be used with aqueous inks.

The conventional continuous ink jet process requires that the droplets be charged after ejection. Therefore the conductivity of the inks used in conventional CIJ heads needs to be high.

3.4 Companies currently active in print head technology

Ink jet technology has been around for many years and many companies have entered and exited this field. In this section we provide the reader a sense of the size of the ink jet print head field by listing all the companies that we believe are actively working on print head technology. The list was constructed from attendance at trade shows, researching the patent literature, and by Internet searches. We do not claim to have a complete list since the field is highly populated but we believe the list captures the major players.

The field of TIJ print heads has been historically controlled by four companies that had enough intellectual property to practice the art. These companies are Canon, Hewlett-Packard, Lexmark, and Xerox. Xerox exited the TIJ business in 2001 leaving only three major players. Patent activity shows that other companies are actively pursuing this field, motivated by the expiration of the some of the first TIJ patents.

In the desktop market the main PIJ player is Epson, followed by Brother. In industrial DOD ink jet the three major players are Epson, Spectra and Xaar with its licensees. The main players in CIJ are VideoJet, Domino and Imaje.

Due to the robustness required by the textile industrial application and the relatively higher viscosity of some textile inks, the textile market is currently dominated by PIJ technology. Most textile inks are also water-based so only those PIJ print heads that are water-compatible are being used. CIJ could also serve this sector, but the constraints coming from the roll-fed media combined with the high carriage speed required to take advantage of the high operating frequency of this technology make the implementation more difficult. Stationary multiple jet arrays could solve this problem but the cost (and throughput) would put such a machine in a completely different class. Osiris has announced a CIJ-based printer but, to our knowledge, the product is not yet commercial. Accordingly, the print heads with significant presence in the textile market are currently those offered by Aprion, Epson, and Seiko.

The list of major print head manufacturers is shown in Table 3.1. The table includes the type of technology and whether the company is known by the author to have commercialized any print heads. We have also included a column to capture the companies that currently serve the digital textile printer market. Note that the table is print head centric. This means that printer integrators that outsource the print head technology are not included.

3.5 Future trends

There are several developments happening at the moment that are likely to shape the future of this technology. A major factor is that many of the original patents are currently or will be expiring in the near future. This is an incentive for new entrants into the various areas of the technology, including print heads. Thus the market may see new players in the future which, in turn, may generate new concepts as well as drive prices down. Companies in the Far East will likely take advantage of this opportunity and we can see this trend already in the patent literature with active players such as Samsung, ITRI, and BenQ, among others.

Another factor that is likely to influence the field in the future is the development of page-wide array systems. From the early days of this technology several companies have worked on the development of a page-wide print head that could print a full page without the need of a reciprocating carriage. One key challenge of page-wide array systems is that they would operate in single-pass mode. Virtually all multi-nozzle printing systems currently have multi-pass printing modes to ensure the highest print quality by minimizing issues of directionality, missing jets, and other nozzle-to-nozzle non-uniformities in the head. Operating in single-pass mode requires a much higher print head quality level than that needed in current products. This is one of the technical reasons why page-wide printers are not widely available. Sony has recently announced a page-wide system using its proprietary double heater TIJ technology. The printer is being sold in Japan. Brother has also announced a page-wide array product and demonstrated it at the 2005 World Exposition at Aichi, Japan ('EXPO 2005') on 25 March 2005. From their disclosure, the print bar is made out of trapezoidal two-dimensional piezoelectric nozzle arrays.

In the CIJ arena, we think that the thermal excitation technology developed by Kodak is quite promising. According to Kodak's disclosures, the productivity cost per nozzle is better than for any other technology. The ability of using the nozzle heaters to correct jet directionality in a large array of nozzles could potentially be very valuable as well.

3.6 Sources of further information and advice

Ink jet is an ever-evolving area and advances are being made constantly. It is therefore common for literature to become dated quickly. However, the funda-

Table 3.1 List of companies currently active in print head technology

No.	Organization	Technology	Sub-type	Commercialized	Textile application
1	Atlantic Zeiser	CIJ	Binary	None known	None known
2	Danaher (Linx)	CIJ	Multiple deflection	Yes	None known
3	Danaher (VideoJet)	CIJ	Binary	Yes	None known
			Multiple deflection	Yes	Special applications
4	Domino	CIJ	Binary	Yes	None known
			Multiple deflection	Yes	None known
5	Imaje	CIJ	Multiple deflection	Yes	Osiris (announced)
6	Kodak	CIJ	Binary	Yes	None known
			Hertz	Yes	None known
			Thermal excitation	None known	None known
7	Matthews	CIJ	Multiple deflection	Yes	None known
8	Scitex (Jemtex)	CIJ	Multiple deflection	Yes	Digital Printing Systems
9	Stork	CIJ	Hertz	Yes	Stork Amethyst
10	Brother	PIJ	Shear mode	Yes	None known
			Bend mode	Announced	None known
11	Epson	PIJ	Push & bend modes	Yes	Epson, Mimaki, Robustelli, Mutoh, Hollanders, USSPI
		Electrostatic	–	Yes	None known
12	IJT	PIJ	Bend mode	Yes	None known
13	Konica-Minolta	PIJ	Shear mode	Yes	Nassenger Series
14	Kyocera	PIJ	Shear mode	None known	None known
			Bend mode	Announced	None known
		TIJ	Roof shooter	None known	None known
			Side shooter	None known	None known
15	Microdrop	PIJ	Squeeze mode	Yes	None known
16	Microfab	PIJ	Squeeze mode	Yes	None known
17	Panasonic	PIJ	Bend mode	Yes	None known
18	Picojet	PIJ	Bend mode	Yes	None known
19	Ricoh (Hitachi)	PIJ	Push mode	Yes	None known

20	Scitex (Aprion)	PIJ	Porous layer feed	Yes	Reggiani
21	Seiko Instruments	PIJ	Shear mode	PIJ	DuPont Artistri 2020
22	Spectra	PIJ	Shear mode	Yes	DuPont Artistri 3210, Leggett & Platt, Kornit
			Bend mode	Announced	None known
23	Toshiba-TEC	PIJ	Shear mode	Yes	None known
24	Trident	PIJ	Push mode	Yes	None known
25	Xaarjet	PIJ	Shear mode	Yes	None known
26	Sharp	PIJ	Bend mode	None known	None known
27	The Technology Partnership	PIJ	Nozzle excitation	None known	None known
		Electro-hydrodynamic	–	None known	None known
28	Samsung	PIJ	Bend mode	None known	None known
		TIJ	Suspended heater	None known	None known
29	Xerox	PIJ	Bend mode	Yes	None known
		TIJ	Side shooter	Yes (abandoned)	None known
			Suspended heater	None known	None known
		Acoustic	–	None known	None known
		Electrostatic	–	None known	None known
30	BenQ	TIJ	Back shooter	None known	None known
31	Canon	TIJ	Side shooter	Yes	Canon
			Roof shooter	Yes	None known
32	HP	TIJ	Roof shooter	Yes	HP, ColorSpan
33	ITRI	TIJ	Back shooter	None known	None known
34	Lexmark	TIJ	Roof shooter	Yes	Encad
35	Microjet	TIJ	Roof shooter	Yes	None known
36	Olivetti	TIJ	Roof shooter	Yes	None known
37	Sony	TIJ	Double heater	Yes	None known
38	Fuji Xerox	TIJ	Side-shooter	TIJ	None known
		PIJ	Bend mode	None known	None known
39	iTi	Electrostatic	–	None known	None known
40	Fuji Photo	Electro-hydrodynamic	–	None known	None known
41	Silverbrook Research	Surface tension	–	None known	None known
		Thermo-mechanical	–	None known	None known

mentals of the technology and a large portion of the drop ejector designs shown in Fig. 3.1 have not changed significantly. For those topics, the book by Stephen Pond (Pond, 2000) is an excellent reference for further reading. Also, the paper by Hue Le (Le, 1998) contains a good description of the more traditional drop ejector designs. All the references cited in the text are listed below.

3.7 References

Anagnostopoulos C *et al.* (2001), US Pat. No. 6,217,163 and references therein.
Arnott M *et al.* (2002), US Pat. No. 6,394,363.
Becerra J *et al.* (2004), US Pat. No. 6,698,862 and references therein.
Eguchi T *et al.* (2004), US Pat. No. 6,817,704 and references therein.
Fishbeck K *et al.* (1989), US Pat. No. 4,825,227.
Freire E (1997), 'Effects of geometry on the drop volume sensitivity to temperature in TIJ printheads', *IS&T's NIP13*, p. 694.
Hadimioglu B *et al.* (1993), US Pat. No. 5,229,793.
Haluzak C *et al.* (2004), US Pat. No. 6,685,302.
Hawkins G (2003), 'Next generation continuous ink jet technology', 11th Annual European Ink Jet Printing Conference, Lisbon, Portugal.
Hertz C *et al.* (1986), US Pat. No. 4,620,196.
Hideyuki S *et al.* (2004), US Pat. No. 6,834,940 and references therein.
Kubby J (1998), US Pat. No. 5,706,041.
Kudo K *et al.* (1998), US Pat. No. 5,821,962.
Le H (1998), 'Progress and trends in inkjet printing technology', *J. Imaging Sci. Technol.*, 42(1), 49–61.
Lee C *et al.* (2004), US Pat. No. 6,749,762 and references therein.
Lubinsky A *et al.* (2002), US Pat. No. 6,428,135 and references therein.
Newcombe G *et al.* (1999), US Pat. No. 5,992,756.
Pond S (2000), 'Inkjet technology and product development strategies', Torrey Pines Research, Carlsbad, CA.
Quate C *et al.* (1991), US Pat. No. 5,041,849.
Rayleigh Lord (1878), 'On stability of jets', *Proc. London Math. Soc.*, 10(4), 4–13.
Silverbrook K (1999), US Pat. No. 5,856,836.
Silverbrook K (2001), US Pat. No. 6,243,113.
Temple S *et al.* (1995), US Pat. No. 5,463,414.
Trauernicht D *et al.* (2002), US Pat. No. 6,460,972.

4
Drop formation and impaction

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4.1 Introduction

The dynamics of formation and impaction of drops are physical processes of clear relevance to design and control of inkjet printing technologies. While the processes are coupled, in the sense that the drop formation process influences the size, velocity and frequency of the impacting drops, the two processes have typically been studied separately. For that reason, the processes are described as distinct in this chapter. Topics which are important for understanding the processes in applications of inkjet printing to textile materials, in particular the role of suspended particulates and nonsmooth surfaces, are discussed in this chapter.

We begin, in Section 4.2, with a discussion of particulate effects observed in drop formation. The studies described focus on slow drop formation from suspensions of noncolloidal particles in order to allow explicit consideration of the mechanical influence of particles, about which little is known. Engineering of processes has proceeded without firm scientific basis, including jetting of ceramic materials (Blazdell *et al.*, 1995; Windle and Derby, 1999) as well as pigments and polymeric binders onto textiles (Tincher *et al.*, 1998). Because the conditions in such applications are more rapid and at smaller scale than those of our studies, we have focused upon the role of particles in the necking and pinch-off processes, events which are thought to be generic as they force the flow scale to that of the particles, regardless of the rate, absolute size, or the relative sizes of particle and orifice. Note that the abundant prior study (as reviewed by Eggers, 1997) and more recent and ongoing research (e.g., Ambravaneswaran *et al.*, 2002; Chen *et al.*, 2002) on drop formation processes involves almost no work devoted to solid–liquid mixtures, with a few notable exceptions (Alaoui, 1991; Ogg and Schetz, 1985; Furbank and Morris, 2004); there are also a few studies involving viscoelastic liquids (Goldin *et al.*, 1969; Christanti and Walker, 2001), but the rheology of suspensions is very different from that of these liquids.

We follow the discussion of drop formation with a consideration of drop impaction. The size of a printed dot in inkjet printing, which greatly affects print quality, is determined by spreading of an ink drop when it impacts the substrate (Asai *et al.*, 1993). The study of impact dynamics is thus important in determining the ultimate spreading and will be covered in Section 4.3. Most prior studies have been conducted using homogeneous liquid drops impacting smooth surfaces. A general description of spreading without splashing for homogeneous liquid drops impacting on smooth surfaces is covered in Section 4.3.1.

In textile printing, an understanding of the interaction of an individual drop with various textile surfaces is needed. However, obtaining sufficiently high resolution images of an inkjet drop impacting on a textile surface is difficult due to the small drop size (less than 100 microns) and high impact speed (around 5–20 m/s). For this reason, the interaction of an individual drop with various textile surfaces has not been studied. However, Park (2003) used a scaled-up experiment to simulate the impaction of an ink drop on a fabric. Drop impaction on a textile-like structure is presented in Section 4.3.2.

As noted, a growing number of nontraditional applications of inkjet technology contain solid particles. These particles have various purposes, depending upon the application. They serve as colorant or binder in the textile printing applications, but may also be ceramic or metallic particles in other applications. Although progress has been made in the design, formulation and utilization of such inks, impaction of particle-laden drops on surfaces has received little attention (Carr *et al.*, 2004). In fact, only one paper was found in the refereed literature on impaction of particle-laden drops on surfaces (Ok *et al.*, 2004). An on-going investigation of the effects of particles on the impaction process is discussed in Section 4.3.3.

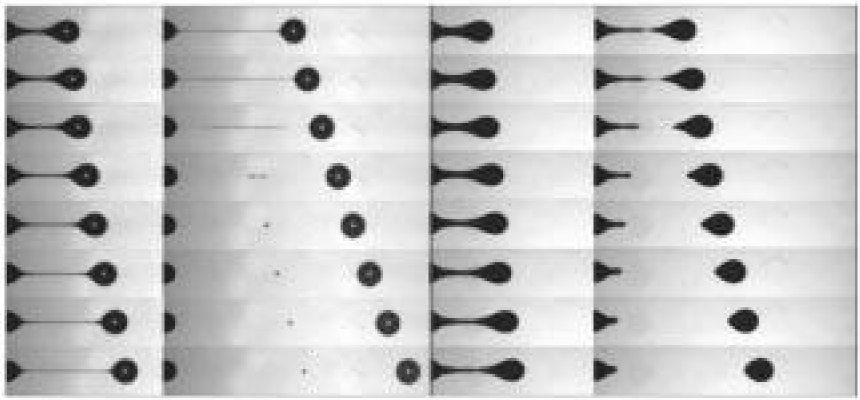
4.2 Drop formation from particle-laden liquids

It is to be expected that the introduction of particles to a liquid from which drops are to be formed adds to the complexity of the problem. The parameter space needed to describe the problem expands, and to the dimensionless groups needed to describe the problem for a pure liquid (typically Reynolds, $\mathrm{Re} = \rho v d/\eta$, and Weber numbers, $\mathrm{We} = \rho v^2 d/\gamma$, or the capillary number, Ca = We/Re in place of We), we must add at least the solid volume fraction ϕ, and the ratio d_p/d of the particle size d_p (diameter if spherical) to the orifice diameter d. The axial velocity v, liquid (or suspension) density ρ, and gas–liquid surface tension γ are used in the above dimensionless numbers. This is by no means a complete description in the actual application, where particles may be small enough that thermal forces inducing Brownian motion (and hence non-infinite Peclet number) as well as colloidal forces need to be considered.

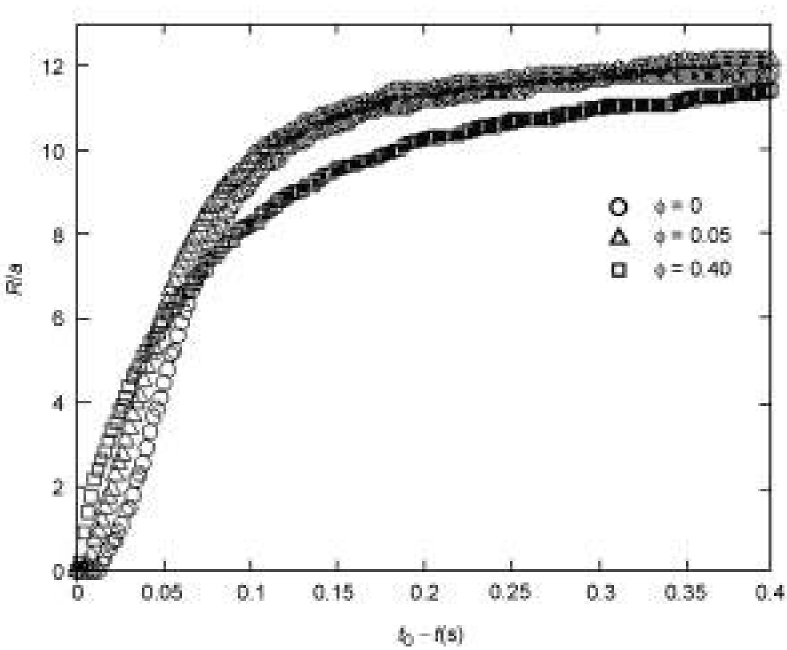
Drop formation from an orifice, regardless of flow rate and length scale of the orifice, involves the formation of a neck which connects the forming drop to the fluid remaining at the orifice. This neck thins and stretches to a thread until the action of surface tension causes a pinch-off, or bifurcation, of the thread to form the drop. The stretching is affected by the liquid viscosity, and it is well known that addition of particles to a fluid causes an increase in the effective viscosity, $\eta_{eff}(\phi)$, of the mixture relative to the suspending liquid. This is by its very nature a continuum description of particle influence, and may only be expected to have validity above some minimum lengthscale (relative to the particle size, with the width of the thread measured in particle diameters using an example relevant to the drop formation). Here, the role of particles identified in slow drop formation (and transition to slow jetting), but believed to be generic to other conditions, is considered. Given space limitations, the manner in which the particles stabilize or destabilize the necking process leading to drop formation is the primary focus.

For slow drop formation, it is useful to consider a two-stage necking model. Early in the process (first stage), η_{eff} describes the added resistance to necking and provides a robust description of particle effects. In the final pinching (second stage), rapid thinning through what must ultimately be a pure liquid region occurs at a relatively localized axial location. The first stage is a continuum description of the particulate effect, with only the need for a solid fraction, ϕ. The second stage is intrinsically a finite-size effect of the discrete particles, as it involves the fluctuations in ϕ, and hence large fluctuations in the ability of the mixture to resist thinning; these may be viewed as fluctuations in the local viscosity.

The two-stage process, and the difference from a pure liquid drop formation event, is illustrated by the sequences in Fig. 4.1: these show that the pure liquid continues to thin and stretch over its entire length right up to bifurcation. The suspension thins in a similar fashion early, and then abruptly pinches at a localized position, leaving relatively thick and slowly retracting cone-like 'spindle' structures up- and downstream of the bifurcation point (Furbank and Morris, 2004, 2006). Quantitative demonstration of this influence for $\phi = 0$, 0.05, and 0.40 is shown in Fig. 4.2, where the evolution with time of the minimum radius for the thread (normalized by the suspended particle radius, $a = d_p/2$) for a drop formed at $Q = 0.25\,\text{cm}^3/\text{min}$ from a 0.16 cm orifice (same conditions as Fig. 4.1) is illustrated as a function of $t_0 - t$, where t_0 is the time of the pinch event; the detected radius determined by automated image analysis reaches zero before t_0 owing to resolution limitations, and the pinch time is corrected based on visual analysis of the image sequence. The behavior is seen to be similar between the various cases for the larger values of $t_0 - t$ plotted, but the pure liquid radius curve shows an inflection to a slower thinning rate near the pinch, while the suspensions from $\phi = 0.05$ and 0.4 thin more rapidly as pinch is approached; other solid fractions behave similarly as shown by Furbank and Morris (2006). This higher thinning rate is the result of a change from uniform thinning over the entire thread to localized thinning through the lower viscosity of the pure liquid. The first stage thinning is found to satisfy a scaling as $Bd \sim (\eta \text{ or } \eta_{eff})^{-1/3}$ for pure liquids of several viscosities as well as suspensions with a range of values of ϕ (and hence η_{eff}). Here B is the thinning rate from the



4.1 Sequence of images approaching pinch-off of a drop in the slow formation of drops from a pure liquid, $\phi = 0$ (left of heavy dark vertical line) and $\phi = 0.20$ suspension, for $d = 0.16$ cm and $d_p = 106–125\ \mu$m in the suspension. The time between images in both sequences is $\Delta t = 0.004$ s. The flow is at $Q = 0.25\ cm^3/min$ (Re = 0.01) in both cases.



4.2 Minimum detected thread radius scaled by the particle radius, *a*, for pure liquid ($\phi = 0$) and suspensions of $\phi = 0.05$ and 0.40; $d = 0.16$ cm and $d_p = 106–125\ \mu$m in the suspension. The flow is at $Q = 0.25\ cm^3/min$ in all cases.

Table 4.1 Fitting parameters to the model equation given in the text for the radius as a function of time from pinch, with the last column giving an indication of the quality of the fit through the value of the regression parameter

d (cm)	d_p (μm)	ϕ	A	B (1/s)	C	R^2
0.16	106–125	0.05	15.7	36.0	−2.3	0.999
0.16	106–125	0.10	14.5	34.6	−1.5	0.999
0.16	106–125	0.20	14.0	32.3	−0.8	0.999
0.16	106–125	0.30	12.4	25.1	0.6	0.999
0.32	212–250	0.05	14.8	19.0	−2.9	0.994
0.32	212–250	0.10	13.7	18.1	−1.5	0.994
0.32	212–250	0.20	12.5	17.5	−0.5	0.995
0.32	212–250	0.30	10.6	14.7	1.2	0.997
0.32	212–250	0.40	9.3	10.8	2.1	0.998
0.32	106–125	0.10	26.5	17.9	−2.7	0.993
0.32	106–125	0.20	24.8	17.9	−0.7	0.995
0.32	106–125	0.30	23.0	13.1	0.2	0.998
0.32	106–125	0.40	21.2	11.5	2.0	0.999

Source: Furbank and Morris (2006).

fit to the experimental $R(t)$ curve to the form suggested by Clanet and Lasheras (1999), $R/a = A(1 - \exp[-B(t_0 - t)]) + C$, where $a = d_p/2$ provides a convenient nondimensionalization. The fitting parameters determined are shown for the suspensions in Table 4.1. The second stage is found also to correspond roughly to the onset of increased fluctuations, both in the position of the minimum radius and in the length of the material attached to the orifice.

Related behaviors found, but not described in detail here, include

- Satellite formation: The introduction of particles is found to cause a pronounced reduction in the number of satellite drops formed in slow drop formation (Furbank and Morris, 2004). This is illustrated by the sequences in the figure, where the pure liquid forms a small satellite, but none appears at $\phi = 0.2$. Note, however, that the few satellites formed from suspension are typically much larger, as these arise from pinch at two points through a much thicker thread.
- Transition rate and length: Particles cause a transition from dripping to jetting at lower flowrates, and the coherent jet is greatly reduced with even 2% solids (Furbank and Morris, 2004). This is evidence of the fluctuations caused by the particles destabilizing the thread or column of fluid.

4.3 Drop impaction

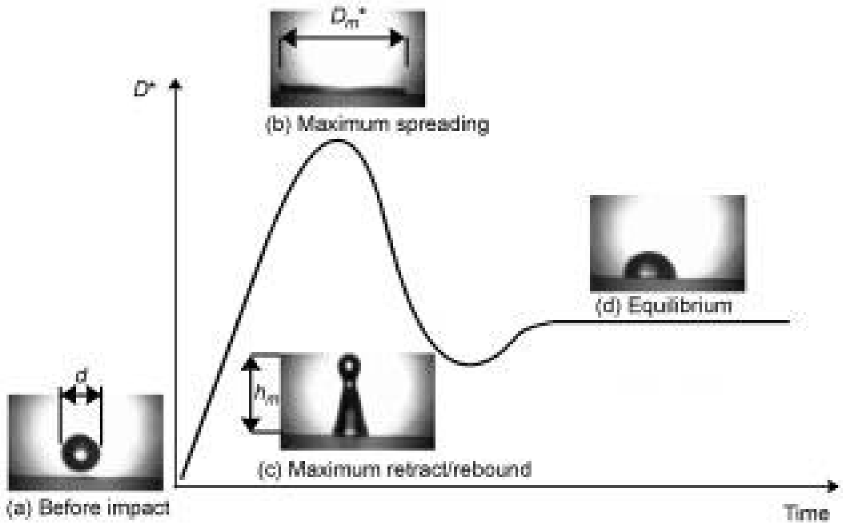
When a drop impacts a rigid solid surface, the outcome depends on several factors including drop speed, drop volume, liquid physical properties (viscosity, surface tension, and density), solid surface energy, drop/surface interaction, and surface characteristics. Certain of these parameters are commonly combined to form the dimensionless Reynolds number ($\mathrm{Re} = \rho v d / \eta$), Weber number ($\mathrm{We} = \rho v^2 d / \gamma$), and equilibrium contact angle (θ). In these relationships, ρ is liquid density, v is drop impact speed, d is drop diameter at impact, η is liquid viscosity, and γ is liquid–vapor surface tension.

At high Re, the drop may bounce or splash, forming secondary or satellite drops. The splashing threshold has been correlated with We, Re, and roughness (R_a) (Stow and Hadfield, 1981). More recently, the experimental results of Range and Feuillebois (1998) indicate that the dimensionless numbers (Ohnesorge number, Oh, and Re) containing viscosity are not important and can be neglected in the description of splashing. For their data, $\mathrm{We_c}$ (critical We for splashing) is found to correlate with the ratio of drop radius (R_o) to the surface roughness (R_a) for a given liquid–surface combination. They also point out that R_a is not the only parameter characterizing the effect of the splashing limit. The surface profile is important, but is not entirely described by R_a. A complete understanding of splashing is still not available, especially about the influence of the solid surface parameters. Clarke *et al.* (2002) show that for typical inkjet printing, splashing will not occur on a smooth surface. For that reason, splashing is not discussed further in this chapter.

Spreading of liquid drops on porous substrates has received much less attention even though it is common and important, for example in inkjet printing on paper and textiles. Experimental study for inkjet systems is challenging since drops are very small and the substrates vary widely in their properties. Dynamic spreading occurs very rapidly, and penetration on porous substrates can result in further spreading. The initial spreading phase after impact occurs very rapidly relative to penetration. Hence the dominant physical processes change, as kinetic and surface energies dominate during spreading, while capillary forces dominate during penetration. A full analysis of the penetration process is a formidable task, but some progress has been made, including a model describing the spreading and imbibition of liquid drops on a porous surface developed by Clarke *et al.* (2002).

4.3.1 Homogeneous-liquid drop impaction on smooth surfaces

Since print quality is related to spreading of an ink drop when it impacts the substrate (Asai *et al.*, 1993), impact dynamics is of central importance to inkjet printing. The parameter usually followed during impaction is the spreading ratio, $D^* = D/d$, where D is the contact diameter and d is the drop diameter before impact. The variation of D^* with time during impaction is illustrated schematically in Fig. 4.3. Before impact, the energy of the impacting drop consists of kinetic energy, surface energy, and potential energy. After impact,



4.3 Schematic of drop impaction process on a smooth surface.

the drop spreads over the surface. Assuming uniform spreading, the wetted contact area remains axisymmetric (circular), and spreading is characterized by the diameter, D, of the circle. Spreading continues until it reaches a maximum, D_m^*. At D_m^*, the surface energy of the drop is at a maximum while the kinetic energy is zero. Excess surface energy causes retraction to occur. The amount of retraction depends on several factors including Re, We and equilibrium contact angle (θ). For very low values of Re and We and θ, little retraction may occur. For this case, viscous and liquid–surface interactions dominate, and D_m^* is close to the equilibrium value of $D*$ which can be estimated using the relationship $D^* = [4\sin^3\theta/(2 - 3\cos\theta + \cos^3\theta)]^{1/3}$ derived by Ford and Furmidge (1967). As equilibrium contact angle is increased, the tendency to retract increases. Also, as Re is increased, the amount of retraction increases. The liquid may retract to the equilibrium position and stop, or retract through the equilibrium position and rise in the region of the initial impact. Sometimes the liquid will separate from the surface, rise a short distance and return to the surface. This phenomenon, referred to as rebounding, is only observed for values of $\theta \gtrsim 90^{\circ}$. After maximum retraction, the drop changes its direction of motion and begins to spread again. The liquid may spread to the equilibrium position and stop or expand through the equilibrium position until it reaches the second maximum spreading diameter which is smaller than initial maximum spreading diameter. This type of damped oscillatory motion will continue until excess surface energy is dissipated, and the drop reaches its equilibrium D^*.

Since Worthington (1876) reported an investigation of drops of liquids falling vertically on a horizontal plate, there have been over 100 published investigations on the subject. While some have been entirely experimental (Bergeron *et al.*, 2000; Šikalo *et al.*, 2002), most studies have included theoretical and/or numerical modeling approaches for predicting the spreading phenomenon. The theoretical approach (Engel, 1955; Ford and Furmidge, 1967; Chandra and Avedisian, 1991; Asai *et al.*, 1993; Fukai *et al.*, 1998) involves the use of an energy balance on the system, which consists of the drop and the impacted surface, to develop an equation for predicting the maximum spreading ratio, D_m^* (ratio of the maximum spreading diameter to initial drop diameter) as a function of drop properties and contact angle. Numerical modeling (Harlow and Shannon, 1967; Fukai *et al.*, 1993, 1995, 1998; Pasandideh-Fard *et al.*, 1996; Bussmann *et al.*, 1999) has been used to simulate the dynamics of transient flow and to predict the drop impacting process. These studies provide firm understanding of the effects of impacting velocity and liquid properties, i.e., viscosity and surface tension, on the impacting process. However, understanding of the influence of solid–liquid interaction during spreading and recoiling is far from complete, especially its relative importance during different stages.

Several equations for predicting D_m^* based on correlations and/or energy conservation are available in the literature. One of the first correlation equations was presented by Engel (1955). Since then, there have been several efforts (Ford and Furmidge, 1967; Chandra and Avedisian, 1991; Asai *et al.,* 1993; Pasandideh-Fard *et al.*, 1996; Mao *et al.*, 1997; Fukai *et al.*, 1998) to improve the accuracy of the prediction. The earlier investigations are summarized by Mao *et al.* (1997) and Fukai *et al.* (1998), who presented two of the most recent predictive equations. Their models accurately predict D_m^* for most cases except at low Re and We, where they overestimate the experimental values, particularly at high and low contact angles, or may give negative or imaginary values at high contact angles.

Mao *et al.* (1997) improved the model of Chandra and Avedisian (1991) and Pasandideh-Fard *et al.* (1996). In the earlier work, surface–vapor and surface–liquid interaction energies during spreading were included, which resulted in $\cos\theta$, where θ is contact angle, appearing in the predictive equation. While Pasandideh-Fard *et al.* (1996) used the advancing contact angle in their predictions, Mao *et al.* (1997) used the static contact angle. Fukai *et al.* (1998) presented a model also based on that of Chandra and Avedisian (1991). They improved the predictions by modifying the model to contain three empirical coefficients, which were determined by fitting to their numerical results. Park *et al.* (2003) developed a model which gives improved predictions for low drop impact velocities by assuming a spherical cap model of the impacting liquid (rather than a circular cylinder). A summary of several models for predicting D_m^* is given in Table 4.2.

The impaction studies discussed above have used a single millimeter-sized drop impinging on a smooth surface. Very little is available to show that these results scale down to micron-sized drops used in inkjet printing, but this is an issue currently under investigation (Carr *et al.*, 2004).

Table 4.2 Summary of previous models for predicting D_m^*

Reference	Models
Chandra and Avedisian (1991)	$\left(\frac{3}{2}\frac{\mathrm{We}}{\mathrm{Re}}\right)D_m^{*4} + (1-\cos\theta_e)D_m^{*2} - \left(\frac{1}{3}\mathrm{We}+4\right) = 0$
Asai *et al.* (1993)	$D_m^* = 1 + 0.48\mathrm{We}^{0.5}\ \exp[-1.48\mathrm{We}^{0.22}\mathrm{Re}^{-0.21}]$
Scheller and Bousfield (1995)	$D_m^* = 0.61(\mathrm{Re}^2\mathrm{Oh})^{0.166}$
Fukai *et al.* (1998)	$\frac{1}{2}\frac{\mathrm{We}}{\mathrm{Re}^{0.772}}D_m^{*4} + 2.29(1-\cos\psi)D_m^{*2} - \left(\frac{\mathrm{We}}{3}+4\right) = 0$
Pasandideh-Fard *et al.* (1996)	$D^* = \sqrt{\frac{\mathrm{We}+12}{3(1-\cos\theta_a)+4(\mathrm{We}/\sqrt{\mathrm{Re}})}}$
Mao *et al.* (1997)	$\left[\frac{1}{4}(1-\cos\theta_e) + 0.2\left(\frac{\mathrm{We}^{0.83}}{\mathrm{Re}^{0.33}}\right)\right]D^{*3} - \left(\frac{\mathrm{We}}{12}+1\right)D^* + \frac{2}{3} = 0$
Park *et al.* (2003)	For high viscosity liquids $(\mathrm{Re} < 81(D_m^*)^4)$ $0.53\frac{\mathrm{We}}{\mathrm{Re}}D_m^{*4} + \left[\frac{1}{2}\left(\frac{1-\cos\alpha}{\sin^2\alpha}\right) - \frac{1}{4}\cos\theta\right]D_m^{*2} - 1 - \frac{\mathrm{We}}{12} + \frac{\Delta E_{SP}}{\pi d^2\gamma_{LV}} = 0$ For low viscosity liquids $(\mathrm{Re} > 81(D_m^*)^4)$ $\left[0.33\frac{\mathrm{We}}{\sqrt{\mathrm{Re}}} - \frac{1}{4}\cos\theta + \frac{1}{2}\left(\frac{1-\cos\alpha}{\sin^2\alpha}\right)\right]D_m^{*2} - 1 - \frac{\mathrm{We}}{12} + \frac{\Delta E_{SP}}{\pi d^2\gamma_{LV}} = 0$

where

Oh (Ohnesorge number), $\mathrm{Oh} = \frac{\mu}{\sqrt{\rho d\sigma}} = \frac{\sqrt{\mathrm{We}}}{\mathrm{Re}}$

ψ = dynamic contact angle

θ_a = advancing contact angle between liquid and solid

$$\Delta E_{SP} = \pi d^2\gamma_{LV}\left(\frac{\cos\theta}{4}g(\theta) + 1 - \frac{1}{2}\left(\frac{1-\cos\theta}{\sin^2\theta}\right)g(\theta)\right)$$

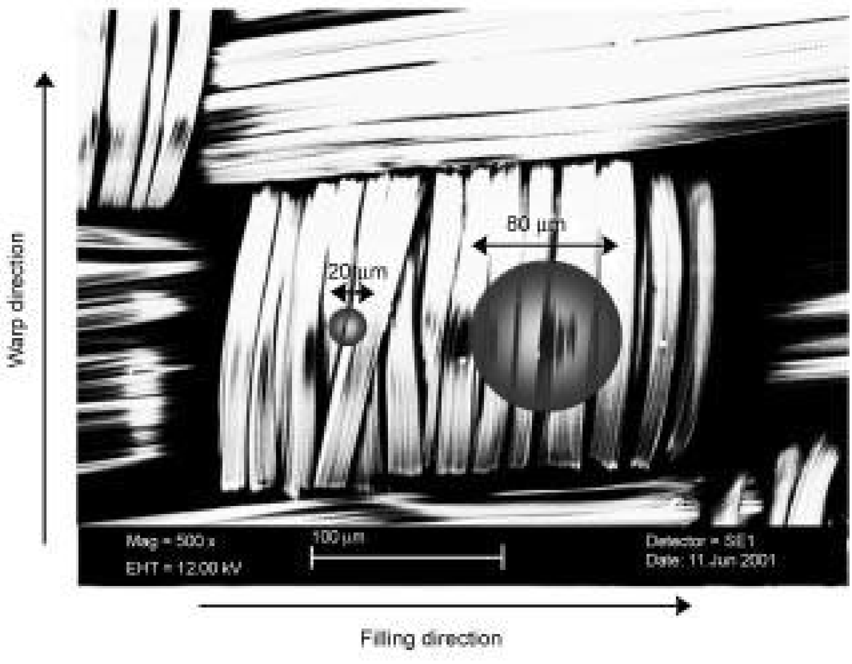
$$g(\theta) = D^{*2} = \left[\frac{4\sin^3\theta}{2-3\cos\theta+\cos^3\theta}\right]^{2/3}$$

$$D_m^{*2} = \left[\frac{4\sin^3\alpha}{2-3\cos\alpha+\cos^3\alpha}\right]^{2/3}$$

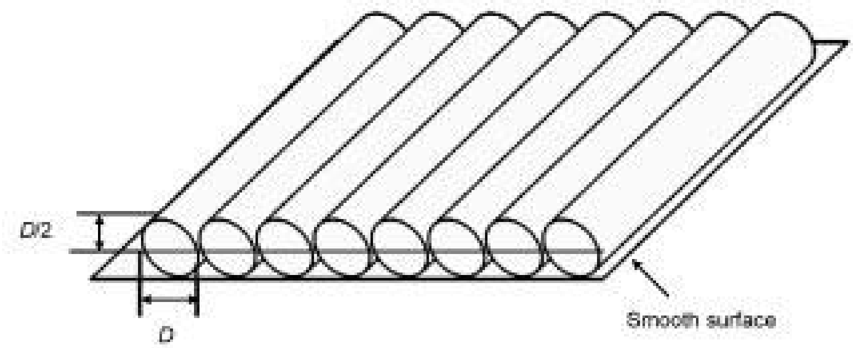
4.3.2 Drop impaction on a textile-like rough surface

In textile printing, an understanding of the interaction of an individual drop with various textile surfaces is needed. However, obtaining sufficiently high resolution images of an inkjet drop impacting on a textile surface is difficult due to the small drop size (less than 100 microns) and high impact speed (around 5–20 m/s). For that reason, Park (2003) used scaled-up experiments to simulate the impaction of an ink drop on a fabric. A micrograph taken by SEM of a woven rayon fabric is shown in Fig. 4.4. Notice that the yarn is made up of many fibers running in the warp direction. The cross-section of the fiber is a serrated circular shape, and the fiber has lengthwise striations. Since the width of the fibers is about 25 microns, approximately 10 fibers will be on the surface of the 250-micron-wide yarn. Circles with diameters of 20 and 80 microns are drawn on one of the warp yarns to indicate the size of typical inkjet drops. The ratio of the diameter of typical inkjet drops to the width of the rayon fibers ranges from 0.8 to 3.2.

A surface was made to simulate a yarn on the fabric surface. Monofilament yarns (polyester coated with ethylene tetrafluoride) with diameter of about 1.3 mm were placed next to each other on a smooth surface and glued together to produce the surface illustrated in Fig. 4.5. The diameter of the drops used to



4.4 A SEM photograph of a rayon fabric (circles with diameters of 20 and 80 microns are the size of typical inkjet drops).



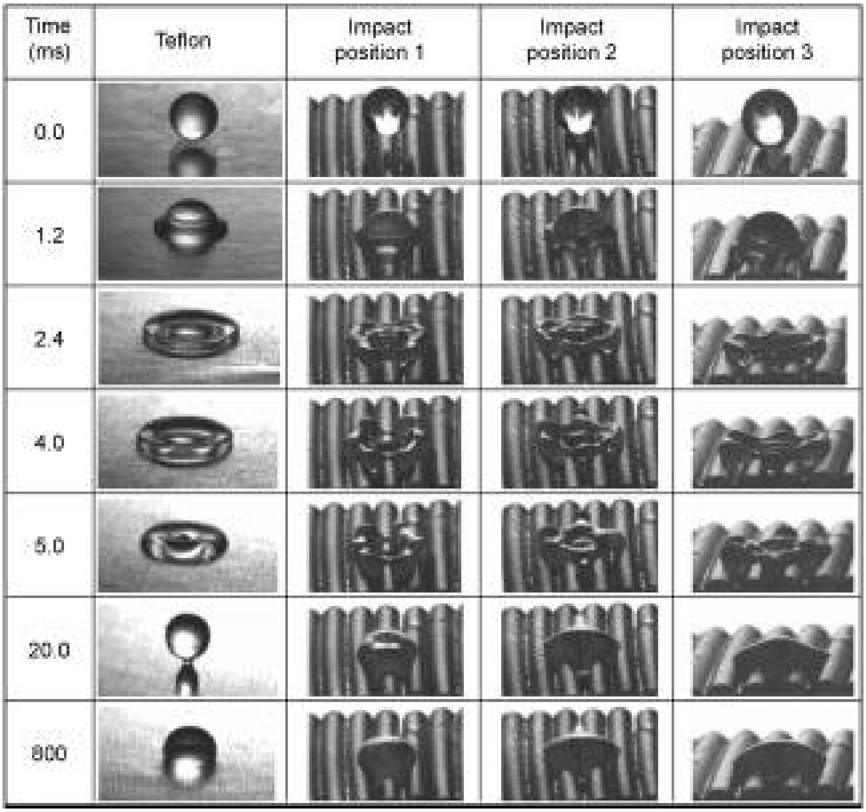
4.5 Schematic of rough surface.

impact on the surface was 2.3 mm. Thus the ratio of diameter of the impacting drop to the diameter of the monofilament is 1.8, which falls in the range for typical inkjet drops on the rayon yarn mentioned above. Figure 4.6 shows the spreading of a water drop on a smooth surface and on the rough surface simulating a continuous filament yarn. Tests were conducted with the impacting drop hitting the rough surface at three different locations: the center of the filament-like structure (position 1), the middle of the valley between two of the filament-like structures (position 2), and between these positions (position 3). A series of images of drop impingement for the three impact positions and the smooth surface were recorded using almost identical time steps.

For the smooth surface, the liquid flows radially outward from the impact point. In contrast, for the rough surface, much of the liquid flows in the filament axial direction rather than strictly radially, because of 'roughness' elements blocking the direction perpendicular to the filament axis. The spreading and retracting shapes and maximum spreading ratios thus depend on the impact position. The maximum radial spreading ratio is largest for impact position 2 while the maximum spreading ratio in the filament axial direction is the largest for position 1. The equilibrium diameters in the radial direction for positions 2 and 3 are almost equal and are larger than for position 1 due to the noted structural barrier. We note that very recent work describing the influence of a small obstacle on a surface upon splashing of impacting drops (Josserand *et al.*, 2005) may provide some guidance to understanding of the role of roughness.

4.3.3 Particle-laden drop impaction on smooth surfaces

Pure fluid drop formation and drop impaction on solid surfaces have been studied for over 100 years. In contrast, impaction of particle-laden drops on surfaces has received little attention despite its importance in a variety of applications including inkjet printing. In fact, only one paper was found in the



4.6 Impact of a 2.3 mm water drop on a smooth Teflon surface and on a rough surface produced by aligning and gluing polyester monofilaments coated with ethylene tetrafluoride on a silicon wafer. Amplitude and texture of roughness: 1.25 and 13 mm, respectively. Impact speed = 0.87 m/s, Re = 2000, and We = 24.

refereed literature on drop impaction of particle-laden drops on surfaces (Ok *et al.*, 2004).

In the study of the impact dynamics of particle-laden liquid, the parameters d_p/d and ϕ must be considered in addition to Re, We, and θ. Here d_p/d is the ratio of particle diameter to drop diameter, and ϕ is the volume fraction of particles in the liquid.

Research by several of the authors is being conducted to provide insight into the effect of particles on drop impaction on solid surfaces (Carr *et al.*, 2004). The goal of the study is to develop understanding of how and why solid particles at a range of concentration affect the drop impaction process. Some of the results of the experimental study on the effects of particles on drop impaction are now discussed. The study has revealed that particles can affect maximum spreading ratio and retracting/rebounding, but the effects depend on the conditions, characterized by dimensionless numbers. Some observations made are:

- At low Re, particles have little effect on impaction process for values of ϕ up to 0.30.
- At high Re, particles affect maximum spreading ratio and retraction if ϕ is sufficiently high. For particle volume fractions typically found in inkjet inks, particles have little effect on the impact process.
- Increasing d_p/d from 0.007 to 0.014 for a 2900-μm drop had little effect on the impact process.
- Particle volume fraction greatly affects rebound behavior for a hydrophilic drop on a hydrophobic surface.

4.4 Future trends

Although drop formation and impaction have been intensively studied, they remain areas of active research interest. Even the best-understood case of drop formation from Newtonian liquids is under active study, in part because of the new experimental tools allowing extremely high rates of imaging and numerical techniques and CPU power allowing detailed calculations of the behavior near the bifurcation, or pinch-off point. Future research is expected to explore the process in detail for particle-laden liquids. This area is of significant and growing interest as it influences nontraditional inkjet technology, such as textile inkjet printing application, in which solids are pigmented particles and/or binder, but is also relevant to metallic inks used in digital application of electronic materials and to ceramics-laden inks (Blazdell *et al.*, 1995; Windle and Derby, 1999; Tay and Edirisinghe, 2001). A key reason for the slower progress in mixtures is the lack of a continuum model, although much progress has been made in this area (Morris and Boulay, 1999); even with a reliable continuum model, such an approach is limited by the fact that eventually the intrinsic graininess of the particle-laden liquid has an influence, as in necking and bifurcation a finite-time singularity yields a flow scale going to zero, and in impacting the film resulting from a drop may be below the particle size.

Studies are needed to further investigate the formation process and the impaction process. For the latter, an emphasis on smooth surfaces seems warranted for drop sizes typically found in inkjet applications, in order to determine whether experimental results for drops of millimeter size have validity down to drops on the order of 10 microns in diameter. Study is needed for pure-liquid drops, particle-laden-liquid drops and predictive models.

- Pure-liquid drops: ‘The size of a printed dot in inkjet printing, which greatly affects print quality, is determined by spreading of an ink drop when it impacts the substrate’ (Asai *et al.*, 1993). Numerous studies on the impacting of pure liquid drops on solid surfaces have been conducted; however, drop size has typically been about two orders of magnitude larger than drops used in inkjet printing. The larger drops ranging in size from 1 to 5 mm have been used because experimental study of the impacting and spreading process is much easier with drops of this size than with smaller drops. Demonstration that these results for the larger drop size apply for drop sizes typically found in inkjet printing is needed. The formation process is quite well understood for pure liquids, and while added valuable knowledge will come from further work, the engineering need is less in this area.

- Particle-laden-liquid drops: Studies of the effect of particles in the liquid on the drop formation and impacting process are needed because solids, serving as colorant or binder, are required in 'inks' needed for a number of nontraditional applications of inkjet technology such as textile printing, as well as in ceramic dispersions applied by the inkjet method. Studies of the basic influence of particulates in the drop formation and spreading, as well as the dependence on particle size, are needed, with particular emphasis on examination of drop formation at the small scales and high rates typical of inkjet applications.
- Predictive models: Predictive models which are physically based, and incorporate best present understanding, should be developed for micron-size pure-liquid drops, millimeter-size particle-laden-liquid drops, and micron-size particle-laden-liquid drops. Such models cannot be expected to be complete given present knowledge, but are nonetheless immediately valuable for development, and also provide a critical framework for further study and utilization of experimental results. Development of continuum models of mixture flow behavior, coupled to a statistical description of the influence of particles when the continuum description breaks down (at small scales), appears to be a fruitful direction for both scientific and engineering advances in the inkjet application of solids-laden liquids.

4.5 References

Alaoui O (1991), *Contribution à l'étude des instabilités de jets injection de liquides et de suspensions dans un autre fluide non-miscible*. PhD thesis, l'Université de Provence (Aix-Marseille I).

Ambravaneswaran B, Wilkes E D, and Basaran O A (2002), 'Drop formation from a capillary tube: comparison of one-dimensional and two-dimensional analyses and occurrence of satellite drops', *Phys. Fluids*, 14(8), 2606–2621.

Asai A, Shioya M, Hirasawa S, and Okazaki T (1993), 'Impact of an ink drop on paper', *J. Imaging Sci. Tech.*, 37(2), 205–207.

Bergeron V, Bonn D, Martin J Y, and Vovelle L (2000), 'Controlling droplet deposition with polymer additives', *Nature*, 405 (15 June), 772–775.

Blazdell P F, Evans J R, Edirisinghe M J, Shaw P, and Binstead M J (1995), 'The computer aided manufacture of ceramics using multilayer jet printing', *J. Mater. Sci. Lett.*, 14(22), 1562–1565.

Bussmann M, Mostaghimi J, and Chandra S (1999), 'On a three-dimensional volume tracking model of droplet impact', *Phys. Fluids*, 11(6), 1406–1417.

Carr W W, Park H, and Morris J F (2004), 'Textile inkjet: drop formation and surface interaction', *National Textile Center Annual Report*, National Textile Center, Wilmington, DE, Project C02-GT07.

Chandra S and Avedisian C T (1991), 'On the collision of a droplet with a solid surface', *Proc. R. Soc. Lond.*, 432, 13–41.

Chen A U, Notz P K, and Basaran O A (2002), 'Computational and experimental analysis of pinch-off and scaling', *Phys. Rev. Lett.,* 88(17), article 174501 (4 pages).

Christanti Y and Walker L M (2001), 'Surface tension driven jet break up of strain-hardening polymer solutions', *J. Non-Newtonian Fluid Mech.*, 100(1–3), 9–26.

Clanet C and Lasheras J C (1999), 'Transition from dripping to jetting', *J. Fluid Mech.*, 383, 307–326.

Clarke A, Blake T D, Carruthers K, and Woodward A (2002), 'Spreading and imbibition of liquid droplets on porous surfaces', *Langmuir*, 18(8), 2980–2984.

Eggers J (1997), 'Nonlinear dynamics and breakup of free-surface flows', *Rev. Mod. Phys.*, 69(3), 865–929.

Engel O G (1955), 'Waterdrop collisions with solid surfaces', *J. Res. Natn. Bur. Stand.*, 54(5), 281–298.

Ford R E and Furmidge C G L (1967), 'Impact and spreading of spray drops on foliar surfaces', in *Wetting. Soc. Chem. Industry Monograph*, London, Society of Chemical Industry, 417–432.

Fukai J, Zhao Z, Poulikakos D, Megaridis C M, and Zhao Z (1993), 'Modeling of the deformation of a liquid droplet impinging upon a flat surface', *Phys. Fluids*, 5(11), 2588–2599.

Fukai J, Shiiba Y, Yamamoto T, Miyataka O, Poulikakos D, Megaridis C M, and Zhao Z (1995), 'Wetting effects on the spreading of a liquid droplet colliding with a flat surface: experiment and modeling', *Phys. Fluids*, 7(2), 236–247.

Fukai J, Tanaka M, and Miyatake O (1998), 'Maximum spreading of liquid droplets colliding with flat surfaces', *J. Chem. Eng. Japan*, 31(3), 456–462.

Furbank R J and Morris J F (2004), 'An experimental study of particle effects on drop formation', *Phys. Fluids*, 16(5), 1777–1790.

Furbank R J and Morris J F (2006), 'Pendant drop thread dynamics of particle-laden liquids', to appear in *Int. J. Multiphase Flow*.

Goldin M, Yerushalmi J, Pfeffer R, and Shinnar R (1969), 'Breakup of a laminar capillary jet of a viscoelastic fluid', *J. Fluid Mech.*, 38, 689–711.

Harlow F H and Shannon J P (1967), 'The splash of a liquid drop', *J. Appl. Phys.*, 38(10), 3855–3866.

Josserand C, Lemoyne L, Troeger R, and Zaleski S (2005), 'Droplet impact on a dry surface: triggering the splash with a small obstacle', *J. Fluid Mech.*, 524, 47–56.

Mao T, Kuhn D C S, and Tran H (1997), 'Spread and rebound of liquid droplets upon impact on flat surfaces', *AIChE J.*, 43(9), 2169–2179.

Morris J F and Boulay F (1999), 'Curvilinear flows of noncolloidal suspensions: the role of normal stresses', *J. Rheol.*, 43(5), 1213–1237.

Ogg J C, and Schetz J A (1985), 'Breakup and droplet formation of slurry jets', *AIAA J.*, 23, 432–439.

Ok H, Park H, Carr W W, Morris J F, and Zhu J (2004), 'Particle-laden drop impacting on solid surfaces', *J. Dispersion Sci. Tech.*, 25(4), 449–456.

Park H (2003), *Drop impingement and interaction with a solid surface*, Georgia Institute of Technology, Atlanta, GA.

Park H, Carr W W, Zhu J, and Morris J F (2003), 'Single drop impaction on a solid surface', *AIChE J.*, 49(10), 2461–2471.

Pasandideh-Fard M, Qiao Y M, Chandra S, and Mostaghimi J (1996), 'Capillary effects during droplet impact on a solid surface', *Phys. Fluids*, 8(3), 650–659.

Range K and Feuillebois F (1998), 'Influence of surface roughness on liquid drop impact', *J. Colloid Interface Sci.*, 203, 16–30.

Scheller B L and Bousfied D W (1995), 'Newtonian drop impact with solid surface', *AIChE J.*, 41(6), 1357–1367.

Šikalo Š, Marengo M, Tropea C, and Ganić E N (2002), 'Analysis of impact of droplet on horizontal surfaces', *Experimental Thermal and Fluid Science*, 25, 503–510.

Stow C D and Hadfield M G (1981), 'An experimental investigation of fluid flow resulting from the impact of a water drop with an unyielding dry surface', *Proc. R. Soc. Lond. Series A, Mathematical and Physical Sciences*, 373(1755), 419–441.

Tay B Y and Edirisinghe M J (2001), 'Investigation of some phenomena occurring during continuous ink-jet printing of ceramics', *J. Mater. Res.*, 16(2), 373–384.

Tincher W C, Hu Q, and Li X (1998), 'Ink jet systems for printing fabric', *Textile Chemist and Colorist & American Dyestuff Reporter*, 30(5), 24–27.

Windle J and Derby B (1999), 'Ink jet printing of PZT aqueous ceramic suspensions', *J. Mater. Sci. Lett.*, 18(2), 87–90.

Worthington A M (1876), 'On the forms assumed by drops of liquids falling vertically on a horizontal plate', *Proc. R. Soc. Lond.*, 25, 261–272.

5

Industrial production printers – DuPont Artistri™ 2020 textile printing system

M RAYMOND, DuPont Ink Jet, USA

5.1 Introduction

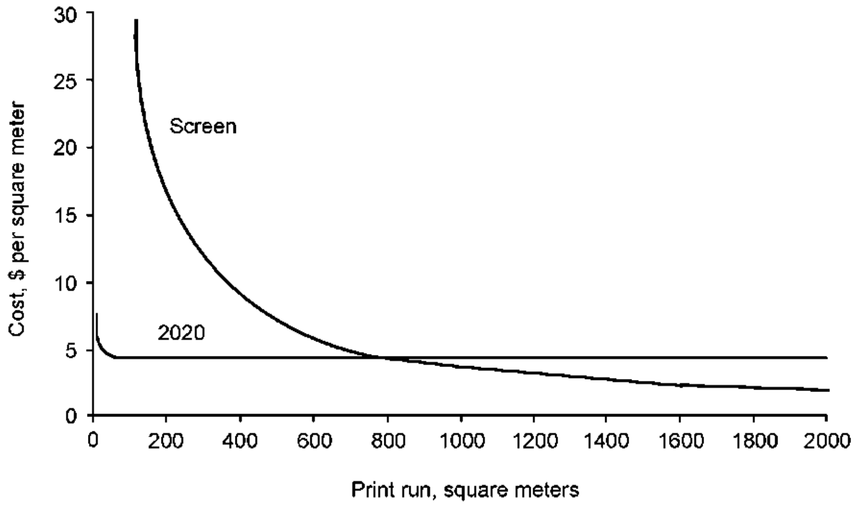
The current worldwide production of printed textile fabric is over 34 billion square meters per year and is dominated by rotary screen-printing. Digital printing for textiles has a compelling value proposition, which could be leveraged into a variety of related businesses. The worldwide opportunity in digital textile printing solutions could range from $4 billion to $6 billion within the next five years. Each 1% adoption from traditional textile printing to digital creates a potential for 3 million liters of pigment ink, 1.3 million liters of reactive dye ink, 800,000 liters of disperse dye ink and 500,000 liters of acid dye ink.

Technology is evolving and partnerships are being created to exploit inkjet textile printing opportunities. Textile ink, inkjet printhead, color management software, fabric handling equipment and fabric pre- and post-processing technologies have been developed to work together as an optimized system. The development of these new technologies is replacing traditional screen-printing techniques and is creating new opportunities and markets that coexist with existing technology.

To meet these opportunities, DuPont offers the Artistri™ 2020 digital printing system to the market. The printing system, developed through a partnership between DuPont, Ichinose Toshin Kogyo and Seiko Printek, meets the production level requirements for short-run textile printing. The printer developed by Ichinose Toshin Kogyo of Japan utilizes Seiko Printek inkjet printheads. DuPont supplies ink and color management technology and markets the system to end-users.

5.2 Industry needs

The run lengths of textile print jobs have decreased dramatically. Designers are providing more options and retailers are demanding more product choices and fewer inventories. A quick restocking of a popular design can increase profitability. As run lengths decrease, the cost of traditional screen-printing rises. Digital printing can be cost-effective against screen printing for shorter run



5.1 The difference in cost between screen and digital printing setup processes.

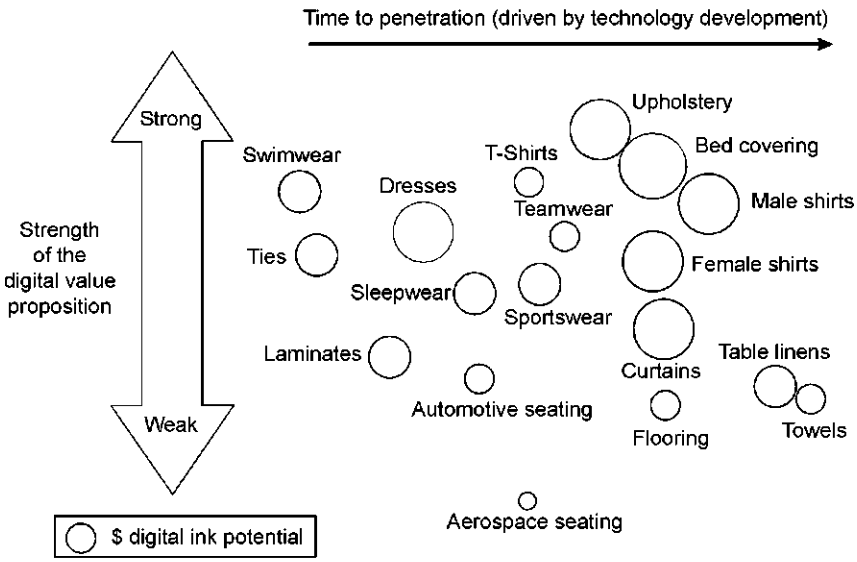
lengths. This is because the cost of engraving screens and setup must be amortized over the length of the print run. See Fig. 5.1 to see how screen and digital printing setup processes differ.

The first and foremost need from the industry is quality. Quality of the image and quality in the fastness characteristics (i.e. rub, wash and light fastness) are required. DuPont Artistri™ inks have been designed and tested to meet or exceed the industry standards for fastness. The DuPont Artistri™ technology provides high quality as demonstrated by the high-value scarves, ties, swimwear and other apparel being sold to the public at retail.

Textile inkjet printing does not yet come close to the printing speeds possible from a rotary screen process. The industry needs higher speed digital printers. Commercially available digital textile printers operate in the range of 2 to 150 square meters per hour, whereas a rotary screen process can easily reach speeds over 1000 square meters per hour. Inkjet printing technologies are constantly improving to meet future demands. Nevertheless, they are still far away from achieving rotary screen speeds at reasonable reliability and cost.

5.3 Markets and applications

Each of the many textile-printing markets has their own requirements for image quality, color and fastness characteristics. Image quality is more important for fine silks, and color quality is extremely important for swimwear and team-wear. All printed fabrics need to be rub fast, wash fast and light fast to varying degrees depending on the market. See Fig. 5.2.



5.2 Textile-printing market requirements from digital printing technology.

The silk accessories market is amenable to digital printing due to the inherent short run lengths and relatively high value to the customer. The quality of the image is extremely important for applications such as ties and scarves. Fine line printing is very important for design patterns. Extra care is taken by the owner with these fabrics so fastness characteristics are secondary to image quality. The market for digitally printed silk ties and accessories could be over $300 million in the next five years.

The swimwear market is a good target for digital printing due to the short run lengths and many design cycles. Fastness characteristics are more important than image quality. Color quality is high on the requirements and spot colors are used for fluorescent and metallic colors. The inks have to meet the fastness requirements for chlorine and salt water exposure and, of course, light fastness is very important as well. The market for digitally printed swimwear could be over $250 million in the next five years.

Home furnishings can be bed coverings, window treatments, upholstery, etc. The home furnishings market is more cost sensitive than silk or swimwear. Wash fastness is a high priority because bedding must stand up to numerous washings. The printing run lengths tend to be longer than those found in swimwear and silk and a lot of printing in this segment is on wide fabrics up to 3.2 meters. The market for digitally printed home furnishings could be over $400 million in the next five years.

Apparel, teamwear and T-shirts comprise a very large market segment. Apparel varies widely in image quality and fastness characteristics. Cotton fabric is the most widely used. Wool, nylons, and polyester are also used. The market for digitally printed apparel could be over $500 million in the next five years.

Soft signage applications fall into these categories: point-of-purchase signage, trade-show signs and wraps, banners, flags and backdrops. Almost all fabric types are used for soft signage, such as silk, cotton, linen, nylon, rayon and polyester. The market for inkjet printed soft signage is expected to reach $713 million in 2006 (IT Strategies). The average retail selling price ranges from $7 to $15 per square foot ($75 to $161 per square meter).

5.4 Artistri™ 2020 printer

The Artistri™ 2020 printing system is offered commercially to meet the needs of short-run textile printing. See Fig. 5.3. The 1.8-meter wide printer has eight color channels available for printing. Greater color range and quality can be achieved than in six-color printers. Usually, the colors offered are cyan (C), yellow (Y), magenta (M), black (K), light cyan (lc), light magenta (lm), C1 and C2. CYMK are the base colors for process color printing while light cyan and light magenta allow smooth tonals to be printed and offer a higher perceived resolution. C1 and C2 can be gamut expanding or used as spot colors depending upon the customer's needs. Printing resolutions are 360, 540 or 720 dots per inch. Print speeds are from 15 to 60 square meters per hour depending upon resolution and other parameter settings. See Table 5.1.

The 2020 printer utilizes Seiko Printek piezo drop-on-demand printheads. The printheads and the printer were developed concurrently with the Artistri™ Ink and the Artistri™ Color Management System. All four technologies were optimized together to achieve the best print quality and machine performance. The printer was developed and is presently manufactured by Ichinose Toshin Kogyo in Japan.

5.3 The Artistri™ 2020 Printing System.

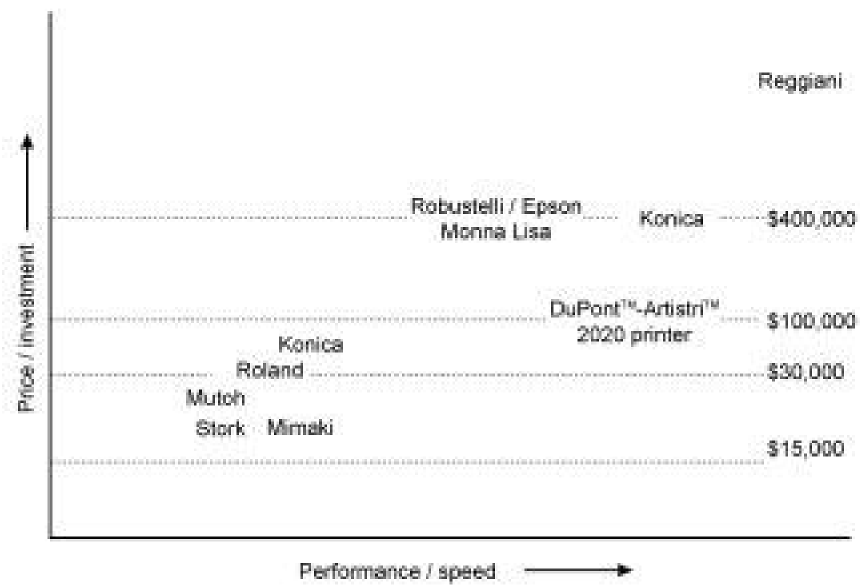
Table 5.1 Print speeds in relation to resolution

Resolution	Print speed (square metres per hour)		
	High speed (draft)	Standard interlacing	Highest quality
360	66	45	23
540	44	30	15
720	33	22	11

5.5 Competitive environment

There are three performance ranges of textile inkjet printers: low-speed (2–15 square meters per hour), mid (15–100 square meters per hour) and high (>100 square meters per hour). The prices of the printers are relative to their performance. See Fig. 5.4.

Most low range printers use Epson printhead technology and Mimaki is the leader in this range with the TX-1, TX-2 and TX-3. Other, Epson printhead-based textile printers are offered by Mutoh and Roland. There are Konica printers in this range that have been sold primarily by Stork. Konica's printers use their own printhead technology, which is based on a Xaar license. These low-end textile printers are typically wide format printers modified for printing on fabric. The primary applications are sampling due to the low speed. Prices in this arena are under $100,000.



5.4 The price of printers in relation to their performance.

The DuPont Artistri™ 2020 printer is in the mid-range category in both speed and cost. The Robustelli Monna Lisa™ printer, based on Epson printheads, is also in this range. Konica-Minolta has recently launched a new printer, the Nassenger V, using their own printhead technology. Printers in the mid-range category are used for sampling and short run production. Prices for printers in this range vary from \$185,000 for the Artistri™ 2020 to approximately \$250,000 for the Robustelli Monna Lisa.

At the high end is the Reggiani DReAM printer. Performance is up to 150 square meters per hour. The DReAM utilizes Aprion (Scitex Vision) printhead technology. It is capable of printing up to six process colors. The primary application is short run production. The DReAM printer price is over \$500,000.

5.6 Artistri™ 2020 textile printing technology

The Artistri™ technology employed in the 2020 printing system is a triumvirate of ink development, color management and the printer/printhead system. All three areas of technology affect the output quality and performance of the printer and have been developed concurrently, to ensure that the DuPont Artistri™ 2020 provides a total, optimized, turnkey solution for DuPont's customers. Customers do not have to shop for a printer, determine where to get ink or obtain third party software for color management. Peak productivity is achieved months earlier than would otherwise be possible.

5.6.1 Ink, pretreatment and post-treatment

There are four ink types to cover the full range of fabrics and applications: acid dye, reactive dye, disperse dye and pigment. DuPont has developed these inks to meet production level requirements for printed fabrics. Pretreatment and post-treatment processes are required for dye-based inks. Pigment inks do not require fabric pretreatment. See Table 5.2. All inks have been optimized to perform with the inkjet printhead technology.

Acid dye inks are generally used for printing on nylon, wool and silk fabrics. Pretreatment of the fabric prior to printing is required to provide fixation between the dye and the fibers. A paste solution is applied uniformly to the material that provides an acid donor for fixation of the dye. Steaming at 100–102°C for 30–60 minutes is required after printing and drying, which redissolves the dyes and swells the fibers, thus fixing the dye to the fabric. Then the fabric must be washed to remove any unfixed dye. For example, acid dye inks are used for silk ties, scarves and Lycra™ swimsuits.

Disperse dye inks are formulated primarily for polyester material. Pretreatment of the fabric is required by applying a solution that will enhance the fixing process during steaming. Fabrics should be post-processed with high temperature steam under pressure at ~160°C for 20–30 minutes. Dry heat at

Table 5.2 Ink type, fiber type and required pre- and post-treatments

Ink type	Fiber types	Pretreatment	Post-treatment
Acid dye	Silk, nylon, wool	Acid donor	Steam and wash
Disperse dye	Polyester	Thickener	High temperature steam and wash
Reactive dye	Cotton, rayon	Alkali	Steam and wash
Pigment	Cotton, polyester, blends	Not required	Dry heat

~160ºC can also be used to fix the disperse dyes, but deeper colors are achieved by steaming. Washing is required to remove any unfixed dye. There are many applications for disperse dye on polyester such as soft signage, flags and banners.

Reactive dye inks are used on cotton, wool and rayon fabrics. Reactive dye colors are brighter and deeper than other inks. Pretreatment of the fabric similar to acid dye ink is required. Steaming at 100–102ºC for 10–20 minutes is required to fix the dye to the fabric. Washing removes any unfixed dye. Reactive dye inks are mostly used for sampling due to the larger color gamut they offer.

Pigment inks are applied to cotton, cotton–polyester blends and almost all other fabrics. The pigments are in water dispersion with a binder that attaches the particles to the fabric. Pigment printing is the most economical process because pretreatment and washing are not required. Thermal fixation via a calender or fabric oven is needed to obtain the best fastness characteristics. Pigment inks have excellent fastness to light and very good rub and wash fastness. The handle (softness of feel) of a fabric printed with pigment ink can sometimes be hard. About half of the world's fabric printing is done with pigment ink.

All inks for the 2020 are supplied in one- or two-liter cartridges. A plastic cartridge surrounds and protects a bag inside where the ink resides. Prior to filling the bag, the ink goes through a degassing process. Dissolved air in the ink is removed to improve the jetting performance of the printhead. Dissolved air in the ink can escape during the printhead's jetting process (this is called rectified diffusion) and cause it to misfire or misdirect the drop. The problem is similar with all piezo inkjet technologies and, if ink is not degassed, the printhead will have to be operated at lower firing frequencies, negatively affecting productivity of the printer.

The bag is designed to prevent any air ingestion into the ink. There are four laminated layers constructing the bag: polyethylene, nylon, aluminum and polyester. The aluminum layer is the primary barrier to keep air from reaching the ink. The other layers are for structural support and impact resistance.

The cartridge also provides a clean process. The operator is never exposed to ink and, because it is self-closing, there are no spills. An electronic chip contains data about the ink, such as type, color, level and batch. The chip is read by the printer and the information can be accessed by the operator. If the operator puts the wrong cartridge in a slot, the operator will be notified with an error. When a cartridge is empty the operator is notified and it can be replaced without stopping the printing process, improving productivity. The cartridge also facilitates ease of ink changeover. A flushing cartridge is used to flush ink from the lines and printheads. Then a different ink chemistry or color can be used.

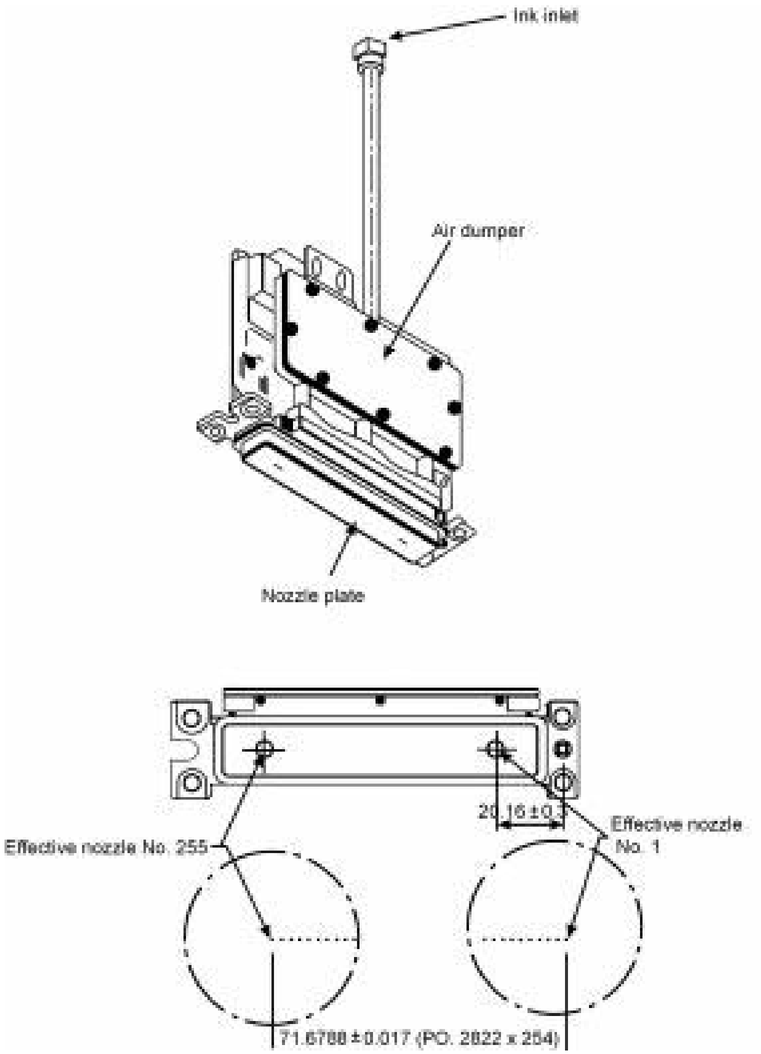
5.6.2 Printhead

The printheads utilized in the 2020 printer are developed and manufactured by Seiko Printek (SPT), Japan. See Fig. 5.5. They employ piezo shared-wall technology and are manufactured under a license from Xaar, Cambridge, UK. SPT developed the printhead to meet DuPont's requirements for aqueous based textile inks. In shared-wall technology, the piezo walls of the chamber are squeezed to eject a drop through a nozzle. A chamber shares its walls with its neighboring chamber. When a nozzle is firing, the adjacent channels cannot be fired. The printhead for the 2020 operates using the same mechanism, but every other channel is not used. Therefore, it is technically not a shared-wall configuration. Each nozzle can be fired without affecting its neighbor. The electrodes that electrically activate the piezo in the printhead are located in the chamber in contact with the ink and every other chamber has the opposite polarity. Making every other channel a 'dummy' channel is required because the textile aqueous based inks are conductive. The ink would short the electrodes if operated in a shared-wall configuration. Of course, there are half the nozzles available for printing, but they operate at higher operating frequencies with less cross-talk between channels. Each printhead in the 2020 printer has 255 active nozzles and each nozzle delivers a 35 picoliter (35×10^{-12} liter) drop at up to 20,000 drops per second.

There are two identical printhead carriages on the 2020. Each carriage has eight printheads, one for each color. Carriage speeds are 20, 40 or 60 inches per second with 40 being the nominal operating point. Each of the printhead carriages adjusts up to 10 millimeters from the belt to accommodate thicker fabrics.

An alignment procedure must be performed during installation or whenever a printhead is replaced. Printhead to printhead alignment must be done for each carriage. Then, a carriage to carriage alignment procedure is performed. Printhead replacement and alignment should take less than one hour.

The printhead is designed for industrial use and has a very long life. Printhead failures most often occur from nozzle contamination or other external harm. The Seiko printheads are very robust and warranted to over 4 billion drops per nozzle. However, printhead life is expected to greatly exceed that.



5.5 The printheads utilized in the 2020 printer.

5.6.3 Color management

Color management is the technology related to the correct interpretation and rendering of color information. Matching colors from design to the digital printer is critical to the customer. It is also important that colors are matched to the screen printing process.

Screen printers will visually look at the printed textile sample and mix different base colors of ink to obtain the final color. This is done in a ‘color kitchen’ similar to mixing paint colors. A typical rotary screen printer can have from 1 to 12 spot colors and from 1 to 12 screens. Each color is mixed individually and is called a colorway. To change a colorway, any one or more of the spot colors change, but will print the same pattern. The color gamut is very large due to the relatively high number of base colors available.

In a digital textile printer the colors are mixed or dithered directly onto the fabric, and almost all systems use the four base colors CYMK. Some systems, such as the 2020, use up to eight colors. The color information is in a digital file and must be converted to the correct color by mixing or dithering the colors available in the printer.

The most common color data format for printers is L*a*b*. L* is the lightness ranging from 0 (dark) to 100 (light). The a* value defines the colors of a red–green axis and b* defines the yellow–blue axis. Using a spectrophotometer to measure the colors in L*a*b* space, a printer's color gamut can be determined and a lookup table can be created. The lookup table tells the printer what colors to mix or dither to create the required color. This is measured against a color standard such as a CIELAB reference. The user can print a 'color book' for a visual representation of the color gamut.

One of the most difficult challenges is to match the process color of the printer to the spot color of the screen system. Digital printers are not economical for printing long run lengths. After sampling and short runs are complete, a large production run may need to be done on a rotary screen printer. If the color gamut of the digital printer is outside the available spot colors or vice versa, a color match may be difficult to achieve. The DuPont Artistri™ Color Management System has been optimized to deal with these issues.

5.6.4 Fabric handling

The Artistri™ 2020 printer receives fabric from a roll on the input and rewinds the material back onto a roll when complete (roll to roll). The fabric must enter the printer without being stretched or otherwise dimensionally unstable. The printer must advance the fabric beneath the printheads after each pass of the printer's carriage. Accuracy is critical to achieving good print quality by reducing the probability for dot placement errors. The motion control system for movement of the belt and fabric must be accurate to the sub-pixel level. At 540 dots per inch, position accuracy needs to be better than ± 12 microns.

The fabric position is controlled by a belt that has a sticky surface. This is technically called an adhesive print blanket but can also be called a 'sticky belt'. It keeps the fabric dimensionally stable during printing. As the fabric is placed on the belt it cannot be stretched or have wrinkles. A mechanism unwinds the fabric roll and keeps as little tension as possible on the fabric. This is especially important when printing stretchy fabrics such as Lycra™ (which is used for swimsuits and other sportswear) otherwise the image could be distorted after coming off the printer. The feed mechanism gently lays the fabric on the sticky belt after it goes over a de-wrinkling roller. The fabric is then pressed to the surface of the belt by a pressure roller prior to entering the print area. After being printed, the fabric is dried by passing over a heated platen. The heater dries the fabric so it can be rewound onto a roll without any ink transfer from the image. It is not intended to cure the ink. The fabric is then rewound onto a roll, that is tension controlled to reduce stretching. The adhesive print blanket is cleaned by a brush with water to remove residual ink and fibers and dried with a squeegee prior to receiving more fabric from the input roll.

5.7 Process color printing versus spot color printing

Textile screen printing is primarily a spot color process and most inkjet printers, such as the 2020, utilize process color. These two approaches differ in that the colorants used to color the textile are premixed in the case of spot color, and mixed on the fabric in the case of process color. Process color printing is generally composed of black, cyan, magenta and yellow inks that are mixed in varying proportions by jetting droplets onto the fabric to create a variety of colors. The color gamut achievable by mixing only four colors of the same chemistry is far less than the colors obtainable in spot color. Spot color printing uses a set of 'mother' colors numbering between four and 12. In an attempt to produce more colors with process color printing, either dilute four-color process inks or up to eight different colors are used. While this provides improvements, it still does not reach the combination of color correctness and functionality of spot color printing in color-critical applications.

5.8 Cost of printing

One of the big advantages of digital textile printing is the ability to print immediately from a digital file without any setup. The other is the lower cost of printing for short runs. The cost per square meter for digital printing is relatively flat and doesn't change much with volume. With screen-printing, the setup required and the cost of the screens must be amortized over the length of the print run. When a printing job is above 1000 square meters, it is most likely economical to run the job on a screen printer. Below that, digital printing can be cost effective. See Fig. 5.1.

The cost of printing of the 2020 consists of the cost of the machine plus the cost of ink, and possibly the cost of a service contract if the customer desires one. A customer may want to include cost of fabric, labor costs and overhead in the cost of printing, but with all else being equal we are discussing only the costs associated with the printer.

Ink printed onto the fabric will usually have between 40% and 150% coverage depending on the pattern. At 100% coverage there is approximately

Table 5.3 Total cost of printing with the 2020

Ink cost (per liter)	$150	$150	$150
Coverage	40%	100%	150%
Printed ink per square meter (mL)	7.0	17.5	26.3
Waste ink per square meter (mL)	2.6	2.6	2.6
Total ink per square meter (mL)	9.6	20.1	28.9
Ink cost per square meter	**$1.44**	**$3.02**	**$4.33**
Machine cost	$185,000	$185,000	$185,000
Number of months	60	60	60
Machine cost per month	$3,083	$3,083	$3,083
Machine speed (square metres per hour)	25	25	25
Hours per shift	7	7	7
Shifts per day	2	2	2
Days per month	22	22	22
Square meters per month	7700	7700	7700
Machine cost per square meter	**$0.40**	**$0.40**	**$0.40**
Total cost per square meter	**$1.84**	**$3.42**	**$4.73**

17.5 ml of ink per square meter. Therefore ink coverage can be expected to be from 7 ml to 26.3 ml per square meter, more or less.

Waste ink must also be calculated into the equation. Ink used for priming and cleaning the printheads is considered waste ink. If the printer has been idle for a length of time, a priming operation may be necessary prior to starting a new print job. Periodically during printing, the machine will pause and move the printheads to a maintenance station. Some ink will be purged through the printhead to clean the nozzles and then the nozzle face is wiped of any excess ink before returning to the printing operation. The period for maintenance operations is set by the operator. For this analysis the waste ink is considered to be 15% for 100% coverage. Therefore, the amount of waste ink is 2.6 ml per square meter.

Total ink usage will be from 9.6 ml to 28.9 ml per square meter. If ink costs $150 per liter, this equates to $1.44 to $4.33 per square meter. If the machine costs $185,000 and is amortized over five years, the cost will be about $0.40 per square meter, operating two work shifts per day. The total cost of printing for the 2020 will be approximately $1.84 to $4.73 per square meter. Again, this does not include labor and overhead expenses. See Table 5.3.

5.9 Opportunities and new markets

Digital inkjet printing of textiles opens doors to new opportunities and creates new markets. Creative designs can be digitally printed that cannot be screen-printed. The largest screen printers have no more than 12 screens, which equates to a limitation of 12 spot colors. With process color there can be an almost unlimited number of colors in a design, allowing much more than 12 colors in a specific design.

Design cycle times are reduced and sample production can be done immediately. The ability to do economical short runs allows reductions in the size of inventories. Restocking of a ‘hot’ apparel item is made easy by digital printing and the store doesn’t have to discount its prices.

Today’s markets are changing faster and customers are becoming more demanding than ever. Digital textile printing allows the production of goods and services to match individual customers’ needs. Personalization allows people to be unique. Customized auto upholstery, a room’s upholstery, wall coverings and window treatments can all be decorated with an exclusive design. Gaming table covers in a casino can be printed with designs of a specific convention or trade show. Pool table covers can have a targeted advertising message. The ideas and opportunities are growing rapidly.

5.10 Artistri^{TM} Technology Center

The Artistri^{TM} Technology Center (ATC) is located in Wilmington, Delaware, USA, at the DuPont Experimental Station. The ATC supports customer demonstrations, sampling, training and technical development. There are over 100 personnel supporting the center including ink chemists, color experts, applications engineers and technicians. The ATC also has the resources of DuPont’s Experimental Station readily available, including research, engineering services, metalworking and materials support.

The Artistri^{TM} Technology Center supports the sales effort by providing demonstrations and printing samples for customers. The normal course of a sales cycle starts with providing printed fabric samples to a customer. A customer’s application can be pretreated, printed, post-treated and returned very quickly from a number of the ATC’s printing systems. Customers are also invited to visit the technology center for personal demonstrations.

The Artistri^{TM} Technology Center also supports customers after the sale. Further education and training after installation is provided in a classroom setting and a hands-on learning environment. The customer can also work with a team of experts to solve new application problems or create color profiles. Training for maintenance of the printing systems is provided if the customer wants to service their own equipment.

Product improvements and developments are ongoing at the ATC. The type of developments include new ink chemistry, color science and calibration, pretreatment, post-treatment, raster image processing and workflow. All product improvements are tested thoroughly at the ATC before customers get newly developed ink or upgrades to their printing system.

5.11 Applications support, technical service and training

When a customer purchases an Artistri^{TM} 2020 textile printer, they are fully supported by DuPont's technical service and applications organization. Support is provided worldwide and is centrally organized into three regions: the Americas; Europe, Africa and Middle East; and Asia and Australia. The goals of the service group are to get customers productive as soon as possible and to provide support to maintain productivity.

When a customer buys an Artistri^{TM} printing system, a technical service team will install the printer and train the users on the proper operation and maintenance of the machine. They are taught how to calibrate the printer and handle various types of fabric. The operators learn the proper handling and maintenance of the piezo inkjet printheads and the ink supply system.

An applications specialist then trains the users on workflow, raster image processing and color management. They learn how to move jobs from the designer or other source, to the printer for processing. If wanted by the customer, the specialist teaches how to create color profiles and match them to the correct job. After the file is RIPped (Raster Image Process) it can then be queued for printing.

5.12 Future trends

Customers are always asking for faster, better and cheaper. All three areas will progress as the nascent digital textile market grows from the present adoption phase. Print quality and color gamut will improve, machines will get faster and printing costs will come down.

The speed of an inkjet printer is highly dependent on the number and operating frequency of the printhead nozzles. Productivity can be measured by the rate at which ink can be applied, so more nozzles and fast jetting can produce higher speed printing. The present limitations to speed are primarily the number of printheads you can economically design into a printer. At present, the cost per nozzle is prohibitive to getting to speeds over 200 square meters per hour at under $1,000,000 machine cost. As manufacturing techniques improve the cost per nozzle will come down.

Enhancements in image quality will be achieved by smaller drop sizes. Gray scale capability (rather than present single drop size technology) will improve tonals and smooth gradations. Expanded color gamut will be achieved by better dye and pigment ink technology.

The cost of printing is primarily driven by the price of ink. The increasing penetration of printers into the market is being supported by higher ink production. As ink volumes increase, the costs decrease, allowing reductions in pricing. As the cost of printing is reduced, the market will grow faster.

Digital textile printing will not replace screen-printing in the near future. The two technologies will coexist. Software and ink technology will improve to provide a seamless workflow from digital inkjet to screen-printing.

Ink type changeover in an inkjet printer is time consuming and wasteful. It would be wonderful if there was one ink type that printed well on all fabrics. Presently four ink types are required to cover the range of fabrics but only one can be in a printer at a time. Research and development resources are working to discover the 'universal' ink.

5.13 Sources of further information and advice

DuPont Inkjet: http://www.inkjet.dupont.com/
Inteletex: http://www.inteletex.com – World Textile Publications Ltd.
Reggiani DReAM Textile Printer: http://www.cibasc.com/index/ind-index/ind-txt_fib/ind-tex-textile_processing/ind-tex-inkjet_tex/ind-txt-ink-dream_industrial_printing.htm
Techexchange.com: http://www.techexchange.com/textile-printing.html

5.14 Bibliography

F Cost, *Pocket Guide to Digital Printing*, Delmar, 1997.
L W C Miles, *Textile Printing*, Society of Dyers and Colourists, 1994.
S F Pond, *Inkjet Technology and Product Development Strategies*, Torrey Pines Research, 2000.

6
Industrial production printers – DReAM

L CACCIA and M NESPECA, Reggiani Macchine S.p.A., Italy

6.1 The DReAM project in the present textile printing scenery

Inkjet printing of textiles has been developing in the last few years but has not brought about a rapid development of supporting technologies, because of limited practical success with inkjet printers, their experimental nature and their high costs. For some years most newly designed inkjet machines have been just a mere adaptation of the best graphic plotters available on the market to meet the latest textile printing needs. These machines are nevertheless only printing machines originally designed for paper printing.

The maximum growth is actually being reached in new markets of textiles for home furnishing, fashion, advertising and automotive, where new commercial opportunities are offered by innovative applications, trying to satisfy customers who demand more and more personalized products. The industry of traditional textile printing, which is probably not yet ready for these big changes, is now facing a dilemma in entering this new market. On the other hand, the companies that have specialized in digital printing, often only recently established, come from completely different fields. Nonetheless, moving to this new technology could actually become crucial for the future survival of the textile industry in developed countries.

The growing interest in textile printing solutions with the development of inkjet printer technology is based mainly on several factors (notwithstanding some limits such as speed, adaptability to different weaves, etc.) that are definitely more innovative than those for other conventional printing systems. These positive factors are rapid transformation from paper drawings into printed patterns, easy selection of colours, complete elimination of screen-engraving processes, a print cost almost independent of the volume of production, extreme reduction in the number of operations required, low environmental pollution, and small installation footprint. It has to be noted that the current developments in the field of inkjet inks have enlarged the application scope of inkjet systems to almost all fibres, pure or blended.

Nevertheless, most inkjet printing machines still face severe limitations, such as slow printing speeds (generally strictly related to the fabric width); problematic alignment between the textile surfaces and the printing nozzles; difficult application on elastic or knitted fabrics, or on relief or flat weaves; insufficient colour homogeneity on large surfaces; sparse or poorly controllable penetration of the dye; and inaccurate reproducibility of printing samples produced on rotary or flat printing machines. Notwithstanding the above-mentioned drawbacks, interesting results (considered sufficient and economically interesting for certain niche applications) have been achieved. Some textile machinery manufacturers have committed themselves to quickly overcome the current shortcomings. From a global point of view, the technology available up to now has not provided the characteristics needed for a suitable printing process able to satisfy industrial application requirements.

Until now, digital printing of fabrics has in fact been confined to extremely short runs of 10–20 square metres, producing strike-offs and samples of new designs, and occasionally small production runs of up to 50 square metres. For anything approaching production volumes, banks of these printers must work in parallel. This approach is dated and impractical; the other and more innovative one is simply to use a faster machine. Even so, there are many hurdles to be overcome to reach this target, because in order to manufacture machines suitable for the textile printing process it is necessary to select the right printing system among a wide range of inkjet technologies, from the head technology to the inks available. Alternatively, the software applications used to drive this technology from a digital file standpoint should be developed with specialized and innovative technology specifically designed for textiles. This complex task can be solved only through strict cooperation and synergistic interaction between specialists from three different sectors: textile machinery, information technology and colouring.

For this reason, a collaboration has been established between three leading international technology companies: Reggiani, providing extensive knowledge of textile handling and print machine manufacturing; Scitex Vision, which has wide experience of digital printing on different substrates, providing the print engine using its proprietary Aprion technology, unique piezoelectric drop-on-demand print heads for the DReAM printer; and Ciba Specialty Chemicals, with its wide expertise and long-standing experience in chemicals and the pioneering role it has played in inkjet printing, which has developed suitable inks especially designed for the Aprion print heads, thus ensuring accurate performance.

A few words need to be said about the three companies which have cooperated for the development of the whole system:

- Reggiani Macchine is a leading manufacturer of traditional printing machines for textiles (rotary and flat screen-printing machines for clothing and household fabrics) as well as conveyance and control systems for fabric feeding. It was originally founded as a supplier of specialist textile enhancement services, and later expanded into developing its own web-fed machines for this purpose. Reggiani, which has been synonymous with innovation and quality worldwide for more than 50 years, is regarded as the supplier of reference and considered by customers for the high standard and reliability of its printing machines and for its focus on today's market needs and trends. The company now has a worldwide base of over 1000 customers. Located in Grassobbio, Bergamo, 40 km from Milan, with a staff of 190 people, Reggiani has been certified to ISO Standard 9001 since 1995 and to UNI EN ISO 9001 since 2000.

- Scitex Vision is a leading developer, manufacturer and service provider of cutting-edge digital printing presses and consumables for industrial applications including ultra-wide-format graphic arts, packaging and textiles. Backed by global marketing and support networks, Scitex Vision is committed to continuously providing high-quality, flexible and cost-effective solutions to printing houses all over the world. The company owns a core technology based on Aprion's patented drop-on-demand piezo-inkjet print heads and water-based inks. Scitex Vision employs more than 460 people worldwide with headquarters located in Netanya, Israel, and subsidiaries in Atlanta, Hong Kong and Brussels.
- Ciba Specialty Chemicals (SWX: CIBN, NYSE: CSB) is a leading company dedicated to producing high-value effects for its customers' products. It strives to be the partner of choice for its customers, offering them innovative products and one-stop expert service. Ciba creates effects that improve the quality of life – adding performance, protection, colour and strength to textiles, plastics, paper, automobiles, buildings, home and personal care products and much more. Ciba Specialty Chemicals is active in more than 120 countries around the world and is committed to be a leader in its chosen markets. In 2004, the company generated sales of 7 billion Swiss francs and invested 288 million SFr in R&D.

Years of hard work and commitment have led to the creation of a new machine, the DReAM: this is not an adaptation of a wide-format graphics printer but a new generation of inkjet printing machine specifically designed for textile printing processes. It is supplied in a standard roll-to-roll configuration; the transport mechanism can, however, be tailored to meet special customer requirements. Many of the innovations featured by DReAM are really unique and ground breaking, such as the following.

- The machine can print on virtually any flat surface (from textile to leather) thanks to its adjustable-height printing heads.
- Its output rate exceeds 150 square metres per hour (DReAM 160) and 190 square metres per hour (DReAM 220).
- The fabric width can reach 1600 mm and 2200 mm.

- It can easily print on elastic and knitted fabrics, since the fabrics are not retained during the printing process but are permanently bonded to a non-deformable blanket.
- It washes the blanket continuously with optimized washing intensity.
- It allows direct and instantaneous change of design pattern.
- It uses high-level inks produced by Ciba Specialty Chemicals and adapted to the needs of Scitex inkjet heads:
  – reactive inks for cellulose fabrics
  – acid inks for silk and polyamide/Lycra blends
  – disperse inks for polyester inkjet printing by transfer or direct, and for fashion and high light fastness applications
  – pigment inks for all fabrics.
- It dries the fabric in-line after printing with adjustable temperature, and polymerizes the bonding agent.
- It reduces ink consumption remarkably in comparison to similar applications.
- It allows continuous ink feeding during the printing process.
- It applies piezoelectric Scitex Vision Aprion heads featuring the 'drop-on-demand' technology.
- It utilizes seven printing heads for each of the six colours available (42 printing heads on one bridge).
- It prints with 600 dpi resolution (real).
- It grants maximum reliability, stability and reproducibility.
- It is equipped with a software program allowing perfect matching between digital and conventional prints.
- It integrates with all graphics software.

All these features combined deliver characteristics superior to other inkjet printing systems: high productivity; very short response time to market requirements; excellent cost-effectiveness for the production of small lots and samples; reduction of environmental pollution to a minimum; and reduction of the staff to a single operator.

6.2 Goals of the project and description of the DReAM machine (technical and technological parts: Reggiani, Ciba Specialty Chemicals and Scitex Vision)

6.2.1 Goals of the project

There has been a dramatic change in global trends in textile manufacturing over the past decade. Average production runs in developed countries have been reduced to less than 1000 square metres per design. An industrial inkjet printing machine such as the Reggiani DReAM is ideal because it ensures the high-quality and cost-effective production demanded by the market. The new digital technology is in fact appropriate for applications requiring high-quality printing for short to medium production runs. It is suitable for printing top fashion apparel, including high-end fashion niche markets, as well as home furnishing applications, flags and banners, swimsuits and technical textiles as well as new applications.

The advantages are numerous. First of all, the cost saving aspect should not be underestimated. Since there is no cost for preparing cylinders/screens, this digital printing system is cost-effective for runs up to 1000 metres. Storage space for the cylinders/screens is no longer required. Production time can be cut down, also. Preparing the cylinders or screens and colours for traditional printing is a time-consuming task and takes at least 3–5 weeks. This is compared with just a couple of minutes with the DReAM system, making it much easier to produce samples, short runs or even medium runs in a short time.

The Reggiani DReAM is the first and so far unique digital printing system perfected to work on an industrial scale with high resolution (600 dpi). A new collection can be printed in just a couple of days. With current inkjet plotters, roughly 20 machines and several weeks are required to achieve the same production output. The Reggiani DReAM inkjet printer is effective from creation to production, and facilitates the production of highly differentiated, added-value printed fabrics.

Moreover, according to DReAM partner Ciba Specialty Chemicals, inkjet printing is 'clean, creative and competitive'. It is clean because all the colour goes onto the fabric and not into the waste water; the inks are liquid and thus non-dusting; water and energy consumption is low, and there is no cleaning of equipment between runs. It is creative – as well as fast and flexible – because not only can any design be printed, but also colours and designs can be changed with a click on the computer, making short runs efficient and cost-effective. It is competitive because it is highly cost-effective, with fully reproducible results – 'a short cut to customized and personalized production'.

6.2.2 The DReAM machine

The DReAM machine is quite compact, occupying approximately 3 m × 6 m (see Fig. 6.1). A slightly larger footprint is necessary for models with additional drying or polymerizing units. The standard configuration is a roll-to-roll system. However, Reggiani also provides alternative configurations to suit specific customer needs. The standard operating power is about 10 kW (excluding the power needed for the eventual auxiliary drying unit).

Machine installation is quite simple and does not require special connections. The machine must be connected to the mains, water and drainage system (its operation needs only electricity, compressed air, de-ionized water and normal water, but in any case before installation Reggiani provides DReAM users with a detailed guide for site preparation). The recommended printing conditions are

6.1 The DReAM machine.

room temperature of 20–25ºC (68–75.2ºF) and 50–60% humidity. The DReAM therefore requires a ventilated, temperature-controlled environment.

All the operations are programmed according to the desired printing sequence by means of an on-board computer connected with another remote PC, which transmits the digital file with all the instructions about the print, its colours and variants. Once the setup of all the variables has been carried out following the operator's instructions, the digital file is stored in the PC for possible repetition. The DReAM runs a Windows NT operating system.

Concerning RIP and printing process, the DReAM is provided with an entry-level RIP utilizing standard Photoshop software and a Pantone plug-in (Hexachrome), which has been designed specially for use with six-colour process printing. This RIP software is provided as a standard integral part of each delivery. It is very simple to use and takes advantage of Photoshop being an industry standard. The entry-level RIP package, including the Photoshop RIP with the Pantone Hexachrome plug-in, is included in the package. Other options for RIP software may also be purchased with the system if more complex functions are required. In any case, RIP software is a must with the system.

To be more precise, the DReAM currently supports the following RIPs: Photoshop with Pantone plug-in (entry-level), Ergosoft, Wasatch, Hightex, NedGraphics and Aleph. Ergosoft, Wasatch, Hightex, Eidocolor and Aleph provide more complex features and capabilities which may be required for certain applications. In the event that the customer wishes to use alternative software, a special driver must be developed to interface between the chosen RIP software and the printer.

It is here necessary to explain what exactly is the input for the printing system. There are in fact two types of files that can be entered into the DReAM workflow (into the RIP):

- Combined colour information (either RGB or LAB) in TIFF or other graphical formats; or

- Separated colour information (suitable for traditional printing) in TIFF or other graphical formats. In this case each individual separation may be provided as a grey-scale TIFF.

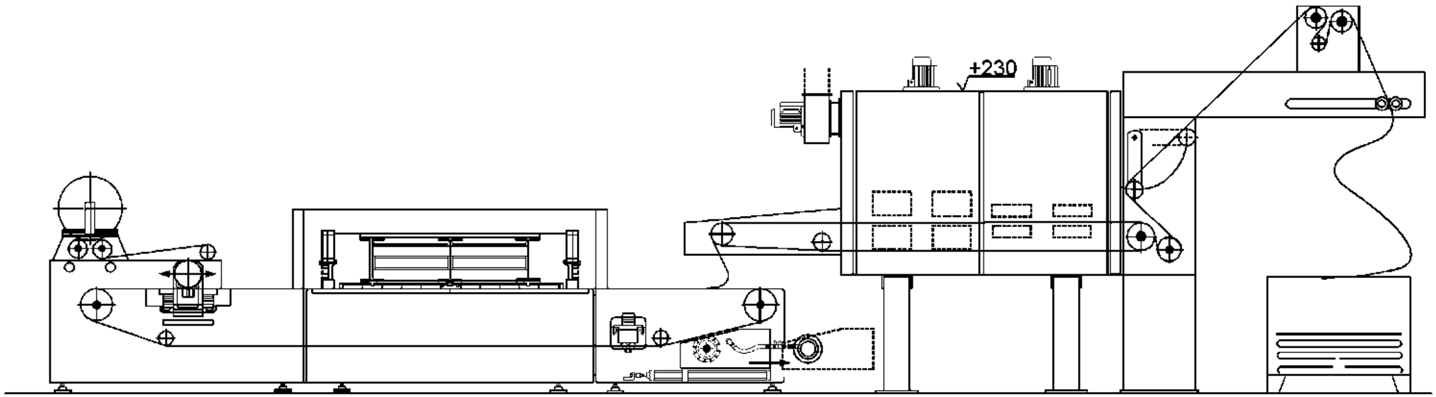
The operator may develop unlimited colourways via the RIP software or in the CAD software used to prepare the files, depending on the workflow that he or she implements. Before starting to print, the system has to be calibrated for each fabric–ink combination, and after calibration a colour book can be created using the ‘recipes’ chosen by the user. A spectrophotometer allows (after calibration) sample colours to be measured, for colour matching. The measurement gives a recipe that can be used for the colourways. A certain number of colour calibration profiles (tables) are provided by Reggiani together with the RIP. In addition, the customer may develop and define additional colour profiles. (Instructions for creating additional colour profiles may be provided as part of the Reggiani training package.) Figure 6.2 shows the sequence of machine operation.

A single application specialist can manage alone all the above-mentioned operations. He or she should have a working knowledge of pre-press software, colour management and printing processes and know how to use the RIP software for preparing files for printing. The pre-press person performs basic calibration procedures like producing linearization curves. An expert in this field can also perform colour calibration and create colour profiles. Training on the specific software provided as part of the DReAM is also provided by Reggiani.

In addition to the application specialist who is recommended to prepare the files for printing, as is done today with computerized workflows (CAD/CAM operators), a single operator is sufficient to control the machine and oversee printing. This operator should have a technical background, know the machine components, and know how to operate the machine to print different jobs. Furthermore, the operator performs routine maintenance activities.

The DReAM machine prints starting from standard rolls or from a single big roll. The inkjet printer (whose design is quite similar to conventional continuous printing machines) delivers the printed fabric in the form of a roll or a folded piece ready for subsequent fixing processes. Any fabrics in fact may be printed on the DReAM system. The appropriate pre-treatments have been developed by Ciba in order to maximize print quality for each fabric type together with the appropriate ink type. Moreover, the fabric should be treated before and after printing, in order to allow fixation of the colours as well as to improve the colour depth and visual quality. Reggiani Macchine S.p.A. and Ciba Specialty Chemicals Inc. will provide specific recommendations for the preparation, pre-treatment and finishing of the fabric.

It is now interesting to examine some technical details of the DReAM inkjet printing system.



6.2 Schematic of the DReAM machine.

Entry to the machine

On entering the machine, the fabric roll to be printed slides on two cylinders that unwind the fabric and automatically adjust the speed with respect to the preset tension level. A load cell system detects the tension, while a reciprocating compensating device transforms the constant motion of the unwound fabric into forward stepping motions. These movements are controlled by the blanket on which the fabric is bound by means of a permanent thermoplastic adhesive. The bonding power is the minimum required to retain the fabric (the high bonding performance required for flat screen printing is not necessary in this case).

The printing phase

The printing unit, which includes six colours, travels crosswise through the machine at a controllable speed. The quantity of ink sprayed by each head is adjusted by means of software and ranges between +200% and −70%. In any case the ink consumption, based on CMYKOB reactive inks for medium coverage with medium-dark colours, is approximately 10–11 g/m^2.

The distance between the spraying nozzles and the blanket surface can be adjusted from 0 to 40 mm, thus granting excellent handling for any type of fabric, velvets, non-woven, leather, finished garments, etc. Each head is fed from both sides for more uniform spraying. The feeding system for each of the six colours is continuously recirculated into a system equipped with microfilters and gas exhausts, ensuring maximum efficiency of the spraying nozzles. On one side of the machine the ink feeding system is equipped with six tanks, each containing 10 kg of ink (one for each colour). Moreover, there is a buffer quantity of ink in the machine at all times (supporting approximately 30 minutes of printing) so that the empty tanks can be replaced while printing without hindering machine operation.

The blanket

The flat and non-deformable blanket is tensioned continuously and uniformly. The special stepper motors connected with encoders grant an accuracy of a few microns, as a result ensuring optimum fabric feeding and transport. After passing the return rollers, the external surface undergoes a powerful washing carried out by means of a large rotating brush sprayed with water and followed by a squeegee that removes the excess water. The intensity must be adjusted according to the degree of dirt on the surface and to the type of fabric. The maximum water consumption is approximately 300 litres per hour.

The drying phase

The printed fabric is separated from the blanket and conveyed into a drying unit operating according to the hot air impulse principle, which can be adapted to different manufacturing requirements. The printed and dried fabric is wound on rolls (or folded according to the customer's requirements) which are then sent out to the subsequent development, fixing and washing stages depending on the type of dye applied.

The inks: Ciba Specialty Chemicals

The inks are developed and manufactured at Ciba Specialty Chemicals Inc. in Basel, Switzerland, and are sold and distributed via Ciba's international distribution structure. Ciba Specialty Chemicals has been a market leader in digital printing ink development and manufacturing for many years and is thus a reputed partner in the field. The chemistry and R&D teams of Ciba Specialty Chemicals and Scitex Vision have worked extensively together to develop Ciba's unique inks, which are designed exclusively for the Aprion inkjet heads, thus ensuring optimum results. Reggiani offers a package to the customer, a seamless integration of the DReAM printer with Aprion heads and Ciba inks. In addition, the one-year inclusive warranty covers only the use of Ciba Specialty Chemicals inks. Finally, using Ciba's inks ensures the overall quality of the printed results as well as reliability of the DReAM system.

Today, the following reactive, acid, disperse and pigment inks are available:

- CIBACRON® RAC reactive inks, specifically designed for cellulose fabrics (cottons, viscose, etc.)
- Ciba® LANASET® RAC acid inks, for silk, polyamide and wool fibres
- Ciba® TERASIL® RAC disperse inks, suitable for polyester applications and transfer printing
- Ciba® TERASIL® RAC TOP disperse inks, suitable for apparel and automotive polyester direct printing applications
- Ciba® IRGAPHOR® RAC pigmented inks, suitable for all fabrics.

On the DReAM machine six process colours are used: yellow, orange, magenta, blue, turquoise (cyan) and black (CMYKOB), allowing the widest colour gamut. Alternatively, the customer may choose to use four process colours together with light colours in order to maximize colour smoothness (CMYK and lights turquoise and magenta).

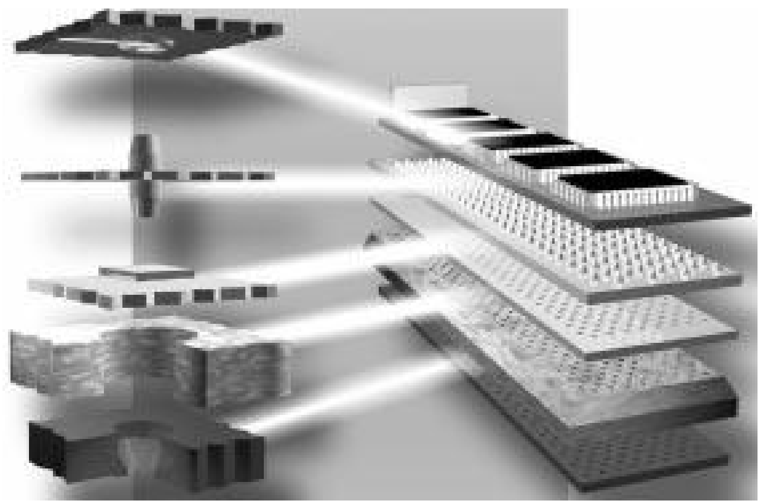
If the difference between using spot colours and process colours is not clear, we can say that spot colours in traditional printing require that the specific, and exact, colours needed for each job and each colourway are mixed in advance in the colour kitchen. Subsequently, each colour is loaded onto its screen for printing. After printing, the screen needs to be cleaned and the new colour loaded.

Digital printing uses process colours, whereby the print heads are always loaded with the same basic colours: cyan, magenta, yellow, black, orange and blue (or light magenta/cyan). Using sophisticated software, unlimited combinations of colours can be created from these basic colours. In such a manner, many advantages and benefits are achieved: there is no need to prepare colors in the colour kitchen, there is no need to load and unload inks from the printer, and there is no need to clean the printer between jobs or colourways. Moreover, this is a much faster way to produce short to medium jobs or jobs with a large number of colourways. Most digital printers available on the market today, including the DReAM, use process colours, based on CMYK and either light colours or supplementary colours (such as orange and blue).

The print heads: Scitex Vision

The secret of the Aprion technology provided by Scitex Vision lies in the multi-layer construction of its inkjet heads (Fig. 6.3). These are only 1.5 mm thick. The heads measure 5.9 × 0.8 inches and print at 600 dpi resolution. The top layer of the 'sandwich' is a grid consisting of hundreds of piezoelectric drivers. Next is a layer of porous metal, which allows the ink to flow to the bottom layer, which contains the nozzles. This structure allows the ink to flow reliably at high firing rates over a very wide cross-section – as opposed to other technologies involving micro-channels (unlike continuous-flow inkjet technology, there is no ink waste and unnecessary recycling).

The heads are of the drop-on-demand type, which means that the piezoelectric driver above each nozzle creates a shock wave, causing a droplet to be emitted only when required. Although the ink flows slowly through the porous layer, each shock wave pulls it through rapidly, thus eliminating crosstalk between nozzles. The print heads installed on the DReAM run at



6.3 Scitex Vision digital drop-on-demand print heads.

Table 6.1 The principal technical characteristics of the Aprion print heads

Head dimensions	5.9 inches × 0.8 inches
Resolution	True 600 dpi
Number of nozzles per print head	512
Ejection frequency	Over 30 kHz
Mode	Binary drops
Structure	Rooftop piezo drop-on-demand; multi-layer structure that enables high rate, reduced crosstalk
Printing method	Scanning array

speeds exceeding 30,000 droplets per second; however, the Aprion inkjet heads already demonstrate a potential of up to five times that speed.

For each of the six colours on the machine there are seven heads. The total number of heads in each DReAM printer is 42. Each head has 512 nozzles. The printing resolution is true 600 dpi (dots per inch). The principal technical characteristics of the Aprion print heads are listed in Table 6.1. The technology is protected by numerous patents and pending patents that have been awarded in the USA, Europe, Japan, Canada and Israel.

6.3 New opportunities offered by the new Reggiani digital printing machine: Digital Technological Center (DTC)

6.3.1 What is the DTC?

The DTC, or Digital Technological Center, is a recent realization by Ciba Specialty Chemicals Inc. and Reggiani Macchine S.p.A., aimed at furthering industrial digital printing. Established on 1 March 2004 in Grassobbio (Bergamo) at Reggiani Macchine, the DTC is an independent organization and the result of a common project between the two partners. This modern structure is dedicated to the study and research of the digital workflow, production process and the pre/post treatment of digital printing. It is specifically geared to:

- Development of new products with Ciba: inks, pre-treatment and post-treatment
- Development supporting Reggiani: software and hardware, colour calibration, CAD driver releases, upgrades and workflow research
- Coordinating and hosting events and conferences to foster industrial digital print penetration
- Supporting textile universities in promoting the vision of industrial digital printing.

6.4 The Reggiani Digital Technological Center (DTC).

The DTC's scope is to provide a higher added-value service, offering clients constant improvement in the digital printing experience and consistent service. See Fig. 6.4.

6.3.2 The DTC's activities

The facility will include a DReAM system, RIP and software facilities in a demonstration center, training facilities, and a lab and offices. The DTC's mission is research and development into the specific technology aimed at promoting industrial digital printing; contributing to new business development by offering clients complete assistance and aiding their industrial needs; and leading clients to attain the know-how necessary to set a benchmark for digital printing internationally. The technological center offers the following services:

- Sampling
- Printer driver acceptance for third parties
- Short-run production
- Collection development
- Colour calibration
- Pre-treatment service
- Post-treatment service

- Online technological support
- Education
- Client start-up
- Set up of turnkey industrial textile processes.

The DTC's team of highly qualified personnel display a gamut of experience unmatched in the industry with experts in machine engineering, industrial textile know-how, inks, chemistry, software and colorimetric science. The DTC has been structured to efficiently offer clients support and know-how through all phases of industrial growth from start-up to uptime guarantees, pointing on technology as a tool and asset. The applied technology offers:

- Live monitoring between the DTC and client machinery
- On-site and remote support and service.

DTC offers training to fulfil all client needs (machine operators will be trained by Reggiani staff and their partners); all DTC courses are offered at the Reggiani Macchine Grassobbio location and can also be held at a client site. Training includes books and materials. Training materials (student manuals) and the training schedule will be shipped to the client site one to two weeks before classes start. Reggiani's presentations are delivered using a high-resolution PC projection unit (1024 × 768 resolution) and an erasable whiteboard writing surface, both required for each class.

6.4 Bibliography

Fabio Viviani, *Sinergia di competenze*, Tecnologie Tessili, May 2003, Reed Business Information.

Internal documentation.

7

Industrial production printers – Mimaki's Tx series

H KOBAYASHI, Mimaki Industries, Japan

7.1 Evolution of digital printing

Fabric printers using ink-jet technology were introduced to textile printing vendors at the end of the 20th century. The growth of the ink-jet printer market is attributed to advances in ink-jet technology and rapid acceptance of industrial wide-format color ink-jet printers (WFP) for sign graphics starting approximately 10 years ago. Establishing textile printing technology, WFP manufacturers aimed to expand print targets to fabric, which would provide a much larger market than sign graphics. After careful consideration, WFP manufacturers adopted one of three approaches according to their business circumstances:

- Developing original textile printers based on WFPs for paper or film printing
- Leaving such development to customizing companies that modify and market such printers
- Taking no action for textiles.

At the International Textile Machinery Exhibition in 1999 (ITMA 99), six printer manufacturers exhibited printers they had specially developed for textiles to fulfill the first of the above options. Also, several manufacturers showed printers they had extensively modified in terms of fabric feed mechanism, bulk ink system, etc., based on WFPs for graphics.

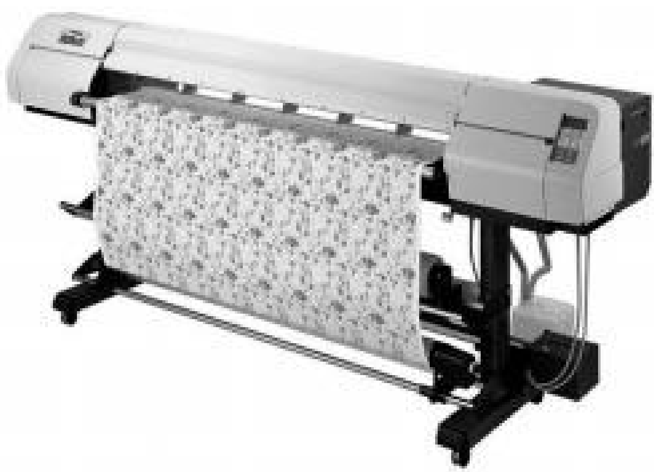
Both ITMA 99 in June 1999 and another textile show, HimeTex 2000 in January 2000, contributed much to gain recognition and spread textile ink-jet printers rapidly into the market. Especially, HimeTex 2000 introduced 24 textile ink-jet printers at 11 stands in total, announcing that textile ink-jet printing was finally becoming available commercially. Of the 24 textile ink-jet printers at HimeTex 2000, 15 machines (62%) were manufactured by Mimaki Engineering Co., Ltd. Also, five printers based on WFPs modified for textiles were all modifications of Mimaki's Tx-1600S. This machine, the first version of the Tx series, was easy to modify for textiles because of its high quality piezo-head and low cost.

To meet market needs for production of sample products in small lots, printer manufacturers and customizing companies have enhanced printer functionality, including the print speed, fabric transportation, allowable weight of rolled fabric, supported ink types, and dryer equipment. These improvements have further accelerated the marketing of textile ink-jet printers and continue to do so today.

7.2 Marketing profile of Mimaki's Tx series

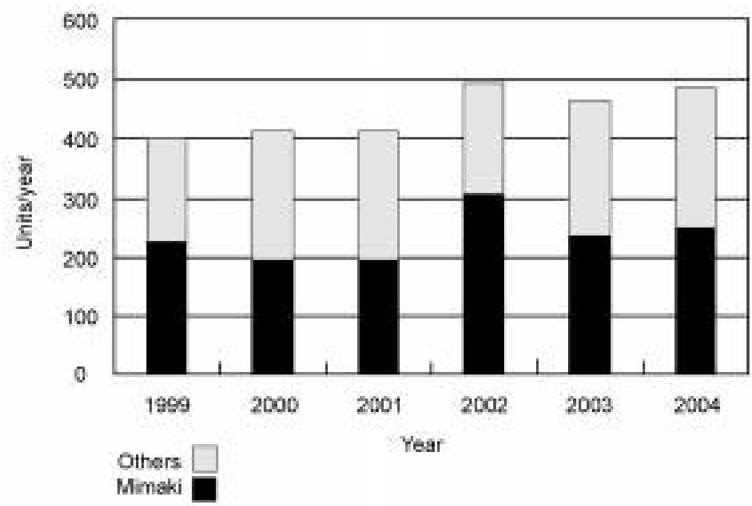
The Tx series lineup includes the Tx-1600S, the first model released in October 1998 (the year before ITMA 99), the Tx2-1600 (August 2001), and the Tx3-1600 (October 2004), with total sales of approximately 1500 units: see Figs 7.1–7.3. Figure 7.4 shows annual worldwide sales of the Tx series (three models) and those of digital fabric printers in the market (our estimation). Figure 7.5 shows a regional sales breakdown of the Tx series.

7.1 Tx-1600S.

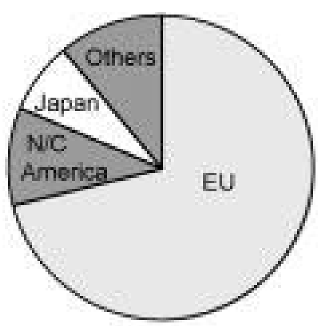


7.2 Tx2-1600.

7.3 Tx3-1600.



7.4 Annual worldwide sales of the Tx series (three models) and those of digital fabric printers in the market (our estimation).



7.5 Regional sales breakdown of the Tx series.

7.3 Market needs for digital textile printing

There are various market needs for digital textile printing that differ from WFPs for graphics, compared to conventional screen textile printing:

- Productivity: 20–30 m^2/h print speed for practical use
- High resolution: enabling printing of fine tie patterns
- Support of various fabric types: stretching/shrinking, thin, raising fabric, etc.
- Color reproduction: equal or higher color gamut to screen textile printing; high color reproduction when reprinting or between different models
- Strike-through: color permeability to rear surface (especially for scarves)
- High fastness: equal fastness to screen textile printing
- Low running costs: slightly higher printing costs than manual textile printing.

The importance and achievement level of these needs differ depending on the intended purpose of the digital textile printing. For small lot production, productivity and running costs are especially important because of printing end products. For color correction printing, color reproduction and high resolution are important. Before now, many users who introduced the Tx series had used several printers for small lot production. Therefore, the highest market need is demand for productivity and running costs.

7.4 Technical issues and solutions

7.4.1 High resolution images

The quality of digitally printed images is determined by printer resolution, variable dot size, and fabric feed accuracy of digital textile printers, and those factors are now discussed.

Resolution

Printers with finer resolution produce higher-quality output. Conventional screen printers typically use 100 to 300 mesh screens, resolution of which is comparable to 254–770 dpi (100 μm down to 33 μm) for the resolution of digital images. For textile printers, 720 dpi is a practical and necessary plotting resolution. To print actual images with resolution equivalent to that of paper ink-jet printers, it is important to inject the proper amount of ink that gives the right dot length on the textile appropriate to the resolution from the nozzle.

The Tx series adopts a 720 dpi plotting resolution. Realizing 80–100 μm print dot length by 5–25 pl (1 pl $= 10^{-12}$ liter) ink drop size, high-resolution printing is available. The nozzle hole pitch of the ink-jet head incorporated in the Tx series is 180 dpi (141 μm). However, it is capable of performing real 720-dpi resolution (35 μm) printing by scanning four times separately between nozzles. Also, for enhancing image quality, it is possible to print a scanning dot line every dot using two types of nozzle. In this case, 720 × 720 dpi meshes will be coated by scanning eight times. In the same way, a printing mode using 16 times scanning is available. Printing using multiple scanning is time-consuming. So it is necessary to use the appropriate mode depending on the desired print quality.

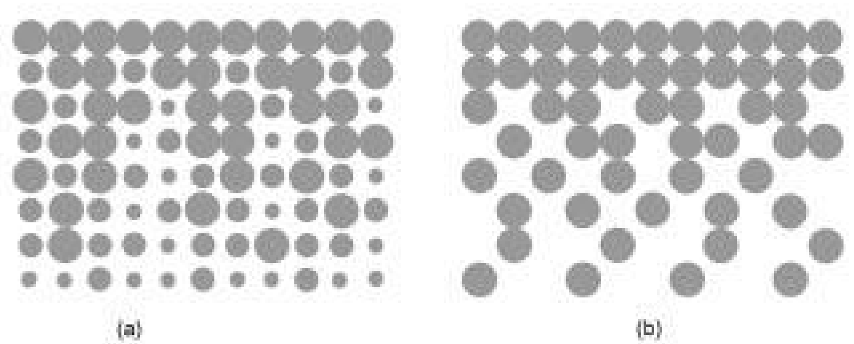
Variable dot size

Popular methods for color tone control are digital dithering, pseudo halftone reproduction using an error diffusion method, and combination with light colors. In gradation of dark colors only, graininess is often apparent in the highlight area where basic dots are large and dark. Use of smaller dots with those methods is effective in reducing graininess and preventing a tone-jump phenomenon. Tx2 and Tx3 printers are capable of manipulating dots in three sizes as shown in Fig. 7.6. These dots in different sizes allow smooth tone gradation with less graininess.

Fabric feed accuracy (banding prevention)

When feed fluctuations for every head scan occur, a striped pattern in the scanning direction (banding) is seen on the resulting print and leads to poor image quality. Banding occurs chiefly because of faulty fabric feed and irregularities in the fabrics themselves. Its causes are as follows:

- Existence or nonexistence of slippage at fabric clamping mechanism part (printer)
- Tension uniformity of fabric (printer)
- Stretch fabric or not (fabric, material)
- Fabric wet expansion/shrinkage by ink (fabric, material)
- Slippery surface of fabric (fabric, material)



7.6 Tone gradation by variable-sized dots: (a) with variable dot sizes; (b) with a single dot size.

- Concavity and convexity of fabric (embossment, crape) (fabric, material)
- Uniformity of edge of roll fabric (in shape) (fabric, pre-treatment)
- Meandered or curved fabric (fan-like, deformation to s-shape) (fabric, pre-treatment).

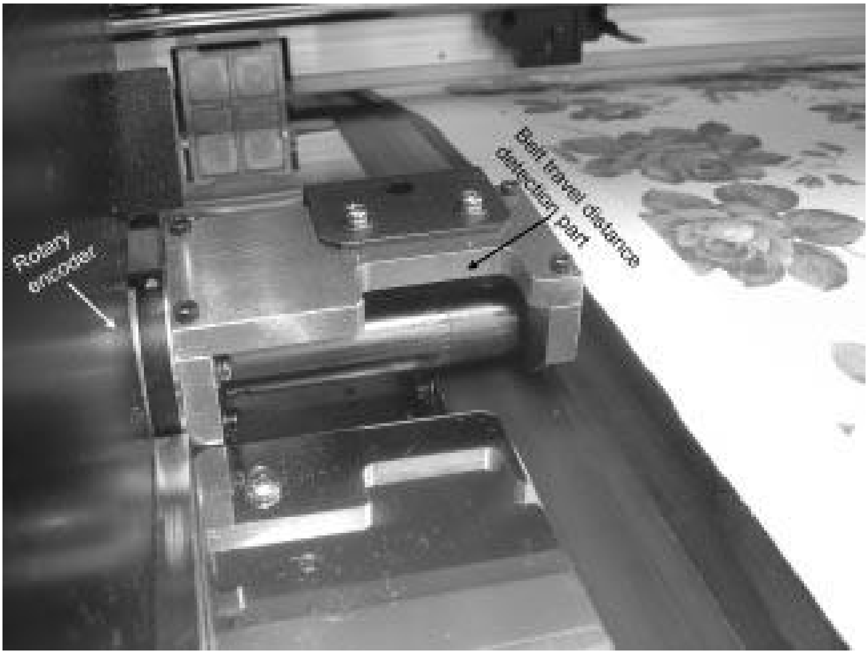
The feeder must be equipped with a mechanism that prevents a fed fabric from slipping, and fabric can withdraw easily from it to prevent fabric from imperfection. As the anti-slip mechanism, the Tx2-1600 (Fig. 7.7) and Tx3-1600 (Fig. 7.8) have knurled rollers and a feed system using an adhesive belt (table adhesive method), respectively. The knurled rollers of Tx2 have fine projections on the stainless-steel surface and have strong friction in the thrust direction when winding fabric. If the height of toothing is too great, the amount of toothing to be pierced into the fabric will increase and lead to imperfection in the fabric. Also, fabric cannot be easily withdrawn.

Feeding is performed under fixed tension, pulling the entire fabric by the roller with special surface treatment at the point immediately after printing (Fig. 7.9). Applying clingy paste to the wide endless belt surface, an adhesive belt feeds fabric by sticking it to the belt. Because the entire fabric sticks to the belt, stretch material such as knit can be fed and textiles are prevented from wet expansion/shrinkage by ink. As the adhesive power of paste will deteriorate with use, it is necessary to put paste on the belt periodically. Also, varying thickness

7.7 Tx2 feeding roller.

7.8 Tx3 feeding belt.

7.9 Tx2 fabric tension mechanism.

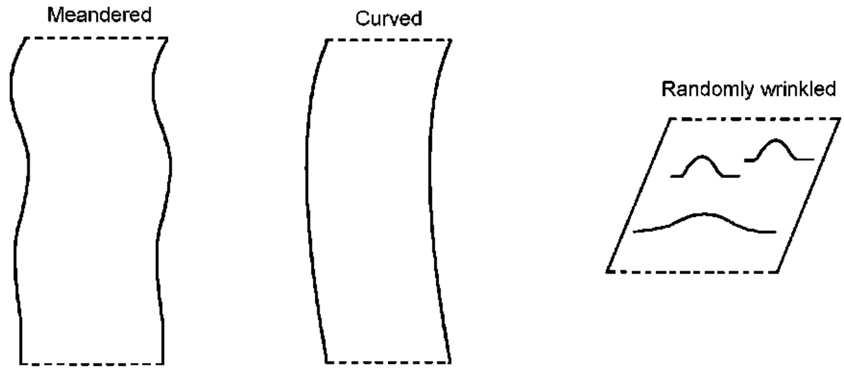


7.10 Tx3 detecting the travel distance of the belt.

of the feeding belt and non-uniform paste lead to accidental errors in fabric feed accuracy. In order to correct feed fluctuations, movement of the belt is controlled by detecting its travel distance at the final stage by a rotary encoder with a feedback system to the belt driver motor (Fig. 7.10).

To reduce variations of the tension applied to the fabric, the Tx2-1600 has a torque limiter and a conditioning roller mechanism followed by the drive section; the Tx3-1600 has parallel tensioning bars. Generally, when feed accuracy has $\pm 20\,\mu$m or more accidental error, visible banding tends to occur. As mentioned above, fabric characteristics such as expansion/shrinkage, wet expansion/shrinkage by ink, slippery surface, concavity and convexity also affect banding.

Pre-treatment of fabric consists of impregnation by an agent mainly consisting of paste and then drying. This pre-treatment can prevent bleeding of dye inks and improve feed performance. (Section 7.4.3 explains the details of prevention of bleeding.) For fabrics woven with a hard twist and large expansion/shrinkage, pre-treatment paste coating should be increased to improve feed performance. Adjustment of the composition of the agent, width of the tenter, speed and strength of take-up by the fabric all affect the result. If the make-up of the agent is not suitable, fabric may be starched or stressed, causing skewed feeding, meandering, and non-uniform pitch. These cause banding. Figure 7.11 shows typical examples of results of pre-treatment. Skewing of the fabric causes banding, fabric slip upon feeding, and wrinkles, eventually leading



7.11 Skewing caused in the pre-treatment.

to the head nozzle dragging on the print fabric surface and to fabric jamming in the printer.

7.4.2 Color reproduction

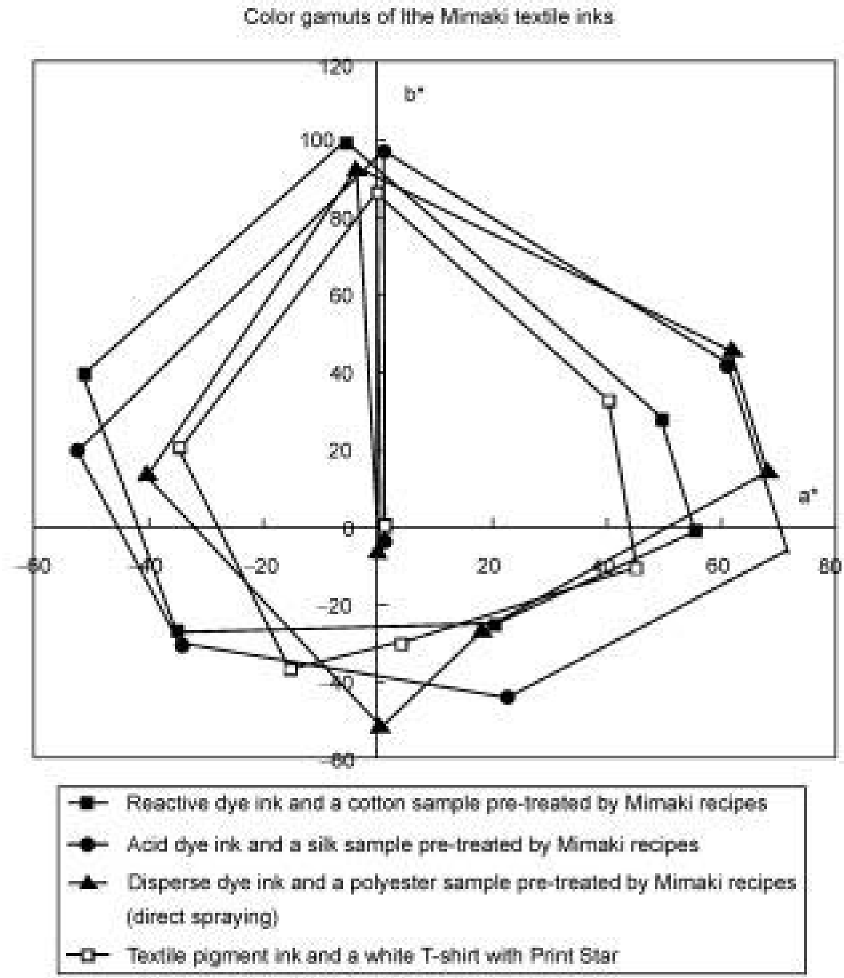
Figure 7.12 compares the color gamuts of reactive dyes, acid dyes, disperse dyes, and water-based pigment inks. The figure suggests that the color gamut of dye inks compares favorably with that of pigment ink.

7.4.3 Prevention of bleeding

Conventional screen printing and ink-jet printing use different pastes for print inks. To prevent ink bleed, screen printing uses a volume of pastes that makes inks much more viscous than those for ink-jet printing for dye. We call the mixture of textile dye ink and pastes 'printing pastes'. Hand screen printing, automatic flat-bed screen printing, and rotary screen printing use pastes with lower viscosity in that order. Generally, screen printing uses pastes with viscosity of some hundreds to tens of thousands of mPa·s. Ink-jet printing adopts pastes with much lower viscosity, from a few to over 10 mPa·s. It requires light pastes for spraying ink droplets of a few to several tens of picoliters in size at a high jet frequency of approximately 10 kHz from the printer head nozzles. Ink droplets with low viscosity pastes would produce ink bleed on a fabric. Therefore, coating the target fabric with a pre-treatment agent, the main element of which is a paste, is necessary.

Ink bleed and strike-through on the printed fabric occur due to a capillary phenomenon. The ink penetration length through the capillary is calculated with the Lucas–Washburn equation, which expresses the relation between the penetration length L and the viscosity δ as follows:

$$L \propto \delta^{-1/2} \tag{7.1}$$



7.12 Color gamuts of fabric printing inks.

This equation proves that the penetration length becomes shorter as the ink viscosity increases. In conventional screen printing, an appropriate ink viscosity is chosen according to the fabric type for printing, the amount of ink to be applied, and the print speed to achieve the optimum print quality and avoid ink bleed. In the ink-jet printing, however, the nature of the ink-jet head prohibits the use of high-viscosity ink. For this reason, fabrics need to be coated with pastes in the pre-treatment to minimize risk of ink bleed in ink-jet printing.

Pastes used in pre-treatment contain various agents to improve overall print quality: coloring, color stability and print fastness against washing. These agents are usually added to inks for conventional screen printing. Only small amounts of those agents are contained in the ink-jet inks to control dye properties, help the dyes to be dissolved in the liquid, and preserve inks (required for assuring ink-jet performance and extending ink life). Without application of those agents in the pre-treatment of target fabrics, ink-jet printing would be unable not only to prevent ink bleed but also to ensure sufficient coloring. Agents included in conventional pastes to keep their functionality are as follows:

- Paste and anti-dyeing agents
- Penetrating agents
- Preservatives
- Dye dissolving agents
- Level dyeing agents
- Softeners
- Anti-color bleed agents
- Discharging agents
- Adhesive: for foils and gold pigments.

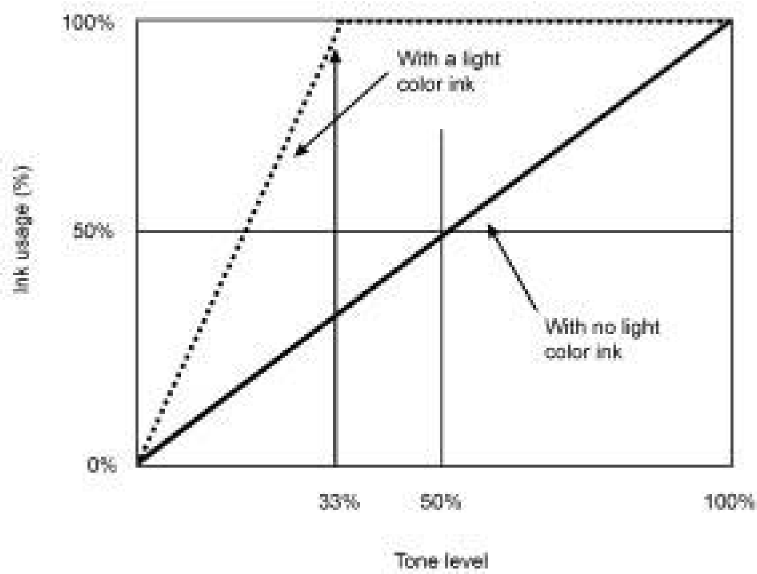
For ink-jet printing, ink consists of dyes, dye dissolving agents, moisturizing agents, small amounts of binders, preservatives, pH adjusters, and surfactants.

7.4.4 Strike-through

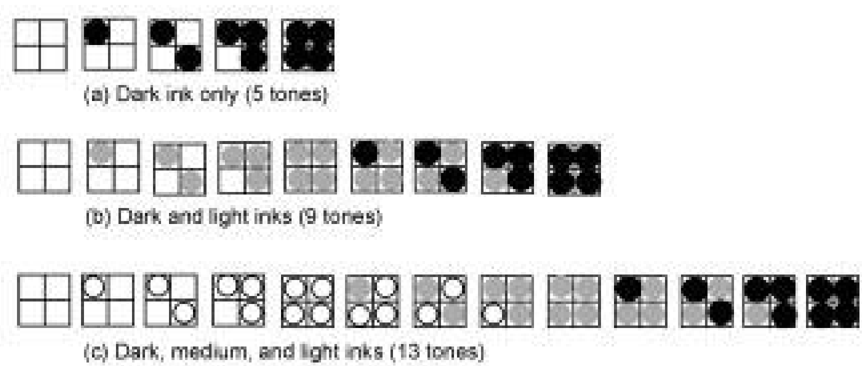
Uniform strike-through is one of the important factors in determining textile printing quality. In conventional screen printing, inks of all colors and tones are prepared according to screens to be used in the printing. Therefore, amounts of the inks applied on the fabric are irrelevant to color tones, and the amount of inks consumed is almost constant regardless of color or tones, resulting in uniform strike-through.

Ink-jet printing, however, controls color tones by the amount of YMCK inks injected; thus, the amount of inks consumed can be varied depending on tones. Strike-through in ink-jet printing is, therefore, reduced in light-colored print areas, which clearly contrast in strike-through by color tones when observing them from the opposite face of the printed areas. Strike-through spotting can be effectively prevented by using a variation of inks blended for required color tones. For reproduction of YMCK colors in ink-jet printing, use more inks of light colors and spray them on as large an area as possible to consume them evenly. Figure 7.13 shows the difference in ink consumption with and without gradation inks (the light color is 33% of the dark color) for a solid color shading model.

Another advantage of using dark and light inks is that smoother gradation can be achieved with more flexible tone control. Figure 7.14 gives 2×2 matrices to distinguish differences between three gradation methods: (a) a dark ink only and no ink (two-level dither method), (b) dark and light inks and no ink (three-level dither method), and (c) dark, medium, and light inks and no ink (four-level dither method). Assuming the matrix size is expressed as $N \times N$ and the number



7.13 Gradation and consumed ink volume.



7.14 Smoother gradation using light and dark inks.

of ink types is represented as k, the number of reproducible tones L can be expressed as:

$$L = (k \times N^2) + 1 \qquad (7.2)$$

7.4.5 Fastness

Table 7.1 shows ink fastness on fabrics used in the test. Tables 7.2 to 7.4 show the results for the fastness of digitally printed images with acid dye, reactive dye, and disperse dye inks, respectively, by a digital textile ink-jet printer.

Table 7.1 Inks and fabric fibers tested

Type of ink	Cellulose fibers (cotton, hemp, rayon, Tencel®)	Protein fibers (silk, wool)	Polyester fibers	Nylon fibers
Reactive dye	Available	Can be used under a certain condition	Not available	Not available
Acid dye	Not available	Available	Not available	Available
Disperse dye	Not available	Not available	Available	Available
Pigment	Available	Can be used under a certain condition	Can be used under a certain condition	Can be used under a certain condition

7.4.6 Applicability of fabrics: feed mechanism

Fabrics can be grouped as follows in terms of fabric feeding:

- Type 1: Stretch (including knit)
- Type 2: High wet expansion/shrinkage
- Type 3: Low strike-through resistance.

Type 1 fabrics are elastic and stretch literally by external forces; they need to be conveyed with minimum tension applied or with a certain degree of tension constantly applied in pre-process or during plotting. It must be noted, however, that conveyance without tension will easily meander (move) the fabric by distortion inherent to the fabric itself (variation of strand/thickness/weaving density) and from the pretreatment, which eventually causes skew and dislocates the fabric position. Thus, it is best to convey the fabric by applying the minimum tension required for correcting fabric distortion inherent in the fabric or caused by the pretreatment.

Type 2 fabrics, similar to Type 1, exhibit numerous sags or wrinkles due to fabric stretching in the printing process. Type 2 wet shrink fabrics will shrink toward the fabric center; both right and left edges lose straightness, shaping like steps according to the scanned bandwidth. Those fabrics start shrinking just after being scanned (printing) and will be shrunk upon the next scanning. Thus, the edges are deformed as shown in Fig. 7.15. The shrinkage causes greater deviation toward the fabric edges; print images are thus distorted, although white and black stripes do not appear. To solve this problem, some means for controlling the fabric is necessary; flat belt printing used for screen printing is effective.

Type 3 fabrics involve a problem where inks running through webs or penetrating to the back of woven fibers leave spots on the platen surface, which makes the fabric stained as conveyed. To avoid this stain problem requires either a contact-free system in which the fabric is not in contact with the platen, or a synchronized conveying system in which the fabric is conveyed with the platen.

Table 7.2 Color fastness – reactive dye ink and a cotton fabric pre-treated with Mimaki's recipes

Unit: grade

Item	Test method	Category		Fabric pre-treated with the Mimaki recipes										
				BL	C	GR	GY	K	LC	LM	M	O	R	Y
Light	JIS L 0842	E reactive ink cotton		4 or higher	4 or higher	3–4	4 or higher	4 or higher	3–4	3–4	4	4	4 or higher	4 or higher
Laundering	JIS L 0844	Fading/discoloration		5	5	5	5	4–5	5	5	5	4–5	4–5	5
		Staining	Cotton	5	5	4–5	4–5	4–5	5	5	4–5	4–5	4–5	5
			Silk	5	5	5	5	4–5	5	5	5	5	5	5
Drycleaning	JIS L 0860 Perchloroethylene	Fading/discoloration		5	5	5	5	5	5	5	5	4–5	4–5	5
		Staining		5	5	5	5	5	5	5	5	5	5	5
	JIS L 0860 Petroleum-based	Fading/discoloration		–	–	–	–	–	–	–	–	–	–	–
		Staining		–	–	–	–	–	–	–	–	–	–	–
Sweat	JIS L 0848 Acid	Fading/discoloration		5	4–5	4–5	5	4–5	5	5	5	4–5	4–5	5
		Staining	Cotton	4–5	**3**	4–5	4	4	4	4	3–4	4	4–5	4–5
			Silk	4–5	3–4	5	5	5	4–5	4–5	4	4–5	4–5	5
	Alkali	Fading/discoloration		5	5	4–5	5	4–5	5	5	5	4–5	4–5	5
		Staining	Cotton	4–5	**2–3**	4–5	4	4	4	4	3–4	4	4	4–5
			Silk	4–5	4	5	5	5	4–5	5	4–5	4–5	4–5	5
Water	JIS L 0846	Fading/discoloration		5	5	5	5	4–5	5	5	5	5	4–5	5
		Staining	Cotton	4–5	3–4	4–5	4–5	4–5	4–5	4–5	4	4–5	4–5	4–5
			Silk	4–5	4–5	5	5	5	5	5	5	5	5	5
Friction	JIS L 0849 Type II	Dry		**3**	**3**	4–5	**3**	**2–3**	4–5	3–4	**2–3**	**2–3**	**2–3**	3–4
		Wet		3–4	3–4	4–5	3–4	**2–3**	4–5	4	**3**	**3**	**2–3**	4
Hot pressing	JIS L 0850 A-2 Dry	Fading/discoloration		5	5	5	5	5	5	5	5	5	5	5
		Staining		5	5	5	5	5	5	5	5	5	5	5
	DTK no.			2697										

The test was commissioned to the Tokyo Office of Japan Dyer's Inspection Institute Foundation/Japan Textile Finisher's Association.
The mark '–' means that the test was not conducted.
Printing condition on each medium: 720 dpi, four-pass, 100% of single color. Post-treatment conditions for the test media were all the same.
The bold numbers mean a failure.

Table 7.3 Color fastness – acid dye ink and a silk crêpes de chine fabric pre-treated with Mimaki's recipes

Unit: grade

Item	Test method	Category		Ink color						
				K	Y	M	C	LM	LC	R
Light	JIS L 0842			7	5	3–4	3–4	3–4	3	4
Laundering	JIS L 0844	Fading/discoloration		4–5	4	3	3–4	3	3–4	3–4
		Staining	Cotton	4–5	4–5	4–5	4	4–5	4–5	2–3
			Silk	4–5	4–5	4–5	5	4–5	5	4–5
Drycleaning	JIS L 0860 Perchloroethylene	Fading/discoloration		5	5	5	5	5	5	5
		Staining		5	5	5	5	5	5	4
	JIS L 0860 Petroleum-based	Fading/discoloration		–	–	–	–	–	–	–
		Staining		–	–	–	–	–	–	–
Sweat	JIS L 0848 Acid	Fading/discoloration		4–5	5	5	4–5	5	5	5
		Staining	Cotton	4–5	4	4	4–5	4–5	4–5	4
			Silk	4–5	3	1–2	5	3	5	3–4
	Alkali	Fading/discoloration		4–5	5	5	4–5	5	5	5
		Staining	Cotton	4–5	4	3–4	4	4–5	4–5	3–4
			Silk	4–5	3	1–2	4–5	2–3	5	2–3
Water	JIS L 0846	Fading/discoloration		4–5	5	5	4–5	5	5	5
		Staining	Cotton	4–5	4	3–4	4–5	4–5	4–5	4–5
			Silk	4–5	2–3	2	5	3	5	2–3
Friction	JIS L 0849 Type II	Dry		5	5	5	5	5	5	5
		Wet		2–3	3–4	3–4	3–4	4–5	4	2–3
	DTK no.						1043			

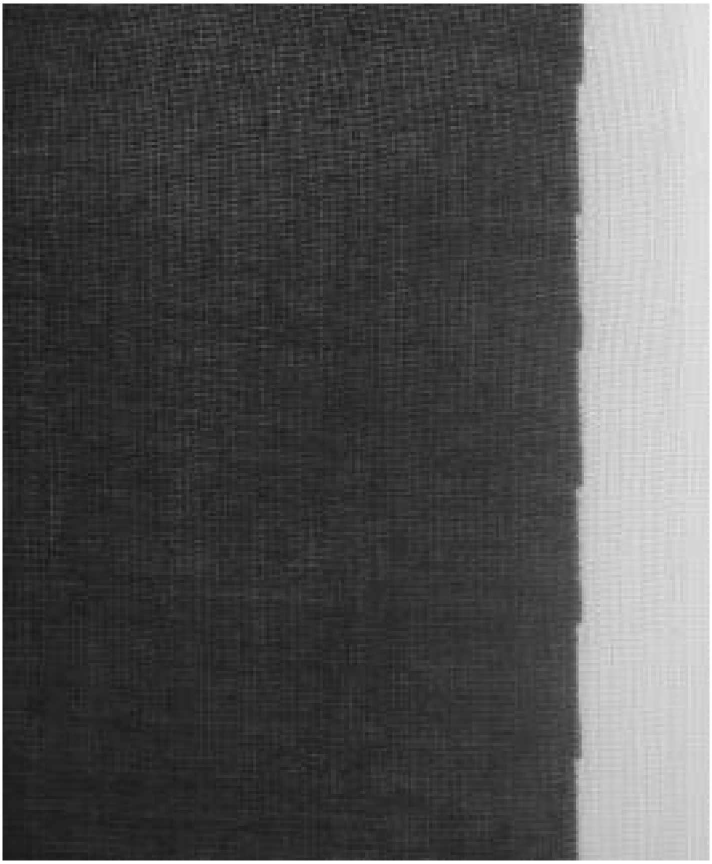
The test was commissioned to Japan Dyer's Inspection Institute Foundation/Japan Textile Finisher's Association.
The mark '–' means that the test was not conducted.
Pre-treatment: pre-treatment 1 for acid dye inks of Mimaki Engineering Co., Ltd (Mimaki's original recipe: see page 4 of the ink guidance).
Post-treatment: same as pre-treatment.
Fabric used for the test: silk crêpes de chine.
Printing condition: 720 dpi, eight-pass, uni-direction, 100% of single color.

Table 7.4 Color fastness – disperse dye ink and a polyester fabric pre-treated with Mimaki's recipes

Unit: grade

Item	Test method	Category		Ink Color							
				K	Y	M	C	LM	LC	GR	BL
Light	JIS L 0842			3	6	5	Less than 3	4	Less than 3	3	3
Laundering	JIS L 0844	Fading/discoloration		4–5	4–5	4–5	4–5	4–5	4–5	4–5	4–5
		Staining	Cotton	4–5	4–5	4–5	4–5	4–5	5	4–5	4–5
			Silk	5	4–5	5	5	5	5	5	5
Drycleaning	JIS L 0860	Fading/discoloration		5	5	5	5	5	5	5	5
	Perchloroethylene	Staining		5	5	5	5	5	5	5	5
	JIS L 0860	Fading/discoloration		–	–	–	–	–	–	–	–
	Petroleum-based	Staining		–	–	–	–	–	–	–	–
Sweat	JIS L 0848 Acid	Fading/discoloration		4–5	4–5	4–5	4–5	4–5	4–5	4–5	4–5
		Staining	Cotton	4–5	4–5	4–5	4–5	5	5	4–5	4–5
			Silk	5	4–5	5	5	5	5	5	5
	Alkali	Fading/discoloration		4–5	4–5	4–5	4–5	4–5	4–5	4–5	4–5
		Staining	Cotton	4–5	4–5	4–5	4–5	5	5	4–5	4–5
			Silk	5	4–5	5	5	5	5	5	5
Water	JIS L 0846	Fading/discoloration		4–5	4–5	4–5	4–5	4–5	4–5	4–5	4–5
		Staining	Cotton	4–5	4–5	4–5	4–5	5	5	4–5	4–5
			Silk	5	4–5	5	5	5	5	5	5
Friction	JIS L 0849	Dry		5	5	5	5	5	5	5	5
	Type II	Wet		5	5	5	5	5	5	5	5
Hot pressing	JIS L 0850	Fading/discoloration		5	5	5	5	5	5	5	5
	A-2 Dry	Staining		5	4–5	5	5	5	5	5	5
	JIS L 0850	Fading/discoloration		5	5	5	5	5	5	5	5
	A-2 Wet	Staining		5	4–5	5	5	5	5	5	5
Chlorinated Water	JIS L 0884 Method B	Fading/discoloration		5	5	5	5	5	5	5	5
	DTK no.			1213/3162							

The test was commissioned to Japan Dyer's Inspection Institute Foundation/Japan Textile Finisher's Association.
The mark '–' means that the test was not conducted.
Pre-treatment: pre-treatment for disperse dye inks of Mimaki Engineering Co., Ltd.
Post-treatment: same as pre-treatment.
Fabric used for the test: polyester specially designed for evaluation by Mimaki's Development Department (microfiber).
Printing condition: 720 dpi, four-pass, uni-direction, 100% of single color.

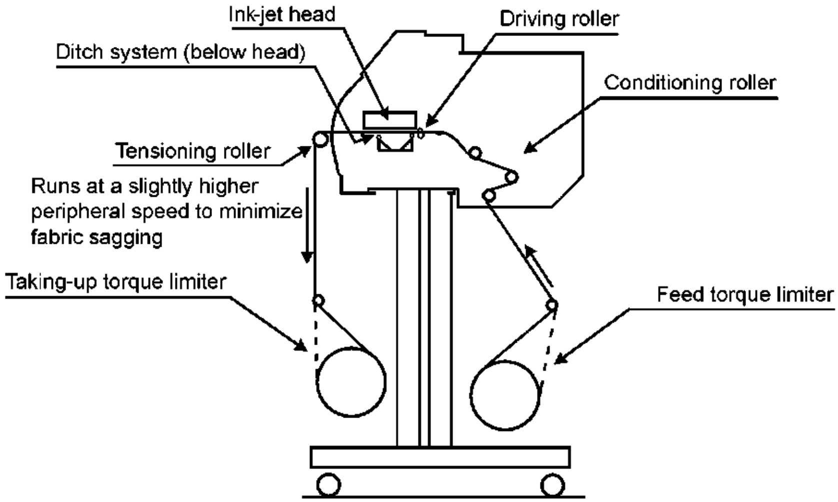


7.15 Step-shape edges due to wet shrinkage.

The former provides an open space between the printing area and the platen, and the latter conveys the belt or table itself, keeping the printed fabric on it.

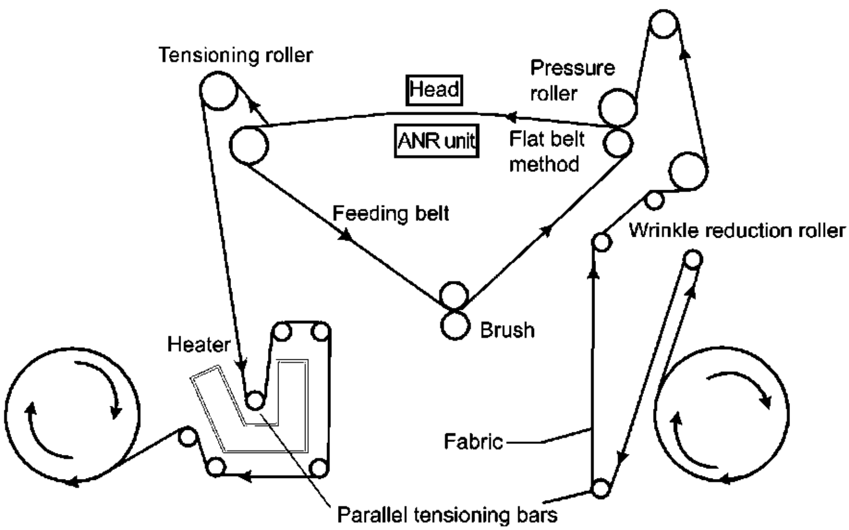
The model Tx2-1600 has adopted features that avoid such problems inherent in the fabrics (see Fig. 7.16). For Type 1 fabrics, the unit suppresses abrupt fluctuation of fabric tension with a feed torque limiter and a conditioning roller mechanism located just before a driving roller. A tensioning roller, located ahead of the printer head, runs at a slightly higher peripheral speed to minimize fabric sagging. And finally, a roll-up torque limiter rolls up the fabric with no abrupt fluctuation of the tension. For Type 2 fabrics, addressing applicable fabrics for the unit helps users to determine the choice of machines for their specific task. For Type 3 fabrics, the contact-free (ditch) system is adopted. A tensioning roller is provided ahead of this ditch system to prevent the fabric from sagging by gravity.

The model Tx3-1600 solves the problems by the following features (see Fig. 7.17). For Type 1 fabrics, parallel tensioning bars are provided. The feed/take-up



7.16 Tx2-1600 textile path.

control mechanisms control the bar positions via feedback and suppress the fluctuation of tension. For Type 2 fabrics, the table adhesive method is adopted. For Type 3 fabrics, the flat belt method is adopted to prevent the fabric back from becoming stained by inks.



7.17 Tx3-1600 textile path.

7.4.7 Running cost

Ink-jet printing does not require stencils; it achieves cost-effective printing for a much smaller print run than does conventional screen printing. Table 7.5 compares costs of ink-jet printing to conventional screen printing. Figure 7.18 shows the production cost (variable cost) per square meter depending on the production volume. As shown below, 1200 m^2 or less is a rough standard below which ink-jet printing is more economic. Actually, extinguishing of facilities, cost of washing stencils, number of production staff, etc., also affect the curve chart of cost and favour ink-jet over screen printing. As the cost of ink accounts for a high proportion of ink-jet printing cost, to reduce this ink cost is the key to wider adoption of ink-jet printing.

7.4.8 Ink-jet stability and reliability

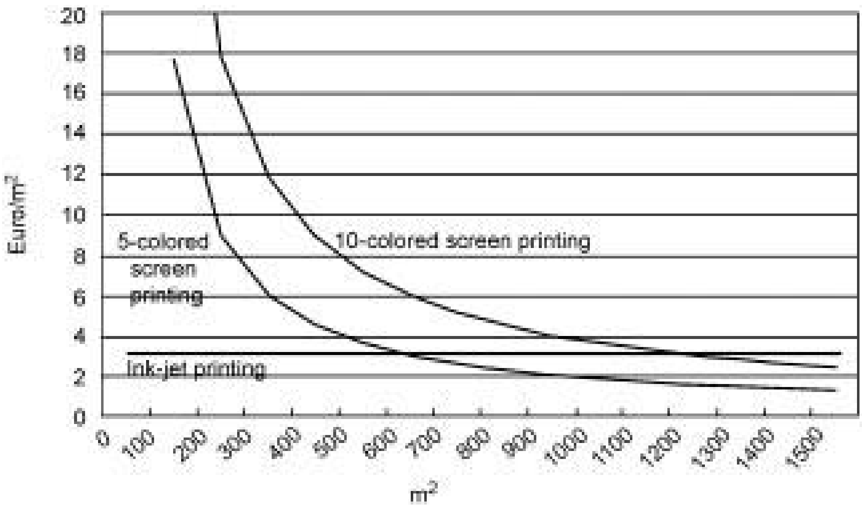
Disincentive elements of stable and reliable ink-jet performance

As ink-jet printing tends to be used more in production, stable and reliable performance is very important. For ink-jet printing, possible disincentive elements of stable and reliable performance are the injected inks themselves and fabric feed. This section explains how to ensure ink-jet stability and reliability. Stable and reliable performance is hampered mainly by the following causes and leads to defects such as white lines, non-uniformity of colors, spots, etc.:

- Ink physicality and mismatch with head. As mentioned in Section 7.4.1, the Tx series printers inject a very small ink drop of 5–25 pl (1 pl $= 10^{-12}$ liter) at high speed with a frequency of about 10 kHz from the nozzles. Therefore, the

Table 7.5 Comparison of costs of ink-jet printing to those of conventional screen printing

	Ink-jet printing	Screen printing
Cost of inks and color pastes	€150–222 per kg	€1.48–2.22 per kg
Volume of inks and color pastes	20 g/m^2	100 g/m^2
Cost of pre-treatment	Required $<$ €100 per m^2	Not required
Stencil	Not required	Required
Printing cost	€3.7–5.2 per m^2	€0.15–0.22 per m^2 + stencil cost: €296–370 per stencil
Environmental impact	Minimum	Serious
Quality comparison:		
Concentration	Poor	Good
Definition	Good	Poor
Texture	Poor	Good



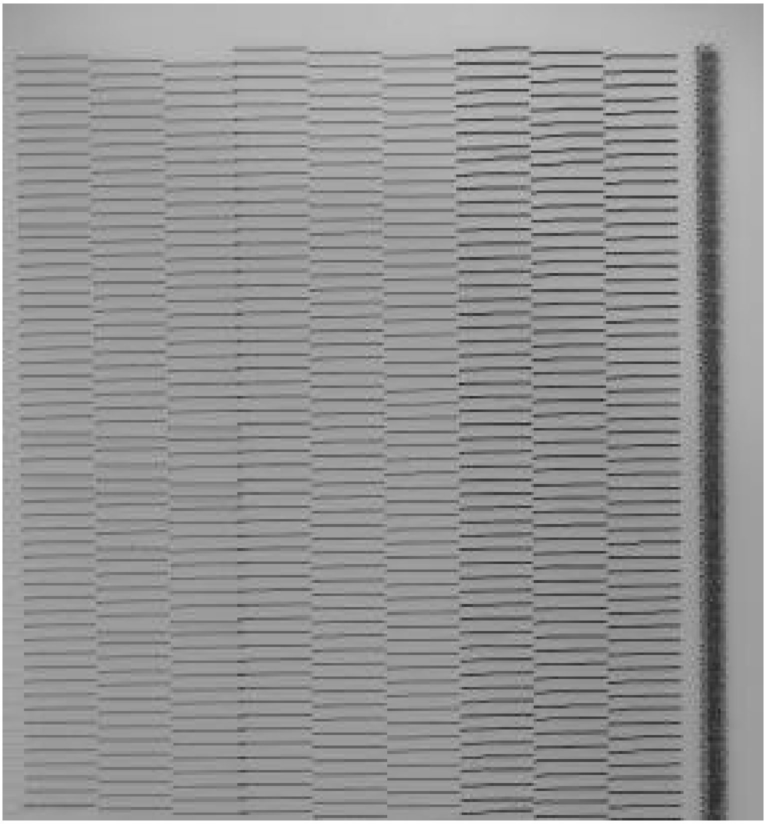
7.18 Comparison of 1 m^2 unit cost.

flow channel geometry of ink in the head is complicated by fine processing technology. If ink grains that have too wide a diameter are mixed in the ink, clogging will occur in the head. Also, if ink physicality values cannot follow the high-speed movement of the piezo head, ink drops will not be injected but ink mists are generated instead, or ink will not be injected at all.

- Lint and dust adhered to the head nozzles. Tiny lint particles and dust adhered to the fabric are stirred up by the air current of the scanning head and easily adhere to the surface of nozzles wet with aqueous ink. Adhered substances near the nozzle hole prevent ink from injecting and lead to white lines. In addition, adhered substances may get into nozzles during cleaning or wiping operations. In this case, unrecoverable deflection will occur or ink will not be injected at all. Though fabric pre-treatment can reduce such problems, it is realistically impossible to eliminate them totally.
- Dirt on nozzle surface generated by ink mists. If ink mists are generated from any cause while ink is injecting, the mists may be floating in the air and they land on the head and become a bigger ink drop. When the drop reaches a certain size, it may drop onto the fabric during scanning and make stains.

Measures taken for the Tx3

The Tx3-1600 is equipped with the function to detect an injection failure automatically. The ANR (Automatic Nozzle Recovery) unit is designed to assist users to check for clogging. It outputs a unit-unique print check map periodically, as shown in Fig. 7.19, on a designated medium and reads by a sensor. The unit itself is shown in Fig. 7.20. Users can configure the unit



7.19 Print check pattern used for ANR unit.

according to their designed print parameters, including checking intervals, thresholds for error determination (nozzle(s) causing void), and recovery procedures (cleaning levels). The Tx3-1600 is also equipped with the function to vacuum mists up while they are floating in the air and trap them in one place.

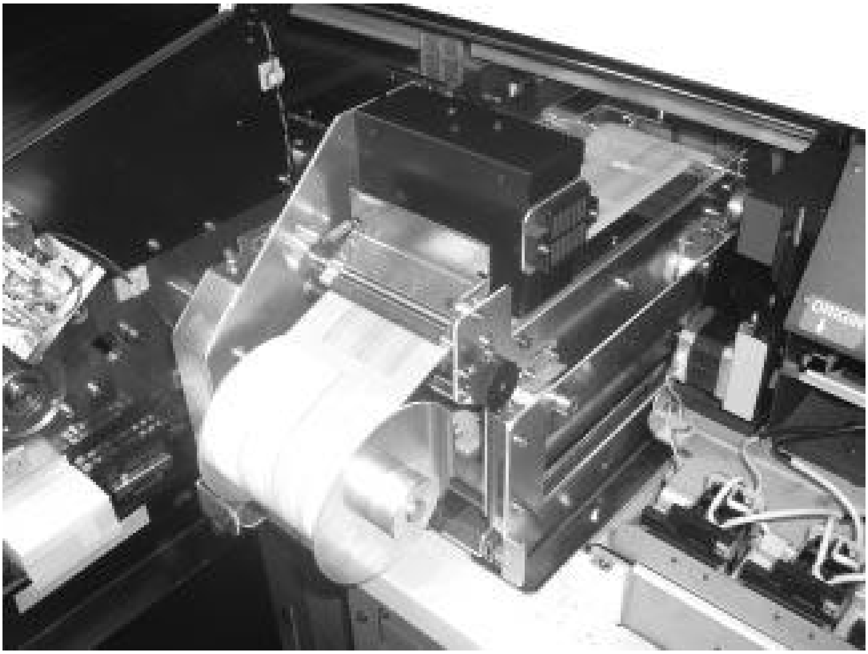
7.4.9 Productivity

Direct ways to improve the productivity of the ink-jet printer while maintaining print quality can be as follows:

- Improving the print head speed (improving the jet frequency)
- Increasing the ink-jet nozzles of the print head.

Indirect ways can be as follows:

- Capability for a large-sized long roll-type fabric (reducing the process steps)



7.20 ANR unit.

- Capability for a large-sized ink tank and a toggle cartridge (reducing the process steps)
- Improving stability and reliability of unattended operation.

Some of these are explored below.

Increasing nozzles by introducing a stagger head

Improving the print head speed means developing a new head; this requires time and the initial investments. Multiplying nozzles of a printer head may be technically difficult; however, aligning multiple heads can solve the difficulty. This modification involves undetermined technical and maintenance tasks, such as head–head position adjustment (inclination, gap), head variations, and maintenance work for the service shops.

Toggle-switch type cartridge

To reduce the process steps, adoption of a large-sized roll-type fabric or a large-sized ink tank seems an easy option. In reality, a toggle-switch type ink cartridge is much superior to those options. It is a device for switching an ink cartridge when its ink level calls for replacement. One-color ink cartridge or one-color multiple cartridges that simultaneously operate (in parallel) must be replaced when the ink runs short or the predetermined ink-end level is reached. If the ink runs short while the printer is running at night without operators, printing must be stopped until operators return, causing unnecessary downtime. Users often reluctantly install a new cartridge much earlier than the ink-end level indicates because of forecast downtime during operator absence. As a result, they discard cartridges in which much usable ink remains. Conventional ink cartridges can be replaced only as long as an operator attends the printer; however, the operator must reset the printer quite frequently. The toggle-switch type cartridge, in contrast, allows users to use the ink right to the end, freeing the operators from frequent cartridge replacement. Therefore, the Tx2-1600 has adopted the toggle-switch type.

Stability and reliability of unattended operation

To maintain productivity, it is very important to ensure stability and reliability of unattended operation, including night operation. As explained, fabric print performance can be assured by lint and dust control. Without thorough control, an all-night print job may end up in vain the next morning because of voids and defects on the print. Tx3-1600 models, equipped with ANRS, assure users reliable non-stop printing.

7.5 The future of digital printing

This section discusses tasks that need to be overcome for digital printing to grow in the future.

7.5.1 A simple and easy digital printing system

A digital printing system is not limited to the ink-jet printer itself; it involves many other operations to provide a simple and user-friendly printing system that will gain wider acceptance in society:

- The fabrics to be printed
- Agents, techniques, tools, and vendors for pre-treatment
- A textile ink-jet printer of low cost but high performance
- Post-treatment (steaming, washing).

Currently, one company, Seiren Co. Ltd, has successfully established such a complete printing system on its own and has been the only player so far in the digital printing market. Some of the keys to popularizing digital printing are disclosure of pre/post-treatment recipes, encouraging vendors to welcome small lot printing, and marketing and publicizing printing vendors for easy accessibility for self-print users. Mimaki has been making efforts to collect information on pre/post-treatment and to disclose technical information to a wide range of users in support of fabric treatment vendors and users.

7.5.2 Improving productivity

Once digital printing speed exceeds 200 m^2/h, it will be able to replace conventional screen printing in terms of printing speed. Currently, digital printing speed is 30 m^2/h or less for practical use; thus, multiple printer operations cover the productivity. As well as improving the printing speed, maintaining high quality of printed images is essential. Achieving 30–50 m^2/h in a high quality mode of 720 dpi is the market demand that is technically expected. At the same time, ink cost must be reduced, as mentioned in the following section.

7.5.3 Promotion of digital printing technology to a higher stage

In Italy and France, digital printing technology has been widely promoted. Mimaki has shipped 1000 sets of textile ink-jet printers to both countries in total. Successful promotion of digital printers in those countries has been backed up with branding of digital printing.

The ability of digital printing to create eye-catching designs and brands, as well as to mark smash hits by small runs of special or luxury items, should facilitate the popularizing of digital printing. In addition to the hardware package, such as offering the print technology as a system, fostering its software side, including collaboration with high-fashion designers and hosting a T-shirt design contest for future designers in fashion design schools, for example, will gain further recognition for digital printing.

7.5.4 Creating new markets for digital printing – high-resolution images and small-lot production of a variety of products

Now, entirely new and revolutionary possibilities for digital printing are being explored: gradation printing of photographs and graphical paintings, printing on leathers, to name but two. Here, digital printing is not replacing conventional techniques. Creating novel products is an essential factor to make this technology distinctive.

7.5.5 Lowering the cost

Lowering running costs, including cutting costs of printers, inks, and pre/post-treatment, is also one of the essential factors for digital printing to become attractive, competitive and acceptable in the printer market.

7.5.6 Developing more advanced technologies

Increase of ink-jet heads, creation of special color inks and additional lighter/deeper colors are some of the important tasks to increase color reproduction capability and uniform strike-through. The technical problems of current digital ink-jet printing technology will be solved one by one.

8
Integration of fabric formation and coloration processes

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8.1 Introduction

Traditionally, fabric formation and coloration processes have been two separate distinct processes. First the fabric was produced via weaving, knitting, or through other methods such as those employed in nonwovens, and was wound onto a take-up roll. In the case of weaving, a polymeric coating must be employed on the warp yarns for additional strength and resistance to abrasion during the weaving process.[1] Specifically known as warp sizes, starch, polyvinyl alcohol, and carboxymethyl cellulose are most commonly used when working with a cotton warp. A typical sizing mixture consists of a combination of starch, partially hydrolyzed polyvinyl alcohol, and a small amount of a lubricating agent, such as fat, to ensure a more secure weaving process.[1] After fabric production, the fabric is desized to remove the sizing agent, cleaned to remove any undesirable particulate matter, and sometimes bleached to provide a uniformly white surface on which to print. The fabric is then printed, usually through the use of roller screens, with a screen for each color in the design. Although roller screen printing is a fast process, from 30 up to 100 meters per minute, setting-up is time consuming, as each screen must be individually created, and changing patterns requires creation of new screens, thereby rendering roller screen printing time intensive and relatively inflexible.[2]

Digital inkjet printing on fabric is similar to the inkjet printers utilized with many computers to print on paper. Currently it has a relatively slow production speed, approximately 12 meters per hour, especially when compared to roller screen printing.[3] Although the speeds of digital inkjet printers are increasing, their use in the textile industry has mostly been limited to producing samples and small production runs of exclusive designs.[1] However, digital inkjet printing on textiles shows promise as speeds increase, especially as it offers the possibility of quick pattern changes and as such can be used to produce mass customized textiles.[1,4]

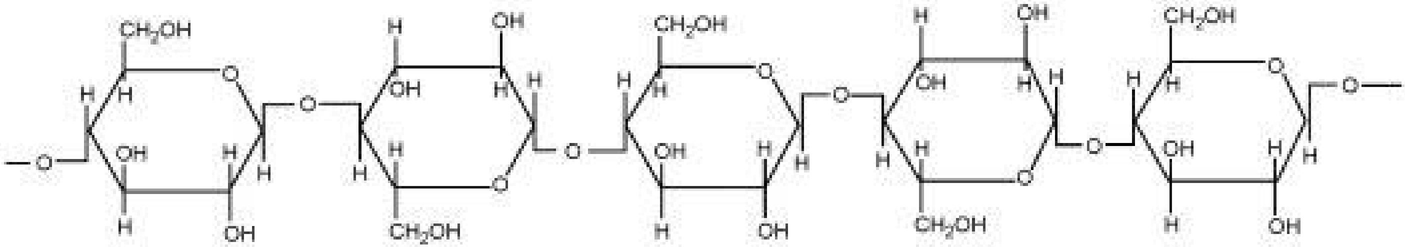
As the speeds of digital inkjet printing approach those of weaving looms, it might be possible to combine these two processes so that woven fabric is printed as it leaves the weaving area prior to take-up, enabling the creation of mass customized textiles as well as fast pattern changes. This could revolutionize fabric formation and coloration, as less time and handling would be required for processing which could result in lower cost and improved fabric quality.

However, for this idea to be successful a link needs to be established between weaving and printing. One possibility is to desize the fabric on the loom so that it can then be printed. This would require several additional pieces of equipment to desize and dry the fabric after weaving. Additionally, the fabric would have to be treated with a print fixative, required to affix the dye to the fabric, prior to printing. This would not be much of an improvement upon the current process of fabric production and printing as it would still require several processing steps.

An alternative link exists: utilizing the print fixative as a sizing agent. With this scenario the fixative would be applied to both warp and weft yarns prior to weaving, and would protect the warp yarns from abrasion during the weaving process. After weaving, the fabric would move directly into a printing area where it could be printed without the need for additional dye fixation treatments to be utilized. Thus, the goal of reducing processing steps and time may be realized.

This idea has been undergoing research at Philadelphia University for the past several years and exhibits promising results for the integration of fabric formation and coloration, in this case weaving, and digital inkjet printing. In the research conducted thus far, the fiber type being examined is cotton while the dye type being utilized to print on cotton fabric is reactive dye. Cotton is the most widely used of the natural cellulosic fibers and is well known to most consumers, making it a critical area of investigation for integration. Cellulose is a polysaccharide made up of cellobiose units, which combine to form a cellulose molecule, as depicted in Fig. 8.1. In this figure, the hydroxyl (OH) groups are clearly present. These hydroxyl groups are critical for several reasons, but most importantly directly pertaining to integration, cellulose fibers absorb water-soluble dyes and finishes, which aids in chemical processing.

Reactive dyes are water-soluble anionic dyes, which react with the hydroxyl groups of cellulose to become covalently bonded to the cellulosic fiber.[1] The chemical reaction between a reactive dye containing a chlorinated reactive group (RG) and a cellulosic fiber takes place in the presence of a base, such as sodium carbonate (Na_2CO_3).[1] Urea ($(NH_2)_2$–C=O) is used in the fixation step to absorb moisture. The resultant covalent bond provides good washfastness properties, and is much stronger than the weak hydrogen bonds formed between direct dyes and cellulose, making reactive dyes the preferred choice when working with cotton.



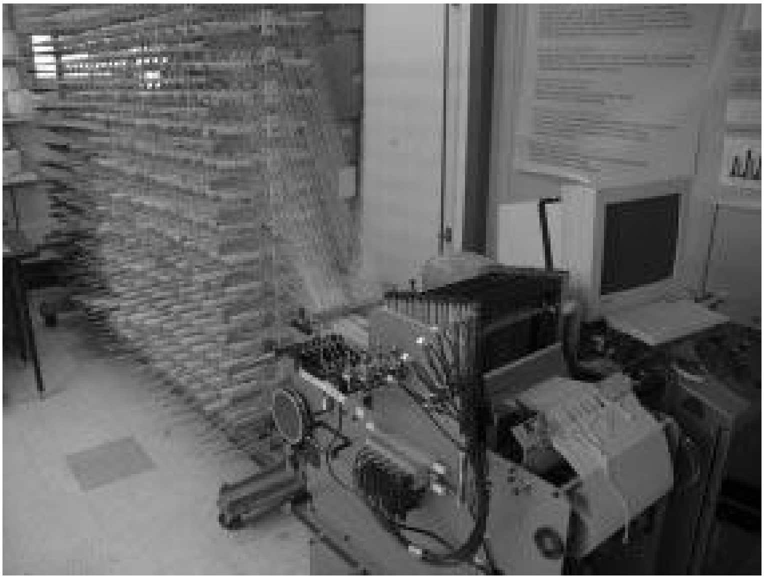
8.1 Schematic diagram of a cellulose molecule.

8.2 Experimental

8.2.1 Size evaluation

In order to determine the feasibility of combining weaving and digital inkjet printing, it is necessary to find a chemical solution that can function as both a size and a dye fixative for a particular fiber type. In the case of cotton, there are several possibilities for this solution. The first possibility is size, currently utilized by the textile industry to protect the yarns from abrasion during the weaving process. Another possibility is the solution of sodium carbonate, urea, thickener, and silica, currently utilized as a cotton fabric pretreatment prior to digital inkjet printing using reactive dyes. In this solution the thickener and silica are added to increase the viscosity of the solution, required to prevent the dye solution from wicking to other areas of the fabric where that dye is not desired. There are also the possibilities of a basic pretreatment solution consisting of sodium carbonate and urea, and a solution with a slightly higher viscosity of the preceding solution but lower than the first pretreatment solution: sodium carbonate, urea, and thickener.

The first experiments conducted were to determine the effectiveness of size as a fabric pretreatment solution for digital printing. To do this, 20/2 Ne cotton yarns, supplied by Huntingdon Mills, were woven into a plain weave fabric with a Sumagh 400 end sample loom, depicted in Fig. 8.2. The fabric was divided into three pieces: a control with no treatment, one treated with traditional size, and one treated with sodium carbonate, urea, thickener, and silica. To



8.2 Weaving cotton fabric on a Sumagh 400 end sample loom.

approximate traditional size, corn starch and water in a ratio of 15% starch and 85% water was used. The pretreatment solution consisted of 85% water, 10% urea, 2.5% sodium carbonate, 1.5% Noveon Carbopol 2491 WC thickener, and 1% Degussa Aerosil 200 silica. The solutions were padded onto the fabrics with a Werner Mathis lab padder at a wet pickup of 80% and dried with a Tsuji Senki Kogyo through air oven at 130ºC for two minutes.

The three fabrics were then digitally printed with four pure color stripes of Ciba reactive dyes: CIBACRON Turquoise MI700, CIBACRON Red MI500, CIBACRON Yellow MI100 and CIBACRON Black MI900, using a Mutoh inkjet printer with an Epson print head, as displayed in Fig. 8.3. Afterwards, the fabrics were subjected to the usual post-inkjet printing processes of steaming, rinsing, and soaping at the boil, which are used to affix the dye to the cotton fibers and remove any unfixed dye from the fabric. Steaming was performed with an Arioli steamer at 103ºC for eight minutes, which was followed by a five-minute cold water rinse. The final process consisted of soaping the fabric at a boil for two minutes with a mixture of water and Synthrapol detergent, done with a beaker and a laboratory hotplate.

After conditioning at standard temperature and humidity levels for 24 hours the fabrics were evaluated for colorfastness to laundering, wet and dry crocking, and light. Laundering colorfastness was determined via AATCC 61 with an Atlas Launderometer. Lightfastness testing, performed via AATCC 16 with a Q-Sun 1000 XENON test chamber, was done for both 20 and 40 hour exposure times. Crockfastness was evaluated with an Atlas vertical rotary crockmeter according to AATCC 116.

8.3 Printing plain weave cotton fabric with color stripes on Mutoh inkjet printer.

8.2.2 Print fixative as a possible sizing agent

Based on the results of the fastness evaluations, the three possible pretreatment solutions of water, sodium carbonate and urea; water, sodium carbonate, urea, and thickener; and water, sodium carbonate, urea, thickener, and silica were applied to yarns to evaluate their potential as sizing solutions. The untreated control is hereafter referred to as Solution A. The formula for water, sodium carbonate, and urea, hereafter referred to as Solution B, is 85% water, 10% urea, and 5% sodium carbonate. The formula for water, sodium carbonate, urea, and thickener, hereafter referred to as Solution C, is 86% water, 10% urea, 2.5% sodium carbonate, and 1.5% thickener. Solution D consists of 85% water, 10% urea, 2.5% sodium carbonate, 1.5% thickener, and 1% silica. All components of these solutions were those mentioned previously.

Solutions B–D were padded onto 20/2 Ne yarns, supplied by Huntingdon Mills, which were also utilized for the control, Solution A. The yarns were padded with the solutions and dried via the same method that was used to pad and dry the initial fabrics. Afterwards, the yarns were allowed to condition under standard temperature and humidity conditions for 24 hours prior to evaluation. The yarns were evaluated for tenacity before and after abrasion in order to determine if solutions B–D would be effective as sizing agents. Twenty yarn specimens of solutions A–D were evaluated for single end tenacity according to ASTM D2256 with a Testometric SDL constant rate of elongation tensile tester. These yarns were the pre-abrasion specimens. The 20 post-abrasion specimens from solutions A–D were subjected to an abrading force of 454 grams for 75 cycles of a CSI flex tester, usually utilized to measure flat abrasion, similar to the type and amount of abrasion that would be incurred on a loom during the weaving process. After abrasion these yarns were also tested to determine single end tenacity, as described previously.

8.2.3 Evaluation of different print fixatives

Based on the results of the initial sized fabric evaluations as well as the results of the single end yarn tenacity tests, it was decided to evaluate the effects of Solutions B–D when utilized to affix dyes to fabric via digital inkjet printing. Solutions B–D were padded onto cotton plain weave fabric produced with 20/2 Ne yarns on the Sumagh loom. The padding and drying process utilized was that aforementioned. The control in this instance was photo quality glossy paper, which currently provides the highest quality print line. The three fabric samples and the paper sample were digitally printed with CIBACRON Black MI900 reactive dye using a Mutoh Full Color Inkjet printer. Printed on each sample were lines of 0.25, 0.50, 0.75, and 1.0 points width. Afterwards, the textile samples were steamed, rinsed, and soaped at the boil utilizing the method described previously.

The four samples were then analyzed to determine the line quality. As the paper provides the best printed line quality, the fabrics were compared to the results of the paper to determine which solution provides the best results. The line quality was measured with a Personal IAS (Image Analysis System) by Quality Engineering Associates, and three variables were evaluated according to ISO 13660: line raggedness, line width, and line density. Line raggedness, commonly referred to as rag, is the average value of the leading and trailing edges of the line. Generally, the leading edge is the left edge of the line, while the trailing edge is the right side of the edge for a vertical line, whereas for a horizontal line the leading edge is the top edge and the trailing edge is the bottom edge. Rag is used to determine geometric distortion of a line from its ideal position. Line width is a measure of the actual width of a line compared to its theoretical width. Line density is the evaluation of the darkness of the line, expressed in terms of optical density (OD) units, determined with a density standard and color filter, as specified in ISO 13660.

8.2.4 The final evaluation

Based on the results of all evaluations completed thus far, it was decided to focus on solution D – thickener, silica, urea, sodium carbonate, and water – as a combination size and print fixative. To determine its appropriateness for this task, solution D was padded onto yarns which were then woven into fabric, which was then printed, treated, and finally evaluated. The yarns utilized for this segment of the project were 100% cotton 12 Ne rotor spun yarns, produced on a Rieter rotor frame. The yarn was wound into 70 skeins each with a length of 210 yards and then padded with solution D with a Werner Mathis lab padder to give a wet pickup between 60% and 80%. After padding, the yarns were dried with a Tsuji Senki Kogyo through air oven at 150ºC for 6 minutes and 15 seconds. Using a Sumagh 12 SL 7900 sample loom, the treated yarns were woven into plain weave fabric, utilizing the treated yarns in both the warp and weft directions. Using the four previously described reactive dye colors, color swatches were printed on the fabric using the Mutoh inkjet printer previously described. Lines of the four point sizes, as described previously, were also printed on the fabric at this time, with the Mutoh printer, but only with the black dye. The fabric was then steamed, rinsed, and soaped at the boil, as described previously. The fabric was subjected to line quality analysis after printing, after steaming, and after steaming, rinsing, and soaping to understand how each process affects line quality as well as to determine if solution D survived the weaving process to also function as a print fixative.

8.3 Results and discussion

8.3.1 Size evaluation

The first experiments compared traditional size to the current print fixative used for cotton printed with reactive dyes, as well as to untreated fabric. This was done in order to determine if the traditional size could also function as a print fixative as well as to establish a baseline of print fixation with the control, untreated fabric. Both the control and the starch treated fabrics lost the dye applied to them during the steaming and soaping at the boil post-print treatments, while the sodium carbonate and urea treated fabric retained its dye. This indicates that the desired bond between the polymer chains of the cotton fibers and the reactive dyes did not form in the control and starch treated fabrics, while it did form in the sodium carbonate and urea treated fabric. As the control and starched fabrics did not retain color, their colorfastness properties were not evaluated. However, the sodium carbonate and urea treated fabric was evaluated in terms of its colorfastness properties, with the results listed in Tables 8.1, 8.2, and 8.3. In these tables the grades are based on the AATCC colorfastness scale which ranges from 1 (poor) to 5 (excellent).

For the colorfastness evaluation, the fabric was evaluated after 20 hours of exposure and again after 40 hours of exposure. For each exposure time, the four shades exhibited good colorfastness properties, as displayed in Table 8.1. However, with the increase in exposure time the colorfastness properties did degrade slightly. The four shades all displayed excellent resistance to color loss during laundering as depicted in Table 8.2. Table 8.3 displays the results of both

Table 8.1 Results from AATCC test method #16: colorfastness to light

Sample		Colorfastness to light	
		20 hours	40 hours
A: Control		N/A	
B: Cornstarch		N/A	
C: Sodium carbonate/urea formula with thickener and silica	Cyan	5	5
	Magenta	4–5	4
	Yellow	5	4–5
	Black	4–5	4

Table 8.2 Results from AATCC test method #61: colorfastness to laundering

Sample		Colorfastness to laundering (color change)
A: Control		N/A
B: Cornstarch		N/A
C: Sodium carbonate/urea formula with thickener and silica	Cyan	5
	Magenta	5
	Yellow	5
	Black	5

Table 8.3 Results from AATCC test method #116: colorfastness to crocking

Sample		Colorfastness to crocking	
		Wet	Dry
A: Control		N/A	
B: Cornstarch		N/A	
C: Sodium carbonate/urea formula with thickener and silica	Cyan	4	5
	Magenta	3	5
	Yellow	4	5
	Black	4	5

wet and dry crocking, or rubbing, evaluations. These tests measure the amount of dye transferred from the test specimen to a white cloth via rubbing. The colors all exhibit excellent resistance to color transfer via crocking when dry, but transfer some color when wet, which may be indicative of some unfixed dye within the fabric. This could lead to problems with staining of lighter colored fabrics under certain conditions, such as drying of recently washed fabrics, if this problem is not remedied. In particular, the decrease in magenta was much greater than that of the other shades. Cotton dyed with shades of red has exhibited difficulty with wet crocking. This is often due to problems affixing the red dye to the polymer chains of the cotton, and the dye remaining in the fiber, unaffixed, until the fiber swells when wet, at which time the dye is released. This problem may be minimized, as could the other decreases in wet crocking values, with a more vigorous soaping process.

Overall, the initial size evaluations indicate that traditional size cannot be used to assist in the bonding of reactive dyes to cotton and as such may be ineffective for combining weaving and printing into one process. Additionally, the fabric cannot be untreated prior to printing, but requires a solution such as sodium carbonate, urea, thickener, and silica in order to retain the dye and hence color. The treatment of sodium carbonate, urea, thickener, and silica promotes bonding between the cotton polymer chains and the dye molecules, which in turn provides good to excellent colorfastness properties.

8.3.2 Print fixative as a possible sizing agent

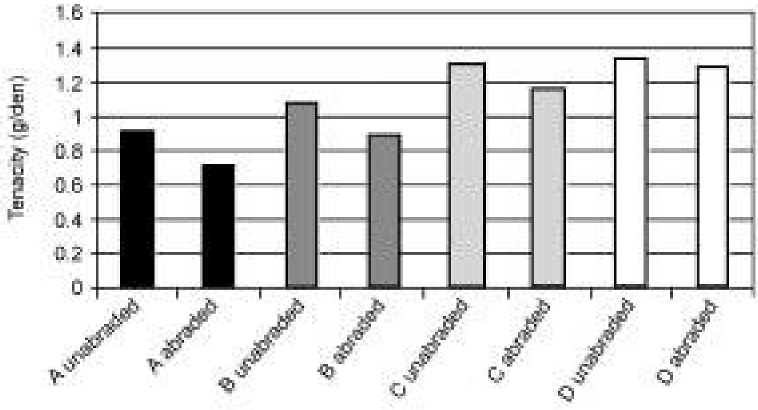
Although sodium carbonate, urea, silica, and thickener is the usual formula used to affix reactive dye to cotton in digital inkjet printing, an investigation into variations of this formula was undertaken to determine if modifications could result in similar properties in adhering the dye to the fiber as well as in the area of sizing. To determine the effectiveness of the three different print fixatives as sizing agents, yarns coated with the different formulas were evaluated for the

Table 8.4 Tensile properties of yarns treated with different print fixative solutions

Substrate	Average tenacity (g/den)	Tenacity standard deviation (g/den)	Average modulus (g/den)	Modulus standard deviation (g/den)
A unabraded	0.92	0.09	18.95	2.33
A abraded	0.72	0.08	18.15	3.66
B unabraded	1.08	0.10	12.22	2.06
B abraded	0.89	0.13	11.51	3.01
C unabraded	1.30	0.11	11.32	2.65
C abraded	1.15	0.20	13.42	3.03
D unabraded	1.34	0.08	14.24	2.80
D abraded	1.29	0.12	13.19	2.55

tensile properties of tenacity and modulus, in both abraded and unabraded forms. The abraded yarns were subjected to enough abrasion to simulate that encountered during weaving to determine if the fixatives would function as a typical size and protect the yarns from loss of properties during weaving. The results are depicted in Table 8.4 and Figs 8.4, 8.5, and 8.6, where substrate A refers to the control without any fixative, substrate B refers to yarns padded with sodium carbonate and urea, substrate C refers to yarns coated with sodium carbonate, urea, and thickener, and substrate D refers to yarns treated with sodium carbonate, urea, thickener, and silica.

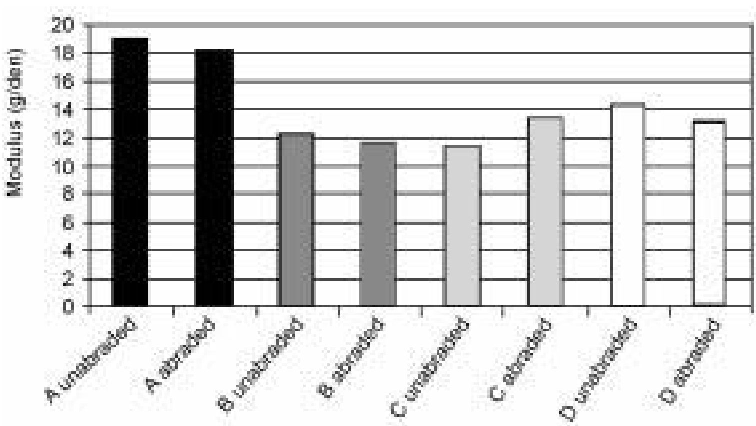
As depicted in Table 8.4 and Figs 8.4 and 8.6, the yarn tenacity decreased with abrasion, which is to be expected. However, the percentage change in tenacity loss has a wide range depending upon the different solutions utilized. The untreated control lost 14.9% of its original tenacity after abrasion, while formula B lost 17.3% of its original tenacity. Yarns treated with formula C lost 11.4% of their tenacity after abrasion compared with unabraded formula C yarns. Yarns treated with formula D had a much lower tenacity loss of 3.7% after abrasion compared with the unabraded yarns. The addition of some sort of solution to the yarns usually provides an increase in tenacity retention compared to the untreated yarns, as the finished solution generally abrades off the yarn prior to the yarn itself abrading. The addition of silica to the solution of sodium carbonate, urea, and thickener to make solution D provides a great increase in tenacity retention compared to the two other solutions evaluated, indicating that



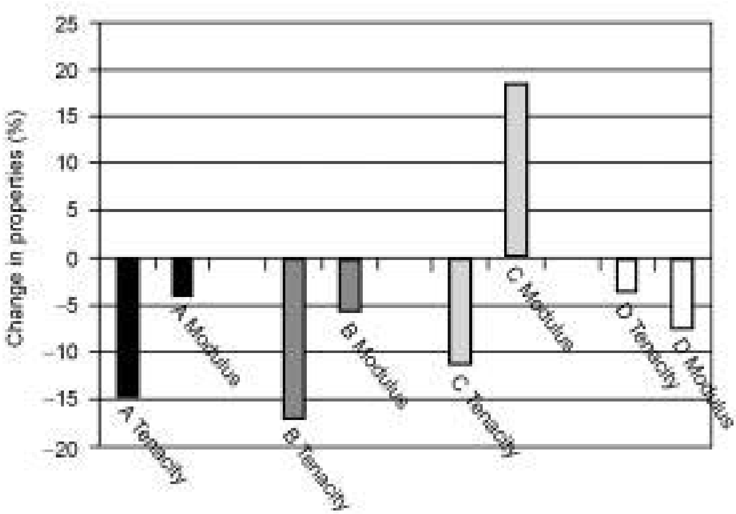
8.4 Average tenacity values of yarns treated with different print fixative solutions.

the silica itself may play an important role in preventing damage to the yarn during abrasion.

As with the tenacity evaluations, most of the yarns suffered a decrease in modulus, the initial resistance to deformation, after being abraded. With the exception of formula C, the range of loss in modulus values is not as great as that for tenacity. In terms of modulus, formula A, at 4.2% loss, had the least amount of loss after abrading, compared to the non-abraded yarns. Out of the solutions applied to the yarns, solution B, at 5.8% loss, had the closest modulus loss values to the untreated control, while formula D had a value of 7.7% loss. The abraded yarns of solution C exhibited an increase in modulus compared to the non-abraded yarns. This is unexpected, as abrasion should lead to a decrease in



8.5 Average modulus values of yarns treated with different print fixative solutions.



8.6 Tensile property changes between unabraded and abraded yarns.

modulus. The cause of this abnormality is unknown, but may stem from handling or errors in the abrasion process. It would be expected that the yarns coated with solutions B–D should have a greater modulus than the untreated control, A, as increased modulus generally accompanies increased tenacity. However, in this instance A has greater moduli values in both abraded and unabraded forms. As solutions B–D exhibit lowered unabraded moduli values compared to the control, it is possible that handling of these yarns during padding and drying or in preparation for evaluation degraded the coatings on them, thereby leading to a decrease in stiffness and thus lower moduli values. However, the average values of the non-abraded and abraded yarns within each sample are within one standard deviation of each other, and as such, the exact extent of changes in modulus due to abrasion require further evaluation.

Although the change in modulus as a result of abrasion for each set of treatments cannot be effectively gauged, the losses in tenacity values of the different treatments are easier to discern. The yarns with a treatment generally displayed a lower tenacity loss than those without, and among the treated yarns those of substrate D, treated with sodium carbonate, urea, thickener, and silica, had the greatest retention of tenacity values after abrading. Therefore, it can be concluded that formula D may provide the greatest protection from abrasion to the yarns during the weaving process.

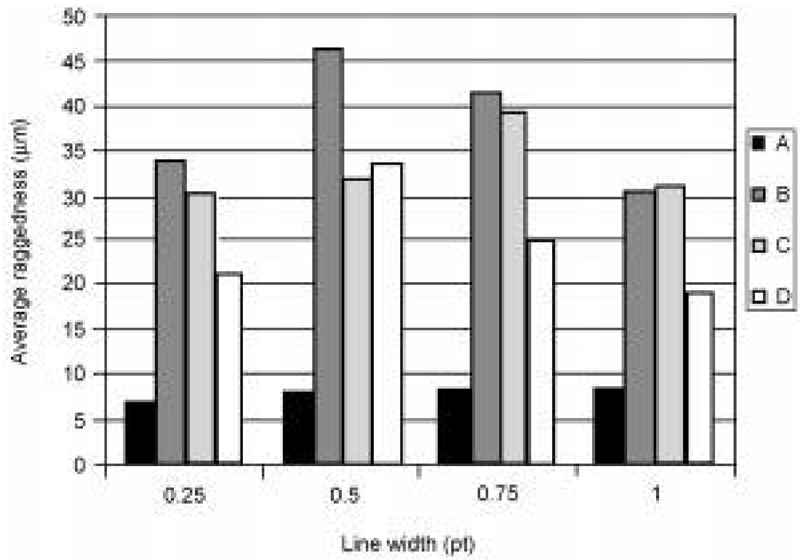
8.3.3 Evaluation of different print fixatives

After evaluating solutions B–D as possible sizing agents, they were evaluated for their ability to provide quality when printed upon. Although inkjet printing has been used in conjunction with paper for years, digital inkjet printing upon fabric is relatively new. Print quality of digitally inkjet-printed textiles is often related to the appearance of the print upon the fabric, and line quality analysis plays a major role in determining the quality of the print.[5] Line quality often pertains to text quality as they share many of the same desirable properties: line density, sharpness, accurate width, and edge quality.[5] ISO, the International Organization for Standardization, has created standard ISO 13660 to address some of these issues. Included in this standard are the properties of line raggedness, line width, and line density. The printed textile samples were compared to printed photo glossy paper, depicted as substrate A in Tables 8.5–8.7 and Figs 8.7–8.9, because this material provides the highest quality print line possible. Therefore, the closer the values of the printed textiles to that of the printed paper, the higher the quality of that print. The results of the various line quality evaluations are depicted in Tables 8.5, 8.6, and 8.7, as well as in Figs 8.7, 8.8, and 8.9.

The first evaluation of line quality analysis measured average line raggedness, or straightness, of the four line sizes for solutions B through D in comparison with the glossy paper, A. In three of the four point sizes, solution D obtained average values closest to those measured for the glossy paper. This is extremely important as one of the most crucial roles of the thickener and silica in solution D is to increase viscosity and create as precise a print as possible. Solution C obtained the closest value to the control in the remaining point size not obtained by solution D, and was second in two of the remaining three point sizes. Solution B, which did not contain thickener nor silica, did not allow for the production of a straight line in comparison with glossy paper. These results are expected, as the decrease in line quality follows the decrease in print ingredients from that of solution D to that of solution B, which contains only sodium carbonate and urea. This analysis indicates that thickener and silica are essential in providing decreased line raggedness. However, the results seem to indicate that the lines printed on fabric are not as straight as those printed on paper. This could be related to the hairiness of the surface of the fabric in relation to the smoothness of the paper or to other physical or chemical differences between the substrates.

Table 8.5 Line quality analysis results: average line raggedness (μm)

	Point size			
Substrate	0.25 pt	0.50 pt	0.75 pt	1.00 pt
A	7.0	7.8	7.8	8.2
B	33.9	46.7	41.6	30.6
C	30.3	31.6	39.3	31.0
D	21.4	33.5	24.7	19.1

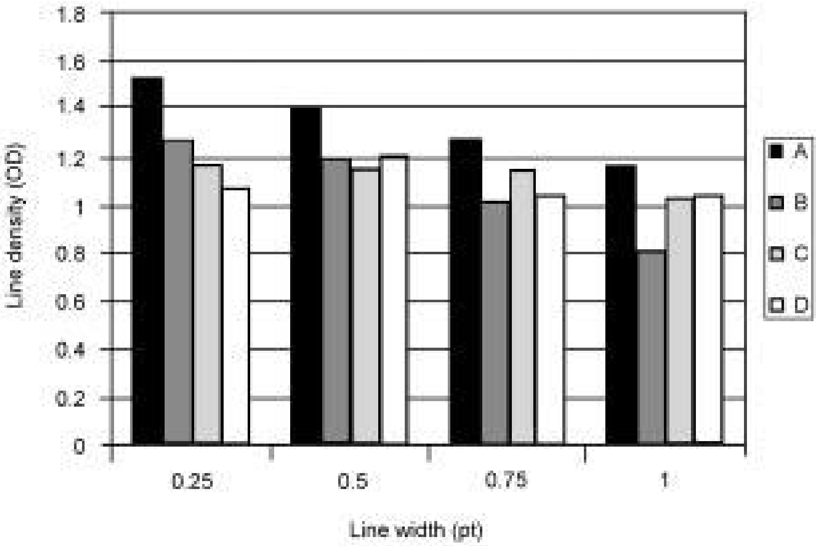


8.7 Line quality analysis results: average line raggedness (μm).

The second line quality analysis component measures the average line density, or darkness, of each printed line. Line density is extremely important in digital inkjet printing because it measures the amount and quality of dye that is bonded to the surface of the substrate. A low value of line density is indicative of reduced chemical bonding or mechanical print issues, such as clogged print heads. As expected, the control glossy paper measured the highest values of line density, with solution D possessing averages second highest to the control in two of the four point sizes. The line density value range was much smaller than that of the average line raggedness, yet large enough to see definite strengths by specific solution for each point size. As solution D outperforms the other two solutions in two of the line widths, it appears that the addition of silica assists in adhering the dye to the surface of the fabric. Although the three solutions provide some results similar to that of the control, it is obvious that there is

Table 8.6 Line quality analysis results: average line density (OD) for a given line width (pt)

	Point size			
Substrate	0.25 pt	0.50 pt	0.75 pt	1.00 pt
A	1.54	1.41	1.27	1.16
B	1.27	1.21	1.01	0.81
C	1.17	1.15	1.14	1.03
D	1.08	1.21	1.04	1.04



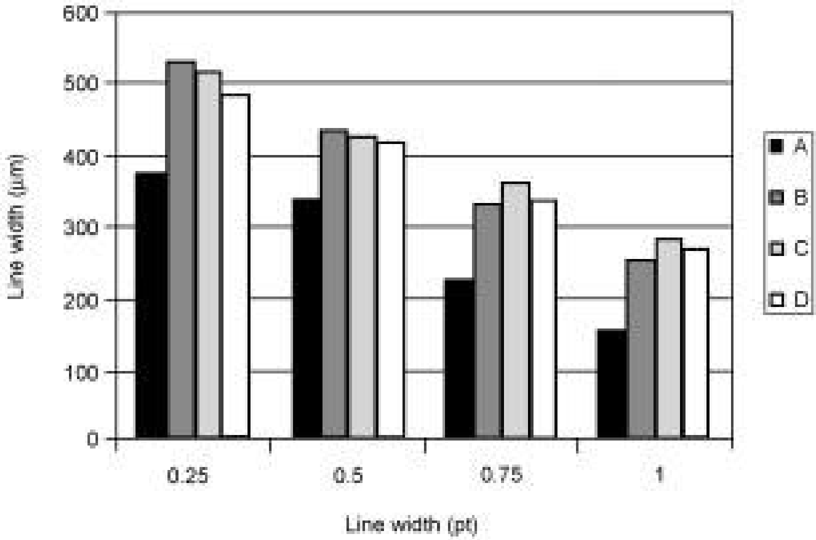
8.8 Line quality analysis results: average line density (OD) for a given line width (pt).

slightly less bonding between the fibers and the dye then there is between the paper and the dye.

Average line width was the third and final print quality property evaluated in this study. Interestingly, this analysis demonstrated the smallest variation between the three solutions. Although the control glossy paper is much closer in width to the actual point size than the remaining samples, the range of averages for solutions B, C, and D is much smaller. Solutions B and D were each closest to the control in two out of the four point sizes. As a result of the close range in data for this portion of the line quality analysis, the results for line raggedness and line density are crucial in determining which solution is most successful. The results of measuring the average line width indicate that although solutions B and D have the potential to provide a line closer in width to the control than

Table 8.7 Line quality analysis results: average line width (μm) for a given line width (pt)

	Point size			
Substrate	0.25 pt	0.50 pt	0.75 pt	1.00 pt
A	374.9	335.9	221.7	152.1
B	532.0	434.4	333.7	252.1
C	520.8	425.3	363.8	282.7
D	480.3	421.5	335.2	267.0



8.9 Line quality analysis results: average line width (μm) for a given line width (pt).

that of solution C, all three solutions when printed on appear to allow for wicking of the dye, resulting in larger than desired lines.

From the three line quality evaluations it is clear that none of the three solutions provides line qualities quite as good as that of the control, glossy paper. There may be several causes of this, such as fabric hairiness and absorbency compared to the paper, or perhaps differences in the chemical make-up of the treated paper compared to the solutions used on the fabrics. However, given the differences, solution D, composed of water, sodium carbonate, urea, thickener, and silica gives the results closest to the paper in several of the evaluations. It is also more consistent in providing results closer to the paper than the other two solutions. As solution D also provided better results functioning as a size than the other two formulas, it seems that it is a possible link between combining the weaving and printing processes.

8.3.4 The final evaluation

Based on the results of all the yarn and fabric evaluations, it was decided to utilize solution D as a combination size and print fixative. In this use, solution D will protect the yarns from abrasion during the weaving process, but also enough of it should remain on the yarn to act as a print fixative during the printing process. To measure this, yarns sized with solution D, as described previously, were woven into a plain weave fabric on the Sumagh loom. These yarns were used in both the warp and weft directions to provide a fabric that contained solution D on all yarns, in order to provide the best results. After weaving, the fabric was printed, steamed, rinsed, soaped at the boil, and then subjected to a line quality analysis to determine if the print quality changed as a result of a particular treatment. As with previous line evaluations, the results are compared to those obtained for the photo quality glossy paper, reported previously. The results of the different line quality evaluations are depicted in Tables 8.8, 8.9, and 8.10.

Table 8.8 Line quality analysis results: average line raggedness (μm)

	Point size			
Substrate	0.25 pt	0.50 pt	0.75 pt	1.00 pt
Glossy paper	7.0	7.8	7.8	8.2
Fabric after printing	30.9	81.3	36.0	28.6
Fabric after steaming	40.2	41.4	41.4	44.8
Fabric after soaping at the boil	36.4	37.7	36.8	36.2

Table 8.9 Line quality analysis results: average line density (OD) for a given line width (pt)

	Point size			
Substrate	0.25 pt	0.50 pt	0.75 pt	1.00 pt
Glossy paper	1.54	1.41	1.27	1.16
Fabric after printing	0.65	0.73	0.73	0.80
Fabric after steaming	1.10	1.32	1.44	1.51
Fabric after soaping at the boil	0.72	0.83	0.94	0.97

Table 8.10 Line quality analysis results: average line width (μm) for a given line width (pt)

	Point size			
Substrate	0.25 pt	0.50 pt	0.75 pt	1.00 pt
Glossy paper	374.9	335.9	221.7	152.1
Fabric after printing	137.7	205.6	267.7	342.9
Fabric after steaming	462.96	548.4	642.5	756.7
Fabric after soaping at the boil	196.5	241.2	256.0	239.0

The different evaluations all give similar results in that the line quality values for raggedness, width, and density after printing and after the final fixation process of soaping at the boil are similar. However, after steaming, the values increase. The increase in values between printing on the fabric and after steaming may be due to steaming causing the fibers to swell and hence distort the print, resulting in larger values. The steaming process may also cause unfixed dye to migrate to the surface of the fabric. After rinsing, loose dye that was previously on the surface of the fabric has been removed, leading to lower readings, closer to those of the control glossy paper.

Table 8.11 displays the results of crockfastness evaluations for both the initial fabric treated with solution D and then printed as well as the fabric woven with yarns padded with solution D that was then printed. In this evaluation the treatment of the yarns prior to weaving yields increased crockfastness results compared to those of the padded fabric. The cause of this difference in results is currently unknown, but it is possible that since the yarns were treated, dye in the interstices of the fabric was fixed to the yarn, whereas in the padded fabric solution D may not have penetrated the interstices of the fabric, resulting in dye not affixing to the fabric in these areas, and thus being removed during the wet crocking evaluations.

Tables 8.12, 8.13, and 8.14 compare the control glossy paper with the fabric treated with solution D and then printed and with the fabric woven with yarns that were treated with solution D and then printed. It must be noted that the two fabrics are different from each other in that they are made of different sized yarns which may influence the results. However, by comparing the different evaluations, it is evident that there are some differences between the two fabrics, in comparison to the control. In the areas of line raggedness and line density the fabric treatment yields closer results to the control than the yarn treatment. This is not unexpected, as the take-up of solution D during yarn padding varied

Table 8.11 Comparison of fabric treated with solution D, and yarns treated with solution D woven into fabric: crockfastness

Sample		Colorfastness to crocking	
		Wet	Dry
Fabric treated with solution D and printed	Cyan	4	5
	Magenta	3	5
	Yellow	4	5
	Black	4	5
Fabric containing yarns treated with solution D and printed	Cyan	5	5
	Magenta	5	5
	Yellow	5	5
	Black	5	5

Table 8.12 Comparison of control, fabric treated with solution D, and yarns treated with solution D woven into fabric: average line raggedness

Substrate	Point size			
	0.25 pt	0.50 pt	0.75 pt	1.00 pt
Glossy paper	7.0	7.8	7.8	8.2
Fabric treated with solution D and printed	21.4	33.5	24.7	19.1
Fabric containing yarns treated with solution D and printed	36.4	37.7	36.8	36.2

Table 8.13 Comparison of control, fabric treated with solution D, and yarns treated with solution D woven into fabric: average line density (OD) for a given line width (pt)

Substrate	Point size			
	0.25 pt	0.50 pt	0.75 pt	1.00 pt
Glossy paper	1.54	1.41	1.27	1.16
Fabric treated with solution D and printed	1.08	1.21	1.04	1.04
Fabric containing yarns treated with solution D and printed	0.72	0.83	0.94	0.97

Table 8.14 Comparison of control, fabric treated with solution D, and yarns treated with solution D woven into fabric: average line width (μm) for a given line width (pt)

Substrate	Point size			
	0.25 pt	0.50 pt	0.75 pt	1.00 pt
Glossy paper	374.9	335.9	221.7	152.1
Fabric treated with solution D and printed	480.3	421.5	335.2	267.0
Fabric containing yarns treated with solution D and printed	195.6	241.2	256.0	239.0

between 60% and 80%, as opposed to a constant 80% for the fabric padding. This, combined with abrasion of the yarns during the weaving process, would give the yarn treated fabric decreased levels of solution D, and thus result in greater line raggedness and lower line density, or lighter line shades.

This trend is also evident in the line width evaluations. However, in this instance, the line width values at 0.75 and 1.0 points of the yarn treated fabric are closer to the control than those of the treated fabric. The cause of this is unknown, but it is likely that lower wet pickup and abrasion from weaving may result in greater width variability.

8.4 Conclusions

The idea of combining weaving and printing may be feasible if a link connecting the two processes can be discovered. In weaving, a size is required to protect the warp yarns from abrasion during the weaving process. For printing with reactive dyes on cotton, a print fixative solution must be applied to the fabric prior to printing, in order to adhere the dye to the polymer chains of the fiber and prevent loss of dye during the steaming and soaping processes. In order to combine the weaving and printing processes, the sizing agent and print fixative agent must be the same compound. This will allow fabric that has just been woven to be immediately printed without requiring any preparation processes. By combining these two processes, handling of the fabric is reduced, which may result in less fabric or print defects due to fabric handling. The combining of the two processes also allows for increased production, as the fabric does not have to be further prepared for printing, nor does it have to be moved manually from one process to another.

Various solutions that could be used to combine the weaving and printing processes together have been evaluated. Additionally, printing on fabrics without a treatment was also attempted. Some solutions displayed good results in some areas but poor results in others. However, one solution seems to offer good results in both areas: a mixture of water, sodium carbonate, urea, thickener, and silica. This treatment has been applied to yarns that were then woven into fabric and printed upon. It has functioned as both a size and a print fixative and appears to be successful in both.

The fact that this solution has displayed good results in laboratory evaluations as well as in both weaving and printing indicates that it has the potential to link weaving and printing for cotton. A solution of water, sodium carbonate, urea, thickener, and silica appears to be the key to integrating weaving and printing.

8.5 References

1. Rivlin, Joseph, *The Dyeing of Textile Fibers, Theory and Practice*, 1992, p. 137.
2. Zoomer, Wim, 'Get production rolling with rotary screen printing'. *Screen Web*, http://www.screenweb.com/index.php/channel/4/id/689, 16 December 2002.
3. 'New high speed digital textile printer'. *Melliand International*, March 2003, pp. 68–71.
4. Hudson, Peyton B., Anne C. Clapp, and Darlene Kness, *Joseph's Introductory Textile Science*, 6th edn. Harcourt Brace Jovanovich, Fort Worth, TX, 1993, pp. 51–52.
5. Tse, Ming-Kai, and John C. Briggs, 'Measuring print quality of digitally printed textiles'. IS&T NIP14 International Conference on Digital Printing Technologies, Toronto, Ontario, Canada, October 1998.