

Progress and Trends in Ink-jet Printing Technology

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Abstract

This paper provides a brief review of the various paths undertaken in the development of ink-jet printing. Highlights of recent progress and trends in this technology are discussed. The technologies embedded in the latest ink-jet products from current industry leaders in both thermal and piezoelectric drop-on-demand ink-jet methods are also described. Finally, this article presents a list of the potential ink-jet technology applications that have emerged in the past few years.

Ink-jet Prin1ting Development Path

Ink-jet is a non-impact dot-matrix printing technology in which droplets of ink are jetted from a small aperture directly to a specified position on a media to create an image. The mechanism by which a liquid stream breaks up into droplets was described[1] by Lord Rayleigh in 1878. In 1951, Elmqvist of Seimens patented the first practical Rayleigh break-up ink-jet device.[2] This invention led to the introduction of the Mingograph, one of the first commercial ink-jet chart recorders for analog voltage signals. In the early 1960s, Dr. Sweet of Stanford University demonstrated that by applying a pressure wave pattern to an orifice, the ink stream could be broken into droplets of uniform size and spacing.[3] When the drop break-off mechanism was controlled, an electric charge could be impressed on the drops selectively and reliably as they formed out of the continuous ink stream. The charged drops when passing through the electric field were deflected into a gutter for recirculation, and those uncharged drops could fly directly onto the media to form an image.[4] This printing process is known as a continuous ink-jet. By the late 1960s, Sweet's inventions led to the introductions of A. B. Dick VideoJet and the Mead DIJIT products. In the 1970s, IBM licensed the technology and launched a massive development program to adapt continuous ink-jet technology for their computer printers. The IBM 4640 ink-jet printer was introduced in 1976 as a word processing hardcopy-output peripheral application.[5]

At approximately the same time, Professor Hertz of the Lund Institute of Technology in Sweden and his associates independently developed several continuous ink-jet techniques that had the ability to modulate the ink-flow characteristics for gray-scale ink-jet printing. One of Professor Hertz's methods of obtaining gray-scale printing was to control the number of drops deposited in each pixel.[6] By varying the number of drops laid down, the amount of ink volume in each pixel was controlled, therefore the density in each color was adjusted to create the gray tone desired. This method was licensed to companies such as Iris Graphics and Stork to produce commercial high-quality color images for the computer prepress color hardcopy market.[7]

While continuous ink-jet development was intense, the development of a drop-on-demand ink-jet method was also popularized. A drop-on-demand device ejects ink droplets only when they are used in imaging on the media. This approach eliminates the complexity of drop charging and deflection hardware as well as the inherent unreliability of the ink recirculation systems required for the continuous ink-jet technology.

Zoltan[8] and Kyser and Sears[9] are among the pioneer inventors of the drop-on-demand ink-jet systems. Their inventions were used in the Seimens PT-80 serial character printer (1977) and by Silonics (1978). In these printers, on the application of voltage pulses, ink drops are ejected by a pressure wave created by the mechanical motion of the piezoelectric ceramic.

Many of the drop-on-demand ink-jet ideas and systems were invented, developed, and produced commercially in the 1970s and 1980s. The simplicity of the drop-on-demand ink-jet system was supposed to make ink-jet technology more reliable. However, during this period, the reliability of ink-jet technology remained poor. Problems such as nozzle clogging and inconsistency in image quality plagued the technology.

In 1979, Endo and Hara of Canon invented a drop-on-demand ink-jet method where ink drops were ejected from the nozzle by the growth and collapse of a water vapor bubble on the top surface of a small heater located near the nozzle.[10] Canon called the technology the bubble jet. The simple design of a bubble jet printhead along with its semiconductor compatible fabrication process allowed printheads to be built at low cost and with high nozzle packing density. Apparently, during the same time period or shortly thereafter, Hewlett-Packard independently developed a similar ink-jet technology.[11]

In 1984, Hewlett-Packard commercialized the ThinkJet printer. It was the first successful low-cost ink-jet printer based on the bubble jet principle. Hewlett-Packard named the technology thermal ink-jet. The cost of a ThinkJet printhead consisting of 12 nozzles was low enough that the printhead could be replaced every time the ink cartridge was empty. Hewlett-Packard's concept of a disposable ink-jet printhead was brilliant and original. They solved the reliability problem of ink-jet technology by throwing away the printhead at the end of its useful life. Since then, Hewlett-Packard and Canon have continuously improved on the technology. Their efforts were rewarded with a series of successful product introductions. Ink-jet printer models with higher printing resolution and color capability were made available with very affordable prices. Since the late 1980s, because of their low cost, small size, quietness, and particularly their color capability, the thermal ink-jet or bubble jet printers became the viable alternative to impact dot-matrix printers for home users and small businesses. Currently, thermal ink-jet printers dominate the low-end color printer market.

Throughout the course of ink-jet development, ink chemists and media engineers realized that when a liquid ink droplet contacts the surface of paper, it tends to spread along paper fiber lines as well as penetrate into paper sizing and voids. The

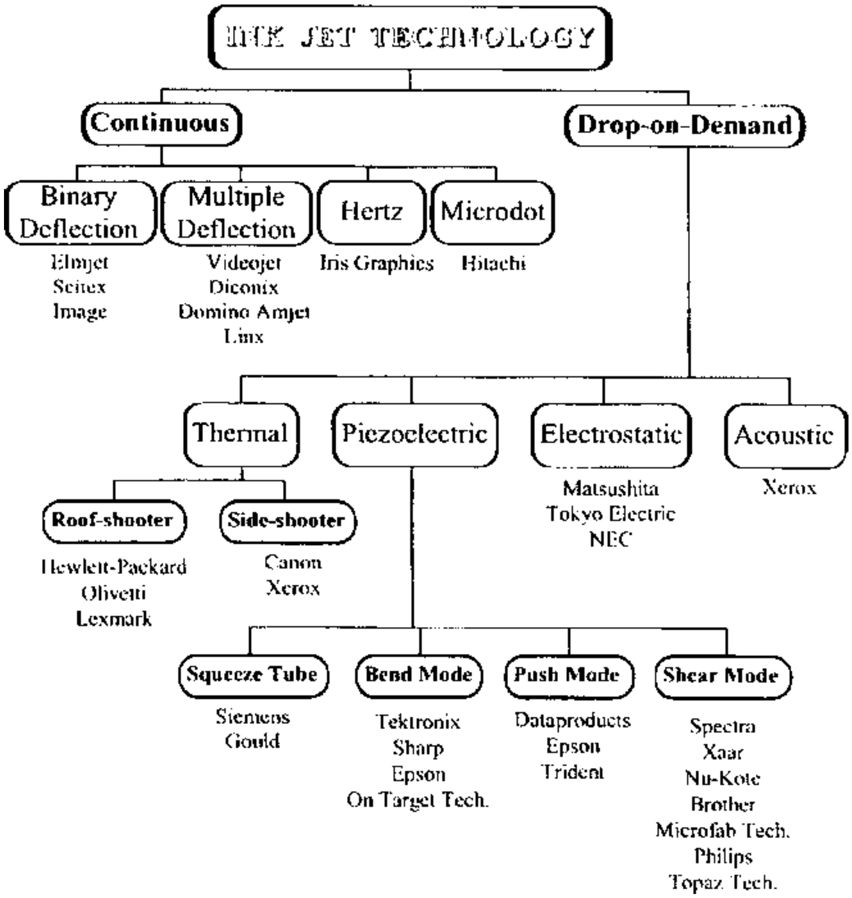

Figure 1. Ink-jet technologies map.

spreading of ink droplets is often too excessive and too irregular to maintain the resolution required. The penetration of ink into the paper is often too slow to absorb multiple ink drops on the same spot within very short time intervals. The poor color image quality due to ink spreading and intercolor bleeding is recognized as the critical issue in the development of ink-jet technology.

To obtain a high-quality color ink-jet image, the surface of the media requires a special coating. The special ink-jet-coated media must balance between many design parameters such as drop volume, evaporation rate, penetration rate, coating thickness, porosity, etc. Development activities in ink-jet media were started in the early 1980s, predominantly in Japan with paper companies such as Jujo Paper and Mitsubishi Paper Mills leading the industry. Today, because of the popularity of color ink-jet printers, the market demand for better media such as ink-jet glossy and photomedia is more significant. This has attracted a number of companies to ink-jet-media development. Canon, Xerox, Asahi Glass, Arkwright, Folex, 3M and Imation are among the many companies currently active in this field.

Another approach to obtaining better image quality without relying on special media is the use of solid ink (or hot melt or phase-change ink). In operation, the ink is jetting as molten liquid drops. On contact with the media, the ink material solidifies, very little spreading and absorption occurs so that brilliant color and high resolution can be realized almost independent of the substrate properties. The early development of solid ink was initiated at Teletype for electrostatic ink-jet devices.[12] The later application to drop-on-demand devices occurred at Exxon[13] and Howtek.[14] Today, Tektronix, Dataproducts, Spectra, and Brother are among active companies pursuing solid ink-jet technology.

For more details of the ink-jet printing development paths, there are at least four excellent reviews of ink-jet printing in the past literature.[15–18]

Technology Map

Ink-jet printing has been implemented in many different designs and has a wide range of potential applications. A basic map of the ink-jet technologies is shown in Fig. 1. Fundamentally, ink-jet printing is divided into the continuous and the drop-on-demand ink-jet methods.

Depending on the drop deflection methodology, the continuous ink-jet can be designed as a binary or multiple deflection system. In a binary deflection system, the drops are either charged or uncharged. The charged drops are allowed to fly directly onto the media, while the uncharged drops are deflected into a gutter for recirculation (Fig. 2). In a multiple deflection system, drops are charged and deflected to the media at different levels (Fig. 3). The uncharged drops fly straight to a gutter to be recirculated. This approach allows a single nozzle to print a small image swath. Both of these methods are widely used in the industrial coding, marking, and labeling markets. Companies such as VedioJet, Domino,

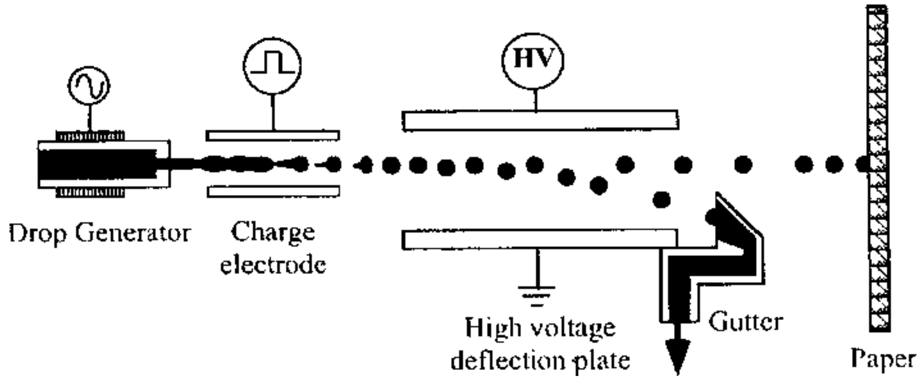

Figure 2. Continuous ink-jet: A binary-deflection system.

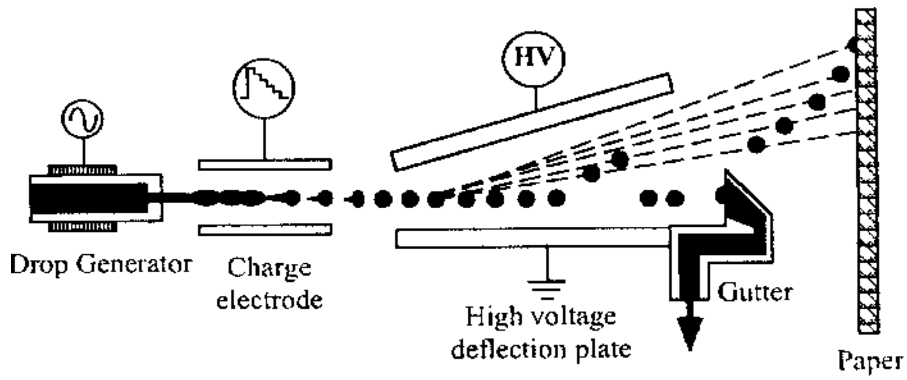

Figure 3. Continuous ink-jet: A multiple-deflection system.

Imaje, Toxot, and Willet are actively developing and marketing products in this area. Recently, Nur Advanced Technologies demonstrated an up to 16.4 ft billboard size ink-jet printer using continuous ink-jet technology. In addition to the above two methods, Hertz's continuous ink-jet process can be classified as a separate method. This method's success in the market is because of its unique way of obtaining the gray scale through a burst of small drops. Hertz' concept is used in products such as Iris's Realistic for the graphic arts market and Scitex's Digital Press for the high-speed on-demand printing market.

The majority of activity in ink-jet printing today is in the drop-on-demand methods. Depending on the mechanism used in the drop formation process, the technology can be categorized into four major methods: thermal, piezoelectric, electrostatic, and acoustic ink-jet. Most, if not all, of the drop-on-demand ink-jet printers on the market today are using either the thermal or piezoelectric principle. Both the electrostatic ink-jet[19–22] and acoustic ink-jet[23,24] methods are still in the development stage with many patents pending and few commercial products available.

The thermal ink-jet method was not the first ink-jet method implemented in a product, but it is the most successful method on the market today. Depending on its configuration, a thermal ink-jet can be a roof-shooter (Fig. 4) with an orifice located on top of the heater, or a side-shooter (Fig. 5) with an orifice on a side located nearby the heater. The roof-shooter design is used in the printheads from Hewlett-Packard, Lexmark, and Olivetti. The side-shooter design is implemented in the Canon and Xerox printheads.

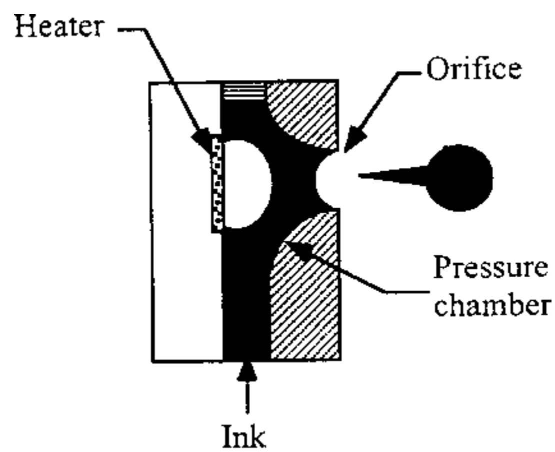

Figure 4. A roof-shooter thermal ink-jet.

In the piezoelectric ink-jet, depending on the piezo-ceramic deformation mode (Fig. 6), the technology can be classified into four main types: squeeze, bend, push, and shear.

A squeeze-mode ink-jet can be designed with a thin tube of piezoceramic surrounding a glass nozzle as in a Gould's impulse ink-jet[25] or with a piezoceramic tube cast in plastic that encloses the ink channel as was implemented in a Seimens PT-80 ink-jet printer.[7] The Seimens PT-80 printer was introduced in 1977. With a printhead array of twelve jets and an innovative maintenance station design, this product was fast and reliable enough to be the first truly successful ink-jet product for the office. Subsequent efforts by the company to in-

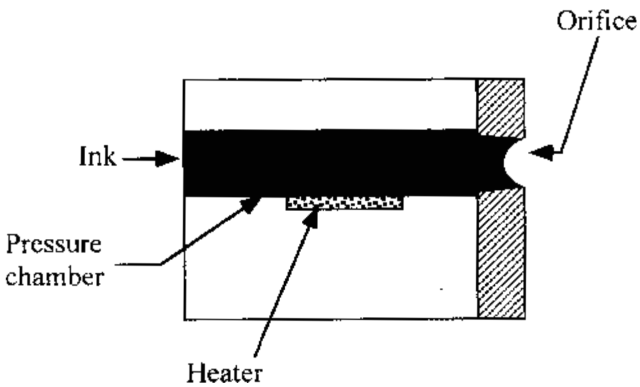

Figure 5. A side-shooter thermal ink-jet.

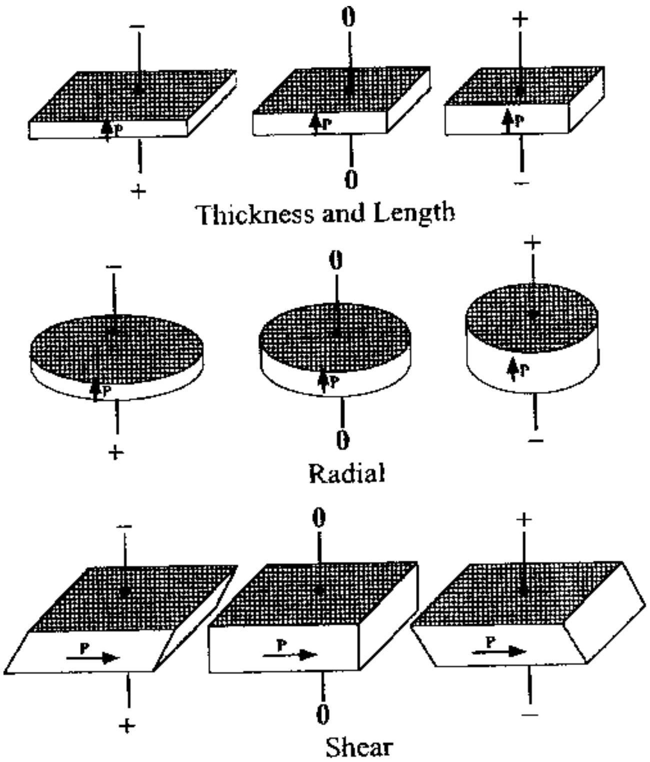

Figure 6. Basic deformation modes of a piezoceramic plate.

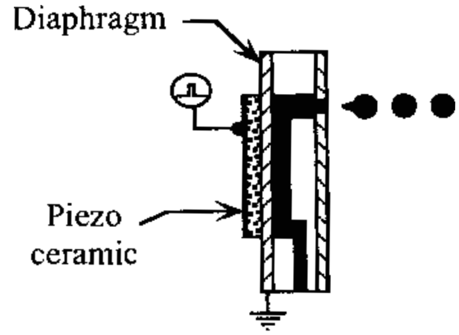

Figure 7. A bend-mode piezoelectric ink-jet design.

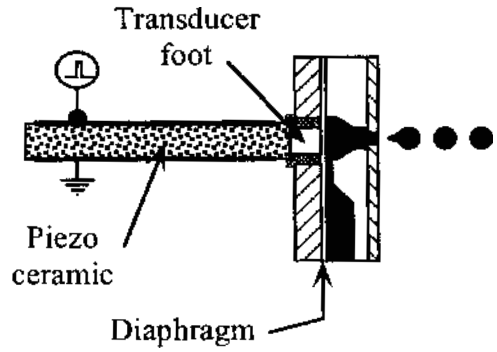

Figure 8. A push-mode piezoelectric ink-jet design.

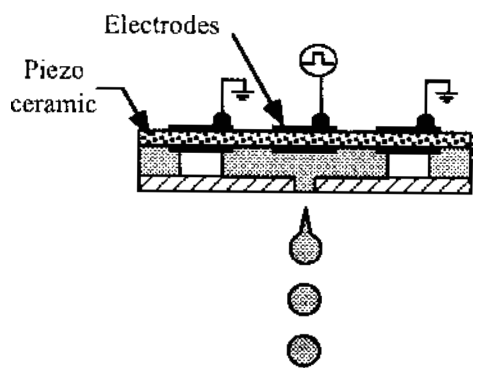

Figure 9. A shear-mode piezoelectric ink-jet design.

troduce a second-generation printhead with a 32-jet array encountered difficulty in achieving jet-to-jet uniformity.

In a typical bend-mode design (Fig. 7), the piezoceramic plates are bonded to the diaphragm forming an array of bilaminar electromechanical transducers used to eject the ink droplets. The printheads in Tektronix's Phaser 300 and 350 and Epson's Color Stylus 400, 600, and 800 ink-jet printers are based on this design principle.

In a push-mode design (Fig. 8), as the piezoceramic rods expand, they push against ink to eject the droplets. In theory, piezodrivers can directly contact and push against the ink. However, in practical implementation, a thin diaphragm between piezodrivers and ink is incorporated to prevent the undesirable interactions between ink and piezodriver materials. Successful implementation of the push-mode piezoelectric ink-jet is found in the printheads from companies such as Dataproducts, Trident, and Epson.

In both the bend- and push-mode designs, the electric field generated between the electrodes is in parallel with the polarization of the piezomaterial. In a shear-mode printhead, the electric field is designed to be perpendicular to the polarization of the piezodriver (Fig. 9). The shear action deforms the piezoplates against ink to eject the droplets. In this case, the piezodriver becomes an active wall in the ink chamber. Interaction between ink and piezomaterial is one of the key parameters of a shear-mode printhead design. Companies such as Spectra[26] and Xaar[27,28] are pioneers in the shear-mode printhead design.

Recent Developments and Trends in Technology

Printhead Design and Fabrication Processes. Today the ink-jet technologies most active in laboratories and in the market

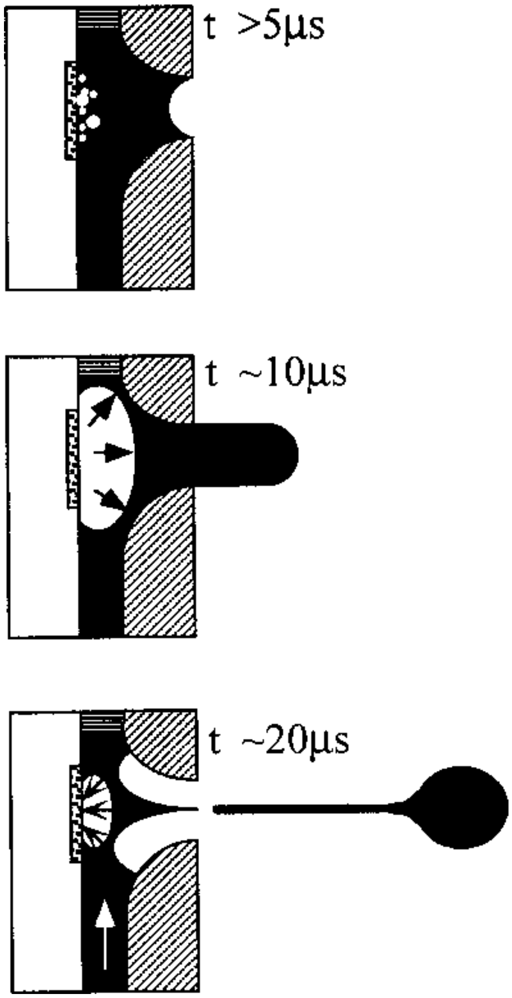

Figure 10. Drop formation process of a thermal ink-jet.

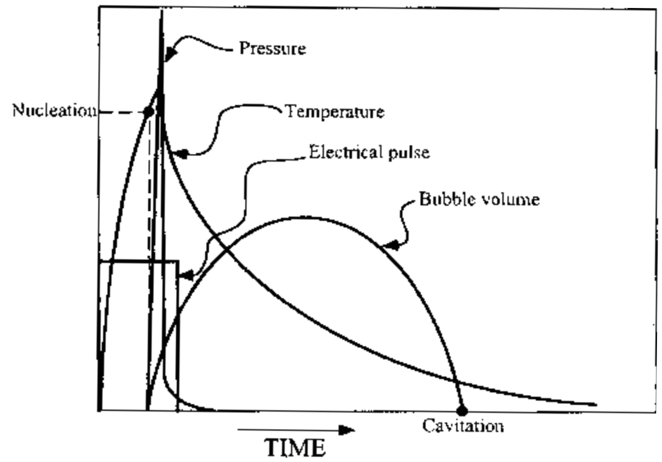

Figure 11. Pressure, temperature, and bubble volume changes during a drop formation cycle of thermal ink-jet.

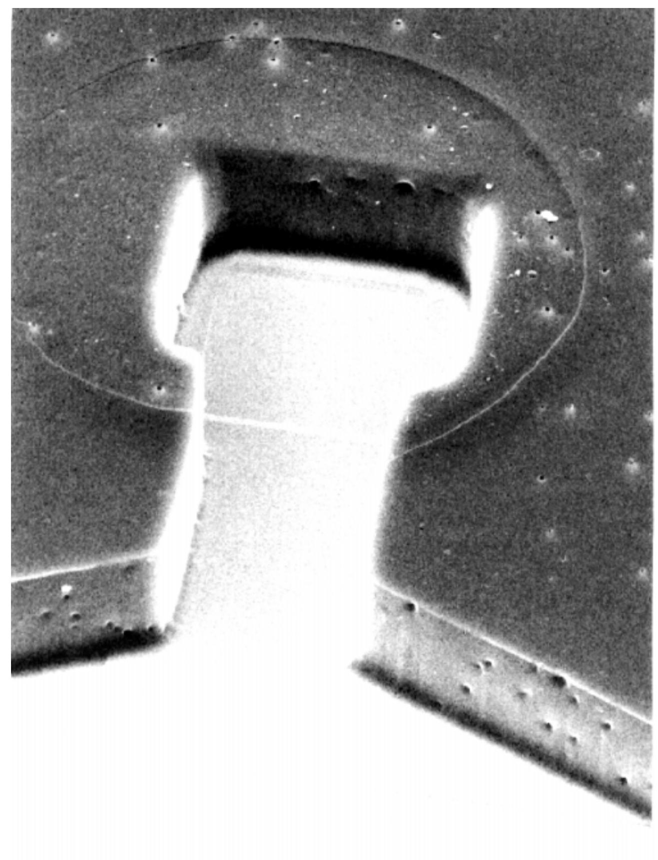

Figure 12. A SEM photograph of a channel in the Hewlett-Packard DeskJet 850C color printhead.

are the thermal and piezoelectric drop-on-demand ink-jet methods. In a basic configuration, a thermal ink-jet consists of an ink chamber having a heater with a nozzle nearby. With a current pulse of less than a few microseconds through the heater, heat is transferred from the surface of the heater to the ink. The ink becomes superheated to the critical temperature for bubble nucleation, for water-based ink, this temperature is[29] around 300°C. When the nucleation occurs, a water vapor bubble instantaneously expand to force the ink out of the nozzle. Once all the heat stored in the ink is used, the bubble begins to collapse on the surface of the heater. Concurrently with the bubble collapse, the ink droplet breaks off and excels toward the paper. The whole process of bubble formation and collapse takes place in less than 10 μs. The ink then refills back into the chamber and the process is ready to begin again. Depending on the channel geometry and ink's physical properties, the ink refill time can be from 80 to 200 μs. This process is illustrated in Fig. 10. Figure 11 reillustrates the same process by plotting the parameters including electrical pulse, temperature, pressure, and bubble volume against time.

Figure 12 shows a scanning electron microscope (SEM) photograph of a Hewlett-Packard 800 series thermal ink-jet channel with heater and ink barrier layer (the aperture plate was removed). This jet was known to produce 32 pL ink droplets at the rate of 6000 drops per second. The ink channel in the SEM photograph is measured at about 0.001 of an inch in thickness and little more in width. However, the dimensional stability, accuracy, and uniformity of this channel are known to have great effects on jet performance such as drop frequency, volume, and velocity. All of these drop performances ultimately determine the quality and throughput of a printed image. The trends in the industry are in jetting smaller droplets for image quality, faster drop frequency, and a higher

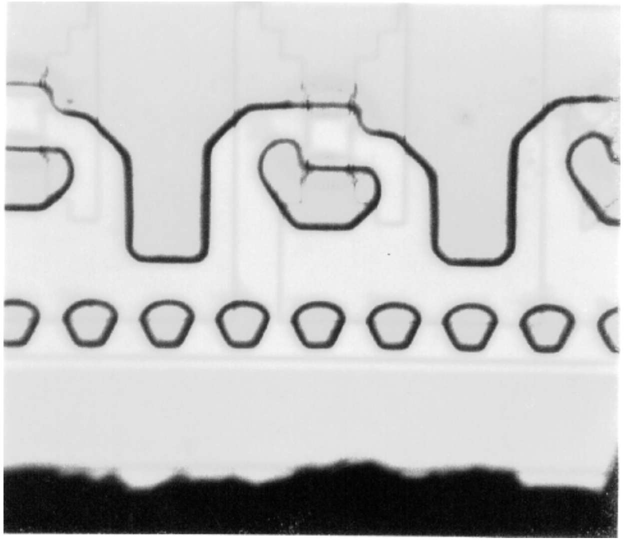

Figure 13. A light microscopic photograph of a channel in the Hewlett-Packard DeskJet 890C color printhead.

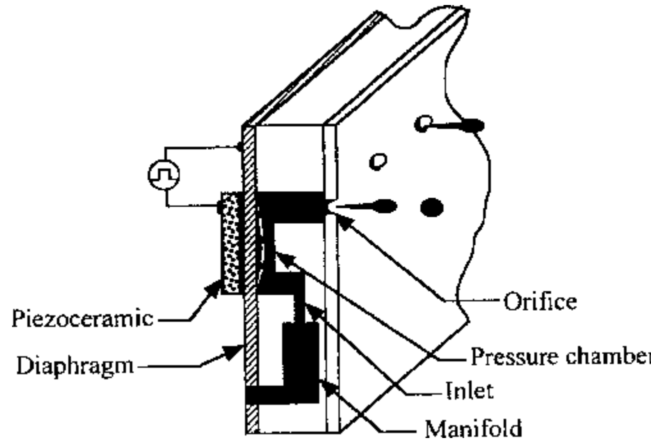

Figure 14. The basic configuration of a piezoelectric printhead.

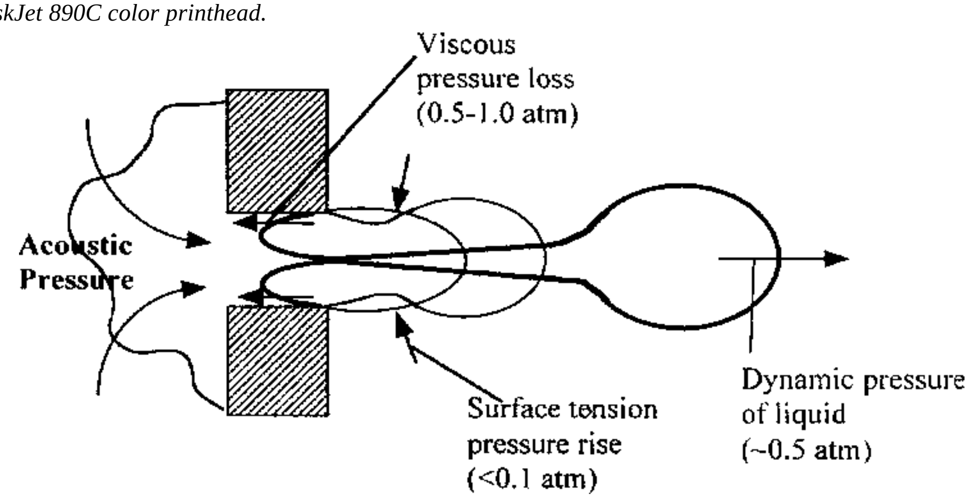

Figure 15. The basic pressure requirement for ejecting an ink droplet.

number of nozzles for print speed, while the cost of manufacture is reduced. These trends force further miniaturization of the ink-jet design. Consequently, the reliability issue becomes critical. In the latest generation of the Hewlett-Packard 800 series, the company introduced a new 192-nozzle tricolor printhead that can jet much smaller ink droplets (10 pL) at the rate of 12,000 drops per second. Figure 13 is a light microscopic photograph of an ink-jet channel from a Hewlett-Packard new tricolor printhead for the DeskJet 890C. The channel heater is measured about one mil square. Ink feeds from both sides of the heater chamber. This fluid architecture would significantly decrease the possibility of nozzle clogging that may result from particulates trapped in the printhead fabrication processes as well as in the process of making inks. A row of small openings between the ink manifold and the heater chamber was also introduced in the new design, in order to improve the reliability of the new printhead.

Another trend in the industry is market demand for lower cost per print. Printhead producers could pack in greater ink volume per cartridge to increase the print count or install a permanent or semipermanent thermal printhead to reduce the cost of new ink cartridges. Again, this trend will demand even higher reliability for thermal ink-jet printheads.

Canon is another major company that develops and produces thermal ink-jet printers. In the latest bubble-jet product BJC-7000, Canon introduced a 480-nozzle printhead. By far, this is the highest nozzle count for a single printhead module marketed to the home and small office color ink-jet printer market. In the BJC-7000 implementation, the 480-nozzle printhead consists of six colors with 80 nozzles per color. Other companies that develop and manufacture thermal ink-jet printheads are Lexmark, Olivetti, and Xerox.

In the piezoelectric drop-on-demand ink-jet method (Fig. 14), deformation of the piezoceramic material causes the ink volume change in the pressure chamber to generate a pressure wave that propagates toward the nozzle. This acoustic pressure wave overcomes the viscous pressure loss in a small nozzle and the surface tension force from ink meniscus so that an ink drop can begin to form at the nozzle. When the drop is formed, the pressure must be sufficient to expel the droplet toward a recording media. The basic pressure requirement is showed in Fig. 15.

In general, the deformation of a piezoelectric driver is on the submicron scale. To have large enough ink volume

TABLE I. A Current List of the Piezoelectric Drop-On-Demand Ink-Jet Printhead Producers

Producer	Piezo Deformation	Printer Example
Tektronix	Bend-mode 350 & 380	Tektronix Phaser
Sharp	Bend-mode	Mutoh RJ-1300 & RJ-1800
Epson	Bend-mode	Epson Color Stylus 400, 600, and 800
Dataproducts	Push mode	Idanit 162Ad
Spectra	Shear mode	Polaroid DryJet, 3D Actua 2100
Nu-Kote	Shear mode PiezoPrint 5000	Raster Graphics
Topaz Technologies	Bend/ shear combination	Calcomp CrystalJet

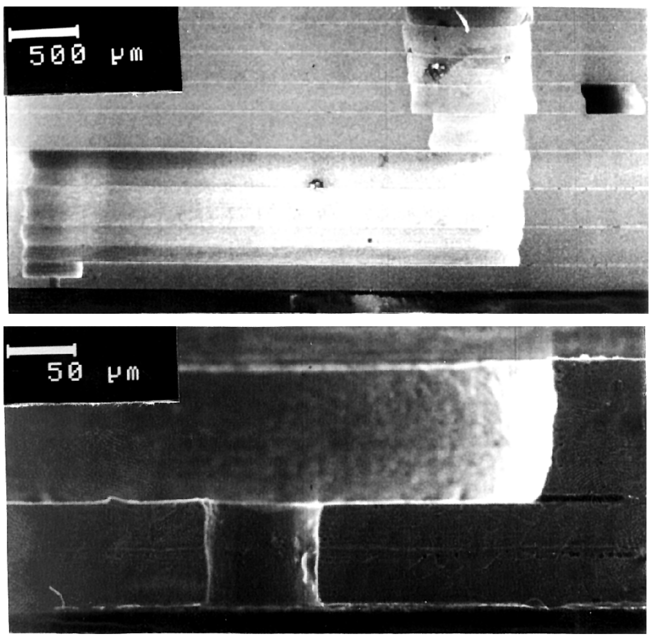

Figure 16. Cross section SEM photographs of a Tektronix stainless steel jet stack.

displacement for drop formation, the physical size of a piezoelectric driver is often much larger than the ink orifice. Therefore, miniaturization of the piezoelectric ink-jet printhead has been a challenging issue for many years. A list of piezoelectric drop-on-demand printhead producers is provided in Table I.

Tektronix (352 nozzle) and Sharp (48 nozzle) printheads are made with all stainless steel jet stacks. These jet stacks consist of multiple photochemical machined stainless steel plates bonded or brazed together at a high temperature. Figure 16 shows a cross section SEM photograph of a Tektronix jet stack. The thin Au intermetallic bonding layers are visible between the brazed plates. The intermetallic bond in ink-jet printhead application requires uniform thickness for design performance consistency and hermetic sealing to prevent inks from leaking externally or between two adjacent ink channels. Similar bonding characteristics are found in a Sharp jet stack. Figure 17 shows a cross section SEM photograph of

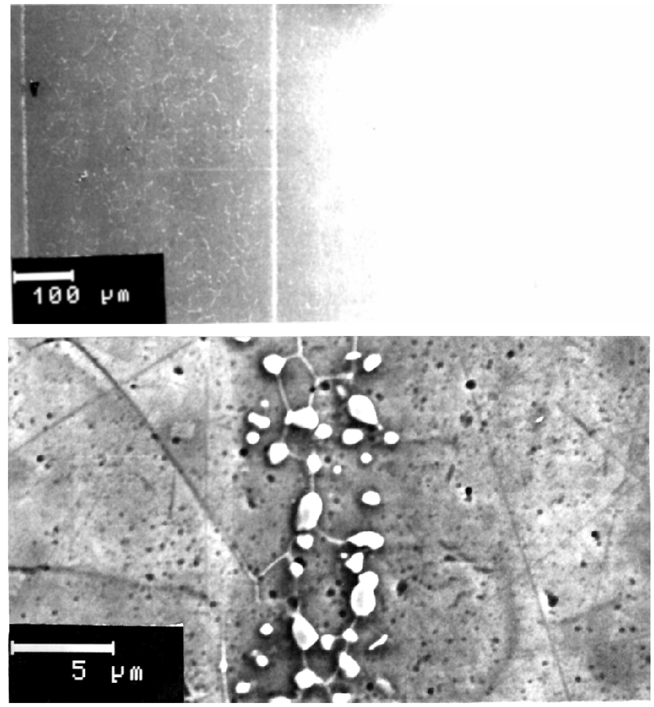

Figure 17. Cross section SEM photographs of a bond line in a Sharp stainless steel jet pack.

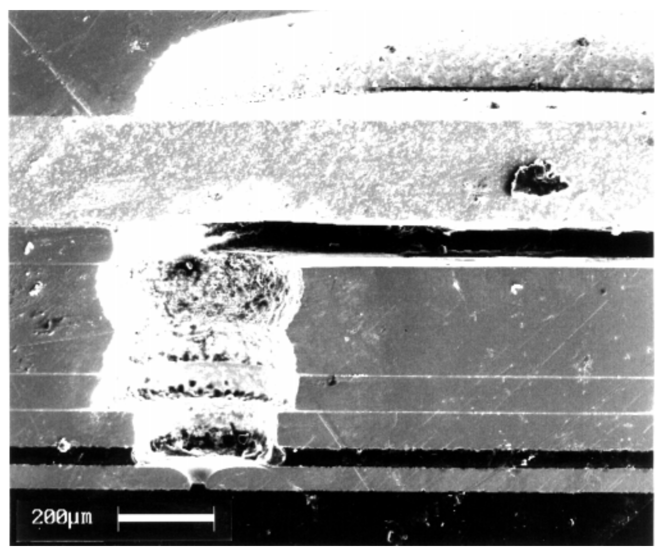

Figure 18. A cross section SEM photograph of a Spectra printhead.

the Ni intermetallic bond between the stainless steel plates of the Sharp printhead.

Besides using Au or Ni to bond metal plates together, solder and epoxy are also used to fabricate printheads. Figure 18 shows a cross section SEM photograph of a Spectra printhead where the electroformed nickel orifice plate is bonded to the jet stack by epoxy. In the same photograph, the solder bonds between multiple steel plates are also noticed. However, due to ink compatibility issues, the selection of epoxy or solder composition must be carefully considered. Given the trends to increasing the number of nozzles, decreasing their physical size, and jetting many different fluids, bond

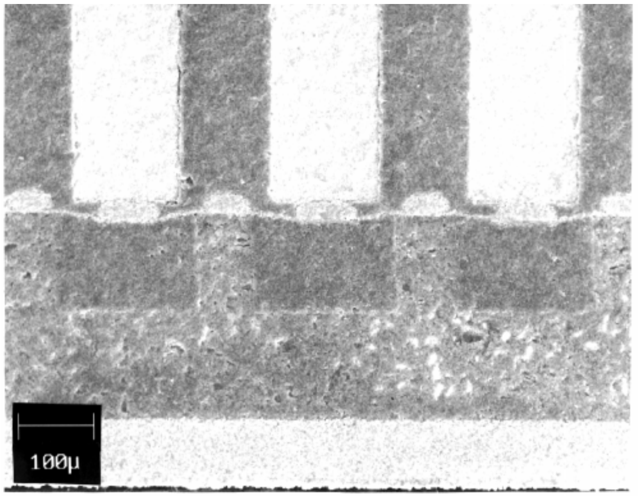

Figure 19. A cross section SEM photograph of an Epson Stylus 800 printhead.

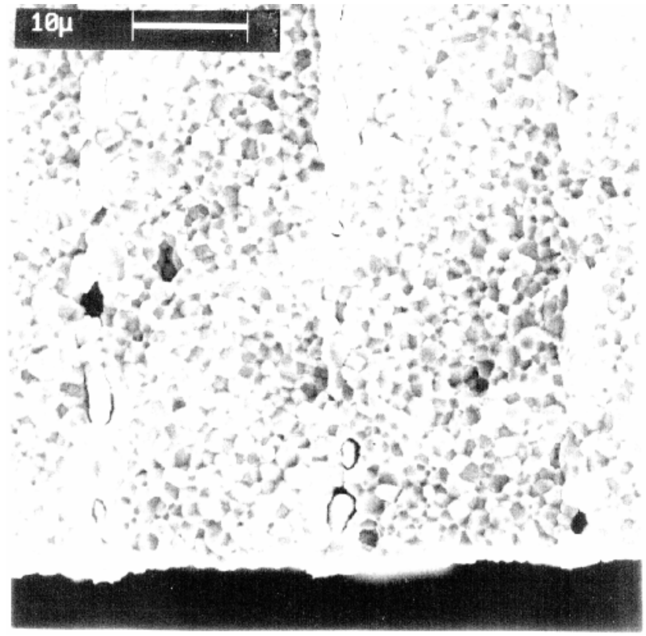

Figure 20. A SEM photograph of a multilayer piezoceramic driver in the Epson Stylus 800 printhead.

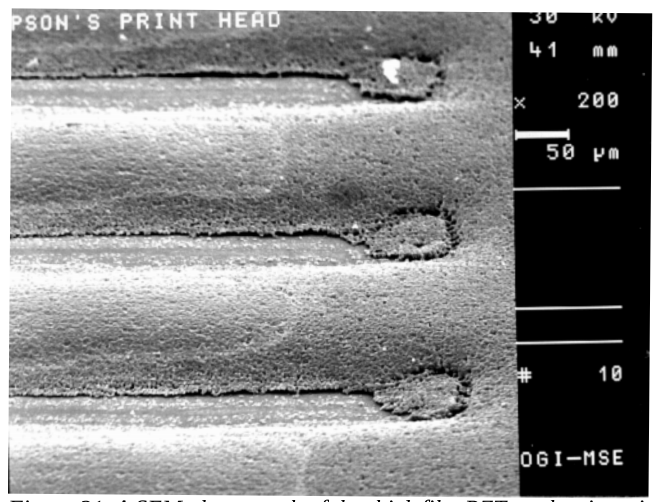

Figure 21. A SEM photograph of the thick film PZT on the zirconia diaphragm in the Epson Color Stylus 800 printhead.

integrity and stability of the printhead become increasingly critical issue.

In 1993, Epson introduced the Stylus 800 piezoelectric ink-jet printer to compete directly with thermal ink-jet or bubble-jet technology in the low-end home and small office printer market. This product introduction was very significant in the sense that it was the first time a reliable low-cost piezoelectric ink-jet with a permanent printhead was successfully introduced in a low-end printer. This Epson printhead is based on a push-mode design with a multilayer piezoactuator.[30] Based on the same printhead technology, Epson introduced Stylus Color in 1994 and Color Stylus II in 1995. A cross section SEM photograph of an Epson push-mode jet is shown in Fig. 19. Figure 20 shows a SEM photograph of a multilayer PZT actuator with 20 μm thickness per layer. Alternate electrodes are seen in both sides of each PZT layer. With this design, Epson fabricated a 64-nozzle printhead with a nozzle-to-nozzle spacing of 140 μm to achieve a nozzle density of 180 dpi.

In 1997, Epson introduced Color Stylus 400, 600, and 800 with a bend-mode design piezoelectric printhead. Color Stylus 800 employs two printheads: 128-nozzle for black and 192-nozzle for color (CMY). The technological breakthrough in this new bend-mode piezo printhead introduction is in the unique fabrication method for the thick film PZT sintered on top of the zirconia diaphragm to make piezoelectric drivers. A SEM photograph of the PZT/diaphragm drivers is shown in Fig. 21. These PZT/diaphragm structures measure less than 1 mils in total thickness. In contrast to the PZT/diaphragm structures in a Tektronix bend-mode printhead, PZT thickness is about 6 mils and stainless steel diaphragm thickness is about 3 mils. Significant reduction in the thickness of driver structures allows Epson to miniaturize the 192-nozzle printhead to about 18×34.8 mm with a nozzle density of 180 dpi. Note that, as compared to the push mode with a long PZT structure design, the new Epson thick film PZT bend-mode device has a planar structure. The fabrication process for the new design is simple and less costly. Furthermore, with a small, flat and thin printhead structure, any addition of heaters to control the operating temperature of the printhead is much easier to design. The trends here are to increase the number of nozzles and add more flexibility in ink formulations, as was potentially realized with Epson's new printhead technology.

Nu-Kote 128-nozzle and Topaz Technologies 256-nozzle piezoelectric drop-on-demand printheads are the two newest additions to the ink-jet market. The Nu-Kote printhead is based on the development of a Xaar shear-mode shared wall design.[31] Raster Graphics uses three 128-nozzle printheads per color in their newly introduced PiezoPrint 5000 large-format color ink-jet printer. The technology is about 10 years old, but the field experience is new. A key challenge for the Nu-Kote printhead is its reliability in the market.

The Topaz 256-nozzle printhead is also new to the industry. It is known to combine both the bend and shear modes to jet ink droplets at a relatively high-drop-ejection frequency.

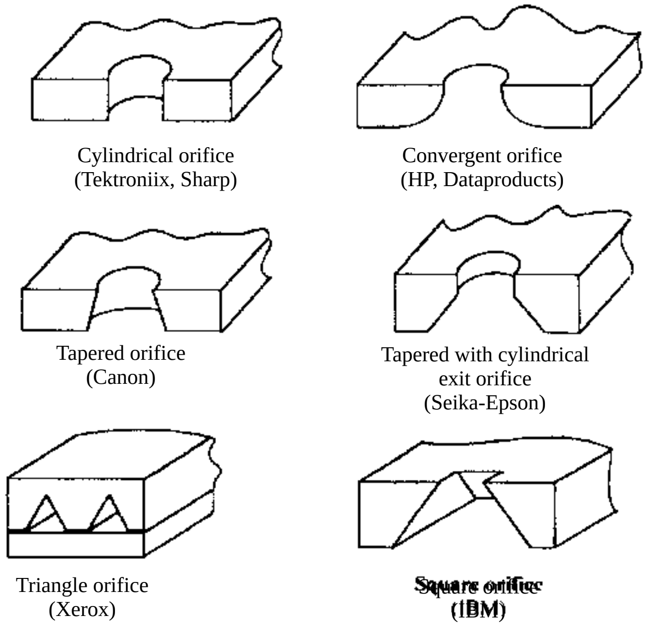

Figure 22. Various types of ink-jet printhead nozzle designs.

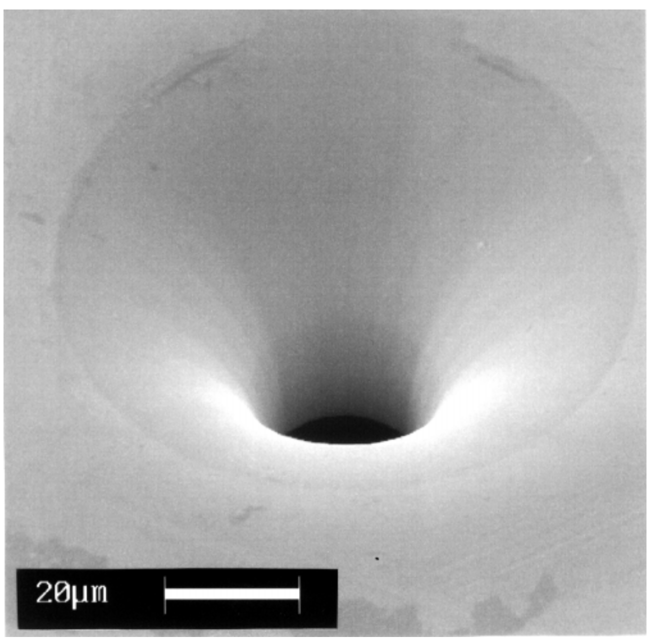

Figure 23. A SEM photograph from the entrance side of an electroformed Ni nozzle.

The technology was introduced in the Calcomp CrystalJet large-format ink-jet printer. Thus far, no product has been shipped yet.

Independently from the thermal or piezo ink-jet method, bend or shear mode, one of the most critical components in a printhead design is its nozzle. Nozzle geometry such as diameter and thickness directly effects drop volume, velocity, and trajectory angle. Variations in the manufacturing process of a nozzle plate can significantly reduce the resulting print quality. Image banding is a common result from an out-of-specification nozzle plate. Various nozzle geometries designed for the ink-jet printheads are summarized in Fig. 22. The two

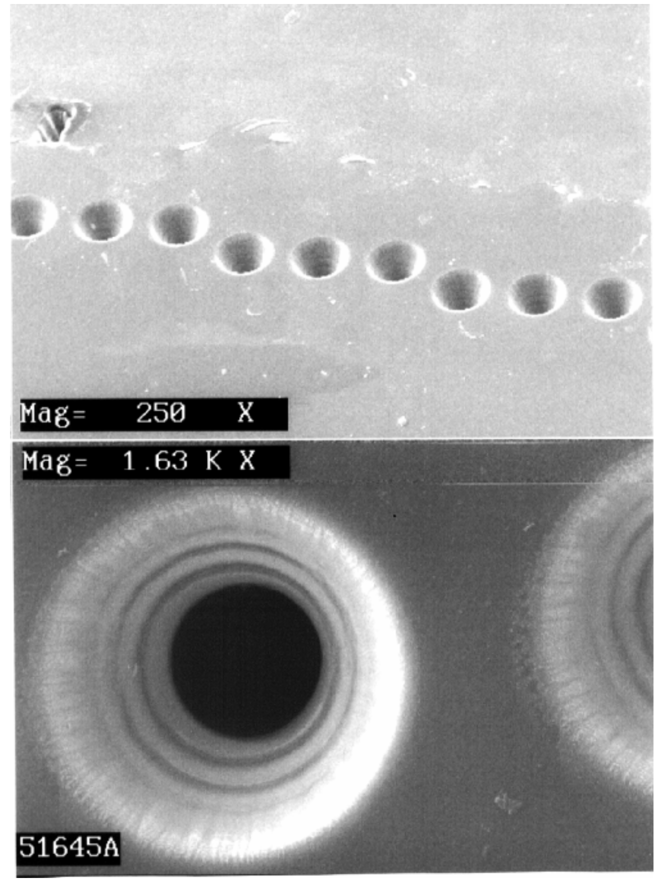

Figure 24. SEM photographs from the entrance side of a laser ablation polyimide nozzle plate.

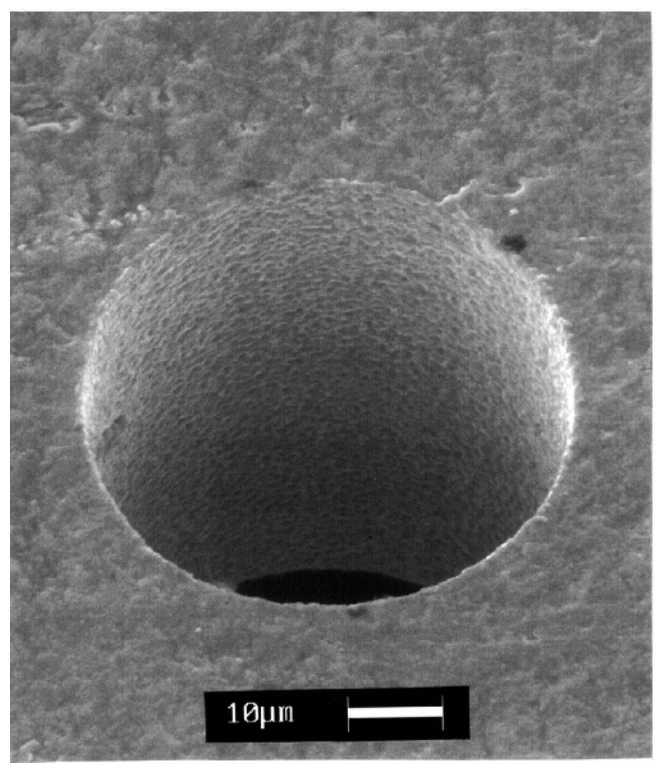

Figure 25. A SEM photograph of an EDM stainless steel nozzle.

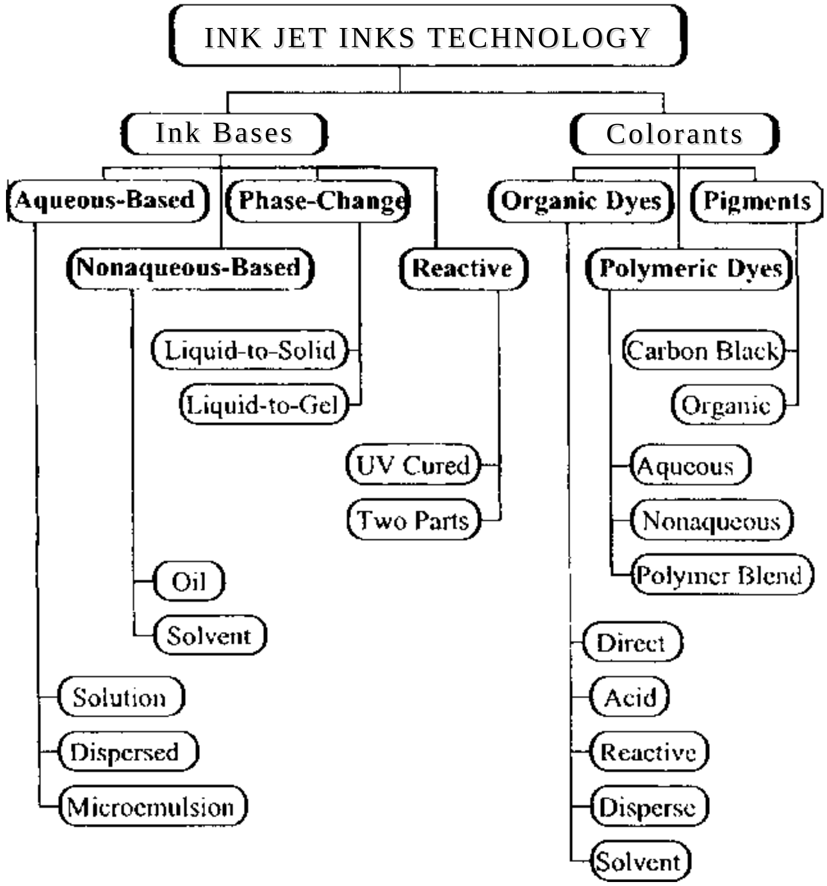

Figure 26. An ink-jet ink technologies map.

TABLE II. Water-Based Ink-Jet Ink Composition

Component	Function	Concentration, %
Deionized water	Aqueous carrier medium	60 - 90
Water soluble solvent	Humectant, viscosity control	5 - 30
Dye or pigment	Provides color	1 - 10
Surfactant	Wetting, penetrating	0.1 - 10
Biocide	Prevents biological growth	0.05 - 1
Buffer	Controls the pH of ink	0.1 - 0.5
Other additives	Chelating agent, defoamer, solublizer etc.	> 1

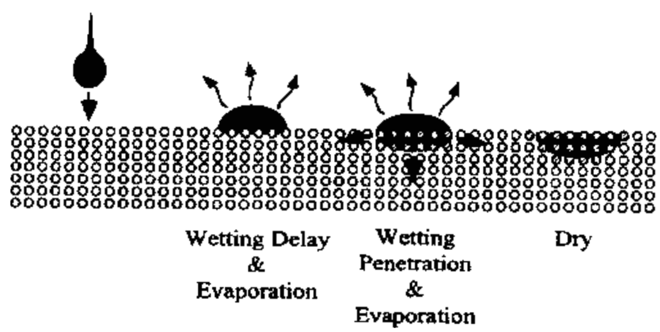

Figure 27. Drying mechanisms of a water-based ink-jet drop on a plain paper.

most widely used methods for making the orifice plates are electroformed nickel (Fig. 23) and laser ablation on the polyimide (Fig. 24). Other known methods for making ink-jet nozzles are electro-discharged machining (Fig. 25), micropunching, and micropressing.

Because smaller ink drop volume is required to achieve higher resolution printing, the nozzle diameter of printheads has become increasingly small. For jetting an ink droplet of 14 pL, Epson Color Stylus 800 printhead has nozzle diameter of less than 30 µm. For 10 pL droplets, Hewlett-Packard DeskJet 890C color printhead has nozzle diameter of around 20 µm. With the trends towards smaller diameters and lower cost, the laser ablation method has become popular for making ink-jet nozzles.

Ink Chemistry. The most critical component of ink-jet printing is probably the ink. Ink chemistry and formulations not only dictate the quality of the printed image, but they also determine the drop ejection characteristics and the reliability of the printing system. Many different types of inks have been developed and used in ink-jet applications. Figure 26 illustrates a technology map of different types of ink-jet inks.

Aqueous- or water-based inks are commonly used in home and small-office ink-jet printers such as in the Hewlett-Packard DeskJet series, Canon BJC series, and Epson Color Stylus series ink-jet printers. In the case of thermal ink-jet, due to the basic vapor bubble formation process, water seems the material of choice for the method. Typical composition of a water-based ink for ink-jet printing is presented in Table II. Viscosity of water-based ink-jet inks range from 2 to 8 cps.

Figure 27 illustrates the behavior of a water-based ink droplet when it lands on the surface of an uncoated media such as bond, copy, or plain papers. The ink tends to spread

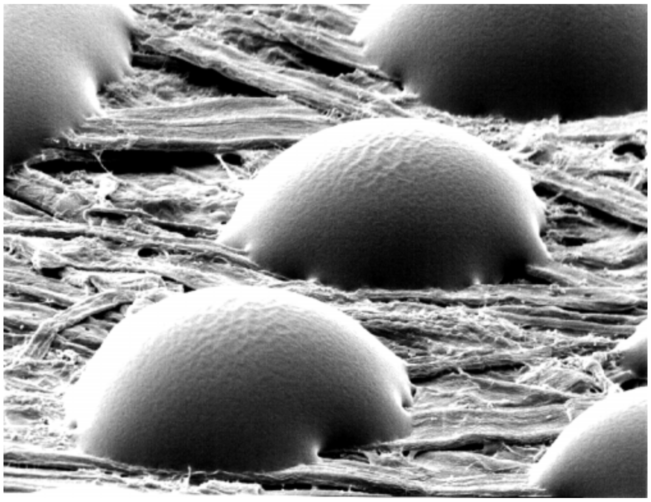

Figure 28. A SEM photograph of phase-change ink drops on the surface of a bond paper.

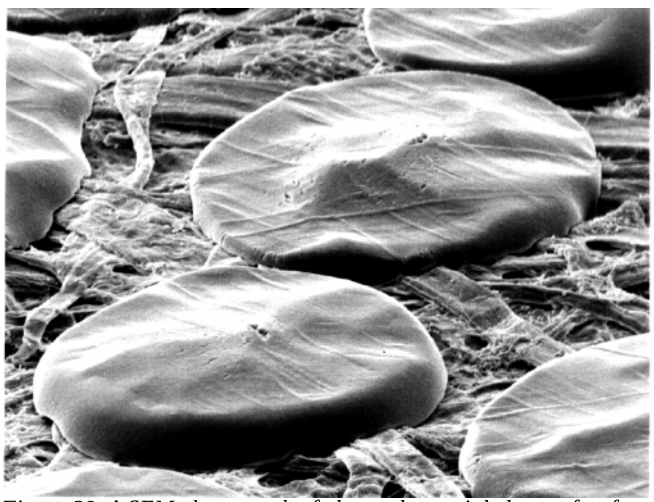

Figure 29. A SEM photograph of phase-change ink drops after fuse by cold pressure rollers.

along the paper fibers and penetrate into the bulk of the paper. The water-based ink actually depends on penetration and absorption for its drying mechanism. Some evaporation of water is taking place, but this drying mechanism is often very slow. Such ink behavior lowers color density and spot resolution on paper. It has been known for some time that paper or other media with a coated water-receiving layer can greatly improve both color density and resolution by controlling the ink spreading and penetration at the coated layer. However, just within the past few years, the market for the specialty-coated ink-jet media has exploded, especially in the home photo quality and large-format ink-jet printing areas.[32] Recent availability of printhead technologies with high resolution (such as 1440 dpi Epson Color Stylus 800, 1200 × 1200 dpi Lexmark 7000, 10 pL drop Hewlett-Packard DeskJet 890C), multilevel dye load gray-scale (such as in photo pens from Epson, Canon, and Hewlett-Packard), and multilevel dot volume gray-scale capability (such as in Hewlett-Packard DeskJet 720C and 890C) certainly have made a positive impact on this trend.

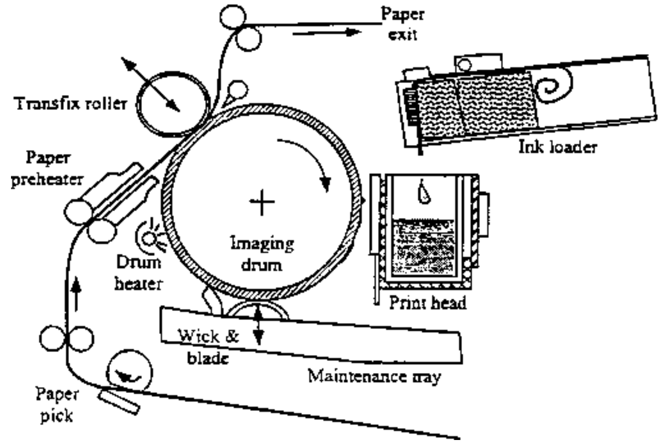

Figure 30. The basic configuration of the Tektronix's Phaser 350 offset drum transfer ink-jet printer.

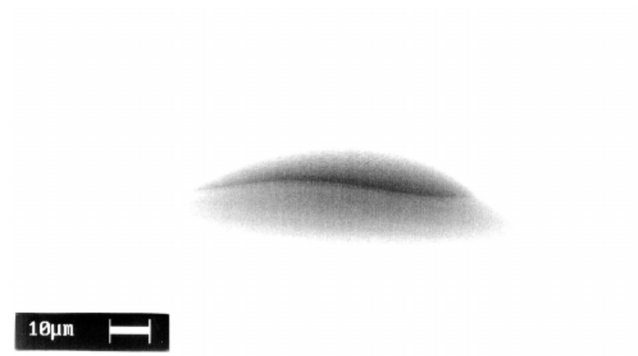

Figure 31. A SEM photograph of a phase-change ink drop on the surface of aluminum substrate.

TABLE III. Phase-Change Ink Composition

Component	Function	Concentration, %
Solid wax mixture	Ink vehicle	40 to 70
Viscosity modifier	Lowers viscosity	5 to 20
Tackifier	Imparts adhesion	1 to 15
Plasticizer	Provides flexibility	1 to 15
Dye or pigment	Provides color	1 to 10
Antioxidant	Heat stability	0.05 to 2

Phase-change ink is also called hot melt or solid ink which is solid at room temperature. The ink is jetted out from the printhead as a molten liquid. Upon hitting a recording surface, the molten ink drop solidifies immediately, thus preventing the ink from spreading or penetrating the printed media. The quick solidification feature ensures that image quality is good on a wide variety of recording media. Figure 28 shows a SEM photograph of phase-change ink drops printed on the surface of a Xerox 4024 bond paper. Notice that the ink drops maintain their hemisphere shape with little or no evidence of ink spreading, even along rough paper fiber structures. Tektronix currently implements phase-change ink-jet technology in the Phaser 300 ink-jet printer. However, in practice, the solidified ink drops need to be fused on top of paper to increase ink adhesion and prevent light scattering owing to the lens effect of the hemisphere shaped ink dot.[33]

Figure 32. A SEM of a fused phase-change ink drop on a paper that results from a offset drum transfer process.

Figure 29 shows a SEM photograph of several Tektronix Phaser 300 phase-change ink drops after being fused by a cold pressure fusing roller.

Another successful implementation of phase-change ink-jet technology is in the Tektronix Phaser 350 offset transfer printing architecture. Figure 30 describes major components of a Tektronix Phaser 350 color ink-jet printer. Basically, the printing process starts with coating a thin silicon oil film onto a warm rotating aluminum drum. Ink is then jetted onto this intermediate drum. Once an entire image is printed, it is then transferred from the drum onto a preheated media via a pressure nip. It is very critical for the drum to be heated at a temperature above the glass transition temperature and below the ink melting point so that the phase-change-ink material is soft enough to fuse into paper with moderate pressure, but still strong enough to prevent the ink from cohesive failure when exiting the pressure nip.[35]

A SEM photograph of a phase-change ink drop on an aluminum surface is shown in Fig. 31. A SEM photograph of an offset-transferred phase-change-ink dot on an aluminum surface onto a bond paper is showed in Fig. 32. Because of its ability to print good color quality images on a variety of bond and plain papers at speeds of up to 6 ppm, Tektronix's Phaser 350 phase-change ink-jet printer has been very successful in the office network printer market. Other companies that actively develop and commercialize the phase-change ink-jet-printing method are Spectra[36] and Dataproducts.[13]

Table III describes a typical composition for a phase-change ink formulation. Operating temperatures for phase-change inks range from 120 to 140°C. Viscosity at the operating temperatures are from 8 to 15 cps.

Solvent-based inks are commonly used in industrial marking or coating applications where the printing is done on a nonporous substrate such as plastic, metal, or glass. Because no absorption or penetration occurs, the printed image relies on quick evaporation of the ink solvent to be fixed onto the substrate.

Another type of nonaqueous-based ink is oil-based. This type of ink was recently used in several large-format ink-jet printers including the Raster Graphics PiezoPrint 5000 and the Xerox ColorgrafX. Both of these printers utilize Nu-Kote piezo shear-mode printheads. This printhead requires its ink to be compatible with the PZT electrode that is located on the walls of its ink chambers. The use of nonpolar oil-based ink minimizes the effect of electrical fields on ink and printhead materials. However, the ink manufacturer (Zeneca) for the Nu-Kote shear-mode ink-jet printhead also claims that the advantages of oil-based inks, when compared with water-based are faster drying time and the absence of cockle on paper substrates.[37] With the proper paper coating design, the above claim can be realized.

TABLE IV. Drying Mechanisms for Different Ink-Jet Inks

Ink	Printhead	Drying Mechanism
Aqueous	Thermal/Piezo Continuous	Absorption/ Penetration Evaporation
Oil	Piezo continuous	Absorption/ Penetration
Solvent	Continuous piezo	Evaporation
Hot melt	Piezo	Solidification
UV curable-based	Piezo continuous	Polymerization
Reactive-based	Piezo Continuous	Oxidation Polymerization

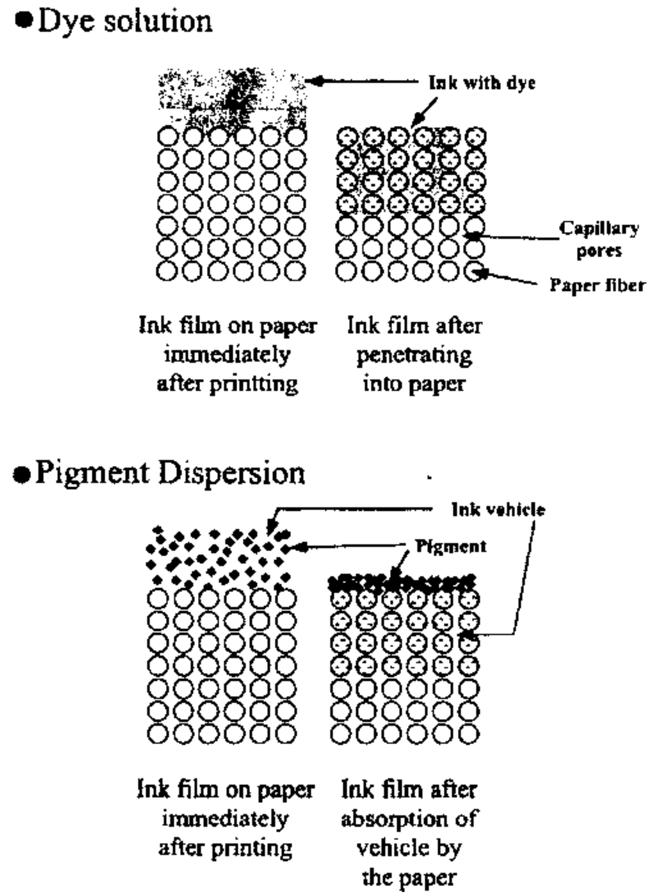

Figure 33. Comparison between dye solution and pigment dispersion behaviors on paper.

Image quality and durability for water-based, phase-change, and oil-based ink-jet inks are generally acceptable when they are printed on ink-jet papers or coated substrates. However, when printing on nonabsorbent substrates such as metal, glass, and plastic, the above ink systems are not adequate to produce durable and sharp images. To solve this problem, the idea of using a UV curable ink system for ink-jet printing has been discussed for a long time. However, many factors (such as ink-jet printhead capability, photoinitiator and

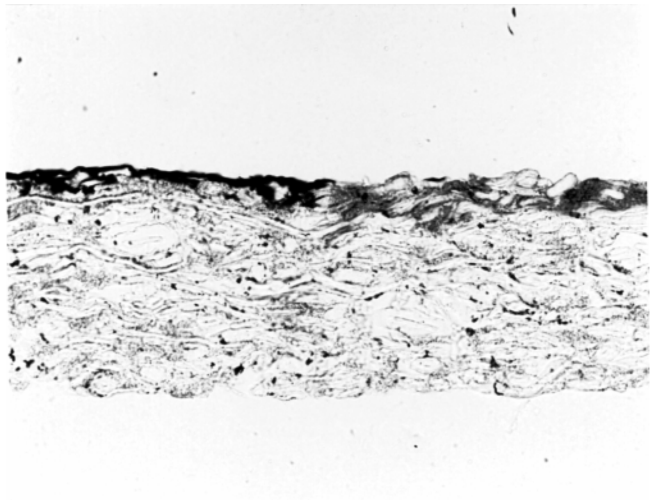

Figure 34. A cross section light microscope of pigment-based (on the left) and dye-based (on the right) inks on paper.

TABLE V. Applications in Ink-Jet Printings

	Market/Application	Key Player
Current Markets and Applications:	Small home small office	Hewlett-Packard, Canon, Epson
	Office network	Tektronix, Hewlett-Packard
	Graphic arts	Iris, Tektronix, Epson
	Industrial/postal marking	VideoJet, Marsh, Image, Willet
	Large format	ColorSpan, Encad, Hewlett-Packard, Mimaki
Emerge Markets and Applications:	Home photo	Hewlett-Packard, Epson, Canon
	Color copier	Hewlett-Packard, Canon
	Multifunction	Hewlett-Packard, Canon
	Digital color press	Scitex, ACS, Tektronix
	Grand format	Idanit, Vutek, Nur, ColorSpan, Mutoh
	Textile	Canon, Seiren, Stork, Toxot
	Medical imaging	Iris, Sterling Diagnostic
	3-D printing	3D System, Z Corporation
	Computer-to-plate	Polychrome, Iris

low-toxicity monomer availability, and market needs) have hindered the progress of UV curable ink-jet ink development. Today ink-jet printheads are more capable and available; UV photoinitiators, monomers, and oligomers are readily available at economic scale; and market needs are strong. Successful development of UV curable inks for ink-jet applications are predicted in the near future.

Drying mechanisms for various ink-jet ink systems are summarized in Table IV.

Another major development in the ink-jet printing industry is the successful implementation and commercialization of pigment-based inks in color printing applications. Many companies including 3M, Dupont, and Kodak have already had pigmented ink-jet ink products on the market. With such focus by the industry, the color quality, image durability, and jetting reliability of the inks will be improved. In addition, severe competition for market share will likely result in significantly reduced cost for pigmented ink-jet inks.

Figure 33 compares the ink and paper interactions between dye solution and pigment dispersion. Dye molecules are dissolved into an ink base that tends to penetrate or absorb into a paper or coating substrate. Pigment particles are dispersed into the ink base. While the ink base penetrates into the bulk of the paper substrate, pigment particles tend to remain on the surface of the paper. Figure 34 is a cross section light microscope photograph showing the behavior of pigmented black and cyan dye ink-jet inks throughout the thickness of a bond paper.

One significant advantage of pigment-based as compared to dye-based ink is its color durability when exposed to light or outdoor weather conditions. This feature is definitely critical to applications such as billboards or other large-format displays. However, as compared to dye base, pigment-based ink-jet ink has the inherent disadvantage of particle dispersion instability that may lead to nozzle clogging. Even though the pigment dispersion chemistry and process of making ink-jet ink has improved significantly in the past few years,[37–40] the trend in the ink-jet industry is toward smaller nozzle diameter for high resolution and a higher number of jets for print speed. The reliability issue should be a part of the decision process when it comes to the pigment or dye-base question.

Another recent development in the ink-jet ink area is the introduction of the Canon BJC-7000 ink-jet printer. This new printer implemented a new process called Plain Paper Optimized Printing (P-POP). The black printhead contains black ink and a precoat fluid applied to the paper surface a few microseconds before dye-based ink drops hit the paper. The precoat fluid is clear and believed to contain a compound that will aggregate with the dye, thus fixing it instantly on the surface of paper.[41] This unique approach is proven to provide excellent waterfastness. The P-POP process not only improved waterfastness of the printed image but fixed the ink on the top surface of the paper, making a plain paper perform like a coated media. If this approach does not impact the overall reliability of the system in any way, the P-POP process will become one of Canon's significant technological breakthroughs.

Ink-jet Applications

Ink-jet printing technologies are used in a wide range of applications including home, office, industrial, three-dimensional, medical, and textile printings. Table V summarizes different market segments and key players in each of the fields.

Summary

This paper provides a partial review of the recent developments in the various ink-jet printing technologies. The market for ink-jet printers has grown at a tremendous rate in the last few years. Due to an intense competition for market share among ink-jet producers, many innovative ideas and technological breakthroughs have occurred that are clearly shown in today's color ink-jet products. With the capability of printing vivid color images at relatively low cost, drop-on-demand ink-jet has dominated the home, small office, and large-format color printer markets. In the office network color printer market, the battle between color laser and color ink-jet printing technologies is still ongoing. The delicate balance between print speed, image quality, image durability, purchase price and operation cost will determine the survival of ink-jet technology in the network office color printer market.

In other newly emerging markets and applications such as medical imaging, 3-D printing, and the digital printing press, significant improvements in printhead design and ink formulations are needed to fulfill the high expectations for printer reliability and image durability required for these new applications. However, the amount of ink projected for use in applications such as 3-D printing, digital printing presses, and medical imaging is enormous.

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