CHAPTER II

THEORETICAL BACKGROUND AND LITERATURE REVIEW

Theoretical Background

2.1 Inkjet printing

2.1.1 Review of Historical Inkjet Ink

Inkjet printing 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. Rayleigh[2] described the mechanism by which a liquid stream breaks up into droplets in 1878. In 1951, Elmqvist of Sieimens patented the first practical Rayleigh break-up inkjet driver. This invention led to the introduction of the Mingograph, one of the first commercial inkjet chart recorders for analog voltage signals. In the early 1960s, 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. In the 1970s, IBM licensed the technology and launched a massive development program to adapt continuous inkjet technology for their computer printers.[3] At approximately the same time, Hertz of the Lund Institute of Technology in Sweden and his associates independently developed several continuous inkjet techniques that had the ability to modulate the ink flow characteristics for gray scale inkjet printing. Many of the drop-on-demand inkjet technologies and systems were invented, developed, and produced commercially in the 1970s and 1980s. In 1979, Endo and Hara of Canon invented a drop-on-demand inkjet 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. Canon called the technology **"Bubble Jet"**. In 1984, Hewlett-Packard commercialized the inkjet printer. It was the first successful low cost inkjet printer based on the bubble jet principle. Hewlett-Packard named the technology **"Thermal Inkjet"**. Inkjet 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 inkjet or bubble jet printers became the viable alternative to impact dot-matrix printers for home users and small businesses. Inkjet printers offer quiet operation, high speed, and compatibility with various substrates. The inkjet technology is one of the most fittings for using in the production of color graphics. With its ability to reproduce video image quickly and with consistent color fidelity and fine detail, inkjet technology is the best current candidate for use as a hard copy device.[3]

2.1.2 Principles of Inkjet Printing

Inkjet printing is a non-impact printing, which microscopic ink drops are emitted under pressure through the print head nozzle onto a substrate. In 1878, Rayleigh first analyzed the mechanism by which a stream of liquid becomes unstable and breaks into droplet.[2] The size of print head nozzle can vary from 10-100 micrometers depending on the technology. There are two main technologies applied to inkjet printers, continuous inkjet and drop-on-demand. Their application can be further subdivided as indicated in Figure 2-1.[2]

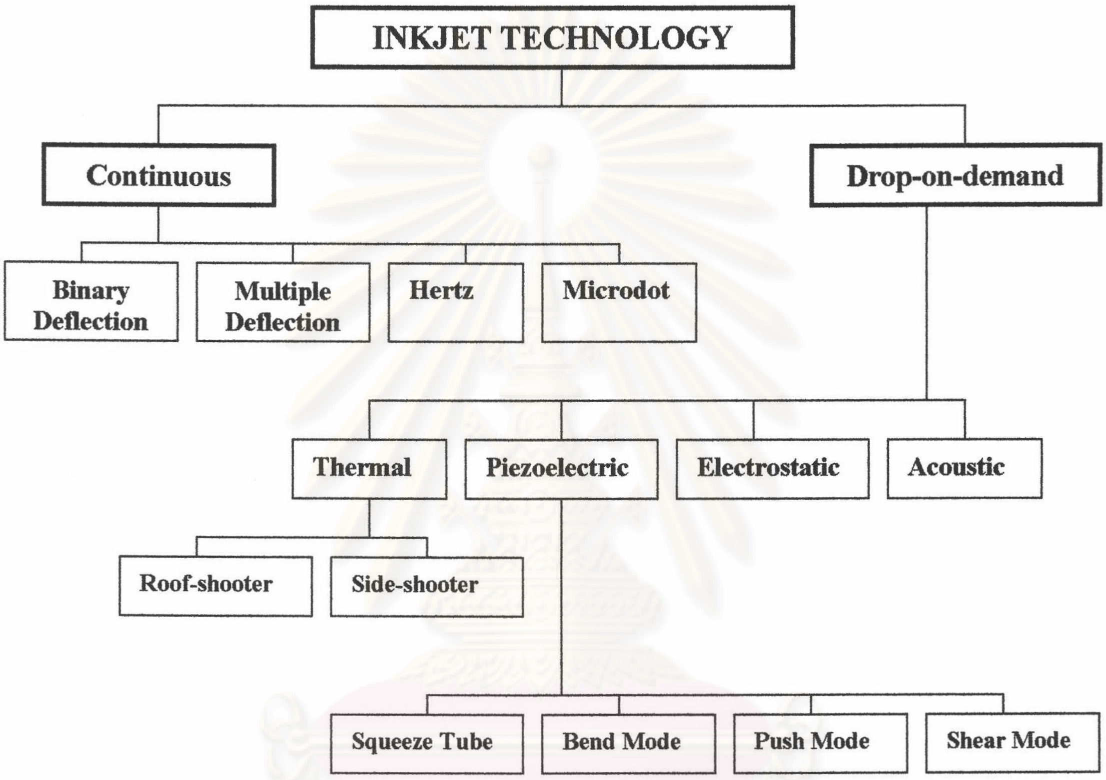
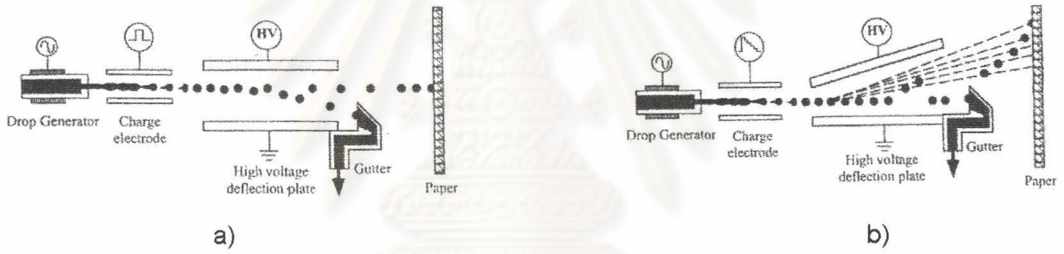


Figure 2-1 Map of inkjet technologies

2.1.2.1 Continuous Inkjet

Continuous inkjet printer is the primary inkjet system formed by forcing ink under pressure (about 3 x 10^5 Pa) out of one or more nozzles. The working principle of this system is shown in Figure 2-2.[2] A liquid jet tends to break up into a stream of droplets of a size and frequency determined mainly by the surface tension of the liquid, the pressure applied to it, and the size of the nozzles. Applying a high-frequency alternating voltage (possibly up to 1 MHz) to a piezoelectric crystal in contact with the ink in the reservoir is a method to regularize a stream of uniformly sized and spaced droplets. The ink droplets are moved towards at a speed of 5-35 m/s. The ink stream undergoes a charge/no charge condition by the binary switching. Each individual ink droplet passes through a high voltage field of approximately 2000 V. Uncharged drops pass through the high voltage field, which are deposited onto the substrate to form part of an image. Unwanted drops have a 200 V charge applied to them. When these charged drops pass through the high voltage, they are repelled by the 2000 V electrode and are then deflected into a reservoir.[3]



a)

b)

Figure 2-2 The continuous inkjet designs: a) binary-deflection system b) multiple-deflection system

2.1.2.2 Drop-on-demand

The difference between continuous and drop-on-demand inkjet technologies is that in the latter, the pressure applied to the reservoir is not continuous, but is only applied when a droplet is needed. The pressure is applied in response to digital electronic signals from the imaging computer. The velocity of ink droplets usually ranges 10-20 m/s. Depending on the mechanism used in the drop formation process, the technology can be categorized into four major methods:

piezoelectric, thermal or bubble, electrostatic and acoustic. Both the electrostatic inkjet and acoustic inkjet methods are still in the development stage with many patenrs pending and few commercial products available.

a. Piezoelectric

The ink drops in piezo technology are ejected from the print head nozzle by the driving pulse, created by a piezoceramic deformation. At rest, the force of hydrostatic pressure causes the ink to form a concave meniscus. One end of the ink chamber may be in the form of a diaphragm, the other end open as an orifice. An electrical driving pulse acts on the chamber, causes the volume of ink to decrease. The ink droplet is then directly emitted from the nozzle onto a print substrate so that the deflection part of ink droplet is not required to form an image. The driving technology can be classified into four types: squeeze, bend, push, and shear mode as shown in Figure 2-3.[2]

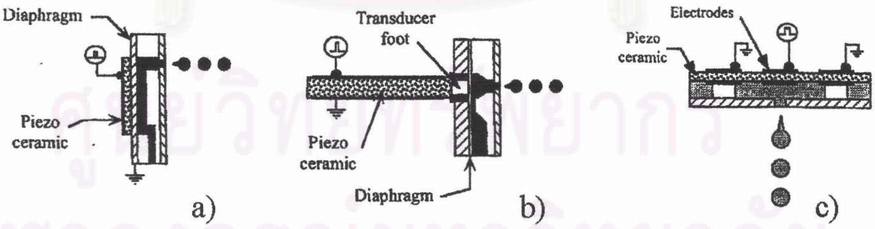


Figure 2-3 Piezoelectric inkjet designs: a) bend mode b) push mode c) shear mode

b. Thermal inkjet or Bubble jet

The bubble jet printer (Canon) uses a small heating element to create pressure droplets on demand within the ink reservoir. The small quantity of ink presented in each nozzle is heated by a resistive heating element actuated by the digital data stream. The ink boils creating a bubble which forces an equivalent volume of ink droplet through the nozzle and onto the substrate. This system is shown in Figure 2-4.[5] A disadvantage of this method is that the dye in the ink would precipitate and build up at the internal surface of the print element by evaporation caused by super-heating of ink layer. This phenomenon is called "Kogation", the build up of decomposed ink on the resistors.

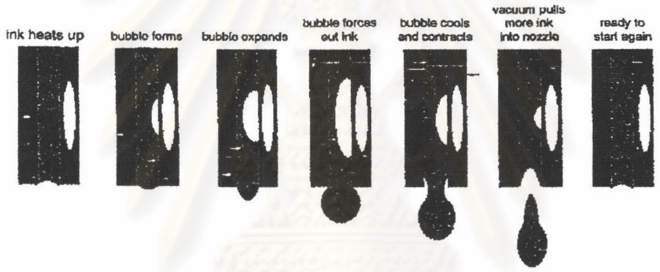


Figure2-4 Principle of Thermal ink jet printer

c. Hot melt or phase change inkjet

This is an extension of the bubble jet principle in that an impulse heater is used to create droplets on demand. The difference lies in the nature of the ink, which is a hot and melt formulation. The ink is supplied as solid sticks of colored wax, one for each printing color. The wax is melted into a reservoir where it is kept fluid by a heating element. Figure 2-5 shows the schematic diagram of a working principle of a hot melt inkjet printer[4]. The hot, liquid ink is pumped through set of a nozzle using thermal drop-on-demand technology. On reaching the substrate, the ink solidifies on its surface. Because the ink is not substantially absorbed by the substrate, high color saturation with a wide color gamut is achieved.

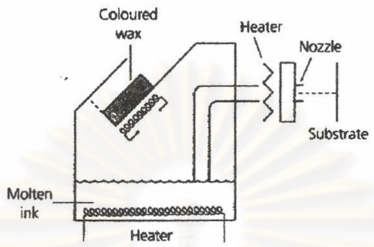


Figure 2-5 Hot melt inkjet

2.1.3 Physical Properties of Inkjet Ink

2.1.3.1 Viscosity

The viscosity is an important property of the inkjet ink for jetting the ink from the print nozzle. It is used as a starting point for formulating an inkjet formula. The low viscosity is important not only for transport of the ink through the nozzle, but also for drop formation and integrity. The viscosity range of inkjet ink is around 2 to 8 mP s depending on the process.[3] A humectant such as ethylene glycol is another primary constituent besides resin binder that affects ink viscosity and the degree of dye crusting precipitated in the bubble inkjet system.

2.1.3.2 Surface tension

Surface tension is one of the primary factors determining where the actual drop will formm in continuous inkjet printers. In drop-on-demand printers, it helps to regulate the controlling of concave meniscus to hold ink in the system.

Surface tension also influences the dot spreading on the surface of the printed substrate. The range of surface tension is around 22-55 mN m^{-1}.

2.1.3.3 Conductivity

The conductivity of inkjet ink is higher than 1,000 μS cm^{-1} at 25°C. In the case of a continuous inkjet printer, the ink droplet must be able to accept an applied voltage. The charged and uncharged droplets fly to the different trajectories when they pass through the high voltage field. Because of the charge repelling, the charged droplet is deflected into the gutter. For the uncharged droplet, it passes directly to the printed surface to form an image. However, in some printing processes, the destination of the charge/uncharged droplet is alternated.

2.1.3.4 pH

The pH of inkjet ink has an impact on many factors of the ink such as hue, pigment dispersion and dye solubility. The lower pH of the anionic pigmented ink causes the pigment coagulation in a storage container or clogging in the print nozzle. The orifice of some inkjet printers may be corroded if the pH of the ink is highly acidic. Pigmented inkjet inks that are suitable to use with inkjet printing system should have a pH in the range of 5 to 9.[3]

2.1.3.5 Particle size

The particle size of any materials in the ink has to be smaller than 1 micrometer. Most typical by, a central range is 80 nm to 300 nm as a mean value.

The large particle size in the ink leads to the jet instability or clogging the nozzle. These problems are usually found in the pigmented ink.[6]

2.1.4 Inkjet Ink Composition

Ink 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. Inkjet ink mainly consists of a colorant in a vehicle, which is composed of aqueous organic solvents to give high reliability on a drop formation and preventing evaporation. Furthermore, these essential ingredients, some binder resin, and additives are added to the inkjet inks, for improving color density, adhesion strength on printing substrate, and smear resistance. The water-based inkjet ink composition is shown in Table 2-1.[2]

Table 2-1 Water-based inkjet ink composition

Composition	Function	Concentration (%)
Deionized water	Aqueous carrier medium	60-90
Water soluble solvent	Humectant, prevent evaporation of water, viscosity control	5-30
Colorants	Provides color	1-10
Surfactant	Controls the flow property on the print head, wetting, penetrating	0.1-10
Biocide	Prevents biological growth	0.05-10
Buffer	Controls the pH of ink	0.1-0.5
Other additives	Chelating agent, defoamer, solubilizer etc.	>1

2.1.4.1 Vehicle

The role of vehicle is to transfer ink from the printer to the printed substrate. The majority of inks used in home and small office inkjet printer, are water-based ink. The vehicle often comprised of water and other relative low surface tension liquid, such as humectant.[7] Some typical humectants are glycol, glycerol, and poly (ethylene glycol). Humectants are added to ink for two purposes: the first one is to retard the evaporation of the ink in the printhead, and the second is to act as a dye solubilizer. If the quantity of humectant is decreased, the orifice nozzle may be clogged. If the quantity is too high, the ink takes too long time to dry on the printed substrate resulting in too much spreading and infiltration. There should be a fine line in determining the optimal percentage of humectant for the ink to avoid both failures.[3]

2.1.4.2 Colorants

The two general classes of colorant used in inkjet formulation are dye and pigment. Dyes are generally used in the small office or home office (SOHO) inkjet printer or indoor applications, but pigments are preferred to use for outdoor applications and wide format inkjet printers.

Pigmented inkjet ink generally shows high weatherability such as light fastness and water fastness. In pigmented-based ink, colorant exists as discrete particles, typically ranging in size from 0.05 to 0.3 micrometer. Each pigment particle contains a large number of molecules. These pigment particles are usually pretreated with functionality known as dispersants or stabilizers, which serve to keep the pigment particles from agglomerating and settling out of the carrier.[8,9] The pigmented inks have the limited use in inkjet application because of the problem with solubility, particle size, and opacity. Pigment is sometimes coagulated when the ink is kept for a long time.

Dyes have the advantage of being water-soluble. However, the most dye-based inkjet inks have the problem about poorly water fastness, smear fastness, light fastness, and bleed control between colors.[7] The ink also reacts to humidity, oxidative molecules like singlet oxygen, ozone and NO_X. Besides, the light fastness is a thoughtful problem for dye-based inkjet inks, consequently they are not appropriate for outdoor applications. Fortunately, dye-based inkjet inks predominate the pigmented inkjet inks in some ways, such as brighter color, more transparency, bigger color gamut volume, etc. Storage stability of dye-based inkjet inks is long with less coalescence and sedimentation.

Whether a dye or pigment is chosen for a particular application depends on which properties such as color gamut, transparency, coloring power, choice/synthetic flexibility and ease of use are ranked against excellent light fastness, insolubility and crystallinity. The current usage of dyes and pigments in non-impact printing is shown in Table 2-2.[8]

2.1.4.3 Binder resin

Inkjet inks usually contain a small amount of binder (0-10% depending on the type of resin and print application) because of the viscosity limitation. If the level of resin in the ink is raised up, the viscosity increases, and it also affects the ink stability and nozzle clogging. In some applications, a binder is added into the ink for some requirements such as increasing adhesion, gloss, abrasive and water resistance. In the inkjet textile printing, more binders are used to form the same printing atmosphere as that of screen printing.

2.1.4.4 Additives

Dispersant, defoamer and surfactant are added into an inkjet ink to adjust the properties to meet the requirement of printing.

Table 2-2 The current usage of dyes and pigments in non-impact printing

Non-impact printing technology	**Colorant**	
	Dye	**Pigment**
Inkjet		
• Aqueous (SOHO use)	✓	
• Aqueous (Industrial use)		✓
• Solvent type	✓	✓
• Oil type		✓
• Phase change		✓
EP		
• OPCs		✓
• Colorants		✓
• CCAs	✓	
Thermal		
• Wax		✓
• D2T2	✓	

2.2 Screen Printing

2.2.1 Review of Historical Screen Printing

Screen printing is considered by many historians to be the oldest of the printing processes, although some individuals believe block printing to be older. The actual beginning of screen printing was in vague and difficult to prove. The Chinese, Egyptians, and Japanese are generally credited with the first use of a stencil process. The Japanese were the first to combine a screen with a stencil.[10]

In Japan, the artist cut stencils from two sheets of paper. Silk or hair was sandwiched between the paper sheets forming a screen. The process of stencil printing spread to Europe in the 15th century and eventually to the American colonies.

In America, many people contributed to the process by experimentation. In 1914, Jonh Pilsworth[10], a San Francisco commercial artist, perfected a multicolor screen printing process.

In 1929, Louis F. D'Autremont, a screen printer in Ohio, developed the first material for knife-cut stencils. His stencil, called Profilm, was hard to cut and adhere.

Several years later, Joe Ulano, a New York screen printer, developed his own knife-cut stencil called Nufilm. D'Autremont, and Ulano became involved in a court battle over the patent light, which was eventually settled in favor of D'Autremont. However, Ulano's Nufilm was a better, more easily used stencil, and it became the standard of the industry.

With a working stencil now available, paint manufacturers saw the potential of a new market for their products, and screen printing became an established industrial process.

The applications for screen printing were limited by the available stencils (all hand cut) and inks. With the advent of World War II, screen printing began to have wider applications, especially as a method of identification for military vehicles and related equipment.

Modern screen printing began in the 1940s and 1950s, new materials and production techniques were developed. Today, screen printing is still the slowest printing process, yet rapid technological advances continue to improve the process and lead to expanded markets.

2.2.2 The Principles of Screen Printing

Screen printing (formerly called silk-screen printing) is a stencil process whereby ink is transferred to the substrate through a stencil supported by a fine fabric mesh of silk, synthetic fibers or metal threads stretched tightly on a frame. The pores of the mesh are "blocked-up" in the non-image areas and left open in the image area. This image carrier is called the screen.

During printing, the frame is supplied with ink which is flooded over the screen. A squeegee is then drawn across it, thereby forcing the ink through the open pores of the screen. At the same time, the substrate is held in contact with the screen and ink is thereby transferred to it. The principle of screen printing is shown in Figure 2-6.[11]

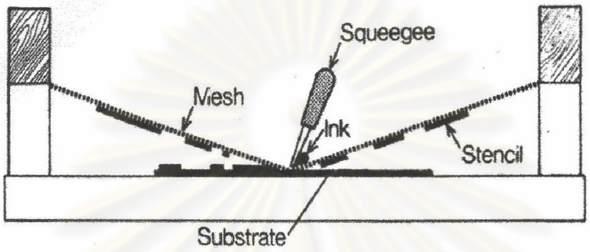


Figure 2-6 The principle of screen printing

2.2.3 General properties

Screen printing inks are carefully formulated to conform to the certain printing and finish specification:[11]

2.2.3.1 Viscosity

The consistency of screen inks is often described as short and buttery. As discussed earlier, this is advantageous in giving a clean, sharp print. If screen ink has excessive flow, there will be a tendency towards bubbling on printing and slurred prints. Although lack of flow is desirable, ink with very poor flow will not flow out once printed to remove the pattern of the mesh from the printed ink film. Average printing viscosity of the screen ink would be 15-20 Poise (1.5-2.0 Pa s), but it may be much higher.

2.2.3.2 Drying

Screen printing is almost unique in that it is possible to employ all available methods of drying. However, the most important drying method is evaporation. Most screen inks contain volatile solvent, sometimes representing 70 % of the formulation. In addition, drying by oxidation method and ultraviolet curing is also used.

2.2.3.3 Film thickness

Screen printing has been traditionally characterized by thick and opaque ink film. However, various developments in mesh materials, stencils and ink technology have made it possible to achieve a film thickness approaching that obtained with gravure. Average film thickness of screen ink would be 8-30 μm.

2.2.4 Screen printing ink composition

In common, all screen inks are made up of two basic components, which composed of vehicle and pigment.[12]

2.2.4.1 Vehicle

The vehicle contains a volatile solvent and a binder. The solvent with a necessary flow property renders the ink adaptable for printing. When the solvent evaporates, the binder remains on the printing surface to form a protective film around the pigment particles, keeping them permanently adhered to the surface. The component ingredients in the vehicle determine the finish and other working properties of the ink mixture.

2.2.4.2 Pigment

Pigments are preferred to use for outdoor applications, because of pigments have excellent light fastness, water fastness, weather resistance, heat and chemical resistance such as acids and alkalis. For most applications, of course, it is the optical properties of pigment, which are of prime importance. The most obvious of these properties is the ability to impart the desired color. However, a pigment may also be required to impart opacity, most critically in paints which are generally required to obscure the surface to which they are applied. The high transparency may be essential, for example ink used in multicolor printing processes, where the optical effect of first color printed must not be obscured by subsequently printed colors.[13] The end-use requirement is very important in selecting a suitable pigment. Due to the numerous applications of screen printing, the properties required of a colored pigment can vary considerably.

2.3 General Colorants for Textile Printing

The dyed style is probably the earliest method of textile printing, for 2,000 years ago. Many types of dye formulations: direct dyes, vat dyes, acid dyes, basic dyes, reactive dyes, etc are in use. In the family of dye compounds, vat dyes have excellent fastness to light and washing, and therefore are used extensively in commercial textile printing.[14] Another essential feature of dyes used on textiles is that they are expected to be 'substantive', which means that the dye molecules must enter the fibers and become physically or chemically attached, so that they are not removed in subsequent processing, for example when a garment is being washed. However, another problem is the difficulties to improve lighfastness from ink composition. Of course, pigment once designed and implemented in textile printing system can be used.[15] Pigment appeared by 1930's, pigment printing are becoming more popular due to their enhanced durability of the ink systems. Here the main driving force for choosing pigments instead of dyes is the elimination of wet post-processing needed for fabric dyeing. Pigment printing promises lower cost of both materials and processes compared to dye printing. Pigments have to be applied to the substrate in a vehicle or binder form, which helps to hold them in place, there are no chemical operation to be done on the fabric, the result immediately appears, and the colors may be applied to all the fibers, even glass fibers.[16]

2.4 Cotton

2.4.1 Review of Historical Cotton

The origin of cotton is unknown. Archeologists have contributed valuable information concerning the fiber's early use, but there is a dearth of evidence to indicate when or where cotton first grew. Data suggestion that cotton was grew in Egypt about 12,000 B.C. remain inconclusive, however, most authorities agree that cotton was produced in India about 3,000 B.C. and that India was the principal country in which cotton was widely utilized before 2,500 B.C.[17]

The word "cotton" derives from the Arabic word *quoton* or *qutun*, which means a plant found in conquered lands. *Muslin* is also taken from the Arabic language and was applied to cotton woven in Mosel. Ancient writers described this cloth as being "so sheer that it was invisible when spread over the ground and saturated with dew."

Cotton is the most widely used of the textile fibers. Cotton has a combination of properties of durability, low cost, easy washability, and comfort that have made it desirable for summer clothes, work clothes, towels, and sheets. This unique combination of properties has made cotton a standard for great masses of the world's people who live in warm and subtropical climates. Even through the man-made fibers have encroached on the market that were once dominated by 100 percent cotton fabrics, the cotton-look is still maintained and cotton forms up to 65 percent of the fibers in fiber blend fabrics.[18]

2.4.2 Cotton Fiber

The cotton fibers composed of cellulose molecule, which consists of series of the *glucose unit*, which is the same for both natural and regenerated fibers. The glucose unit is made up of the chemical element carbon, hydrogen, and oxygen. The cellulose molecule is made up of a number of units linked together, as shown in Figure 2-7.[19]

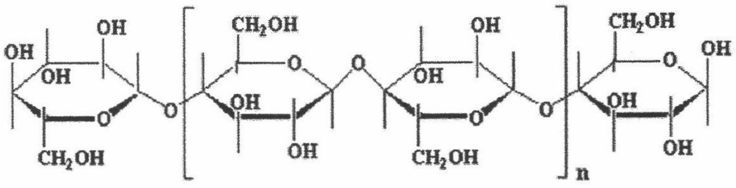


Figure 2-7 Cellulose chain

It is a long-chain molecule, made up of groups that are linked together by valence bonds. The strength of these bonds is such that, if the whole strength of the chain could be utilized, it would have strength more than ten times as great as that of the strongest cellulose fiber. It is a ribbon-like structure, which can bend and twist to some extent, particularly at the oxygen bridges between the rings of atom, so that it is flexible. Protruding from the chain are hydroxyl (-OH) groups, which can link up with other hydroxyl groups by means of hydrogen bonds. This results in the linking together of neighboring chains as shown in Figure 2-8.[16] Water molecules can also be attached by the same sort of bond. The chemical structure of cellulose is very important in determining the properties of cellulosic fibers.[20]

In the crytalline regions, the molecules would be arranged in a regular order linked together by hydrogen bonds. The non-crystalline regions (about one-third of the total in native cellulose) are often referred to as amorphous or disordered regions. There is, however, no evidence that the arrangement of the molecules is completely irregular, and there will be some degree of order in the non-crystalline regions.

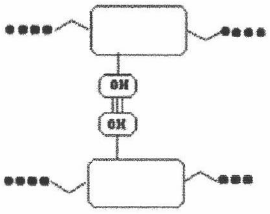


Figure 2-8 Linkage of cellulose molecules by hydrogen bonds

2.4.3 Properties of Cotton

Cotton, except for the longest, finest fibers, is a dull fiber with low luster. It is often bleached to improve its whiteness and light reflection.

2.4.3.1 Thermal Property

Cotton burns readily and quickly with the smell of burning paper. It leaves a small amount of fluffy gray ash. Long exposure to dry heat above 149°C (300°F) will cause the fiber to decompose gradually and the temperature which is greater than 246°C (475°F) will result in rapid deterioration. Normal exposure to heat encountered in routine care and processing will not damage cotton, but fabrics will scorch if ironed with too-high temperatures. Finishes, such as starch or durable press, increase the tendency to scorch.

2.4.3.2 Chemical Property

Cotton is highly resistant to alkalies; in fact, they are used in finishing and processing the fiber. Most detergents and laundry aids are alkaline, so cotton can be laundered in these solutions with no fiber damage.[17]

Strong acid destroys cotton, and hot dilute acids will cause disintegration. Cold dilute acid causes gradual fiber weakening, but the process is slow and may not be immediately evidenced. Cotton is highly resistant to most organic solvents and to all those used in normal care and stain removal. Prolonged exposure to sunlight will cause the cotton fiber to become yellow and will gradually result in loss of strength. This damage is accentuated in the presence of moisture, some vat dyes, and some sulfur dyes. If properly stored in dry and dark areas, cotton will retain most of its strength and appearance.[18]

2.3.4.3 Biological Property

Various microorganisms damage Cotton. Mildew will produce a disagreeable odor and will result in rotting and loss of strength. Certain bacteria encountered in hot, moist, and dry conditions will cause decay. Moths and beetles that damage some fibers will not usually attack cotton. But silverfish does eat cotton cellulose, especially if it is sized.[17]

2.4.3.4 Comfort property

Cotton makes very comfortable skin-contact fabrics because of its absorbency and its good heat and electrical conductivity. It is lacking in any surface characteristics, which might be irritating to the skin. Cotton has a moisture regain of 7 percent. When cotton becomes somewhat plastic, this property makes it possible to give a smooth, flat finish to cotton fabrics when they are ironed, and makes high count woven fabrics for water repellent.[21]

2.4.3.5 Durability property

Cotton is a medium strength fiber having a breaking tenacity of 3.5 - 4.0 g/d, it is stronger when wet. Long staple cotton makes stronger yarns because there are more points of contact between the fibers when they are twisted together. Cotton can stand rough handling during laundry. The elongation of cotton is low, 3 percent, and it has low elasticity, making it a rigid fiber.[18]

2.4.3.6 Care property

Cotton fibers are stable. They do shorten a bit when wetted but on drying their original length is restored. Shrinkage of cotton fabrics is not the result of any property of the fibers but rather is a result of the finishing of the fabric.

Acids harm cotton. It is not greatly harmed by alkalis. Cotton can be washed with strong detergents and under proper conditions, as it will withstand chlorine bleaches. Cotton is resistant to organic solvents so that it can be safety dry-cleaned. Fungi especially in starched fabrics attack Cotton.

Cotton oxidizes in sunlight, which causes white and pastel cottons to yellow and all cotton to degrade.[18]

2.5 The textile testing

The two groups that have developed the most widely used textile testing methods are the American Association of Textile Chemists and Colorists (AATCC) and the American Society for Testing and Materials (ASTM).[22]

The American Association of Textile Chemists and Colorists is composed of persons from the textile wet processing industry, textile chemists, others working in varying segments of the textile industry, and educators. The Association establishes testing methods, largely in the area of chemical testing, and maintains an active educational program implemented through national and regional meetings, and a monthly journal, the AATCC Review. Specific test methodologies are fully described in an annual publication, the Technical Manual.

Tests established by the American Society for Testing and Materials are more specifically focused on physical testing and the testing of fabric construction. The ASTM test methods published annually in a set are the good source for material evaluations.

2.5.1 Color

The methods attempt to provide a way of expressing colors numerically, in much the same way that we express length or weight. For example, in 1905 the American artist A.H. Munsell devised a method for expressing colors, which utilized a great number of paper color chips classified according to their hue (Munsell Hue), lightness (Munsell Value), and saturation (Munsell Chroma) for visual comparison with a specimen color. After a variety of further experiments, this system was then updated to create the Munsell Renotation System, which is the Munsell system presently in use. In this system, any given color is expressed as a letter/number combination (H V/C) in terms of its hue (H), value (V), and chroma (C) as visually evaluated using the Munsell Color Charts. Other methods for expressing color numerically were developed by an international organization concerned with light and color, the Commission Internationale de I'Eclairage (CIE). The two most widely known of the these methods are the Yxy color space, devised in 1931 based on the tristimulus values XYZ defined by CIE, and the L*a*b* color space, devised in 1976 to provide more uniform color differences in relation to visual differences. These color spaces are now used throughout the world for color communication. Methodology for measuring color is usually classified into three groups: densitometry, colorimetry, and spectrophotometry.[23-25]

2.5.2 Stiffness

Yarn stiffness is related to fiber stiffness. It is not possible to make a flexible yarn from an inflexible fiber. Moreover, the way in which fibers are combined in the yarn will affect yarn flexibility. It is easy to see that more tightly twisted yarns, in which fibers have less freedom of movement, will be less flexible. The most flexible yarn of all should be one in which the filament fibers are combined with little or no twist. The least flexible yarns should be those in which the fibers are boned together by an adhesive or fused by heat or chemical means. An excellent example of this principle can be seen after a heavily-sized fabric with a water-soluble sizing has been laundered. The fabric after laundering will be much softer and more flexible when the sizing that has held the fibers together has been removed.

Stiffness is the ability of a material to resist deformation. In the case of a yarns subjected to a tensile force or pull, stiffness is the ability to resist elongation. The units for stiffness are grams per denier per unit elongation.

Stiffness embodies the combined effect of molecular weight, the natural rigidity of cellulosic chains, the degree of crystallinity brought about by hydrogen bonding and van der Waals forces, and the orientation of the cellulose chains with respect to the axis of the fiber. The correlation coefficients of birefringence and spiral angle with stiffness as reported by Rebenfeld and Virigin[27] were 0.45 and 0.65, which denotes that orientation of cellulose chains is an important factor influencing stiffness. It could, therefore, be concluded that the higher the birefringence, the stronger, tougher, and stiffer the fibers.

Average stiffness is the stiffness of a material from its original state to breaking point. It is the ratio of the unit breaking stress to unit breaking strain, and thus indicates the average stress for the entire range of extensibility of the material per unit increase in strain. Average stiffness is an indicator of the general character of a material with regard to the stiffness quality.

The flexural rigidity or stiffness of fabrics relates to their overall mechanical integrity and comfort. Test methods and fundamental studies have focused on the mechanics of bending, stiffness and the measurement and prediction of fabric drape.[26-28]

2.5.3 Colorfastness

The colorfastness of fabrics to a variety of substances and conditions can be measured by the use of a wide variety of specifics testing methods and machinery.[22] Some fabrics lose color through crocking, or rubbing against another fabric. Some fabrics crock when dry, some when wet, and some when both dry and wet.

Machines have been devised to test fastness to rubbing, or "crocking", but a simple test is to rub the fabric with a piece of white fabric wrapped around the finger, first with the white fabric dry and then with it when wet. If the surface color is not fast to rubbing, it will stain the white fabric.[29]

A laboratory device called a Crockmeter can be used for testing for crocking works on the same principle as the home test, by rubbing a white fabric sample across the fabric to be tested.

2.5.4 Air permeability

Comfortable garment textiles should breathe and the benchmark for this characteristic is air permeability. Poor air permeability and smooth surface structure gave the first synthetic fiber a negative image. Today, microfiber fabrics and/or with a loop structure have sufficient air permeability to ensure wearer comfort. Air permeability depends on the yarn and fabric structure as well as finishing.[30]

Air permeability is the ability of air to pass through a fabric. Obviously, where openings between yarns or between fibers within yarns are large, a good deal of air will pass through the fabric. Contrariwise, where compact yarn are packed tightly into fabrics with little airspace between them, the flow of air through the fabric is diminished.

Some finishes for fabrics such as curing of thermoplastic fabrics decrease air permeability by causing fibers and yarns to fuse slightly. Fabrics may be coated with another material that closes up interstices in the fabric. To make garments warm enough for sports such as skiing in which moving air may cool the athlete, a fabric with low air permeability (such as closely woven nylon) may be combined with materials of low thermal conductivity (such as polyester or acrylic fiberfill or with pile fabrics) that trap air close to the body.[31]

Review of Past Literature

The traditional screen printing uses a master for printing, whereas the digital printing is designated by the computer driving the printheads and has ability to change designs quickly. The pigmented inkjet ink eliminated the wet post processing thus promises low cost of both materials and processes compared to dyes. Nevertheless, the inkjet has very low viscosity, bleeding and wicking properties take place when printing on textile. The pigmented textile inkjet printing has been advanced for agile manufacturing and distributed printing in the future.[32]

The ink droplet is ejected through the nozzle orifice onto the fabric surface, its low viscosity liquid is liable to spread laterally by capillaries effect, i.e., wicking/threading tendency, if the substrate is not pretreated with a thickener/antimigration agent. Printing with dyes requires after-treatment or post-treatment of steaming (100-180°C water vapor), washing, or reduction cleaning (for disperse dyes) to render well-fixed bright colors. It would be the textile industry's most preference to avoid the after-treatment and even pretreatment, i.e., the application of pigmented inks and sublimation printing. However, the pretreatment on fabrics before being printed is still necessary to prevent the entry of ink liquid to the capillary spaces and to increase the availability of surface area for the drops rapidly permeating into the fabric. As a result, the low print-through and high-color intensity are recognized as good print quality with good line definition and no color interference.[33]

Textile applications, speed, quality and appearance in inkjet printed products controlled to a substantial extent by the drop formation characteristics of the system were investigated.[34] Drop size, placement accuracy and substrate coverage are important factors controlled by the compatibility of the inkjet printer, ink and substrate. Dot placement accuracy, of course, affects print quality. Misplacement of adjacent drops may cause ragged edges, void and loss of optical density. The impression of color value is another important aspect of print quality. Whiteness of substrate, definition of character edges, drop uniformity and spatter combined with optical density produce the perceived color value patterns.

The development of low-viscosity inkjet ink to meet the required properties for the printed fabric by inkjet a mixture of monomer and oligomers that can be post polymerized on the fabric, was carried out by Tincher et al.[35] Some properties of the fabric printed with the experimental formulation compared to rotary screen printed fabric. Although the fabric weights and the pick-ups were not identical, the difference in properties before and after printing at least suggest that the inkjet printed fabric showed comparable properties to the conventionally printed fabric.

The research work of Tse and Briggs[36] focused measuring methods for print quality of digitally printed textile. It is found that visual quality of the inkjet printed cotton fabrics was as good as that printed plain paper. The effects of several key fabric properties on print quality were studied. These key properties studied include fabric structure, yarn size, yarn type and fabric pretreatment. The test results suggested that the most significant fabric variables are fabric structure, yarn size and the hydrophilic/hydrophobic nature of the fabric.

The development of inkjet colorant made from polymer emulsion containing water insoluble dye or pigment. Emulsion-containing pigment showed good rub resistance compared with the conventional pigment dispersion, and this could be applicable to high-durable printing material.[37]

Comparing the inkjet printing of textile compared with conventional screen printing, the systems impose some limitations in the number and gamut of shades that must be achieved, in fabric preparation, productivity, and cost. The underlying principles of the formation of the colored pixels, which make up the printed designs using an inkjet printer, have been studied both at the microscopic level and colorimetrical points. The insight reasons for using of inkjet printing system for textile are to help overcome misunderstanding between designers, specifiers and the their customers.[38]

Basically, the water-based inkjet ink for textile application performs in a similar manner to traditional textile screen ink. Through the technology, it is necessary to balance the chemistries of emulsion, pigment and thickening reagent. Adaptation of these factors to inkjet application necessitates reduced viscosity, stability considerations, small particle size, and the ability to adjust surface tension as required, should be less than 35 mN m^{-1}. The acrylic emulsion copolymer with some cross-linker improved wet/dry crockfastness as well as wash resistance. The acrylic copolymer with a Tg near –10 °C appearred to be best for a good balance between stiffness and crockfastness.[39]

Effects of the binder system on the various kinds of the textile fibers such as cotton, polyester, cotton/polyester blend and silk were studied.[40]. The effective binders were of emulsion type, which were NK A12, NK M302, Vanatex S711, and UA150. The NK A12, NK M302, Vanatex S711 are acrylic resins, while the UA150 is a polyurethane type. It was found that the polymeric binders in the form emulsion used as the aqueous-based inkjet inks containing a hydrophilic property and having a good mechanical stability could give smooth ejection and ejection stability of the ink on all fabrics. The hydrophilic/hydrophobic properties of the fabrics affect the print qualities. The ink penetration into the fabrics controls the stiffness of the printed fabrics. The deep penetration of the ink into the fabrics gives the printed fabrics high stiffness. The top surface of the hydrophilic fabrics would, of course, localize the ink. The hydrophilic fabric yielded the lower crockfastness than that of the hydrophobic polyester. Sapchookul[41] studied the effect of pigment/binder ratio produced by various pigment dispersion techniques on the ink property and the cotton printing. The four different pigment-based inks were prepared which pigment dispersions were polymer dispersion, surfactant dispersion, micro-encapsulation, and surface modification. Different ratios of pigment-to-binder (P/B) at 1/0.5, 1/1 and 1/2 were also investigated. Increasing binder content is one the effective parameters to influence viscosity and the optimum color gamut, color gamut volume and crockfastness as found in the pigmented inkjet ink with 1/2 P/B ratio. Poly(ethylene oxide) as a pretraetment reagent deposited on the fabric surface and occupied the inter-fiber spaces produced a smooth surface, which contributed to better air permeability and bending length of the printed fabrics.