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Effects of Printhouse Humidity and Temperature on Quality of Ink Jet Printed Cotton, Silk, and Nylon Fabrics

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Abstract. *The effects of printhouse humidity and temperature on shade depths of three typical colors, black, blue, and yellow, are investigated. Cotton, silk, and nylon 6,6 fabrics were used for this study with reactive, acid, and acid dye inks, respectively. Our study found that a change of 10% relative humidity or* 10 °C *could cause 20% or even more differences in shade depths, although all the other printing conditions were the same. The mechanisms for the variations in shade depths with humidity and temperature are proposed and the possible approaches in minimizing shade variations are recommended. © 2006 Society for Imaging Science and Technology.*
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INTRODUCTION

Based on our knowledge, the earliest textile jet printing concept was filed for U.S. patent on February 8, 1965 by Weber et al. and was granted on May 13, 1969.[1,2] Textile jet printing technology has been available at Milliken and Co. since 1970s.[3] Textile applications of ink jet printing using digital technology similar to paper ink jet printing with high definition attracted much attention since 1980s.[4,5] Although the technology is not new, the researches on ink jet printing still are mainly disclosed in patents.

Textile ink jet printing technology could be roughly separated into four major components: machinery, inks, fabrics, and printing processes. Current efforts are mainly on machinery improvement and ink formulations. Examples of these efforts are machine speed, printing precision and ink delivery.[6–10] Research on the effects of fabric structures and printing auxiliary chemicals on printing quality is also reported.[11–19] Very few endeavors are on print processing conditions and their effects on the quality of the printed goods.

A common problem, that many printers have experienced, of ink jet printing is the reproducibility of shades. Using the same machine, inks, fabrics, and auxiliary chemicals frequently one cannot reproduce the shades. Based on our experience, a $\Delta E(\mathrm{Lab})^*$ or a $\Delta E_{\mathrm{CMC}(2:1)}$ of larger than 2 was common when attempts were made to reproduce the same prints. In a world where the acceptance of a shade variation of $\Delta E(\mathrm{Lab})^*$ or a $\Delta E_{\mathrm{CMC}(2:1)} < 1$ is still questionable to many of our customers, such large and frequently occurring shade variations from ink jet printed goods is certainly a worthy issue to be investigated.

In a previous study, we reported the effect of steaming conditions on shade reproducibility.[20] In that study, it was demonstrated that steaming time and temperature both affected color yield substantially. In addition, if steaming was performed in a batch steamer, either atmospheric or pressurized, the position of the fabric in a roll and in the steamer also caused notable changes of shades of the steamed fabrics. In this paper, we explore the effect of printhouse conditions, temperature, and humidity, on shade reproducibility.

The effects of printhouse humidity and temperature on shade depths of three typical colors, black, blue, and yellow, are investigated. Cotton, silk, and nylon 6,6 fabrics were used for this study with reactive, acid, and acid dye inks, respectively. The mechanisms for the variations in shade depths with humidity and temperature are proposed and the possible approaches in minimizing shade variations are recommended.

MATERIALS

Fabrics for this study included: (1) style 419W cotton broadcloth, bleached, and mercerized, and Style 419W PRE, the same fabric as style 419W with a pretreatment for reactive dye inkjet printing, (2) style 609 silk Habutae, and style 609 PRE-ACID, same fabric with a pretreatment for acid dye ink jet printing, and (3) style 338 nylon-6,6 filament oxford, and style 338 PRE-ACID, the same fabric with a pretreatment for acid dye ink jet printing, The fabrics were obtained from Test Fabrics Inc. Seven reactive dye based inks (black, turquoise, blue, red, orange, golden yellow, and yellow) for cotton printing and seven acid dye based inks (black, turquoise, blue, red, orange, yellow, and grey) for silk and nylon printing were kindly supplied by Ciba Specialty Chemicals Inc. American Association of Textile Chemists and Colorists (AATCC) 1993 Standard Reference Detergent without optical brightener was used to wash the steamed fabrics.[21] An ink jet steaming paper from Jacquard Company was used as wrapping paper for steaming.

EQUIPMENT

The ink jet printer used for this study was the Mimaki Textile Jet TX-1600S, a piezo electric drop-on-demand (DOD) machine with seven refillable color cartridges. Steamjet Fab-

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ric Finisher from Jacquard Company, a high temperature steamer that is equipped with electronic time and temperature controls and also with an angled loading arrangement, was used for steaming. The Kenmore Heavy Duty 70 series washer was used to wash the fabric samples. An UltraScan® XE spectrophotometer from HunterLab was used to measure the shade depth (K/S value) of steamed fabrics. A Chromalox Environmental Conditioning Chamber and a standard conditioning room, together with Holmes model HM 3650 Humidifiers, Whirlpool Dehumidifiers and hotplates were used for the control of humidity and temperature.

METHODS

Conditioning

Fabrics were stored in a dark room in order to avoid any shade variations by light exposure. Before printing, a fabric was conditioned in the conditioning chamber at the testing temperature and humidity for 24 h. The printing was performed in a conditioning room at the same temperature and humidity as the conditioning chamber, with a variation of temperature of ±1 °C, and relative humidity (RH) of ±2%. Six levels of RH (from 35% to 85% RH with a 10% increment) and two temperatures (20 and 30 °C) were evaluated. At 30 °C and 85% RH, ink spread at the surface of the fabrics so much that the quality of the printed fabrics was not acceptable. Therefore, only five RH levels, from 35% to 75% were examined at 30 °C.

Printing

The fabrics were printed with three typical colors: blue ($R=0$, $G=0$, $B=255$ or $C=88\%$, $M=77\%$, $Y=0\%$, and $K=0\%$), yellow ($R=255$, $G=255$, $B=0$ or $C=6\%$, $Y=97\%$, $M=0\%$, and $K=0\%$) and black ($R=0$, $G=0$, $B=0$ or $C=75\%$, $M=68\%$, $Y=67\%$, and $K=90\%$). These three colors were produced by a set of seven inks for both the reactive and acid dye printings. After printing, the fabrics stayed under the same environment as for printing, i.e., same temperature and humidity, for 1 h before steaming. This is to simulate the real ink jet printing conditions, where a fabric takes at least an hour to be printed.

Steaming

Cotton fabrics were steamed at 101.7 °C for 10 min while silk and nylon were steamed at 104.4 °C for 15 min. The steaming conditions were selected based on the shade reproducibility and color yield.[20] The printed fabric was rolled in the middle of ten layers of steaming paper before steaming to assure the quality of the final product.[20]

Washing and Drying

After steaming, samples were washed according to AATCC Test Method 124 with washing condition $1-v$ (60±3 °C for 12 min).[21] Then the samples were air dried and conditioned under standard conditions of 21±1 °C and 65±1% RH in the darkness before being evaluated for their shade depth.

Shade Depth Measurement

Samples were evaluated for their shade depths (K/S values) at the wavelength of the maximum absorbance by a Hunterlab Spectrophotometer. Each sample was evaluated three times for its shade depth value (in three directions: warp, filling, and bias) and an average value was taken as the reading for that sample.

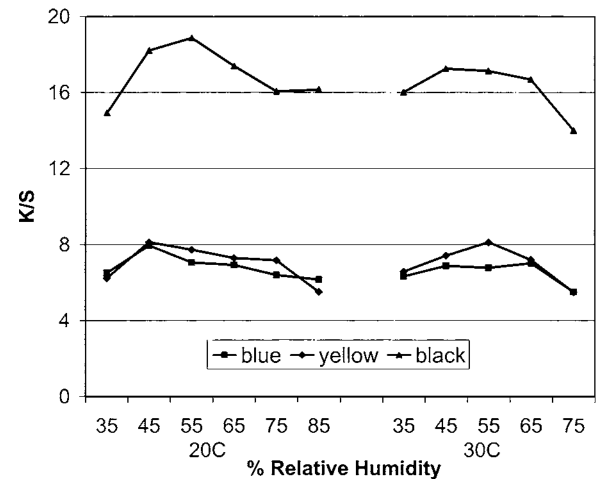

Figure 1. Effect of humidity and temperature on shade depths (K/S) of cotton fabrics printed with reactive dye inks.

Moisture Regain Measurement

Moisture regains of the cotton, silk, and nylon fabrics, with and without ink jet pretreatment, were measured according to ASTM D2654-89a at 35%, 55%, and 75% RH, and 20 and 30 °C, respectively.

Statistics

Four replicas were used for each of the conditions and an average was reported. Each of these replicas was sampled from different warp and filling yarns according to standard fabric sampling.

For the study on shade variations with humidity changes, percent coefficient of variation, $\%CV$, was calculated and reported as shown in Eq. (1),

$$\%CV = \frac{S}{\bar{X}} \times 100, \tag{1}$$

where S is the standard deviation of all the K/S values from different RH values of a specific fabric with a specific color at a specific temperature, and $\bar{X}$ is the mean of these K/S values.

RESULTS AND DISCUSSION

The effect of printhouse humidity and temperature on shade depths (K/S) of ink jet printed cotton with reactive dye inks and silk and nylon-6,6 with acid dye inks are depicted in Figs. 1–3, respectively. As shown, both temperature and humidity affected the shade depth of printed fabrics. A variation of 10% RH or 10 °C in temperature could cause a visible color difference of the printed fabrics, although all other printing conditions were unchanged. Generally, a 5% difference in K/S value represents a visible color difference. The results in Fig. 1–3 demonstrated that a 20% difference in K/S values was common for cotton, silk, and nylon prints

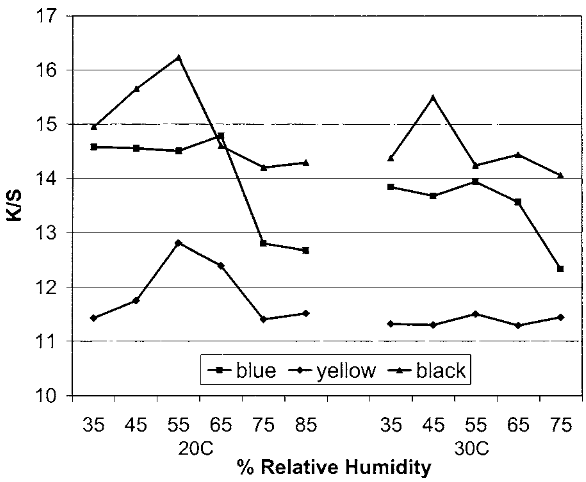

Figure 2. Effect of humidity and temperature on shade depths (K/S) of silk fabrics printed with acid dye inks.

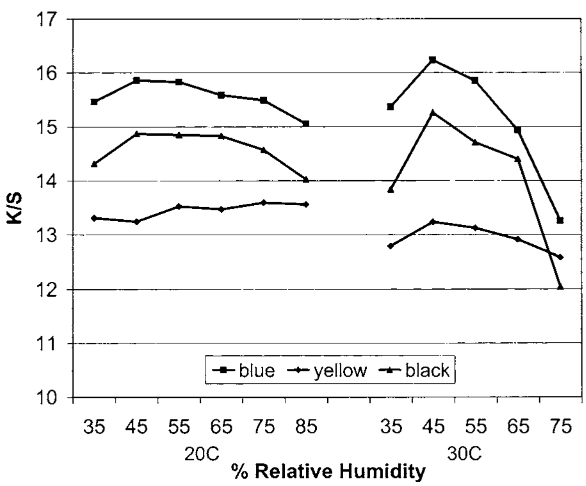

Figure 3. Effect of humidity and temperature on shade depths (K/S) of nylon fabrics printed with acid dye inks.

when the RH values changed 10%. Changing temperature from 20 C to 30 °C did not have as much of an effect on shade variations as changing humidity, especially for cotton and silk, but a K/S difference of 10% was still frequently observed for all the colors and fabrics.

Results in Figs. 1–3 also show that there is a maximum K/S value for each of the prints when humidity changes. In most cases, it was either at 45% and 55% RH. The shapes of most conditions in the figures also displayed that there were smaller changes of K/S values with changes of humidity when RH was near 55%, indicating an appropriate printing humidity at 55% for better color yield and color reproducibility. A broad RH range between 45% and 65% may also be appropriate for selection. Within the range of 45–65% RH, a variation of ±2% in RH probably will not cause a visible shade variation. The selection of RH below 45% or above 65% might cause visible shade differences even if only a slight variation of humidity occurred in the printhouse.

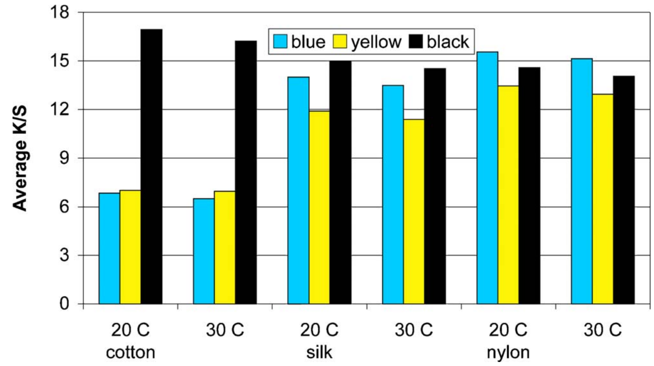

Figure 4. Average shade depths (K/S) of fabrics printed at different relative humidity values at 20 ° and 30 °C, respectively.

When RH was above 65%, we also observed substantial increase in dye migration to the white areas causing decreased boundary clarity and poor quality of fine printing structures.

Shade variations observed in Figs. 1–3 were possibly caused by either the variation in ink delivery from the jets to the fabric or the distribution of inks in the fabric due to the changes in temperature and humidity. If changing humidity changes ink delivery, a continuous increase or decrease in K/S of printed fabrics with increasing humidity should be expected. The observation of a maximum K/S value for most curves in Figs. 1–3 excluded the possibility of ink delivery variations caused by humidity. The possibility of variations in ink delivery caused by temperature changes is also excluded because if temperature has influenced ink delivery, there would have been K/S differences between prints from different temperatures. Averages of the K/S values of each of the curves in Figs. 1–3 were calculated and compared in Fig. 4. As shown, the average K/S values were very similar between 20 and 30 °C for all the inks and fabrics investigated, therefore, temperature did not affect ink delivery.

Since both humidity and temperature did not cause the changes in ink delivery, the reason for shade variations with humidity and temperature is possibly due to the variations in dye distributions onto and into a fabric. Humidity and temperature both can change dye distribution in a fabric, and therefore, change the K/S values.

It is broadly accepted that color yield, i.e., K/S, for a given weight of ink per unit area, increases with decreasing dye penetration into the fabric in printing.[22] However, it is also well documented with experimental results and mathematical calculations that fibers with good dye penetration, e.g., evenly dyed fibers, look darker than fibers with poor dye penetration, e.g., ring dyed fibers, when both fibers were colored with the same quantity of dyes.[23–26] What these statements tell us is that, for printing, even though we want the colorants to stay on the surface of the fabric, certain penetration of the colorants into the fibers, especially those at the top surface of the fabric, improves the shade depth of the prints.

Unlike conventional printing where colorants mainly stay in the printing pastes on the surface of the printed

Table I. Percent of moisture regain of the ink jet pretreated fabrics comparing to their original fabrics without ink jet pretreatment at 35%, 55%, and 75% RH, and 20 ° and 30 °C.

	% Moisture regain		
	35% RH	55% RH	75% RH
Fabrics	20 °C/30 °C	20 °C/30 °C	20 °C/30 °C
Cotton, original	6.0/5.0	6.9/5.9	8.5/7.3
Cotton, pretreated	17.6/16.3	21.0/18.7	31.5/30.9
Silk, original	10.1/9.0	11.1/9.9	12.8/12.2
Silk, pretreated	14.2/13.5	15.8/14.5	21.1/20.6
Nylon, original	2.6/2.5	3.2/2.9	4.0/3.6
Nylon, pretreated	3.0/2.7	3.6/3.1	4.4/4.0

Table II. Percent of K/S increase of the fabrics steamed immediately after printing over these with 1 h duration between printing and steaming. The fabrics were printed with black color at 35% RH and 20 °C. Total printing time was 10 min.

Fabric	% K/S increase
Cotton	4.8
Silk	2.1
Nylon	0.2

fabrics before steaming, colorants in ink jet printing are distributed onto and into fabrics immediately after the jets deliver the liquid inks onto fabric surface. This is because of the very low viscosity of inks and the even distribution of thickeners inside the fabric. Thickeners and other auxiliary chemicals in the printing paste (T&A) in ink jet printing are not applied to the face of the fabric during printing as in conventional printing, but are padded into the fabric during fabric pretreatment[11–13] and are dried before printing.

The effects of pretreatment chemicals, relative humidity and temperature on moisture regain of all three fabrics are presented in Table I. When humidity is low, the fabric is dry and a large quantity of dyes is sorbed by the top surface of the fabric face. Due to the very thin layer of T&A coated on the fiber surface, much of the dyes penetrated through the thin film of T&A and was sorbed by the surface of the fibers at the face of the fabric, although some of the dyes were sorbed by other fibers in the fabric. Also, due to the very slow printing process, usually several hours before steaming, a major portion of the dyes already has very strong interactions with the fibers at the top of the fabric face before steaming. For reactive dyes, they may have formed covalent bonds with cellulose; for acid dyes, the negatively charged dyes may have moved to the positive functional groups of the fiber and be relaxed to very low energy levels. Although steaming will cause further dye penetration, the sorption of dye molecules onto fiber surface due to the long dwell time between printing and steaming limits the dye penetration in steaming. The lack of dye penetration results in low K/S values at low humidity, similar to the low K/S values from the ring dyed fabrics.[23–26] To demonstrate the effect of dwell time in printing on shade depth of the fabric at low humidity, fabrics printed with the black color at 35% RH and 20 °C were steamed immediately after printing. The shade depth of the fabrics were compared with that of the fabrics stored for 1 h, and the percent increases in shade depth of the fabric with immediate steaming are presented in Table II.

The increase in shade depth from immediate steaming compared to that from delayed steaming supported the explanation that long printing time contributed to the sensitivity of ink jet printing to humidity and temperature variations.

Increasing humidity increases the moisture content in a fabric. Therefore, the solvent in the ink will not be completely absorbed by the very top surface of the fabric. Instead, the liquid ink will move into the fibers for better dye penetration. This was probably the reason for the increased K/S values with increasing relative humidity from 35% to 55%. A further increase in humidity results in wet or even filled capillaries within and between fibers and yarns. Because of the hygroscopic nature of T&A, the pretreated ink jet printing fabrics have much higher moisture regains than the untreated fabrics as shown in Table I. When inks are delivered onto a relatively wet fabric, they migrate to different places in the fabric along the capillaries. Such migration was observed during ink jet printing when humidity was high. Dyes were migrated to the middle or even back of the fabric and to the white areas across the edges of the patterns. Similar to conventional textile printing, dye migration thus resulted in decreased K/S values[22] as depicted in Figs. 1–3 when relative humidity was above 65%.

The sensitivity of shade depths to humidity and temperature in the printhouse could be accessed by the %CV values of K/S variations from each of the K/S-% relative humidity curves in Figs. 1–3. The comparisons of the %CV values due to humidity changes are illustrated in Fig. 5. The larger the %CV value, the higher the sensitivity of shade depths to humidity or temperature changes.

Comparing the %CV among all three fabrics at 20 °C, the shade depths of cotton printed with reactive dyes had the largest %CV values while that of nylon had the smallest. This result indicated that cotton-reactive dye ink jet printing had the highest sensitivity of its shade depth to humidity changes and nylon-acid dye ink jet printing had the least. Since the variations in shade depths are caused by the differences in dye penetrations, which, as discussed, are determined by the moisture content of the fabric matrices at different RH values, the shade depths of nylon should be least sensitive to humidity due to its low hydrophilicity, as shown in Table I. The extremely low sensitivity of K/S values of nylon to humidity is also due to the very limited dye accessible pores in nylon at 20 °C. Dyes were mainly retained at the fiber surface until the fabric was steamed, regardless of

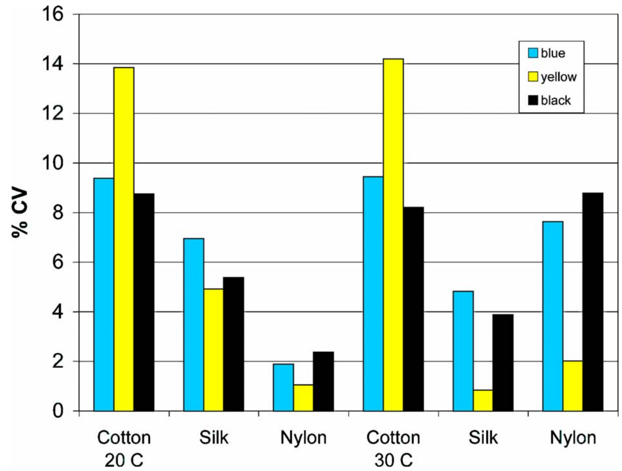

Figure 5. Percent coefficient of variation (%*CV*) of shade depths (*K*/*S*) of fabrics printed at different relative humidity values.

the humidity changes. The highest sensitivity of cotton with reactive dye inks to humidity is probably due to the very high sensitivity of the moisture sorption of the fabric to humidity changes. As shown in Table I, the percent of moisture regain of pretreated cotton increased almost 79% when RH increased from 35 to 75% at 20 °C, the largest increase among all three fabrics studied.

One possibility of the high sensitivity to humidity of shade depth of ink jet printed fabrics is the distribution of T&A in the fabrics due to padding in fabric pretreatment. The existence of T&A in the fibers, between the fibers and between the yarns of the whole fabric, results in a much different dye distribution inside the fabric than the distribution of dyes in conventional textile printing. Such dye distribution, due to the hygroscopic nature of T&A, varies with humidity. A possible method of diminishing the sensitivity of shade depth to humidity is to coat, instead of pad, the T&A onto the surface of the fabric in the pretreatment process. This way, the ink will mainly stay on the surface of instead of penetrating into a fabric, therefore, the dye penetration may mainly be controlled by the steaming conditions with less influence by the humidity changes in the printhouse.

The effect of temperature on the sensitivity of shade depths to humidity is also depicted in Fig. 5. As shown, temperature had the least effect on reactive printing. Increasing printhouse temperature increases dye penetration, which, therefore, should decrease shade variations with humidity. Increasing temperature decreased moisture regain of cotton fabric slightly (Table I), but since temperature affected moisture regain at all three RH similarly, it should not affect shade variations. However, increasing temperature also increases dye reaction with cellulose, and thus decreases dye penetration. The combination of these two opposite effects might result in unchanged sensitivity of shade variation to humidity for reactive dye ink jet printing between 20 and 30 °C.

For silk printing with acid dye inks, increasing printhouse temperature increases dye penetration. A better dye penetration at higher temperature decreases the difference in dye penetration caused by humidity variations. Therefore, shade variations with humidity decreased when the temperature of the printhouse was increased from 20 to 30 °C as shown in Fig. 5. This result suggests that having a relatively high printhouse temperature is probably better for the minimization of shade variations caused by humidity changes in silk ink jet printing with acid dyes.

The effect of temperature on shade variations of nylon with humidity was opposite to that of silk, although both were printed with the same acid dye inks. This was probably due to the thermoplastic and hydrophobic nature of nylon. At 20 °C, there were very limited dye accessible pores in nylon even at high humidity. Most of the dyes were only on the top surface of the fabric without penetration, until the fabric was steamed. Steaming started the dye penetration, at least the penetration of the majority of the dyes. Therefore, humidity did not affect shade depths of nylon as much as it did cotton and silk at 20 °C. At 30 °C, nylon is more easily to swell with water than at 20 °C. When humidity increased, the accessibility of nylon to acid dyes increased, therefore dye penetration increased. This was probably the reason that the similar pattern of shade changes with humidity for cotton (Fig. 1) and silk (Fig. 2) at both temperatures was observed for nylon only at 30 °C (Fig. 3) but not at 20 °C. The increase in the sensitivity of shade variation of nylon to humidity with increasing temperature suggests that a low printhouse temperature is better for shade control of nylon.

CONCLUSIONS

Both temperature and humidity affected the shade depth of ink jet printed fabrics. A variation of 10% in relative humidity or 10 °C in temperature could cause a substantial color difference of the printed fabrics, although all other printing conditions were unchanged. A 20% difference in *K*/*S* values was common for cotton, silk, and nylon prints when the relative humidity in the printhouse changed 10%. Changing temperature from 20 to 30 °C did not have as much an effect on shade variations as changing humidity, especially for cotton and silk, but a *K*/*S* difference of 10% was still frequently observed for all the colors and fabrics. The changes in shade depths with temperature and humidity are probably owing to the differences in dye penetrations into the fabrics caused by the changes in temperature and humidity.

Ink jet printing at 45% to 55% relative humidity provided relatively high shade depths with low shade variations with variations in humidity. Comparing all three fabrics examined, shade depths of cotton with reactive dye inks was most sensitive to humidity, followed by silk and then nylon. Printhouse temperature did not affect shade depths of cotton with reactive dye inks as much as silk and nylon with acid dye inks. For silk printing, increasing temperature decreased shade variations with humidity; for nylon printing, increasing temperature increased shade variations with humidity.

For cotton printing with reactive dye inks, the strict control of printhouse humidity is necessary for shade consistency and reproduction. For silk and nylon printing with acid dye inks, the variation in shade depths with humidity may be minimized by selecting the appropriate printhouse temperatures. A relatively high temperature for silk printing, e.g., 30 °C and a relatively low temperature for nylon printing, e.g., 20 °C, are able to decrease the variations in shade depths caused by humidity differences in the printhouse. The sensitivity of the shade depth of silk and nylon with acid dye inks to temperature suggest that a good control of printhouse temperature is necessary for shade consistency and reproduction.

The more migration of the dyes to the back and edge of the printed fabrics than with conventional printing suggested that padding the hygroscopic thickeners and other printing auxiliaries evenly into the fabric before printing may contribute to the sensitivity of shade depth to humidity of the printhouse. Changing the current pretreatment process from padding to surface coating may decrease the sensitivity of shade depth to humidity changes, and therefore improve the shade reproducibility of ink jet printing.

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