Correlation between Drying Time and Ink Jet Print Quality Parameters

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Abstract

Two major mechanisms by which Thermal Ink Jet images are dried in current printers are "absorptive drying" and "evaporative drying". In absorptive drying, ink penetrates the paper due primarily to capillary forces, while in evaporative drying, methods are employed for removing moisture from the surface of the paper.

This paper presents experimental data which suggest that certain techniques and methods for drying ink jet images could help preserve print quality. First, data is presented on a novel technique for correlating drying time with ink and paper properties, and with print quality parameters. Second, an experimental method for measuring drying effectiveness is described. Drying time and drying effectiveness both refer to drying to the point of no image offset.

Measured data indicates that although the mechanisms which control drying are not driven predominantly by diffusion phenomena, a measurable quantity which resembles a diffusion coefficient could be employed for relating drying time to ink and paper properties, and to print quality.

Introduction

In Ink Jet Printing, the usual method for drying aqueous ink images is to let the ink droplets penetrate the paper, and drying is achieved under ambient conditions. At low throughput speeds less than 5 prints per minute, this method of "inactive drying" is a reasonable drying approach. At higher throughput speeds, the moisture should be removed from the surface of the paper as soon as possible in order to prevent image smear or offset. The mechanisms involved in drying ink jet images, and the problems which accompany rapid drying of ink jet images have been discussed in previous papers[1-3]. With absorptive drying, throughput speeds can be increased by printing on coated papers. The present study deals only with plain papers.

The present paper presents experimental data on drying effectiveness, or the minimum time required for no image offset, as function of (a) print quality parameters, (b) measurable coefficients which resemble diffusion coefficients in a phenomenological sense, (c) ink and paper properties, image feathering due to ink droplet spreading and wicking, and (d) paper deformation due to moisture and thermal gradients induced in paper during drying.

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Drying Methods

Absorptive Drying

In absorptive drying, ink droplets are given enough time (drying time) to penetrate the paper before the printed image comes in contact with any other surfaces. Effective drying does not mean that all moisture is removed from the paper. Rather, the ink droplets are allowed to penetrate the paper to a sufficient degree so that image smear or offset does not become an issue.

The main mechanism by which drying occurs is by capillary movement of ink droplets into the pores of the paper, and the absorption of liquid into paper fibers. The problems which accompany this mode of drying are (a) paper fibers swell and deform the paper, (b) ink droplets spread and wick on the surface of the sheet due to the random distribution of pores and grooves on the surface of the paper, resulting in image feathering.

The extent to which these problems occur will depend to a great extent on ink and paper properties. Some of the important properties are ink viscosity and surface tension, paper surface roughness and surface finish, and paper fiber properties[1,2]. Since these properties depend on temperature, absorptive drying depends also on ambient temperature.

Absorptive drying rates differ significantly, depending on paper properties. Unsized, uncoated papers have short absorptive drying times, while conventional coated, or highly sized papers have long absorptive drying times. Absorptive drying rates also depends on ink properties. For example, low surface tension inks or inks with surfactants will penetrate and spread more readily on paper.

One measurable parameter which is often used to characterize rates of ink penetration into paper is diffusion coefficient, which is measured by Bristow's technique[5,6]. This parameter is obtained by applying a Fickian diffusion model to describe ink penetration into paper in a phenomenological sense. The primary mechanism for driving ink into paper is due to capillary forces. The mechanism is not a diffusion process.

One other effect to be considered is paper deformation due to ink jet printing[3]. The release of internal stresses[4] due to ink penetration creates paper deformation in the form of cockle and curl.

Evaporative Drying

This mode of drying becomes a preferred method when drying should be accomplished within a relatively short time in order to cope with the throughput rates of the ink jet printer. In low throughput printing, air flow over the paper surface under ambient conditions provides the moisture removal mechanism. For enhanced drying, forced hot air flow over the paper surface provides higher mass transfer rates. Other enhancements may be provided by drying at elevated temperatures and by using hot air impingement. These enhancements provide a more efficient method of removing the moisture boundary layer.

In purely evaporative drying (constant rate drying), an aqueous film of ink resides on the surface of the paper. In the moisture boundary layer, the ink film is at saturation vapor pressure and wet bulb temperature, so the drying rate is constant.

In practice, purely evaporative drying is difficult to obtain because ink penetrates paper while evaporation of ink from the paper surface is occurring. Drying to the point of no offset may require that drying continues after the moisture front recedes below the surface of the paper (drying in the falling rate period). Enhanced drying at elevated temperatures will magnify paper deformation. It is usual practice to restrain the paper during drying in order to minimize cockle and curl.

Both absorptive and evaporative drying depend on the drying load, that is, to the minimum amount of ink to be removed for effective drying (no offset). The drying load depends on ink coverage density (the mass of ink per unit surface area). Ink coverage density is a function of the print resolution, spots per inch and required solid area density.

Drying Equations

Although the mechanism for ink penetration into paper is due to capillary forces, most analyses suggest that a diffusion approach yields reasonable results.

In the drying equations given below, it is assumed that moisture flux may exist in the frozen, liquid and gas states (Subscripts 2 and 3 will be used to refer to liquid and gas states respectively).

One set of equations which may be utilized are the following[7]:

For mass transfer

$$\frac{\partial X}{\partial t} = De\nabla^2 X + De\delta\nabla^2 T \qquad (1)$$

and for heat transfer

$$\frac{\partial T}{\partial t} = \alpha\nabla^2 T + \frac{\Delta H_{23}}{C_p}\frac{\partial X_2}{\partial t} \qquad (2)$$

where ΔH_{23} = enthalpy difference for a change between the condensed and vapor states,

- α = κ/Cp , thermal diffusivity, with
- κ = thermal conductivity and
- Cp = mean heat capacity of the moist paper,
- De = $D_2 + D_3$, effective moisture diffusion coefficient with D_2 and D_3 = diffusivity in liquid and vapor phases respectively,
- δ = thermal gradient coefficient, which is a measure of the rate at which moisture is conveyed due to thermal gradients.
- X = mass of moisture per unit mass of bone dry paper
- T = temperature
- t = time.

Other forms of these equations, which provide other enhancements, have been published[8,9].

Experimental Data

Measurement of Drying Time

A novel technique for measuring Drying Time relates image offset to Optical Density. At a predetermined time after an image has been printed, it is sandwiched between an unprinted sheet of paper in the nip of a pair of transport rollers. The nip force is chosen to simulate the maximum force which could cause image offset in the printer. Image offset onto the unprinted sheet represents the amount of free ink on the surface of the sheet at the instant the image enters the nip.

The optical density of the image is related to offset, therefore the dimensionless density parameter defined in equation (1) has been determined to be a good metric for defining Drying Time[2].

$$\phi = (D_0 - Doff)/D_0 \qquad (3)$$

where D_0 = optical density of printed image
$Doff$ = optical density of image offset.

It has been found experimentally that when this parameter, ϕ, exceeds 0.95 (or when $1 - \phi$ falls below 0.05), then adequate drying has been accomplished. Adequate drying means drying to the point of no offset.

Drying Data

Figure 1 shows absorptive drying data for five different ink formulations and one plain paper at ambient conditions. The inks are formulated to yield different penetration rates.

The diffusion coefficient (the measurable parameter used to characterize rates of ink penetration into paper) varies by a factor of 25 among the five ink formulations tested. This indicates that inks could be formulated specifically for absorptive drying . However, since rapid ink penetration and spreading on paper degrade print quality, the ability to design inks for absorptive drying is limited[10].

The trend of this data demonstrates that this mode of drying could be characterized with a measurable diffusion coefficient parameter.

Figure 2 shows ϕ, dimensionless offset density parameter plotted versus sqrt(time) for 3 of the inks in Figure 1 on one paper. Drying time of 50 to 60 seconds (ϕ greater than 0.95) is indicated.

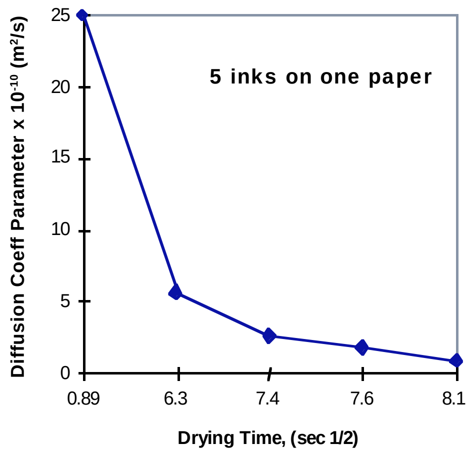

Figure 1. Ink Absorption Rate versus sqrt (time)

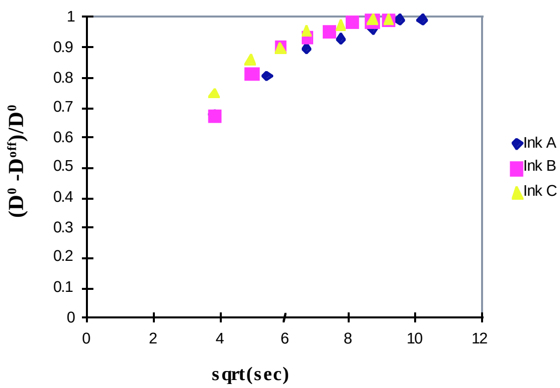

Figure 2. Drying Offset versus sqrt (time)

Figure 3 shows drying time versus ink coverage density. Drying time varies by more than a factor of 2 when ink coverage density varies by more than 25 per cent. Also, drying time varies linearly with ink mass. This suggests that drying should be more easily accomplished at higher printing resolutions.

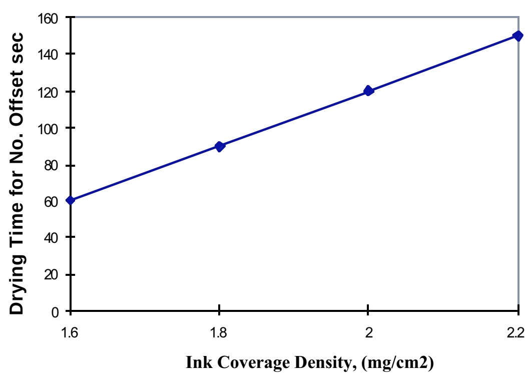

Figure 3. Ambient Drying Time versus Ink Coverage Density

Paper Deformation Data

Figure 4 shows cockle growth versus evaporative drying time, with minimal restraint, for an ink formulation on plain paper. The data indicates that if drying time is long enough for ink penetration to occur, significant cockle growth will occur. In this case, cockle growth is not significant until drying time is about 20 seconds or greater. This type of cockle growth rate is similar to ink penetration data measured by the Bristow apparatus[10].

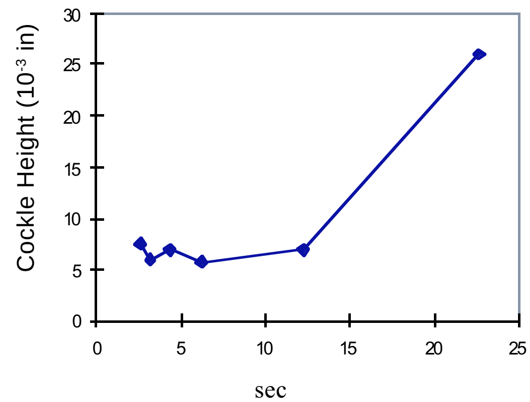

Figure 4. Cockle Height vs. Drying Time

Figure 5 shows the history of paper curl growth under different drying scenario. State **b** represents virgin paper at 6 per cent moisture, hanging curl radius of 25 inches, which is unprinted and undried.

If the paper is actively dried (as described in Reference 2) without having been printed, it would go from state **b** to state **a**. Basically, the sheet looses 2% moisture and remains flat.

The history of curl development in a typical sheet of plain paper, printed and then dried without restraint is as follows:

(a) State **b** to state **c**: the sheet is printed at 100 per cent ink coverage. The hanging curl radius changes from 25 inches TI (toward from image) to 5 inches AI (away from image) while moisture content increases to 28 per cent. At this state there is no active drying;

(b) State **c** to state **d**: the printed sheet of paper is actively dried, as described in Reference 10. The hanging curl radius changes from 5 inches AI to 15 inches TI, while moisture content drops from 28 per cent to 4 per cent;

(c) State **d** to state **e**: the sheet is allowed to dry to equilibrum conditions without restraint. The hanging curl radius changes from 4 inches TI to 2.5 inches TI, while moisture content changes from 4 per cent to 4.5 per cent.

Acceptable curl has been determined subjectively to be the condition in which hanging curl (either TI or AI) exceeds 12.5 inches.

These results have been reported for unrestrained drying. With restrained drying, the results are fairly similar. The important factor to note here is that active drying results in instantaneous flat sheets, as opposed to absorptive drying. However, regardless of the drying mode, over time, curl develops.

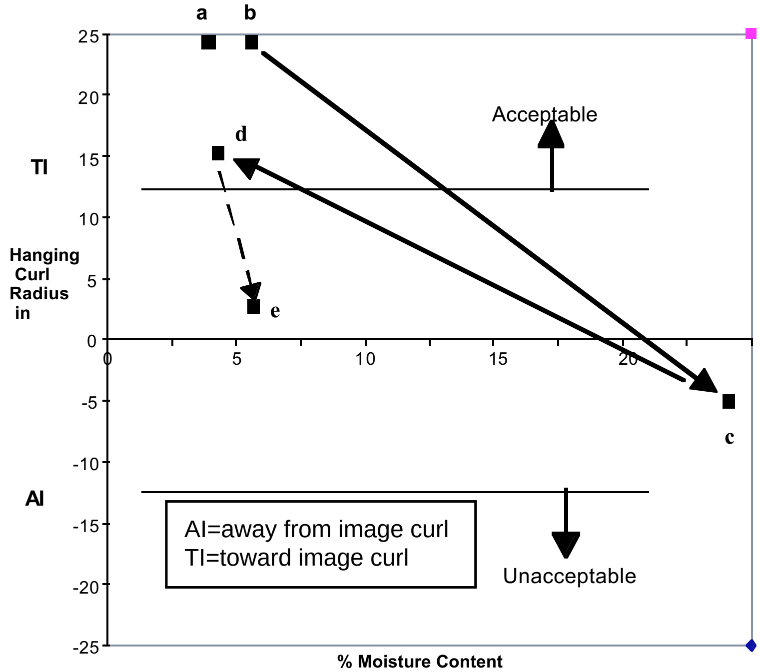

Figure 5.

Summary

Absorptive drying is a reasonable method for drying ink jet images on plain papers, when throughout is low (less than 3 prints/minute). Typical drying times under ambient conditions are on the order of 50 to 60 seconds. Inks could be designed specifically for faster absorptive drying, subject to the limitation that print quality degrades when absorption rates are too high. With the diffusion coefficient parameter known, the absorptive drying time can be predicted fairly reliably and the print quality metrics can be inferred[10].

Drying effectiveness may be measured in terms of a dimensionless offset density parameter. This parameter is determined by measuring offset density on an unprinted sheet of paper which is brought into contact with the printed image in the nip of a transport rolls. The dimensionless offset density parameter is also very useful for predicting drying times.

For higher throughput (over 4 prints/minute), evaporative drying could be utilized for more rapid drying. This method of drying requires that inks be designed for evaporative drying. In addition, elevated temperatures and air flow over the surface of the sheet could be used for enhanced drying.

Drying time depends linearly on ink coverage density. Drying time could vary by more than a factor of 2 when ink coverage density varies by more than 25 per cent. This suggests that drying should be more easily accomplished at higher printing resolutions.

Drying of ink jet images will cause paper deformation in the form of curl and cockle growth when ink has sufficient time to penetrate the paper. Under ambient conditions, for typical inks and plain papers, significant cockle growth and curl may occur when drying time exceeds 20 seconds. Cockle growth as well as curl may be minimized by drying rapidly under restraint. In the case of paper curl, mechanical decurling after drying the sheet may also be effective in minimizing the equilibrium curl which develops over a long period of time.

References

1. Gooray, A. and Agbezuge, L., "Drying of Ink Jet Images on Plain Papers", *1990 SPIE/SPSE, Symp. on Electronic Imaging Science & Tech.*, **1252**. (1990).
2. Agbezuge, L., Gooray, A., "Drying of Ink Jet Images on Plain Papers - Falling Rate Period", *IS&T's 7th Int. Congr. Imag. Sci. & Tech.*, Portland, OR, pp 173-184 (Oct. 1991).
3. Gooray, A. and Agbezuge, L., "Paper Deformation during Ink Jet Printing", *IS&T Int. Congr., Imag. Sci. & Tech.*, Williamsburg, Virginia, 312-317 (Oct. 1992).
4. Agbezuge, L., "Internal Stress Levels in Xerographic Papers", *Polym. Eng. Sci.*, Vol **21** (9), 534 - 537 (1981).
5. Bristow, J.A., *Svensk Papperstidning*, **74** (20), pp. 645 (1971).
6. Lyne, M.B. and Aspier, J.S., "Wetting and the sorption of water by paper under dynamic conditions", *TAPPI*, Vol. **65** (12), 98-102 (Dec. 1982).
7. Keey, R.B., *DRYING : Principles and Practice*, Pergamon Press 54-55 (1972).
8. Luikov, A.V., *Heat and Mass Transfer in Capillary-porous Bodies*, Chapt. 6, Pergamon Press, Oxford (1966).
9. De Vries, D.A., *Trans. American Geophysical Union*, **39** (5), 909-914 (Oct. 1958)
10. Carreira, L., Agbezuge, L. and Gooray, A., "Rates of Aqueous Ink Penetration into Papers and their Effects on printability", *IS&T's 8th Int. Congress on Advances in Non-Impact Printing Tech.* 324-328 (1992).