A MODEL FOR INK/WATER BALANCE IN THE LITHO-GRAPHIC PROCESS

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Abstract: A simple model quantitatively describing the ink/water balance in offset printing has been developed. A new parameter, the water redistribution ratio, is introduced. An analysis of experimental data from the literature indicates that the water redistribution ratio decreases as the water pickup coefficient increases, providing the first indirect evidence that splitting of a composite film, consisting of a water layer and an ink layer, indeed occurs within the low tack, low viscosity water layer, as speculated by many researchers. The model also predicts that the water consumption rate may increase, be independent, or decrease with increased image coverage, depending on the amount of water evaporated.

Introduction

Lithography is unique among printing processes in that the image and non-image areas of the printing plate lie in the same plane. The separation between them is maintained physico-chemically using two immiscible liquids, a water-based dampening solution and an oil-based ink. The printing process involves the application of aqueous fountain solution from dampening rollers to the total plate surface, where it adheres strongly to the hydrophilic non-image areas. The oil-based ink is then applied from inking rollers to the oil-receptive image areas.

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The purpose of the fountain solution in lithography is to maintain an aqueous film on the non-image areas of the printing plate. However, as the dampening roller passes the total plate surface, a certain amount of fountain solution is also applied to the image areas. It is believed (Wilkinson et al, 1975) that if the fountain solution film is too thick or if the ink emulsifies too little water, the fountain solution on the image surface will interfere with ink transfer. This is why lithographic inks are formulated to absorb a certain quantity of water. On the other hand, as the dampened plate passes the inking rollers, a fraction of the fountain solution on the non-image areas is simultaneously emulsified into the ink. If the fountain solution film is not thick enough or if the ink picks up too much water, the water film will be unable to form the barrier that is required to keep the non-image areas free of ink.

Many graphic arts researchers (Lindqvist et al, 1982, Juhola et al, 1984, Juntunen et al, 1984, Cunningham and Moore, 1984, MacPhee, 1985, Fetsko, 1986, Bassemir and Krishnan, 1989) have studied the ink/water balance in the lithographic process. Among others, Lindqvist et al. (Lindqvist et al, 1982) and Juhola et al. (Juhola et al, 1985) measured the amount of water transferred to paper, using tracer element analysis. They found that more water was transferred to paper in the image areas than in the non-image areas, suggesting that water was mainly transferred to paper with ink.

On the other hand, MacPhee (MacPhee, 1985) recently measured ink and fountain solution consumption rates under different printing conditions. He found that the type of substrate, the rate of ink feed and the percent ink coverage have little or no effect on the water consumption rate. The only normal printing variables with a modest effect were pressroom temperature, alcohol content of the fountain solutions, and the ink film thickness on the print. He then suggested that most of the fountain solution supplied to the plate evaporated in the ink distribution system. MacPhee (MacPhee, 1979) also qualitatively modelled ink and water flows in the offset units.

In this paper, a simple model quantitatively describing the ink/water balance in the offset process is proposed. This model is developed on the basis of the lithographic models of MacPhee (MacPhee, 1979) and Lindqvist et al (Lindqvist et al, 1982), by considering mass balance. A new parameter, the water redistribution ratio, is introduced in the model.

The Model

This model arises from the qualitative lithographic models of MacPhee (Macphee, 1979) and Lindqvist and coworkers (Lindqvist et al, 1982). MacPhee (MacPhee, 1979) proposed that as the dampening rollers and inking rollers apply fountain solution and ink sequentially to the printing plate, the fountain solution is distributed in the press units through the following processes:

1) When the dampening rollers pass the hydrophilic non-image areas, a single fountain solution film is present in the nip. At the nip exit, the film splits leaving a water layer on the plate (Fig.1 a).

2) The fountain solution then comes into contact with the oleophilic image areas which are usually covered with a residual ink film. Since the two liquids have been subjected to a converging flow at the nip entrance region, a portion of the fountain solution is emulsified into the ink due to shearing. At the nip exit, splitting of the composite film, consisting of a water layer and an ink layer, occurs within the low tack, low viscosity water layer, leaving a water film (or globules) on the surface of the ink (Fig.1 b).

3) When the dampened non-image areas next pass the inking rollers, a composite film containing a water layer from the plate and an ink layer from the inking roller is present in the nip. A portion of the water on the plate is simultaneously emulsified into the ink film at the nip entrance. This is similar to the nip formed by the dampening roller and the image areas. At the nip exit, splitting of the composite film occurs within the weak water layer, leaving a residual water film on the plate and transferring the remaining water back to the inking train (Fig.1 c).

4) When the dampened image areas pass the inking rollers, two ink films come into contact, with some water drops between them. These water drops are simultaneously emulsified into the ink in the form of very small droplets, so that only a single emulsified ink film is present in the nip. The ink film splits at the nip exit, leaving on the plate an inked image containing emulsified water (Fig.1 d).

To develop a quantitative model, the following additional assumptions are made:

a) As the printing plate passes the dampening rollers, the amount of fountain solution applied to the image and the non-image areas is proportional to their respective percent coverage (Lindqvist et al, 1982):

$$W_i = C\,W \tag{1}$$

$$W_n = (1-C)\,W \tag{2}$$

where W is the total fountain solution feed rate, W_i the fountain solution feed rate to the image areas, W_n that to the non-image areas, and C is the percent ink coverage.

b) As the dampened plate passes the inking rollers, the water applied into the image areas (fig. 1d) is totally emulsified into the ink, while the water previously applied to the non-image areas (fig. 1c) is transferred back to the inking rollers with a constant redistribution ratio, *b*. Thus, the water feed rate into the ink, W_{ink}, is the sum of the water applied to the image areas and that transferred back from the non-image areas:

$$W_{ink} = C\,W + (1-C)\,\underline{b}\,W \tag{3}$$

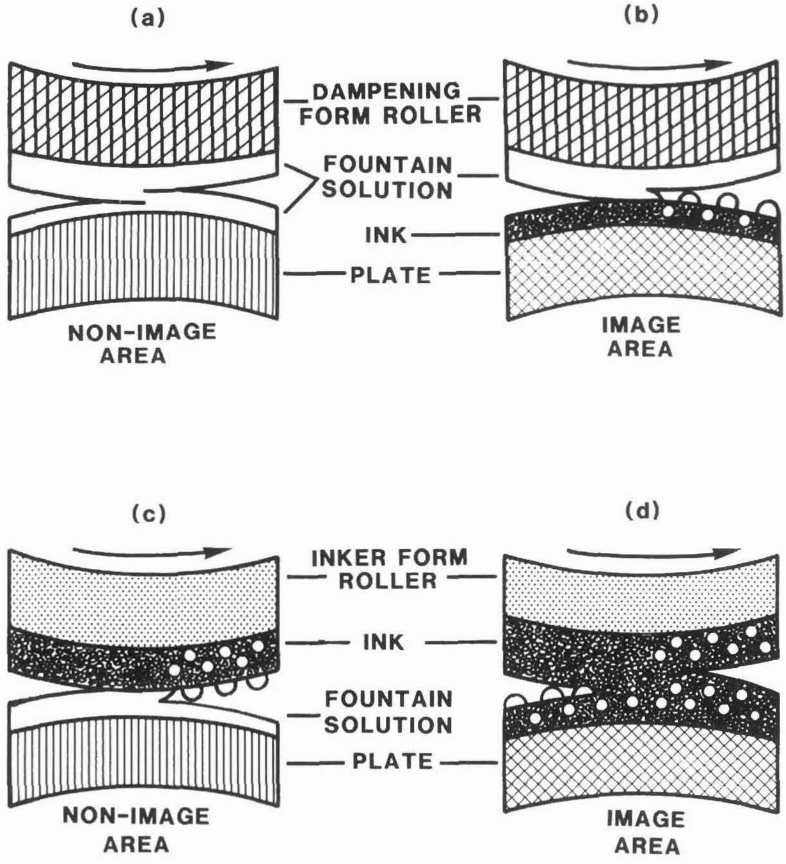

Figure 1: Distribution of ink and fountain solution on a lithographic plate with a conventional dampening system. Solid areas: ink; white areas: fountain solution (from MacPhee, 1979).
1a and 1b: Film splitting between dampening roller and plate,
1c and 1d: Film splitting between inking roller and plate.

c) For a steady state printing operation, the fountain solution applied to the ink is either evaporated in the inking train or transferred to the paper with ink to maintain the mass balance:

$$W_{ink} = W_e + \underline{a}\ I \tag{4}$$

where W_e is the rate of water evaporation, I the rate of ink consumption, and *a* the water pickup coefficient, the amount of emulsified water on the print per unit mass of ink.

Combining equations 3 and 4, one obtains:

$$C\ W + (1-C)\ \underline{b}\ W = W_e + \underline{a}\ I \tag{5}$$

Equation 5 is a mass balance equation. It states that for a steady state printing operation, the fountain solution feed rate W is correlated with the ink feed rate I.

Now we will analyze water transfer to paper. For this purpose, the water feed rate and ink feed rate can be expressed as a function of the water film and ink film thicknesses:

$$W = L\ V\ X_w \tag{6}$$

$$I = C\ L\ V\ X_i \tag{7}$$

where V is the printing speed, L the width of the plate, X_w the amount of water fed to the plate per unit area of printed substrate, and X_i the amount of ink per unit area of printed image.

Combining equations 6 and 7 with equation 5, yields:

$$X_w = (X_e + \underline{a}\ C\ X_i)/\{C + (1-C)\ \underline{b}\} \tag{8}$$

where X_e is defined as W_e/LV, which is the amount of water evaporated per unit area of printed substrate. Equation 8 expresses the fresh water film thickness as a function of the ink film thickness on the print.

If a water film of thickness X_w is applied to the plate, a portion *b* is transferred back to the inking train. Neglecting water evaporation during the transfer between the printing plate and rubber blanket, the amount of water transferred to paper through the non-image areas, X_{wn}, should be equal to the amount of freshly applied residual water on the plate:

$$X_{wn} = (1-b)X_w \quad (9)$$

Similarly, the amount of water transferred to the paper in the printed image areas, X_{wi}, depends on the water pickup coefficient and the amount of ink transferred to paper:

$$X_{wi} = a\ X_i \quad (10)$$

Discussion

1) Correlation between water usage and ink usage

The proposed model suggests that the quantity of water fed into the ink, W_{ink}, is a linear function of the amount of ink transferred to the paper (eq. 4). In order to verify this suggestion, the experimental data of MacPhee (MacPhee, 1985) have been re-examined. MacPhee (1985) measured the amount of water and the amount of ink consumed during press runs of 5000 impressions, at a printing speed of 6000 impressions per hour.

Using MacPhee's data (MacPhee, 1985), the amount of water transferred to the ink, W_{ink}, was calculated as a function of the quantity of ink consumed, I (Figure 2). Here the values of W_{ink} were calculated from the total amount of water consumed using equation 3, assuming different values of water redistribution ratio, *b* (Table I).

Figure 2 shows that a straight line with a correlation coefficient of 0.936 is obtained by assuming no water retransfer ($b = 0\%$). On the other hand, the curve has a correlation coefficient of 0.171 if one assumes that all of the water on the non-image areas is transferred back to the inking rollers ($b = 100\%$). For values of b between 0% and 50%, the correlation coefficients of different curves are similar (Table I). However, for values of b above 50%, the correlations are poor or non-existent. This contradicts the conclusion of MacPhee (MacPhee, 1985), who calculated that 558 grams of water were evaporated during 5000 impressions, (or about 80% of the total amount of water consumed), by assuming that the water consumption depends only on the ink film thickness on the print. In effect, MacPhee's conclusion assumed that most of the water was evaporated and that only a small amount was transferred to the paper emulsified in the ink.

Lindqvist et al. (Lindqvist et al, 1982) reported that at a relative humidity of 50%, the water evaporation rate on a offset press can be calculated from the following empirical equation:

$$W_e = 0.016\ (1 + 2V)\ (\frac{T}{T_o})^{16} \qquad (11)$$

where W_e is the water evaporation rate in g/m /s, V the printing speed in m/s, T the press temperature and T_0 the reference temperature being chosen as 293 K.

Using Lindqvist's equation and MacPhee's experimental conditions (temperature = 289 K and printing speed = 2.75 m/s), one calculates from equation 11 that 250 grams of water were evaporated during MacPhee's 5000 impressions. It is noted from table I that the best fit straight line is obtained by assuming b to be equal to 0.35, with a correlation coefficient of 0.973. From this curve, one calculates that the water pickup coefficient is 0.37 and that 255 grams of water (corresponding to X_e = 0.17 g/m^2, or about 37% of the total amount of water consumed), were evaporated during 5000 impressions. While this may be a fortuitous accident, the agreement is promising, and does suggest that less water is evaporated and that more is transferred to the paper emulsified with the ink that was previously assumed.

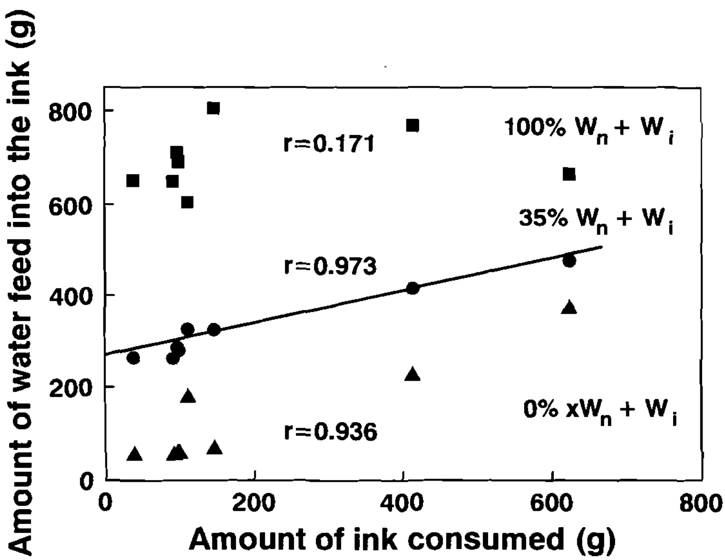

Figure 2: Amount of water transferred to the ink as a function of the amount of ink consumed. (■): *b*=100%, (●): *b*=35%, (▲): *b*=0%. (from MacPhee, 1985).

2) The effect of image coverage

Bassemir and Krishnan (Bassemir and Krishnan, 1988) recently studied the dependence of ink and fountain solution feed rate on percent image coverage. They found that, although the ink feed rate to obtain equal print density increases linearly with increasing image coverage, the fountain solution feed rate to avoid scumming is practically independent of ink coverage.

From equation 7 ($I=CLVX_i$), it is clear that the ink feed rate to obtain a constant ink film thickness is proportional to the percent image coverage at a constant printing speed. On the other hand, the theoretical fountain solution feed rate (corresponding to a given ink film thickness and water pickup coefficient) can be calculated using equation 8. From figure 3 it is seen that if the following constants are assumed: $a = 0.37$, $b = 0.35$ and $X_e = 0.17$ g/m^2, the theoretical fountain solution film thickness (corresponding to a given ink layer thickness of $X_i = 1$ g/m^2, which is typical for coated paper) is virtually independent of percent image coverage. All the above parameters used were obtained by fitting MacPhee's data.

Table I
The values of correlation coefficient* corresponding to different values of water redistribution ratio b.

Water redistribution ratio b	Water pickup coefficient a g water/g ink	Water evaporation g	Correlation coefficient
0%	0.53	25	0.936
20%	0.44	156	0.964
30%	0.39	222	0.972
35%	0.37	255	0.973
40%	0.34	288	0.969
50%	0.29	354	0.940
60%	0.25	420	0.870
70%	0.20	485	0.740
80%	0.15	551	0.556
100%	0.06	683	0.171

*: Calculated from MacPhee's data (MacPhee, 1985) using eq. 5

On the other hand, if one assumes that less water was evaporated, for example, taking X_e to equal 0.10 g/m^2, the theoretical water film thickness increases with increased ink coverage. If one takes X_e to be equal to 0.30 g/m^2, it is seen that the calculated water film thickness decreases with increasing image coverage. This may explain a controversy in the printing industry, where some printers say a light ink coverage requires more water while others say heavy image coverage requires more water (MacPhee, 1985).

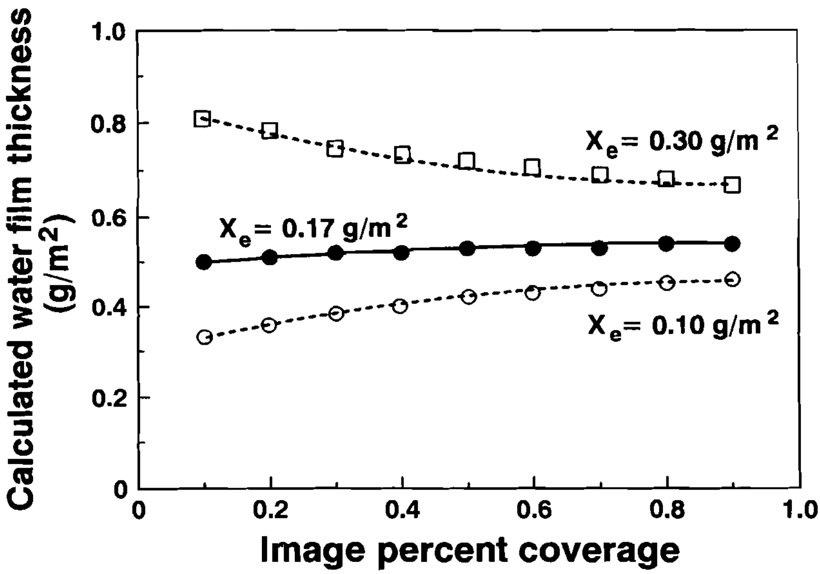

Figure 3: Calculated water film thickness as a function of percent image coverage. (□): $X_e=0.30$ g/m², (●): $X_e=0.17$ g/m², (▲): $X_e=0.10$ g/m².

3) Water pickup coefficient and water redistribution ratio

According to the proposed model, the transfer of water to the substrate is determined by two parameters, the water pickup coefficient a (eq. 10) and the water redistribution ratio b (eq. 9). Water pickup properties of inks have been widely studied in the literature. From on-press emulsification tests (Fetsko, 1986), it is known that for a given ink/fountain solution pair, the ink can emulsify different quantities of water, depending on the fountain solution feed rate. In practical printing, the fountain solution feed rate is limited between the minimum water feed level where scumming occurs, and the maximum water feed level where water marking begins. At the minimum water feed level, figure 4 shows that the water pickup coefficient decreases as ink viscosity increases, indicating a more viscous ink emulsifies less water (Lindqvist et al, 1982). On the other hand, at the maximum water feed level, water content depends not only on ink viscosity, but also on other properties such as surface and interfacial tension of the ink and fountain solution, (Lindqvist et al, 1982, Fetsko, 1986).

The water redistribution ratio *b* is a new parameter, similar to the water splitting parameter C of Lindqvist et al., defined in equation 5 by Juntunen et al. (Juntunen et al. 1984). Both parameters describe the redistribution of water between the plate non-image areas and the inking rollers. However, as the present model deals only with the freshly applied water, it is much simpler. Furthermore, the parameter *b* can be directly determined (using eq. 9) from the amount of fresh fountain solution on the plate, X_w, and from the amount of water transferred to the substrate through the non-image areas, X_{wn}:

$$b = 1 - \frac{X_{wn}}{X_w} \tag{12}$$

However, there is no published work in the literature where both the values of X_w and X_{wn} are available.

By combining equations 8, 9 and 10, *b* can also be estimated from the quantity of water transferred to the image and the non-image areas:

$$b = \frac{X_e + CX_{wi} - CX_{wn}}{X_e + CX_{wi} + (1-C)X_{wn}} \tag{13}$$

Table 2 lists the values of *b* calculated using equation 13 from the data of Lindqvist and coworkers (Lindqvist et al, 1982), assuming C and X_e to be equal to 30% and 0.17 g/m^2 respectively. It can be seen that the water redistribution ratio varies from 25% to 90%, depending on the ink and printing conditions used. It is interesting to note that by measuring the water film thickness on the plate using infrared-absorption technique, Pyliotis (Pyliotis, 1974) found that 30 to 80% of the total amount of water on the non-image areas (including freshly applied water and residual water) was transferred back to the inking train. As the present model only deals with the freshly applied fountain solution, the agreement is fairly good.

Table II
The values of water pickup coefficient and water redistribution ratio[1]

Ink No.	η PaS	Minimum feed level X_i g/m²	X_{wi} g/m²	X_{wn} g/m²	a*	b	Maximum feed level X_{wi} g/m²	X_{wn} g/m²	a*	b
18	4.3	1.6	0.217	0.087	0.14	0.71	0.855	0.627	0.53	0.28
16	4.3	1.3	0.308	0.169	0.24	0.56	1.019	0.54	0.78	0.37
22	5.4	1.1	0.145	0.052	0.13	0.79	0.376	0.295	0.34	0.40
29	5.4	-	0.168	0.038	-	0.85	0.718	0.616	-	0.25
28	5.8	1.6	0.277	0.040	0.17	0.86	0.794	0.415	0.50	0.41
11	6.5	1.0	0.160	0.029	0.16	0.88	0.568	0.236	0.57	0.53
2	11.9	1.8	0.154	0.024	0.09	0.90	0.637	0.705	0.35	0.18
4	13.6	-	0.127	0.016	-	0.93	0.777	0.697	-	0.22

1) Calculated from the data of Lindqvist et al. (Lindqvist et al., 1982) using equations 10 and 13.
*) gram water/gram ink.

From figure 4, it is seen that at the minimum water feed level, the water redistribution ratio increases with increasing ink viscosity, showing that the relative amount of water transferred back to the inking rollers increases as ink viscosity increases. At the maximum water feed level, it seems that there is no apparent correlation between water redistribution ratio and ink viscosity (Table 2).

Figure 5 shows the water redistribution ratios plotted as a function of water pickup coefficient, based on the experimental results of Lindqvist et al. (Lindqvist et al, 1982) and Karttunen et al. (Karttunen et al, 1988). The filled symbols represent the values determined at the minimum water feed level, and the open symbols correspond to that obtained at the maximum water feed rate. Despite some scatter, the trend is seen that at the minimum water fed level, the water redistribution ratio decreases as the water pickup coefficient increases. This means that as more water is emulsified into the ink, less water is transferred from the plate back to the inking train. At high water contents, the water redistribution ratio seems to be independent of water pickup. The constant water redistribution ratio suggests that at high water feed rate, the amount of water transferred back to the inking train is proportional to the water fed to the plate. This may also explain the phenomenon where free surface water will build up in the inking train with increased water feed rate, if the ink picks up too much water. In this case, a steady state operation cannot be established.

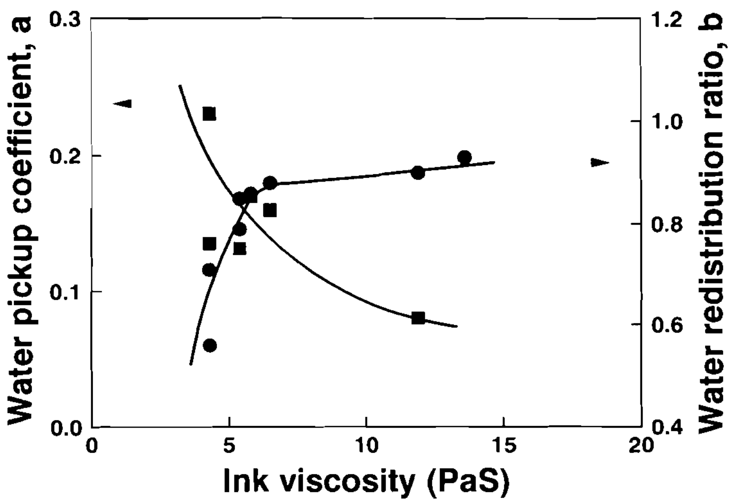

Figure 4: Water pickup coefficient and water redistribution ratio as a function of ink viscosity, at the minimum water feed level. (■) a, (●), b, (from Lindqvist et al, 1982).

The decrease in water redistribution ratio with increasing water pickup coefficient at low water content is a surprise. One would have expected that with more water emulsified in the ink, more water should be transferred from the plate back to the inking rollers. However, the decrease in water redistribution ratio with water pickup coefficient is consistent with the speculation that splitting of a composite film, consisting of a water layer and an ink layer, occurs within the low tack, low viscosity water layer (MacPhee, 1979). If the splitting occurs within the fountain solution layer, the water transferred back to the inking rollers consists of not only emulsified water, but also surface water. Although the amount of emulsified water increases with decreasing ink viscosity, the location of film splitting may move toward the ink/fountain solution interface, thus allowing less surface water to be transferred back to the inking rollers. Consequently, the total amount of water transferred back to the inking rollers may decreases as the ink becomes less viscous. Splitting may even occur within the ink layer, if the ink is less viscous than the fountain solution.

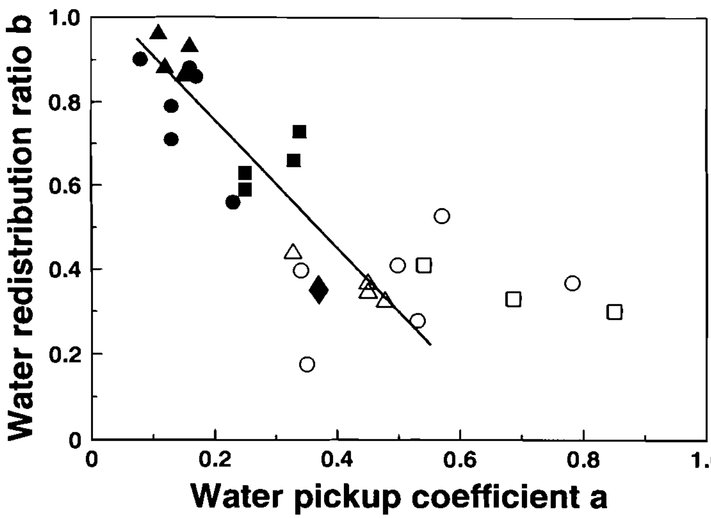

Figure 5: Water redistribution ratio as a function of water pickup coefficient. (•, o): Lindqvist et al, 1982; (▪, ▫): ink W, Karttunen et al, 1988; (▴, ▵): ink R, Karttunen et al, 1988; (♦): from the best fit line in Table I.

Conclusions

A simple model quantitatively describing the ink/water balance in offset printing has been developed, based on the lithographic models of MacPhee and Lindqvist et al. A new parameter, the water redistribution ratio, has been introduced. An analysis of experimental data from the literature indicates that the water redistribution ratio decreases as the water pickup coefficient increases, providing the first indirect evidence that splitting of a composite film, consisting of a water layer and an ink layer, indeed occurs within the weak water layer, as speculated by many researchers. In addition, the model states that the transfer of water to paper is determined by the ink/fountain solution interactions and by the printing conditions, through the water pickup coefficient and the water redistribution ratio. This also provides a basis for choosing the ink and printing conditions for a given printing paper.

Acknowledgements

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