Ink Flow Simulation of Offset Lithographic Printing: Comparison with Actual Print and Introduction of Additional Factors to the Model

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Keywords: Ink Flow, Simulation, Uniformity, Nip

Abstract: Understanding ink flow behavior in offset lithographic printing machines is essential when optimizing process control, ink and water material design. We have developed an ink flow simulator to predict the ink film thickness anywhere on the rollers, plate or blanket of the machine and on printed paper at any time. Ink film thickness is sampled every 1 square millimeter of the surface, and calculated with a simple model that represents ink transfer from a rolling surface to another at a specified transfer rate in an actual roller configuration. The results of the simulation showed a strong correlation to the density measurement of corresponding actual print. Additional factors (degree of ink flow and its direction) were introduced to the model, resulting in a significant improvement in prediction accuracy.

1. Introduction

Despite the long history of offset lithographic printing, its behavior throughout the entire process has not been completely known yet. Comprehension of the process, especially ink flow behavior, is essential when optimizing both process control and material design. Measuring the ink flow behavior by infrared sensors provides our better comprehension of the process. But actual measurement using infrared sensors is costly and measurable points are very limited since the space for sensors is very limited.

Many approaches predicting ink film thickness on paper substrate and/or analyzing comprehensive ink and water flow by means of computer to optimize the material design have been studied. S.M chou et al. made it clear that press time constant and mean ink residence time are inversely proportional to the image coverage (1996). In their second paper, the effect of vibrator oscillation

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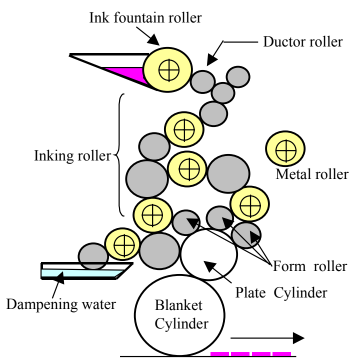
was studied. The range of ink spread by vibrators' action was also investigated by conducting print test (Chu and Sharma ,1998) and this result confirmed the previous report (Chou 1997). C.L.Chu et al. focused on using simulator for ink key presetting and showed that the model-based ink key presetting system has the potential to provide close presetting. In addition, Iwaki et al. (1995) characterized ink and fountain solution emulsification and transfer by experimental methods, then they applied the model to the simulator. A print test was conducted and verified the simulation accuracy.

For the purpose of practical application such as design of roller arrangement, quality control and enhancement of presetting, the validity of the model needs to be examined in further detail by comparing the simulation result with the print test result. We have developed a simulation software incorporating the proposed model in earlier studies and examined the accuracy of ink flow prediction. The simulator features the function of visualizing the dynamic behavior of ink flow, which is helpful in understanding how the ink flows in the press.

2. Developing an ink flow simulator

The inking system of offset lithographic press is composed of an ink fountain roller, a ductor roller and many ink transfer rollers. The series of rollers is often called a roller train. Usually the number and the configuration of rollers vary by machine. Fig.1 shows an example of inking system used in this study.



Figuer.1 Inking system using in this study

First, ink is supplied to the fountain roller via open space between the ink key blade and the fountain roller, and then moves down through many nip points toward form rollers. Form rollers contact the plate cylinder that has image coverage distribution. The form rollers transfer ink on the plate cylinder, and then the ink is transferred to the blanket cylinder and finally reaches to the paper substrate.

2.1. Simulation model

Table.1 enumerates all components of the simulation. As an input to the ink flow simulation, we have taken all these parameters into consideration. The table is followed by detailed explanation of each parameter in the same order.

Table.1 The components of simulation

Parts	Ink Key	number	
		key width	
		distance	
	Fountain	Size	diameter(mm)
			width(mm)
			height(mm)
		speed(rpm)	
	Ductor	with	roller(s)
			the first roller(s)
		Size	
	Roller	oscillation	cycle period(s)
			amplitude(mm)
			phase(degree)
		Size	
	Plate	image	Size(width x height)
			Pixel value
		Size	
	Blanket	Size	
	Paper	Size	

Data	ink	film thickness(μ)
		water content(%)
		viscosity
		temperature
	water	free water
		evaporation
Transfer Model	transfer rate	(α: split coefficient)
	additional factor	
Machine	Operation	speed(rpm)
		printing (on/off)
		ink supply (on/off)
		ink key preset
		auto key controll
	Configuration	location of rollers (nip point/number)
Functions	Visualization (frame/animation)	ink thickness on paper
		ink thickness on rollers

2.1.1. Ink fountain -Ink key - Ductor roller part

In the ink fountain section, many ink keys control the distance between the ink key blade and the fountain roller individually to determine a certain ink film thickness on the fountain roller. (Fig.2 left) The ink film thickness is usually set in proportion to the image coverage of the corresponding ink key zone.

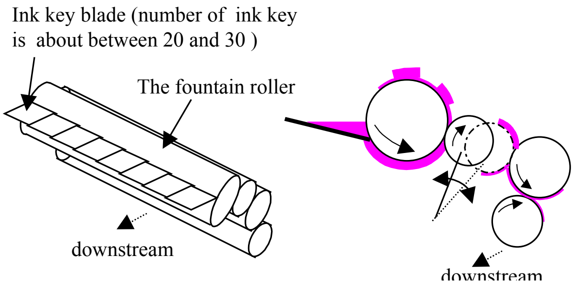


Figure.2 Illustration of ink supply part (L: ink key, R: ductor roller)

The ductor roller alternately contacts the fountain roller and the first roller in the roller train and periodically supplies ink to the first roller. (Fig.2 right) This back and forth motion is required because the surface speed of fountain roller is much slower than that of other inking rollers. The ductor roller bridges between the fountain roller and the first roller.

The following parameters are obtained and fed to the simulation.

- The number of ink keys.
- The width of each key.
- The distance between the key blade and the fountain roller at each key setting.
- Ink key position on the fountain roller.
- Fountain roller size (width and diameter).
- Fountain roller speed
- Ductor roller size (width and diameter).
- The Periodic cycle of the ductor roller and the contact time with the fountain roller and the first roller.
- Contact position between the fountain roller and the ductor roller.

2.1.2. The roller train part

There are a number of rollers in the roller train. In a pair of rollers engaged with each other, the one placed in the upper stream of the ink flow is called "a parent roller" and the other one in the lower stream "a child roller". Some rollers have more than one parent roller and/or one child roller. In a parent-child pair of rollers, the flow of ink is not limited to one-way from the parent to the child, but some portion always goes into the other way. This makes the ink flow more complicated.

There are two types of materials forming the roller surface; rubber and metal. A metallic roller is usually an oscillator roller. Movement of an oscillator roller can be approximated by a sinusoidal function and each roller has its own values of cycle, amplitude and phase. Through the long roller train, the ink is sheared by the oscillator and its viscosity is weakened.

The ink finally reaches the form rollers via several paths. Generally the number of form rollers is three or four for the purpose of supplying the ink uniformly to the plate.

The following parameters are obtained and fed to the simulation.

- Each roller size (width and diameter).
- Nip point of between a parent roller and a child roller.
- The cycle, amplitude and phase of sinusoidal function. (oscillator)
- Nip point between the form rollers and the plate cylinder.

2.1.3. The plate cylinder

The plate model is different from other roller model in that it retains image information. The image is usually represented by halftone dots. Only oleophic image area can receive the ink and transfer it.

In addition to roller size, the image information is required to run the simulator.

- Pixel value of the printing image. (image coverage distribution)
- Image size(width and height)
- Image position on the plate.
- Nip point between the plate and the blanket cylinder.

2.1.4. The Blanket and Paper

Finally, the ink reaches the paper. Mechanical dot gain is not being considered. The following parameters are investigated and imported to the simulation model.

- Blanket size(width and diameter)
- Contact point between the blanket and the paper
- Paper substrate size.

2.1.5. The data

The data related to ink and water are specified in the simulation software. To simplify the simulation, we use only the ink film thickness in this study. (Shaded part of Table.1 is not considered) The simulator calculates every 1 square millimeter of the surface on rollers, plate, blanket and paper. The calculation is based on ink transfer function and after the calculation, all rollers rotate by 1mm segment. The calculation goes on repeatedly. The fountain roller is treated as an exceptional case because it moves more slowly than other rollers. The resolution of the mesh is important. There are two reasons why we select the 1mm mesh. One is to represent smooth movement of oscillator of which the amplitude is 5mm at the minimum. The other is to provide sufficiently high resolution comparable with optical density that is measured by 3.6mm aperture.

2.1.6. Ink transfer model

Fig.3 shows how the ink on the surfaces of a parent-child pair of rollers, A and B, joins and splits when going through the nip. Equations (1) and (2) represent ink transfer functions of this model. (Scheuter and Rech, 1970)

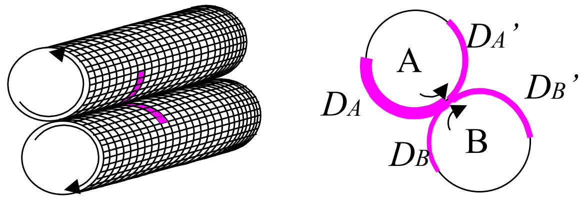


Figure.3 Ink transfer model

$$D'_A = (1-k)\ (D_A+D_B) \quad (1)$$
$$D'_B = \quad k\ \ (D_A+D_B) \quad (2)$$

With,

D_A : ink film thickness on the rollerA before the nip point.
D_B : ink film thickness on the rollerB before the nip point.
D'_A : ink film thickness on the rollerA after the nip point.
D'_B : ink film thickness on the rollerB after the nip point.
k : ink split ratio

The equations are based on the conservation of ink, namely $D_A + D_B$ equals $D'_A+D'_B$, with the parameter k representing the ratio of ink going to the roller B to the total amount of ink. The fraction k, which we call split ratio hereinafter, is influenced by many factors such as printing speed, moisture content and/or viscosity of the ink, air temperature and so on.

The importance of investigating the primitive behavior of ink transfer is not intended to neglect, but just for some practical reasons, the fraction k is assumed to be a constant in this simulation. If k is equal to 0.5, the half of ink goes to the roller B and the other ink stays on roller A.
For the calculation of ink transfer from the form rollers to the plate cylinder, the image coverage must be taken into consideration.
Ink covered area and water covered area are to be formulated in separate terms.
Equations (3) and (4) show ink transfer function between form roller A and plate cylinder B.

$$D'_A = (1-k)\ (D_A+D_B)\ x + D_A\ \ (1-x) \quad (3)$$
$$D'_B = \quad k\ \ (D_A+D_B) \quad (4)$$

With,

x : image coverage

It's to be noted that D_B and D'_B are the thickness of screen dot area and the other area is zero. Equations (3) and (4) also are consistent with conservation of ink expressed in Equation (5).

$$D_A + x\,D_B = D_A' + x\,D_B' \qquad (5)$$

Using equations above, the simulator can calculate the ink flow for various plate images.

2.2. Function of the simulator

2.2.1. Visualization

To facilitate the understanding the details of how the ink flows, the simulator allows users to explore the dynamic behavior. As shown in Fig.4 (right), the simulator displays some visualized images. Each roller surface is opened-up to the face and allocated on the image according to the actual roller configuration. Ink film thickness is, for ease of understanding, represented in thermal images. It is also shown as an animated image.

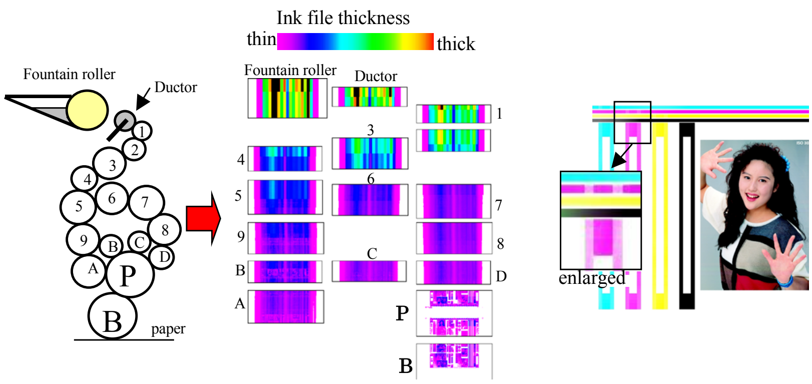


Figure.4 Visualization of the simulator

The users can see how the ink film turns thinner as it goes down from upstream to downstream. As is illustrated, offset press has many rollers. By watching visualized image of roller surface, we can understand two reasons why the machine requires so many rollers; temporal stability and spatial uniformity. The supply system by ductor roller causes periodic change in the ink film thickness on the rollers. We can see that the periodic intensity becomes less obvious as ink is flowing to downstream and it is hardly recognizable on the print substrate.

If the machine had much fewer rollers than it does, ink on print substrate would have more thickness oscillation. This is the temporal stability. As is well known, each ink key controls thickness on the fountain roller by zonal image coverage of the plate cylinder. Generally those thicknesses are uneven, but the difference also turns less obvious as ink is flowing to downstream. It is observed by the animation that three form rollers work together for spatial uniformity on the plate cylinder.

2.2.2. Visualization of ink on print substrate

When the whole image on print substrate is simulated, the simulator outputs the two types of images. One shows where the pixel value is equal to ink film thickness and the other is where the pixel value is multiplied by coverage and is equal to the volume of ink on print substrate. Of these two images, the latter one is similar to actual printed image. All the printed image data from the start to the end can be stored in hard disk sheet by sheet as far as capacity of storage allows. Fig.4 (right) shows a color image composed of ink film thickness on the substrate. Note that the phenomenon called "starvation ghost" which is peculiar to offset-printed images is observed.

2.2.3. Operation

Interactive and automatic operation is available. To imitate an actual printer, we have used the GUI (Graphic User Interface) shown in Fig.5.

We can interactively control many parameters such as printing speed, fountain roller speed, ink key opening, start/stop ink supply and start/stop printing. In addition to the interactive changes of parameters, this simulation software provides a predefined run by setting a control file describing various test conditions.

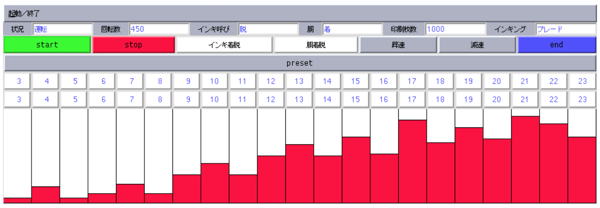


Figure.5 Graphic User Interface

2.2.4. Feedback key control

As to the automatic operation, the simulator has another useful function, automatic key control. In daily production, if the density of a certain area is lower or higher than the target density, the operator raises or lowers the percentage of each key opening of the corresponding area. The simulator works analogously with the human operation and controls the key opening to uniform the ink film thickness.

2.3. Flow chart

So far, we have seen the mechanical model and the data structure part by part. With all these models included, the overall algorithm adopted in the simulator is shown in Fig.6.

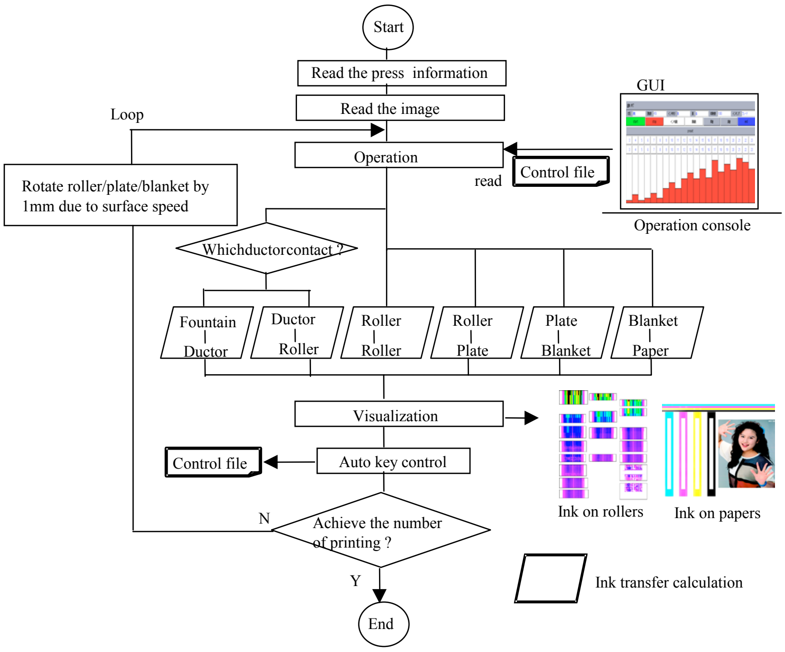


Figure.6 Flow chart

2.4. Developments environment

Computing machine: Sun Eneterprize450 Server (CPU: 480MHz x 2) 2GB memory.
OS: Solaris8, Language C, Compiler gcc-2.95.3,Tcl/Tk-8.4.1.

3. Comparison (I) Uniform tint image

In the beginning, we investigated the ink film thickness in accordance with the number of sheets during the continuous run of the web printer. The steepness of initial rise of ink film thickness depends on the split ratio. Having the simulator run using the uniform tint image shown in Fig.7, we have obtained the thickness curves with some different values of the split ratio k (Fig.8 left). In Fig.8 (left) ink supply is adjusted so that each curve converges to a certain ink film thickness T. If the split ratio is smaller, the larger number of sheets is required until the ink film thickness becomes saturated.

We have also obtained the ink film thickness on paper substrate at a certain ink supply. Fig.8 (right) shows ink film thickness on paper substrate, at a certain number of printed sheet and at a constant k, is proportion to the ink supply.
If the ink film thickness on the fountain roller s (micron) is doubled, the thickness on paper is also doubled at any number of sheets.

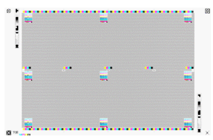


Figure.7 Tint image

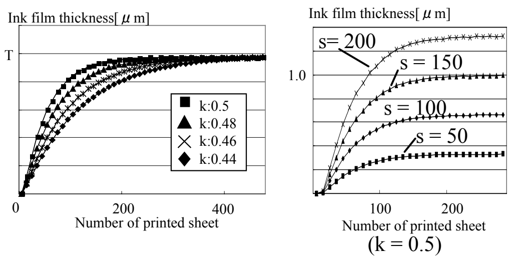


Figure.8 Theoretical curves

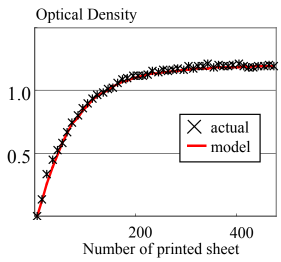


Figure.9 Comprison with actual measurement

So the predicted curves can be represented as Equation (6).

$$y = f(x,k)\ s \qquad (6)$$

With,

y : ink film thickness
x : printed sheet number
k : split ratio (a constant)
s : ink film thickness on the fountain roller
f(x,k) : basic response curve

To compare the simulation results with actual printing test results, which are measured in optical density, we have converted the ink film thickness into optical density using Tollenaar and Ernst equation (7).

$$D = Ds(1-e^{-ay}) \qquad (7)$$

With,
D : optical density
Ds: maximum density
a : a constant
y : ink film thickness

By substituting the right-hand side of Equation.6 for y in Equation.7, we obtain

$$D = Ds(1-e^{-a\, f(x,k)\, s}) \qquad (8)$$

An additional test indicates that Ds is no less than 2.5. When we use Ds as 2.5, the constant *a* is set to 0.65/s for best fitting to a saturation density 1.2.
When K is equal to 0.46, the whole curve best matches the actual test result.
If Ds is larger than 2.5, the split ratio k for best fitting also is larger and if we assume Ds equals infinity, the best-fitting k is found to be 4.8.
This result shows split ratio k is within the range of 0.46 – 0.48, that is not too far off from the previous study.

4. Comparison (II) Varying image coverage

The second experiment is to see how the ink response curve changes as image coverage changes.
In a previous study (Chou et al., 1996,1998), it is stated that the lead press time until the ink film thickness being saturated increases as image coverage decreases, especially in the cases where the ink-feeding mechanism is featured by a ductor-fed open fountain. In our experiment, to confirm the previous studies, we used a sample image in which the image coverage varied from the center to both sides as is shown in Fig.10. The central part of the plate was filled with a 30% uniform tint, and the rest was only dotted with small solid squares for optical density measurement. In order to measure the ink film thickness, two sensors (KURABO RX200) were attached to the No.8 roller (see Fig.4) : one at the center and the other on the right.

Running parameters of the actual test and the simulation are followed by:

- Fountain roller:100 mm/s . Other roller's speed: 3640 mm/s.
- Revolution of the plate : 400rpm.
- The periodic cycle of ductor roller is 1.0s and the contact time with the fountain roller and the first roller is 0.5s each.
- The ink film thickness on the fountain roller is in proportion to the image coverage, so that supply of ink matches the demand of each key zone. (It's up to 250 micron when 100% coverage.)

In advance of this experiment, we had obtained some simulation results, which showed that the ink film thickness curve had some dependency on the image coverage. It took longer time until the ink film thickness becomes saturated as the image coverage decreased. In the cases of both actual printing and the simulation, the graphs of ink film thickness on the roller No. 8 in response to the sheet number are shown in Fig.11 and Fig 12 respectively.

In the actual printing, the response curve of the ink film thickness measured in the higher coverage area (center) showed a steeper rise than the lower coverage area (right side). And the simulation results have well matched the actual ones. This indicates that offset press has the problem of taking a long time until the ink film thickness becomes saturated, especially in the areas of low image coverage. Incidentally, it is also indicated that our simulation model reflects the actuality fairly well.

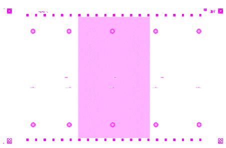


Figure.10 Test image

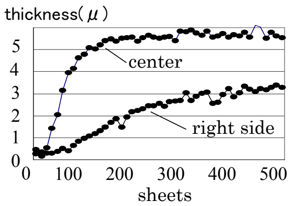


Figure.11 Actual result

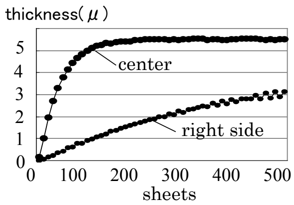


Figure.12 Prediction

5. Comparison (III) Various patterned image

The plate image shown in Fig.13 is designed for the purpose of examining the density uniformity when image placement is complicated to the extent of practicality, and also evaluating the accuracy of prediction by our simulation model. The borderline of each key zone is illustrated in the figure and the image coverage percentage is indicated at the bottom of each zone.

Although some zones have the same image coverage, they have different positions or division numbers to see the effects of those differences. Zones 11,14 and 17 are entirely the same so as to see the effects of the difference of neighbor zones. In the actual test, the plate image was printed up to 2000 sheets. The printing conditions such as the press speed is the same as comparison 2.

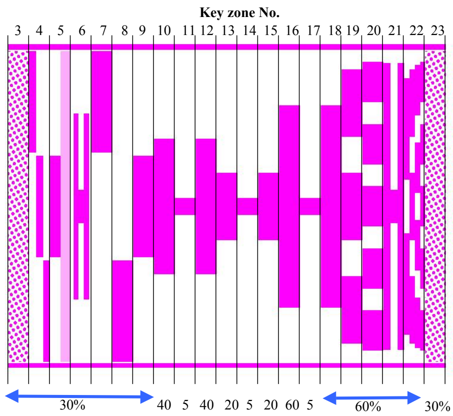


Figure.13 Various patterned image

The whole area of the 2000th sheet was measured by Gretag-Macbeth Spectro Mat. Then the optical density of sheet is converted to color image as Fig.14. We now have obtained the distribution of optical density throughout the sheet. As a result, the following three phenomena were observed.

1. As is indicated in the circle-marked areas in Fig.14, the ink that should be consumed in the neighbor zones seems to have flown into the marked zone.
2. The peaks of optical density at the circle marked area are observed at top and bottom solid color bar too (marked by triangle). The cause of this phenomenon also seems to be the ink flow from neighbor zones.
3. Horizontal streaks of gap are shown in places.

It was also found from the result that the circumferential of image section and the number of sections don't have much effect on the uniformity of optical density. Then we conducted the third comparison between the actual result and the predicted result by the simulator. The same phenomena take place in the numerical result (Fig 15).

The simulator predicts the thickness peaks at the same position marked with circles and triangles and the horizontal streaks are noticeable. But at a glance, we see from the thermal image that ups and downs of thickness are too much emphasized even if the nonlinearly between ink film thickness and optical density is taken into account.
We introduced CV value, where coefficient of variation, which is standard deviation divided by the average, as an index of nonuniformity and recognized that CV value of numerical result is 10.9% and three times as much as the value of actual result 3.3%.

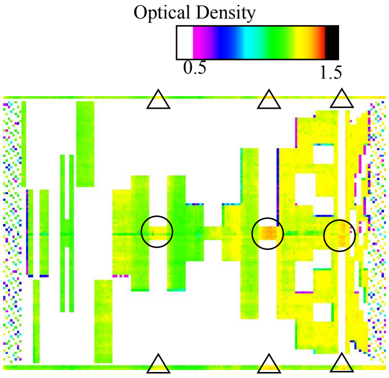


Figure.14 Actual result

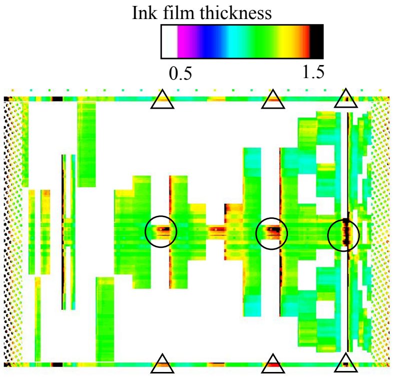


Figure.15 Prediction

6. Discussion

The simulator works well so far in predicting the ink flow of simple pattern image quantitatively and that of more complicated image qualitatively. We see it positively that the simulator emphasizes the actual phenomenon in the third comparison because it implies the simulator has high sensitivity and can predict potential variation.

For practical use, however, when we used this simulator for the application of ink preset, the prediction should be closer to the actual result. So then, we focused on squeeze flow in the nip, which we had neglected, and considered how the ink film thickness is uniformed in actual printing process. We assume the squeeze model composed of two factors; degree of ink flow (cause of ink pile) and the direction (squeeze).

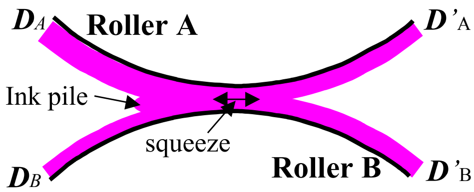


Figure.16 Additional model

We defined the degree of ink flow as b in the equations (9), (10) and (11).

$$D'_A = b\,(1\text{-}k)\,(D_A + D_B + P) \tag{9}$$
$$D'_B = b\,k\,(D_A + D_B + P) \tag{10}$$
$$P' = (1\text{-}b)\,(D_A + D_B + P) \tag{11}$$

With,

b : degree of ink flow

P, P' : ink pile

The variable b means ink passage rate. The ink that can't pass the nip stays at the back as an ink pile, working as a smoother of the incoming ink thickness. The variable P represents the ink pile before the nip passage and P' is after the passage. Equations (9), (10), and (11) also comply with conservation of ink as Equation (12).

$$D_A + D_B + P = D'_A + D'_B + P' \quad (12)$$

We also defined the direction as ink spread function at the nip point. In practical printing dot gain takes place by nip pressure, so, analogously, we assume the same squeeze flow takes place at all nip points and stabilizes the ink film thickness. We simply defined this ink spread function as a square pulse and used it as an convolution filter as is shown in equation (13).

$$D'(x,y) = D(x,y) * ISP(x,y) \quad (13)$$

$$ISP(x,y) = c \ (-a < x < a)$$

$$ISP(x,y) = 0 \ (\text{else}) \quad (14)$$

With,

x,y : position

ISP(x,y) : ink spread function

c : a constant

* : convolution operator

These two additional factors are illustrated in Fig.16. By incorporating those conditions into the simulator, we have found that CV value is reduced in the case where the additional model was adopted only to downstream (Fig.17).

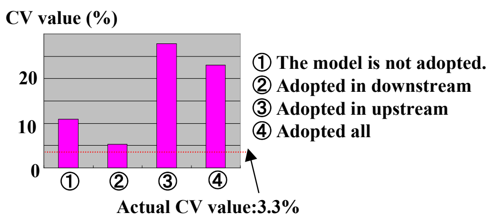


Figure.17 CV value of each case

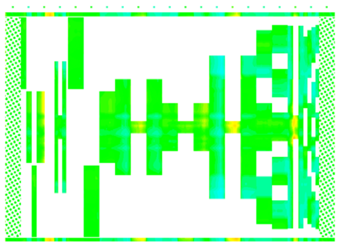


Figure.18 Prediction of new model

Fig.18 shows the uniformity came close to actual result. Note that CV value is rather increased if the model is adopted to all nips or upstream. It can be explained that by the theory that the water changes the ink viscosity. According to Elasto Hydro Lubrication theory, the thickness of passable ink at the nip is formulated by equation (15).

$$H_0 = k \times (\eta^3 U^3 R^3 / WE^2)^{0.2} \tag{15}$$

With,

H_0: degree of passable thickness through the nip
K : a constant
η : viscosity
U: roller surface speed
R : relative curvature that is R1R2/(R1+R2).
W: nip pressure
E : equivalent elastic constant

The equation shows that the less viscosity provides less degree of ink flow. Literature on offset press (Mitsubishi 1992) says that in usual printing conditions, amount of ink passing through the nip is below the limit H_0, and thus no ink pile is left behind. However, we think it possible that the water solution make the ink less viscous at downstream, pushing down H_0.

Although proposed model has close relation to its nature as viscoelastic fluid, the model is intended to make the simulator predict with more accuracy rather than to analyze the complicated mechanism that may depend on the various factors such as the increase of water content, the temperature and so on. In the future, we are using this improved simulator for optimizing for some practical use.

7. Conclusion

We have developed ink flow simulator employing simple ink transfer model and confirmed that density distribution predicted by the simulator is pretty closed to density behavior of actual print. Additional factors were considered in the model. The modified model enables the prediction to be much closer to actual result.

8. Acknowledgment

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