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Analysis on the ink transfer mechanism in R2R application †

Sangwon Lee and Yang Na*
Department of Mechanical Engineering, Konkuk University, Seoul, 143-701, Korea

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Abstract

Ink transfer process from the printing roll to the web was investigated using a Computational Fluid Dynamics (CFD) technique for the roll-to-roll (R2R) printing application. A parametric study was conducted to identify the effects of fluid parameters such as viscosity, surface tension and contact angle. To make the present analysis more relevant to the real printing system, a three-dimensional computational configuration for the commercial software was set up using the information obtained from the typical R2R system. Simplified one-dimensional semi-analytic model based on Reynolds equation was compared with the CFD results to assess the validity of the results. Pressure distribution states that 1-D analysis is reasonably good in capturing the flow physics. The 3-D simulation with VOF (Volume of Fluid) shows that viscosity is the most important parameter. Moreover, the larger surface tension resulted in smaller amount of ink transfer.

Keywords: Gravure printing; Ink transfer; Viscosity; Surface tension; Contact angle

1. Introduction

Continuously running roll-to-roll (R2R) gravure printing technology is receiving much attention these days due to its well-known cost competitiveness. With this attractive feature, this mass production method is being applied to the printing of various types of electronic elements such as radio frequency identification (RFID) tags, flexible displays, biomaterials and miniaturized fuel cells of the next generation. However, to be effectively applied in a wide range of printed electronics, its reliability and printing speed need to be further improved. Thus, much effort is being made in devising better ways of enhancing the reliability in each process of the R2R printing system. Among several technical issues, understanding of ink transfer process (i.e. delivering the ink from the target image engraved on the surface of a printing roll to the tensioned web) plays a significant role for the improvement of both printing quality and the cost.

As a roller is continuously operated, the ink-containing cavities are partially emptied with only a fraction of ink being delivered to the web. As a consequence, both the reliability of printing and the life time of the roll are significantly deteriorated. Unfortunately, fluid dynamics parameters complicate any attempt for the physical understanding of the ink transfer process.

In the past, a series of experimental studies were reported to identify the effect of rotational speed of roll, degrees of impression and ink and material property of the substrate [1-3]. A high cost for the experimental investigation, however, put several limits on the detailed analysis required for a wide range of relevant parameters. In this context, the need for numerical study is increasing with the advance of computer resources.

Most of the previous numerical studies were limited to the coating process [4-5]. However, due to the lack of proper investigation methods of free surface, most of the earlier works were inaccurate. In several investigations, the presence of free surface was handled with the so-called filament stretching method, but omission of the effect of convection and rotation made their analyses less physically realistic [6-9].

In the present study, two different methodologies were attempted. The first method deals with the semi-analytic 1-D model to simulate the flow between printing roll with a cavity and the substrate, as was done by Yin and Kumar [10]. It was assumed that the flow physics can be captured by using Reynolds equation. After determining the physical nature through the 1-D analysis via in-house code, 3-D simulations were conducted by using commercially available software, FLUENT 6.3.26. Results from the two methodologies were compared to establish the effects of crucial fluid parameters.

From our preliminary 2-D studies, the viscosity, surface tension, and contact angle are the three most important fluid pa-

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*Corresponding author. Tel.: +82 2 450 3467, Fax.: +82 2 447 5886
E-mail address: yangna@konkuk.ac.kr

Table 1. Numerical domain.

Roll radius	25mm
Cavity width and length	0.5mm
Cavity Depth	0.25mm
Initial distance between cavity and substrate	0.02mm
Angle of cavity	10°

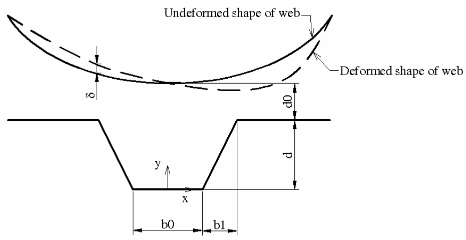


Fig. 1. Geometrical configuration for 1-D analysis.

rameters, as confirmed in several literatures. Thus, focus on the numerical analysis was given to those parameters with the aim of getting physical insight for the ink transfer mechanism.

2. Numerical modeling

2.1 1-D Semi-analytic analysis

Numerical configuration is shown in Figure 1. The gap distance is expressed using the geometric parameters described in the figure as follows:

$$h(x) = h_0 + \frac{x^2}{R} + d - s(x) + \delta_0(x) \tag{1}$$

where R is the radius of curvature of wall, s (x) represents the shape of the cavity, and d_0 is the deformed wall distance. In this study, to conform the geometry to 3-D case $b_0 = 2$, d=1 $b_1 = 0.5$ was selected.

The flow is assumed to be governed by the Reynolds equation,

$$\frac{dP}{dx} = 12\mu\left(\frac{V}{2h^2} - \frac{q}{h^3}\right) \tag{2}$$

For numerical convenience, the governing equation was non-dimensionalized using a length scale d_0 , a velocity scale V , and a pressure scale $\mu V / d_0$ [10]

$$\frac{d\hat{P}}{d\hat{x}} = 6\left(\frac{1}{\hat{h}^2} - \frac{\hat{q}}{\hat{h}^3}\right) \tag{3}$$

$$\hat{h} = 1 + A\hat{x}^2 + \hat{d} - \hat{s} + Ne\hat{p} \tag{4}$$

where $\hat{h} = h / d_0$, $A = h_0 / R$ and if A=0, wall is undeformed. $\hat{P}$ is the non-dimensionalized internal pressure and Ne is defined as follows:

$$Ne = \frac{\mu VL}{Eh_0^2} \tag{5}$$

where E is Young's Modulus; as Ne is approaches zero, thewall becomes more rigid. Pressure was set to zero at both ends of the domain as a boundary condition and a total of 501 grid points were used after several preliminary computations. Relevant geometric parameter A was set to 0 and elasticity parameter Ne was set to 1.

Table 2. Reference ink properties.

Ink properties	Value
Viscosity μ (pa-s)	0.1
Surface tension σ (N/m)	0.033
Contact angle θ (°)	90
Density (kg/m $^{-3}$)	998

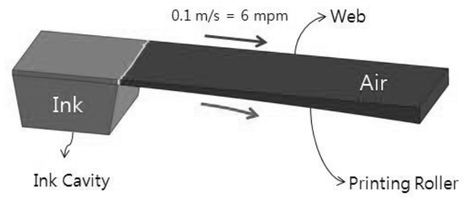


Fig. 2. Simplified 3-D configuration for ink transfer process.

2.2 3-D CFD analysis

Table. 1 and Figure 2 summarize the 3-D computational domain and operational conditions.

FLUENT obtains the solution by solving the following continuity and momentum equations in generalized form:

$$\nabla \cdot u = 0 \tag{6}$$

$$\rho \frac{du}{dt} = -\nabla p + \nabla \cdot \tau + F_b + F_s \tag{7}$$

In order to handle the free surface formed between ink and air, a popular VOF method was used as follows [11]:

$$\frac{\partial C}{\partial t} + u \cdot \nabla C = 0 \tag{8}$$

where C is volume fraction and has the following values:

$$C = \begin{cases} 1, \text{ inside the liquid phase} \\ > 0, < 1 \text{ at the free surface} \\ 0, \text{ inside the gas phase} \end{cases} \tag{9}$$

Using this volume fraction, density and viscosity can be obtained.

$$\rho = C\rho_l + (1 - C)\rho_g \tag{10}$$

$$\mu = C\mu_l + (1 - C)\mu_g \tag{11}$$

To treat surface force of the right hand side of Equation (6), continuum surface force (CSF) was used.

The velocity of moving substrate was set to 6mpm, which is a typical speed for RFID printing process with sufficient curing time. The angular velocity of roller was described as 4 rad/s to get zero relative velocity at the point of contact.

3. Result

3.1 Comparison 1-D with 3-D

Figs. 3 and 4 illustrate pressure distributions obtained from both 1-D and 3-D investigations, respectively. For proper comparison, the centerline was chosen as the reference line for

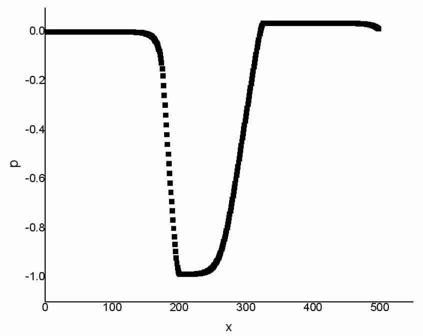


Fig. 3. Pressure distribution in the main direction in 1-D analysis.

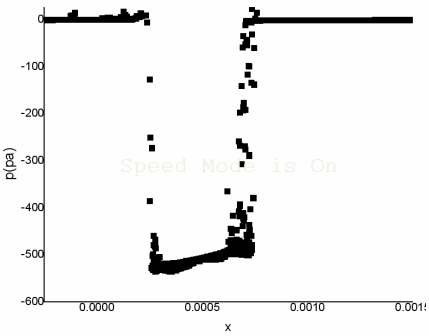


Fig. 4. Pressure distribution in the main direction in 3-D analysis.

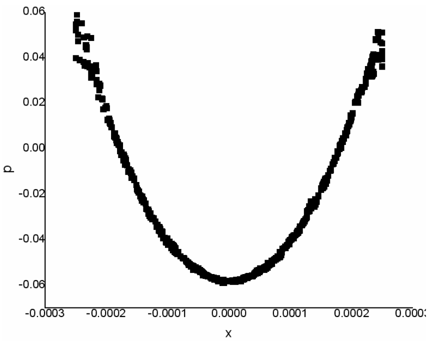


Fig. 5. Pressure distribution among cross (z) axis in 3-D analysis.

3-D results. Surprisingly, the behavior of pressure distribution was remarkably similar. This result strongly suggests that the 1-D model is reasonably good even with very aggressive simplification. The pressure distribution in the cross direction indicates that there is a significant pressure variation in that direction, as shown in Fig. 5. Thus, it is apparent that the end effect cannot be negligible.

3.2 Results from 3-D analysis

3.2.1 Effect of viscosity

Due to temperature dependence, changes of viscosity during R2R process may not be negligible. However, typical R2R process for printed electronics is carried out at normal temperature (20-25^{o} C), thus the variation of viscosity was assumed to be insignificant, as a first step of the analysis. Moreover, viscosity is likely to depend on velocity and shear rate but the web moving velocity is relatively low (i.e., 0.1m/s) and the change of viscosity was also assumed to be negligible. This assumption of constant viscosity could lead to some degree of error, but it was assumed that the basic physics would not be modified significantly in line with the purpose of the present work. Fig. 6 shows the effect of viscosity. Results were obtained 0.05sec from the beginning of simulation. As the viscosity increases, it was apparent that more ink was transferred to the web, as shown in the volume fraction of the ink. In addition, the amount of ink remaining in the cavity decreased and the thickness of the ink column attached to the web increased simultaneously as the viscosity increased.

3.2.2 Effect of surface tension

As the size of geometry becomes smaller, the role of the surface tension increases. Thus, several changes in surface tension were attempted. Fig. 7 clearly represents that surface tension also plays a significant role in ink transfer. The amount of the ink transferred increased as the surface tension coefficient decreased. It may be necessary to investigate the effect of the capillary number which represents the ratio of viscosity and surface tension.

In the present study, the capillary numbers were calculated to be 1.25, 0.3 and 0.14. In general, when capillary number is more than 1, the surface tension force dominates the flow. Thus the effect of surface tension on ink transfer is crucial.

3.2.3 Effect of contact angle

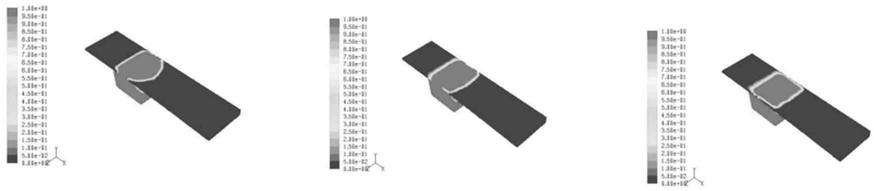
To determine the effect of the hydrophilic and hydro phobic characteristics of the web, simulations with different contact angles between the web and ink were implemented. In general, the smaller contact angle brings about improved amount of the ink to the web when the substrate has a hydrophilic property. As shown in Fig. 8, the amount of transferred ink increased as the contact angle became smaller. However, the contact angle appears to play a less significant role than the viscosity.

4. Conclusion

Ink transfer mechanism was investigated using CFD technique in order to establish the effect of relevant parameters. A relatively larger printing dot pattern than common was considered for simplicity in the present study.

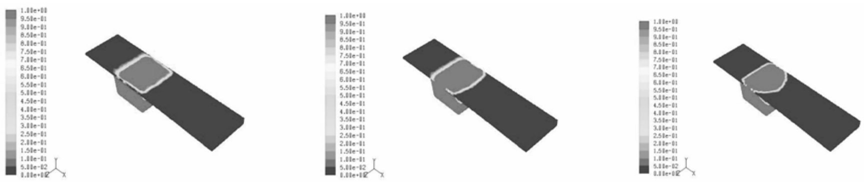
It was shown that 1-D model based on Reynolds equation can reasonably predict the pressure variation between the printing roll and the web. As expected, there exists a significant end-effect in the cross direction and this non-negligible variation implies the limitation of the 1-D analysis.

The effect of ink viscosity is determined to be the most crucial parameter in the ink transfer process. As the viscosity increases, the amount of ink transferred increases in accordance with several experimental results. The effects of surface tension and contact angle are also investigated. As the surface tension and the contact angle decrease, the amount of ink transferred increases, but they have lesser significant influence than the effect of viscosity from the point of ink transfer.



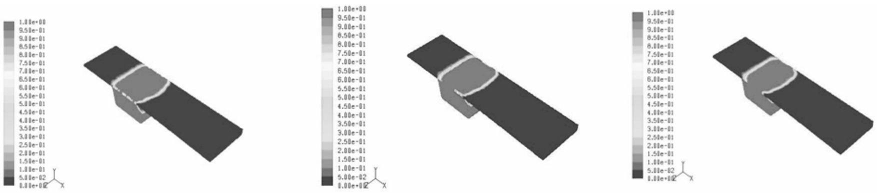
(a) μ=0.05pa-s (b) μ=0.1pa-s (c) μ=0.5pa-s

Fig. 6. Contours of ink volume fraction: the effect of viscosity.



(a) σ =0.008N/m (b) σ =0.033N/m (c) σ =0.074N/m

Fig. 7. Contours of ink volume fraction: the effect of surface tension.



(a) θ=60 ° (b) θ=90 ° (c) θ=120 °

Fig. 8. Contours of ink volume fraction: the effect of contact angle.

Acknowledgment

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Sangwon Lee received his B.S. and M. S. degrees in mechanical engineering from Konkuk University, Korea. Now, he is working with Samsung Electronics. His research interest is in the area of computational fluid dynamics.

Yang Na received his B.S. and M. S. degrees in mechanical engineering from Seoul National University, Korea and Ph. D. degree from Stanford University, U.S.A. His research interest is in the area of computational fluid dynamics and convective heat transfer.