# Impact of Ink Rheology and Surface Hydrophobicity on Shear-Induced Behavior in Gravure Printing Applications

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**ABSTRACT**

This study presents a numerical simulation of droplet transfer under shear force in a gravure-offset printing machine, using a two-phase Volume of Fluid (VOF) method. The investigation begins by examining the effects of advancing and receding contact angles, shear velocity, and surface stress coefficient on droplet shape and transfer efficiency. Following this, the study explores how hydrophobic surfaces impact ink transfer quality. Results indicate that increasing the advancing contact angle from 75º to 105º reduces the transfer ratio by 14%. Furthermore, implementing a hydrophobic surface on the bottom plate significantly enhances ink transfer, allowing nearly all injected ink to transfer to the upper surface.

**KEY WORDS**

hydrophobic surfaces, gravure printing, contact angle, VOF method.

## 1. INTRODUCTION

Gravure-offset printing is one of the most widely used methods in the printed electronics industry [1, 2]. In this process, a gravure is filled with a non-Newtonian fluid, which is picked up by a silicon blanket and transferred onto a surface. The ink used in this process has higher viscosity and lower surface tension compared to Newtonian fluids [3].

Many researchers have studied droplet behavior during the stretching process, often without considering the effects of shear forces in printing machines [4]. Therefore, in this research, a numerical simulation of non-Newtonian real ink transfer during the printing process, influenced by shear forces, was conducted using the VOF method. The study focused exclusively on the ink transfer stage from the plate cylinder to the blanket, simulating the effects of various physical properties on the ink transfer process. Additionally, it is evident that surfaces with micro textures increase the surface hydrophobicity. Because the main goal in the printing process is to maximize the transferred ink, the effect of hydrophobic surfaces on transferred ink is investigated.

## 2. Numerical simulation

Transient two-dimensional numerical simulations of the ink-transfer process were performed. The system consisted of two immiscible fluids, which were represented as liquid and gas phases. The conversion equations for the laminar two-phase flow are as follows:

$$\nabla \cdot \mathbf{u} = 0 \quad (1)$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u}) = -\nabla P + \rho \boldsymbol{g} + \nabla \cdot \left(\mu(\nabla \mathbf{u} + \nabla^T \mathbf{u})\right) + \boldsymbol{F}_{st} \quad (2)$$

According to the VOF method, the liquid volume fraction ($f$) in different parts of domain is:

$$f = \begin{cases} fluid1 & f_1 \\ fluid2 & f_2 \\ at\ interface & f_1 < f < f_2 \end{cases} \quad (3)$$

The process properties are listed in Table 1.

Table 1. Physical and geometrical parameters

| Parameter | Values |
|---|---|
| $\mu_{0,l}$ | 0.227 *kg/m s* |
| $\lambda$ | 0.7 |
| $n$ | 0.733 |
| $\rho_l$ | 2200 $kg/m^3$ |
| $\rho_g$ | 1.1614 $kg/m^3$ |
| $\mu_g$ | $1.846 \times 10^{-5}$ *kg/m s* |
| $\sigma$ | 0.044 *N/m* |
| $V$ | 0.2 *m/s* |
| $\upsilon$ | 32 $\mu m^2$ |
| $L_0$ | 8 $\mu m$ |

## 3. Resulta and disscussion

*2.1 Physical properties*

First, the effect of increasing the advancing contact angle on the ink structure was investigated. For this purpose, three different angles—75º, 90º, and 105º—were considered. The advancing contact angle significantly affects the transfer ratio, as increasing $\theta_a$ from 75º to 105º reduces the transfer ratio by 14%. Additionally, it seems that this angle does not have a substantial effect on the breakup time, as the difference in breakup time between the angles of 75º and 105º is negligible.

The receding angle influences the ink transfer ratio in a manner similar to the advancing angle. At 45º, the transfer ratio was 48.4%, whereas at 75º, the transferred ink amount decreased by 2.6%, reaching 45.8%. Additionally, by increasing the receding angle from 45º to 75º, the break time was reduced by 0.375°.

The surface tension coefficient has a greater effect on the break time, whereas the transfer ratio decreases slightly. The results show that a droplet with a surface tension coefficient of 0.03 N/m would break after a period of 3, while a droplet with a surface tension coefficient of 0.09 N/m would break after 2.5. This also reduces droplet elongation during the process. As the surface tension coefficient increases from 0.03 to 0.09 N/m, the droplet elongation at the time of breakup is reduced by 0.46$L_0$. Additionally, the breakup time and droplet elongation exhibit an inverse relationship due to the increasing surface tension force, which accelerates droplet breakup.

The shear velocity has an optimum value of 0.2 m/s, at which the break time is minimized and the transfer ratio is maximized. In addition, increasing the plate velocity also leads to an increase in droplet elongation. Similar to the break time, the elongation rises between velocities of 0.2 and 0.4 m/s, whereas at the velocity of 0.1 m/s, it tends to remain constant. At the moment of breakup, this increase reaches its maximum, and by raising the velocity from 0.1 to 0.4 m/s, the elongation increases by 0.74$L_0$.

*2.2 Hydrophobic surfaces*

Surface topography plays a vital role in the contact between liquid droplets and solid surfaces. In nature, the wettability and contact angles can be varied by introducing microstructuring. For example, the surface of a lotus leaf shows excellent water repellency owing to the presence of microbumps on its surface. The contact angle of the droplet on the hydrophobic surface is greater than smooth surface and this difference is approximately 40º.

On hydrophobic surfaces, the wetted surface (w) is smaller than on smooth surfaces, meaning the fluid minimizes contact with the surface, forming a compact drople. The wetted area in the hydrophobic case is consistently smaller than that of the smooth surface at all times. By the end of the simulation, in both cases, the droplet reaches equilibrium, and the wetted surface becomes almost constant. However, the wetted surface ratio (w/$d_0$) for the hydrophobic surface is approximately 1.25 times smaller than that of the smooth surface.

Fig. 1 shows the effect of surface topography on ink transfer for two types of surfaces with similar initial conditions. In the (a) mode, the surface is smooth, whereas in (b), the surface has micro textures. As can be observed, by hydrophobizing the bottom plate, the amount of transferred ink approaches nearly 100%.

The hydrophilic surface has the most significant effect on both the breakup time and transfer ratio among the investigated properties. The separation time on the hydrophobic surface is nearly one-fifth that of the hydrophilic surface, while the transfer rate on the hydrophobic surface is reduced by half compared to the hydrophilic one.

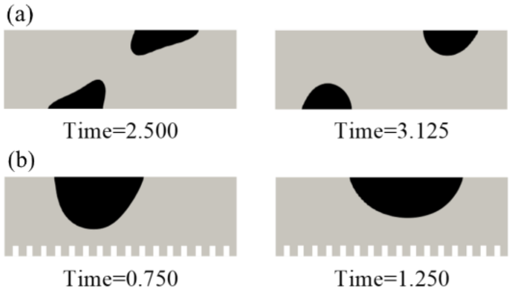


Fig. 4. Ink transfer process on (a) smooth, (b) hydrophobic surfaces.

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