International Journal of Heat and Fluid Flow 30 (2009) 796–803

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

journal homepage: www.elsevier.com/locate/ijhff

Film flow around a fast rotating roller

Seung-Hwan Yu, Kwan-Soo Lee *, Se-Jin Yook

School of Mechanical Engineering, Hanyang University, 17 Haengdang-dong, Seongdong-gu, Seoul 133-791, Republic of Korea

A R T I C L E I N F O

Article history:
Received 23 July 2008
Received in revised form 29 December 2008
Accepted 22 January 2009
Available online 27 February 2009

Keywords:
Film flow
Rotating roller
VOF method

A B S T R A C T

In this study, the film thickness around the roller is numerically estimated using the volume of fluid (VOF) method to clarify the film-formation process around the rotating roller. Parametric studies were performed to compare the effects of ink properties (viscosity, surface tension) and operational conditions (roller rotation speed, initial immersed angle) on film thickness. The viscosity of the ink and the speed of rotation of the roller were found to be the dominant factors that determine the ink film thickness. In addition, a correlation equation is proposed to predict the thickness of the ink film around a printing roller rotating at a speed of 20–30 rad/s, as a function of angular position, angular velocity, and viscosity.

1. Introduction

Recently, the liquid coating is widely used in many industrial applications. For example, gravure printing is adopted to coat paper, fabric or metal sheets with decorative or protective materials. A schematic of gravure printing is depicted in Fig. 1. The printing process is as follows. Ink is supplied into the engraved cell, and the doctor blade removes the excess ink. Subsequently, the force acting on the cell transfers the ink onto the substrate, which is fed between the impression roller and printing roller. To achieve a high-quality print with accurate dimensions, the amount of ink supplied to the cell must be precisely controlled. When the excess ink is doctored, an important factor is the ink film thickness around the rotating printing roller. If the ink film is too thick, the excess ink outside the engraved cell will not be perfectly doctored, resulting in poor quality printing. However, to remove it completely, excessive doctoring will reduce the useful life of the printing machine due to wear of the doctor blade and the printing roller surface. If the ink film is too thin, obtaining uniform prints becomes difficult. Therefore, controlling the ink film thickness before doctoring the excess ink is extremely important in ensuring both uniform print quality and the durability of the printing machine.

Numerous studies have analyzed the liquid film thickness around a rotating roller for a Newtonian fluid. Spiers et al. (1974) divided the film on a vertically moving plate partially immersed in a liquid into three regions, the static meniscus, dynamic meniscus, and constant-film-thickness regions, and proposed theoretical models to predict film thickness. Tharmalingam and Wilkinson (1978) suggested models to predict film thickness around a rotating roller based on the model of Spiers et al. (1974) by considering the effects of the immersion and inspection angles and compared predictions with experimental data. Campanella and Cerro (1984) showed the effects of immersion angle, roller radius and speed of rotation on film thickness using the rapid-flow approximation derived by Cerro and Scriven (1980).

These studies dealt with the film flow around a rotating roller with an angular speed lower than 10 rad/s. When the linear speed of the roller surface is above 50 cm/s, measuring film thickness experimentally becomes difficult due to instability of the flow (Campanella and Cerro, 1984). A theoretical prediction of film thickness is also hard due to the disappearance of the static meniscus region. Furthermore, as the viscosity of ink changes with dilution by the solvent, the effect on film thickness of a change in viscosity must be considered.

In this study, the film flow around a rotating roller partially immersed in ink was numerically analyzed at relatively high speeds of rotation. The parameters that affect film thickness were first categorized into two groups. The "property parameters" were the viscosity and surface tension, which were dependent on the solvent dilution of the ink. The "operation parameters" were the angular velocity and the initial immersion angle of the printing roller. Parametric studies were then performed to compare the effects of these four parameters on film thickness. Based on the results, we propose a correlation equation that can predict film thickness on a roller rotating at high speed.

2. Numerical model

Fig. 2 shows a schematic of the computational domain for this study. The pan was 0.6 m wide and 0.6 m high while the diameter of the roller was 0.15 m. The initial thickness of the ink was

* Corresponding author. Tel.: +82 2 2220 0426; fax: +82 2 2295 9021.
E-mail address: ksleehy@hanyang.ac.kr (K.-S. Lee).

0142-727X/$ - see front matter
doi:10.1016/j.ijheatfluidflow.2009.01.013

Nomenclature

Ca	capillary number $\left(\frac{\mu U}{\sigma}\right)$
F	force (N)
G	gravitational force (N/m^2·s)
h	film thickness (cm)
N	normal vector
P	pressure (N/m^2)
R	radius of a roller (m)
T	film thickness number $(h(\rho g \sin\theta_i/\mu U)^{1/2})$
U	roller surface velocity ($r\omega$)
V	velocity (m/s)
v	tangential vector
We	Webber number $\left(\frac{\rho L U^2}{\sigma}\right)$
x	film position (cm)

Greek symbols

α	volume fraction
κ	curvature (m^{-1})
μ	viscosity (N/m^2·s)
θ	angular position (°)
ρ	density (kg/m^3)
σ	surface tension coefficient (N/m)
ω	angular velocity (rad/s)

Subscripts

i	Immersion
k	kth phase
r	Reference
SF	surface tension source term
w	wall adhesion

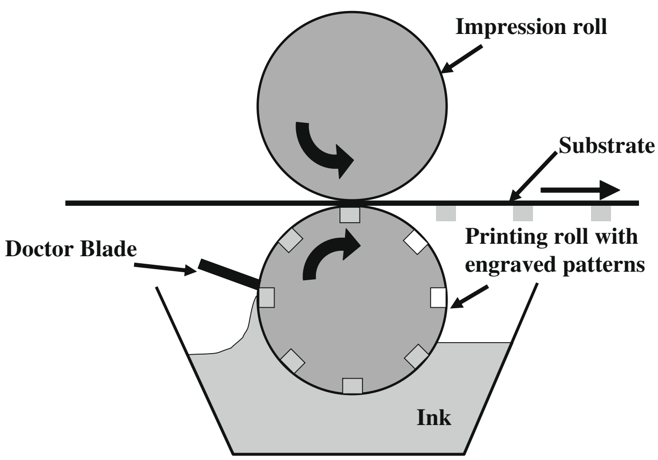

Fig. 1. Schematic of gravure printing.

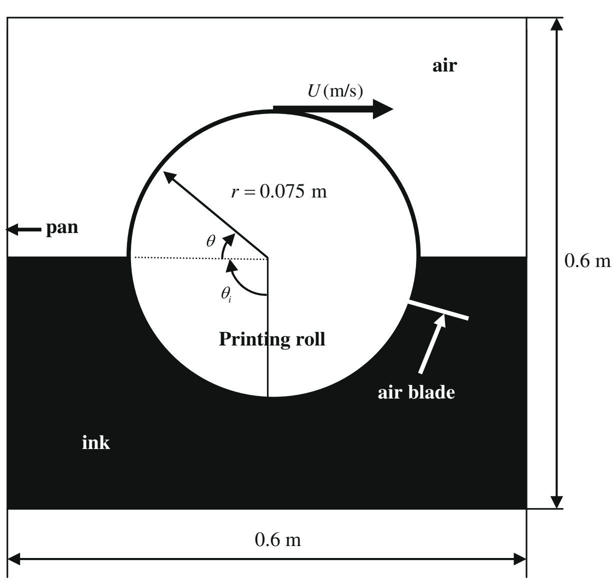

Fig. 2. The computational domain used for gravure printing.

assumed to be half of the pan height as shown in Fig. 2. This corresponds to 90° for the immersion angle (θ_i). The doctor blade used in the actual gravure printing apparatus was not considered in the numerical calculation because it forcibly reduces the film thickness and the characteristics of film flow cannot be observed. For the numerical analysis, the following assumptions were made.

(1) The flow is unsteady, laminar, incompressible and two-dimensional.
(2) The properties of the fluids are independent of temperature.
(3) The two fluids (air and ink) are immiscible, and therefore a free surface exists.
(4) The contact angle between the ink and the roller is 90°. (The contact angle is usually smaller than 90°. However, the effect of contact angle is negligible because the film flow entirely covers the roller surface. Therefore, the contact angle of 90° is assumed for the VOF modeling.)
(5) Air entrainment into the ink at the right-hand side of the roller, caused by the rotation, was prevented by the air-blade. Without an air-blade, air entrainment into the ink at the right-hand side of the roller, caused by the high speed rotation, will happen. Then, air bubbles can move along the roller surface and make the film flows unstable (Bolton and Middleman, 1980). In order to forcibly remove the air entrainment, the air-blade was installed at the right side of roller as shown in Fig. 2.

2.1. Governing equations

The volume of fluid (VOF) method (Hirt and Nichols, 1981) was adopted in the present study. The VOF method was used by many researchers to simulate the flow of two immiscible fluids (Cook and Behnia, 2001; Nikolopoulos et al., 2005; Lan et al., 2008). To calculate the interface between the two fluid phases, the piecewise linear interface calculations (PLIC) method (Rider and Kothe, 1998) was used. It assumes that the interface between two fluids has a linear slope in each cell, and uses this linear shape to calculate the advection of fluid through the cell faces. The first step in this reconstruction scheme is to calculate the position of the linear interface relative to the center of each partially-filled cell, based on the information about volume fraction and its derivatives in the cell. The second step is to calculate the advecting amount of fluid through each face using the computed linear interface representation and information about the normal and tangential velocity distribution on the face. The third step is to calculate the volume fraction in each cell using the balance of fluxes calculated during the previous step.