Chemical Engineering Science 149 (2016) 169–180

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Three dimensional flow of liquid transfer between a cavity and a moving roll

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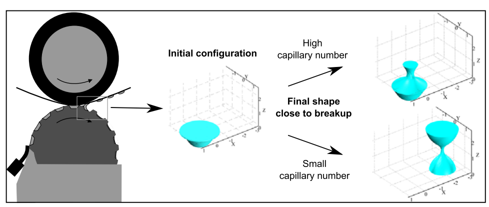
HIGHLIGHTS

- Full three-dimensional analysis of liquid transfer from a cavity to a rotating roll.
- Transferred liquid volume depends strongly on the capillary number of the process.
- At low capillary number, poor printing placement precision (registration) is attained.
- At high capillary number, registration improves and transferred volume is still high.
- Smaller roll diameter contributes to higher transferred liquid volume.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 24 November 2015
Received in revised form
12 April 2016
Accepted 17 April 2016
Available online 19 April 2016

Keywords:
Gravure printing
Liquid transfer
Contact line
Printed pattern
Finite element method
Three-dimensional free surface flow

ABSTRACT

Gravure printing is one of the most promising technologies for high volume production of printed electronics and microscale films and devices. The characteristics of the printed pattern, i.e. ink volume, resolution and pattern placement (registration), are directly related to the fluid mechanics of the liquid transfer process from a cell to a substrate wrapped around a rotating roll; the liquid transfer is mainly controlled by free surfaces and dynamic contact lines. Most of the available analyses are restricted to axisymmetric flows, at which the relative motion between the cavity and the substrate is greatly simplified. Recent results have shown that the use of the complete description of the relative motion in a roll-to-roll process is critical to obtain accurate results on the amount of liquid that is transferred to the substrate. In this work we present an extension of the model describing liquid transfer from a groove to a substrate in a R2R process in order to consider the liquid transfer from a small individual cell; to this end we solve a full 3D free surface flow with moving contact lines. The results show that the liquid transfer dynamics is governed by two different characteristic time scales, one is associated with the contact line motion and the other with liquid filament breakup. Both are dependent on the

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http://dx.doi.org/10.1016/j.ces.2016.04.035

capillary number. The predictions show how the volume, registration and shape of the printed dot varies with operating conditions and liquid properties. These predictions could be helpful in designing high precision printing operations.

1. Introduction

In the last ten years, the development of novel conductive organic materials together with the need to build electronic circuits on flexible substrates has renewed the attention on printing technologies (Willmann et al., 2014; Kang et al., 2013). The effort has been specially directed to roll-to-roll processes (R2R), mainly due to the potential high production rates. Among the different R2R processes, roto-gravure techniques provide a good compromise between production rate and the required printed pattern resolution (Krebs, 2009). In roto-gravure printing, the pattern to be printed is engraved on the surface of a rotating roll; then, as depicted in Fig. 1a, the pattern is transferred to the substrate by pressing it between the engraved and a second soft roll. The fluid mechanics of liquid bridges with moving contact lines between moving surfaces has been the subject of considerable research (see Kumar (2015) for a review) because it is essential for understanding many aspects involved in printing.

Here we focus on the particular aspect of liquid transfer from a single cavity to a flat surface. Because of the small scale, the complex relative motion between two rotating surfaces and the relative high speed of these surfaces, flow visualization is extremely challenging. A common approach is to use scaled-up cavities with simplified kinematics. For example, Yin and Kumar (2006) used a groove with trapezoidal cross section having a width and depth of approximately 1 mm to visualize the liquid transfer from the groove to a curved surface (or a rubber-covered roller) moving horizontally over the groove. They found that the volume of liquid remaining inside the groove increases as a power-law function with the capillary number, while the flow visualization suggested an emptying mechanism mainly controlled by capillary forces. This observation was more remarkable when small gaps were formed between the moving surface and the cavity corners, because in this case high capillary pressure gradients were produced in the menisci driving liquid outside the cavity. Despite the simplified kinematics used and the fact that the range of Stokes number (ratio between gravitational and viscous forces) in the experiments was orders of magnitude higher than in actual gravure printing process, flow visualization revealed the importance of contact line motion on the liquid transfer process. Other experiments using scaled-up gravure cells presented by Chuang et al. (2008) and Lee et al. (2012) show similar results. More recently, Sankaran and Rothstein (2012) used axisymmetric trapezoidal cavities (width and depth ~2 and 1 mm, respectively) to study the effect of the vertical stretching velocity and fluid rheology on the liquid transfer process. The results indicate that, with pure vertical relative motion between the surfaces, the volume of transferred liquid rises with capillary number up to a plateau. As was discussed in a subsequent related work (Lee et al., 2013), the appearance of this plateau was probably due to limitations of the experimental setup for working at high speeds. They also showed that the elastic stresses, which occur when viscoelastic liquids are used, delay the filament breakup. Because gravity had an important effect on the experiments, the impact of the viscoelasticity upon the transfer process was highly dependent on the setup configuration. Despite the interesting results of the aforementioned works, at the real scale of the problem (micrometers), gravity is certainly negligible; therefore, modeling can be a powerful tool to understand the fundamentals of the flow.

Powell et al. (2002) presented a finite element model to study the liquid removal from a groove by the action of a passing meniscus. Inspired in this work, Hoda and Kumar (2008) solved a similar problem but used the boundary integral method to study the liquid removal. The contact line was fixed at the moving plate and it was allowed to slip along the cavity wall. The results revealed that the amount of liquid left inside the groove was a strong function of the kinematics imposed by the moving plate.

Dodds et al. (2009, 2011) presented a 2D axisymmetric analysis of the liquid transfer between a fixed single trapezoidal cavity and a surface moving vertically away from it (see Fig. 1b), to determine

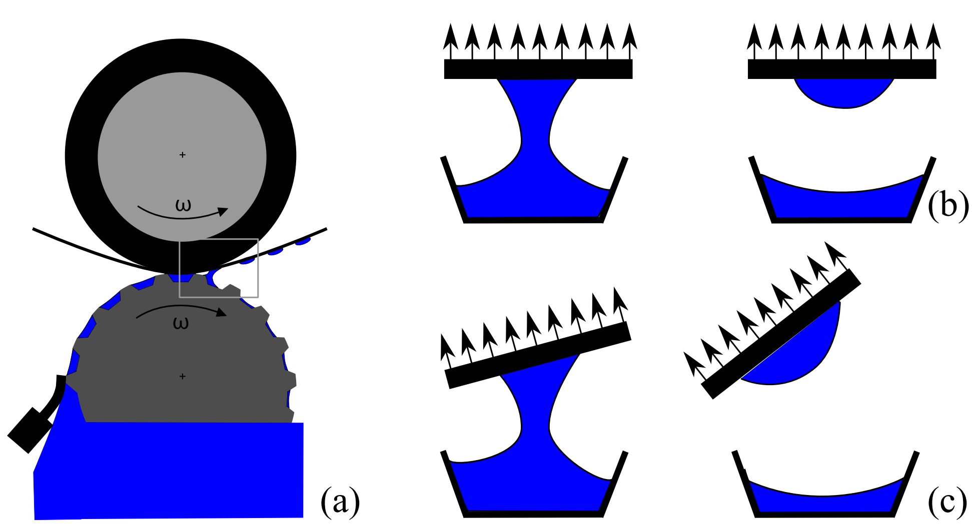

Fig. 1. (a) Sketch of a roto-gravure printing system; (b) simpler model for the liquid transfer between a single cavity and substrate, considering a one dimensional surface motion; (c) a more realistic model, where the surfaces motion tends to mimic the roll-to-roll kinematics.