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Flow visualization of the liquid-emptying process in scaled-up gravure grooves and cells

Xiuyan Yin, Satish Kumar*

Department of Chemical Engineering and Materials Science, University of Minnesota, 151 Amundson Hall, 421 Washington Ave. SE, Minneapolis, MN 55455, USA

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Abstract

The liquid-emptying process in scaled-up gravure grooves and cells is studied using flow visualization in order to better understand gravure coating and printing processes. Water and two different glycerin/water mixtures serve as the test liquids, and the emptying process is initiated by moving over the groove or cell a rotating roller or a glass top with a curved surface. For the scaled-up groove, a region of recirculating flow is observed to attach to the moving glass top. When the glass top is used to drive flow in the scaled-up cell, an air bubble may appear inside the cell when the gap between the bottom of the curved surface and the top of the cell is zero. When this gap is positive, a liquid bridge is formed, dragged across the cell, and then broken, leaving some liquid inside the cell. The amount of liquid remaining in the cell, V_r, is measured for different liquids, surface speeds, and gap distances for both the glass top and the rotating roller. The effect of using a soft elastomeric covering on the glass top and roller is also explored. For each liquid, V_r increases as the speed of the glass top or roller increases. The data are correlated by multiplying V_r by a liquid-dependent shift factor, which leads to a power-law relationship between the shifted V_r and the capillary number. These experimental observations and measurements can be used to benchmark theoretical calculations, which can then be applied to design gravure grooves and cells that empty in a controlled way.

Keywords: Fluid mechanics; Gravure; Laminar flow; Materials processing; Multiphase flow; Visualization

1. Introduction

Gravure coating and printing are processes that can produce very thin films (1–50 μm) or tiny patterns (width < 100 μm) on substrates at high speeds (up to 15 m/s). They are used for adhesives, magnetic tape, magazines, and many other coated and printed products (Booth, 1970). The most important part of a gravure process is the gravure roll, a cylinder patterned with grooves or cells which are engraved onto the roll surface either chemically or mechanically. A typical groove or cell has depth ∼40 μm and width ⩽ 100 μm, and the cell densities are between 220 and 400 cells per inch (Patel and Benkreira, 1991). Fig. 1 shows a typical gravure operation. The grooves or cells are usually filled by rotating the gravure roll into a liquid pool, and the excess liquid on the gravure roll is wiped by a flexible blade. The liquid remaining in the grooves or cells is partly transferred to the substrate directly (direct gravure) or through one or more rubber-covered offset rolls (offset gravure). Then the grooves or cells, which may have been only partially emptied, return to the pool to be refilled. During this process, the unemptied liquid may evaporate, causing accumulation of solid residues and ultimately undesired thickness variations in the final product. Furthermore, the amount of liquid transferred from the grooves or cells will affect coating thickness and print resolution. Therefore, it is important to understand how and how much liquid will be transferred during the emptying process in order to better design and optimize gravure processes. This work studies the emptying process by visualizing the flow inside a single scaled-up groove or cell because it is difficult to directly

* Corresponding author. Tel.: 612 625 2558; fax: 612 626 7246.
E-mail address: kumar@cems.umn.edu (Satish Kumar).

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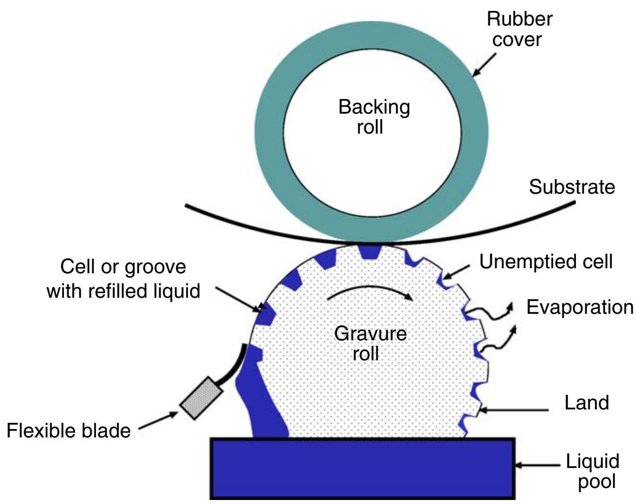

Fig. 1. Schematic of a gravure process.

observe the flow inside actual grooves and cells due to their small size and the fast speed of the gravure roll.

In general, modeling the flow inside gravure grooves and cells is a formidable problem involving a 3D geometry, free surfaces, moving contact lines, and elastohydrodynamic interactions. Electrohydrodynamic interactions are sometimes involved, too, as electrostatic assist can be employed to aid liquid emptying. Substrate porosity is yet an additional factor which will influence emptying. To date, there has been relatively little theoretical work on liquid emptying from gravure grooves and cells. Schwartz and co-workers developed a 2D lubrication model and used it to study the withdrawal of a topographically patterned substrate from the region underneath a meniscus (Schwartz et al., 1998; Schwartz, 2002). Powell, Savage, and Gaskell formulated a 2D model to simulate the evacuation of fluid from a rectangular cavity when a meniscus translates across the cavity (Powell et al., 2000). They found that the evacuation was incomplete, the fraction of liquid evacuated increases as the capillary number (ratio of viscous forces to surface tension forces) decreases or the cavity aspect ratio (ratio of cavity width to depth) increases, and the evacuation becomes independent of capillary number for cavities with a sufficiently large aspect ratio. Related work by Gramlich, Mazouchi, and Homsy (Gramlich et al., 2004; Mazouchi et al., 2004) examines the contact line motion of a viscous liquid flowing over topographical features on a substrate.

Most published experimental work on gravure coating focuses on coating quality as a function of different operational variables. Pulkrabek and Munter (1983) studied the ribbing phenomenon of a roll coater and a rotogravure coater, and found that the knurl line frequency of the knurl roll surface should match the natural fluid ribbing frequency to achieve a stable coating. Benkreira and Patel (1993) and Patel and Benkreira (1991) measured the film thicknesses for direct gravure coating under various operating conditions (coating speeds, roller roughness, substrate wrap angles, and liquid properties) and concluded that the film thickness only depends on the shape of the gravure cell. In particular, the emptying fraction for trihelical and pyramidal cells is larger than for quadrangular cells. Benkreira and Cohu (1998) reported the effects of operating variables on air entrainment and ribbing instabilities in an experimental study of forward direct gravure coating on an unsupported web. They found that ribbing occurs when the gravure roll speed is higher than a critical value for a given substrate speed, air entrainment occurs when the substrate speed is higher than a critical value at a given gravure roll speed, and at lower gravure roll and substrate speeds there is a stable coating region that can be enlarged by increasing the wrap angle. Kapur (1999, 2003) investigated the dependence of film thickness and system stability on operating parameters for both direct and offset gravure, and observed that there exists a critical roll-to-web speed ratio above which the liquid transfer becomes unstable.

In the area of gravure printing, both theoretical and experimental efforts have been made to uncover the mechanisms of liquid transfer from the gravure cells to the substrate. A series of equations was developed (Bery, 1976; Joyce and Fuchs, 1966) to predict the volume of ink transfer as a function of ink properties, substrate properties, and cell area in contact with the substrate. Results from the calculations showed good agreement with experimental measurements (error $< 4\%$). Pritchard and Finkle (1964) measured the ink transfer percentage for different cell depths, ink viscosities, substrate properties, and pressure applied to the substrate. The data showed that the maximum ink transfer attainable is 48% for non-absorbent materials and 60% or above for highly absorbent materials. Pritchard (1965) also used a scaled-up cell (100 times the normal size) to study the ink transfer mechanism. Based on a few experiments, it was concluded that the doctor blade was a dominant factor for ink transfer and that lower speeds, lower ink viscosities, and deeper cells tended to give higher ink transfer fractions. High-speed photography has been widely used in visualizing the gravure roll surface before and after ink transfer to study the effect of cell patterns (Weidemann, 1965), air bubbles (Bery, 1985), substrate properties (Kunz, 1975), and liquid viscosities (Bownes, 1965). The published photos give information about the patterned surfaces, but do not show the flow details inside the cells during the ink transfer.

The work cited in the preceding paragraphs documented *macroscopic* aspects of gravure coating and printing such as film thicknesses, ink transfer percentage, coating quality windows, and the status of the gravure roll surface before and after the emptying process. The complete understanding of gravure processes has to involve *microscopic* aspects—the flow behavior inside individual gravure grooves and cells—since their filling and emptying are critical to obtaining a uniform and stable coating. But it is difficult to observe the flow inside the grooves and cells directly because of their small size and high speed. One way