Numerical Simulation of High Speed Roll Coating with Deformable Rolls

J.P. Mmbaga[1], R.E. Hayes[1], F.H. Bertrand[2] and P.A. Tanguy[2]
[1]*Department of Chemical and Material Engineering, University of Alberta, Edmonton*
Alberta, Canada, T6G 2G6.
[2]*Department of Chemical Engineering, Ecole Polytechnique, Montréal,*
Québec, Canada. H3T 1J7.

Presented at the 12th International Coating Science and Technology Symposium
September 19 -22, 2004 • Rochester, New York
Unpublished

Extended Abstract

The hydrodynamics of the application nip in a forward roll coater are investigated using numerical simulation. The free surface movement of the fluid domain is included in the model, and is coupled to the deformation of the elastomer-covered rolls. An iterative approach is used, whereby the free surface movement is adjusted according to the normal velocity component along the boundary. The finite element method is used, with adaptive re-meshing at each iteration. This paper demonstrates techniques for calculating the flow regime for a wide range of nip gaps; both positive and negative. With the use of a new method for rapidly locating the flow separation point, convergence of the iterative process was found to be rapid, with stable solutions being obtained over a wide range of gap settings and flow conditions. It is further shown that local mesh refinement at the point of flow separation is crucial to obtaining accurate simulation of the coating flow processes. A comparison with recently obtained data shows a close match between experiment and simulation.

INTRODUCTION

Coating flow simulation involves viscous free surface problem where surface tension as well as changes in flow geometry have to be considered. When the effects of deformable media are included, the problem may be approached from lubrication approximation with the deformable media being modeled as an array of 1-dimensional elastic elements [1] or full (2-dimensional) solution of flow equations for both the fluid and the elastomer [2] – [4].

Finite element simulation of free surface problems has generated a lot of interest over the last three decades, with significant contributions [2] – [9]. The solution of the equations of motion and continuity, with appropriate boundary conditions describes the hydrodynamics in the coating nip. However, as the solution domain is a priori unknown, obtaining an appropriate start-up solution to guarantee a successful numerical solution is always a challenge. In the present contribution, we employ an iterative method, which involves the solution of the fluid flow separately from, but linked to the elastic problem and the free surface problem. The flow equations are discretized and solved using the Galerkin finite element method, employing enriched quadratic polynomial basis functions for the velocity and discontinuous linear function for the pressure.

Free Surface Problem

The first significant contribution employing an iterative scheme based on successive substitution for free surface flows was presented by Tanner [7]. Here, from an initial free surface estimate, the method simulates the flow field using only a subset of boundary conditions, with the balance conditions being used to generate a new free surface shape, and the procedure is repeated until convergence. Despite the simplicity of the method, both in formulation and implementation, the application successive approximation techniques to solve free surface problems have been hindered by the difficulty in convergence [2], [8]. When kinematic conditions are used to update the free surface, points of stagnancy at the surface may render the procedure ineffective. To overcome this, Orr and Scriven [9] proposed updating the free surface using normal stress conditions when surface tension effects are significant. In this work, successive approximation methodology is employed to update the free surface position. The kinematic as well as normal stress balance techniques are combined to overcome convergence problems. As well, a rapid method to locate the position of the free surface meniscus is implemented.

Elastic Deformation

In order to incorporate the effect of deformable media, the nodal positions at the interface between the fluid flow domain and the elastomer may be included as unknowns in the problem. It is also possible to include all nodal positions in the flow domain as unknowns as demonstrated [6] for the case of blade and slot coating flows. This, however, may increase the size of the problem significantly.

Coyle [1] developed a simple one-dimensional elasto-hydrodynamic model of forward roll coating based on lubrication approximation. While well received and effective, the range of applicability for the model is limited, as it did not take full considerations of the hydrodynamics over the whole nip, specifically the free surfaces. Carvalho and Scriven [3] – [5] extended Coyle's model to include the effect of the free surface. They also extended the 1-dimensional Hookean model to include 2-dimensional strain effect for the deformation of elastomer. In this work, we solve elastic problem using 2-dimensional static analysis with loading from the fluid flow field as the boundary condition. The same flow solver is used, replacing the velocity with displacement, the viscosity with elastic modulus and the pressure with average stress.

The three problems, i.e., fluid flow, free surface and elastic deformation are solved iteratively.

RESULTS AND DISCUSSION

Fig. 1 shows a typical discretized domain for the flow in the nip as well as a portion of deformable media. A fine mesh at the flow exit is necessary in order to capture the flow details accurately and obtain a smooth profile.

In order to avoid excessive distortion of the free surface, the free surface needs to be moved in small steps. As a result, an iterative scheme may be very slow to converge if the initial domain estimate is far from the equilibrium position. As the final position is not known a priori, different initial solutions are tested in such a manner as to give an initial solution that is in close proximity to the final location. Fig. 2 shows two simulations where the initial flow-split point is estimated close to the nip centre (a) and far from the nip centre (b). As shown, approaching from both sides give approximately the same end point. Following successive approximations, the shape of the free surface is then allowed to adjust until all the boundary conditions are satisfied.

Fig. 3 shows a comparison of the final meniscus profile predicted by the numerical method with experimental profile obtained for two rigid rolls [10]. It is evident that the meniscus profile and position is accurately captured.

As nip loading controls industrial roll coating devices, a typical simulation with a deformable roll is initiated with the rolls at a finite (positive) separation distance. The loading of a nip roll under deformable conditions is simulated by gradual decrease in the separation distance between the rolls. In so doing, the peak pressure in the nip increases while the minimum pressure decreases as expected. In order to obtain the nip load numerically, the pressure field along the nip is integrated. Fig. 4 shows experimental [12] and predicted pressure profiles for a nip load of 2kN/m. Experimental conditions are shown in the caption. The maximum and minimum pressures are correctly estimated by the numerical method.

On the computational efficiency, typically, 3 to 6 iterative steps were required to locate an initial flow split. Thereafter, 20 to 30 additional free surface iterations were required to reach a prescribed tolerance of 0.5%. The number of triangular elements used was between 1200 and 1500 during the initial meniscus location step, and this was increased to 2500 - 3000 for successive steps. The number of elements was allowed change with domain re-adjustment, with a final mesh of 3500 to 4500 elements. Further increase in number of elements did not give significant changes to the solution. A single free surface iteration took about 10 seconds on a 2.4Ghz dual XEON machine.

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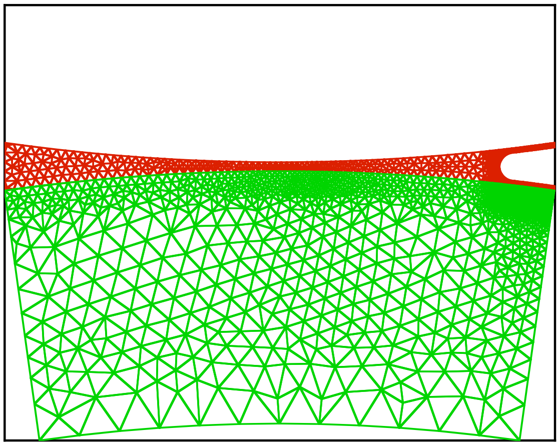

Fig. 1: A typical mesh used for fluid flow and 2-dimensional static analysis.

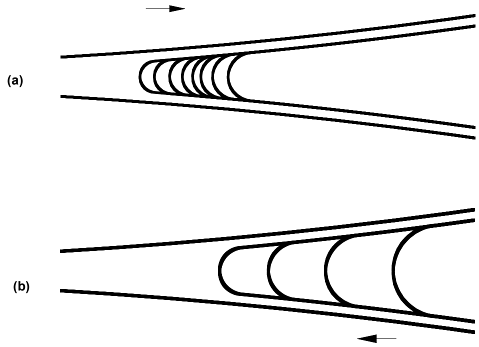

Fig. 2: Trial location of flow split point (a) approaching the split from left side and (b) approaching the domain from the right side.

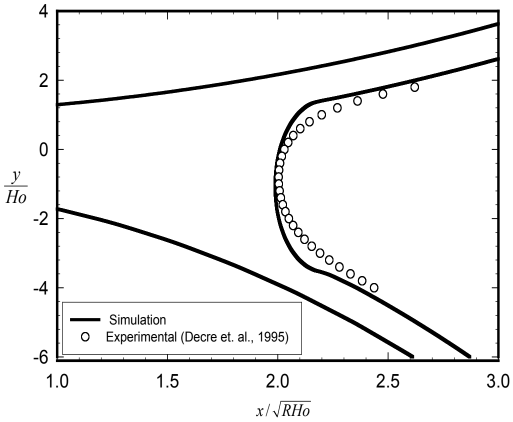

Fig. 3: Comparison between a numerical and experimental meniscus profiles for rigid rolls (Ca=0.6, 2Ho=640μm, S=1, R_2/R_1=2.45).

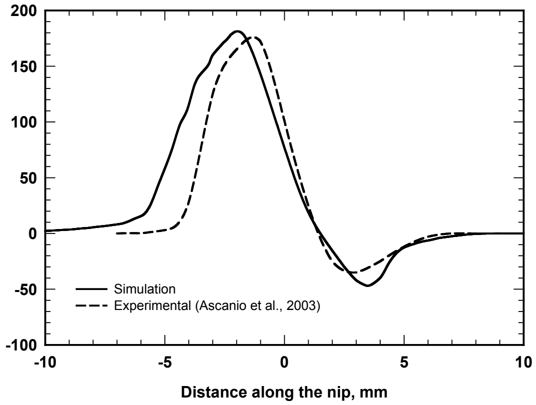

Fig. 4: Comparison between numerical and experimental pressure profiles with a deformable roll (Roll speed = 1100 m/min, nip load = 2kN/m, fluid viscosity = 0.63Pa.s;Elastic modulus E=10 MPa, thickness = 9.5mm).