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Fluid absorption during forward roll coating of porous webs

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ABSTRACT

Forward roll coating is a common process to deposit thin liquid films onto a continuous web. When the web is porous, some amount of the fluid is forced into the web in the nip. This removal of fluid, along with the deformation of the backing material, influences transfer in the nip as well as operational issues such as misting and coating defects. While much has been reported on forward roll coating for non-porous webs, little has been done when the web is porous.

A laboratory roll coating device is used to characterize the pressure profile, the rubber deformation, and the film thickness as the fluid is in contact with a porous web. A pressure transducer is used to record the pressure profile in the nip. The film thickness on the steel roll surface and the gap between the rolls are measured with capacitance probes. Silicone oils, with three different viscosities, are used as test fluids. Three different papers are used in these tests. A model is proposed to describe the pressure profile, rubber deformation, and absorption in a forward roll coating device. The differential equations are solved to describe the nip behavior. A simplified model is also proposed, using an average nip pressure and Darcy's law, to predict penetration in the nip. The proposed models compare well with the experimental results and predict the dependence on viscosity, nip load, and paper permeability. The experimental results with low viscosity fluids show some speed dependence that is not captured by the model, but the high viscosity fluid behavior agrees well with model predictions.

1. Introduction

Forward roll coating is a process that applies a fluid to a web as it moves between two rolls. The fluid is often metered onto one or both roll surfaces upstream from the nip and is deposited onto a continuously moving substrate. Some operations flood the upstream nip with the fluid and metering is determined by the nip loading. At the exit of the nip, the liquid film split occurs, with a portion of liquid deposited on to the substrate and the remainder staying with one or both rolls. Paper coating, fabric coating, film and metal coating as well as printing operations are some of the industrial examples of forward roll coating.

Because of the converging and diverging geometry between the roll coating cylinders, a pressure gradient is developed in the fluid. At the nip exit region, the pressure may drop below the vapor pressure of the liquid and leads to sub-ambient pressures and cavitation within the coating liquid (Zettlemoyer and Myers, 1960). Coating defects as well as misting are common operational issues.

Depending on the roll surface, the roll coating systems can be classified into rigid roll coating and deformable roll coating. In the rigid roll coating system, the details of the nip geometry are well defined. For deformable roll coating systems, one or both the rolls are rubber-covered. This common situation allows for the two rolls to come in close proximity and increases the ability to produce the much thinner films than the rigid roll coating. By using the deformable roll coating system, the risk of clashing two rigid rolls is avoided and the onset of ribbing instability is reduced (Carvalho and Scriven, 1994). The deformation of the roll surfaces alters the actual gap, the flow rate and the meniscus position. The application of the coating to the substrate is controlled by the hydrodynamic viscous forces between the rolls and the elastic forces of the roll cover.

There has been much work published on the roll coating flows in an effort to better understand the process and its flow instabilities. A number of studies have been performed for Newtonian liquids and two rigid rolls with a fixed gap. Pitts and Greiller (1961), Savage (1982), Coyle (1992), Benjamin et al. (1994, 1995) and Coyle (1997) studied the flow in a narrow, fixed gap between two rigid rolls. Decre et al. (1995) measured the meniscus profiles in asymmetric forward rigid roll coating of Newtonian fluids using laser sheet technique to provide an extensive database of more than 100 meniscus profiles. Gaskell et al. (1998) experimentally explored the detailed fluid mechanics of meniscus rigid roll coating of Newtonian fluids in which inlets are starved and flow rates are small. The key features of their

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findings were two large eddies in the forward mode and a single larger eddy consisting of two sub-eddies in the reverse mode.

Many industrial coatings are non-Newtonian and exhibit the viscoelastic behavior in roll coating systems. Triantafillopoulos (1996) and Glass and Prud'homme (1997) discussed the coating liquid rheology in different coating systems. Most of the current work on the non-Newtonian liquids has focused on the stability problems due to the presence of the polymers in the rigid roll coating system. Bohan et al. (2001) measured the pressure profiles and film thickness for Newtonian and non-Newtonian fluids: they detected a large difference at the nip exit between Newtonian and non-Newtonian fluids, with greater sub-ambient pressures due to the fluid rheology for the non-Newtonian fluid and also reported that the fluid flow through the nip was higher for Newtonian fluid. Johnson (2003) experimentally and theoretically, studied the effect of viscoelastic behavior of the coating liquid in the deformable roll coating system.

Many theoretical investigations have been performed on the roll coating flows to better understand the process and to predict the problems encountered during the process. The flow behavior of ink in a printing press was modeled by Taylor and Zettlemoyer (1958) using the lubrication theory. They calculated the pressure distributions and force values. Hintermaier and White (1965) used the lubrication theory to model the water flow between two roll and predicted the results similar to their experimental findings. Greener and Middleman (1975) further developed the theory of the forward roll coating flow of Newtonian fluids, using the usual lubrication approximations and some simple physical notions. Benkreira et al. (1981) modified the model of Greener and Middleman to a general case of two rollers of equal or non-equal size rotating at equal or non-equal speeds and thus developed a model applicable to general case. Their model results were in good agreement with experimental data. Coyle et al. (1986) solved the full Navier–Stokes equations using the finite element techniques and compared with lubrication theory results: the lubrication model was accurate only at high capillary numbers where the effect of surface tension is weak. Using a different boundary condition at the exit, called as "viscocapillary boundary condition", Carvalho and Scriven (1994) found that the lubrication theory agrees well with the finite element methods even at the low capillary numbers. Comparing the finite element results with the lubrication theory, Gaskell et al. (1995) confirmed that the lubrication method is accurate in describing rolling nip flow field if the gap is small. Benjamin et al. (1995) modeled the flow between two rolls for a variety of inlet and outlet conditions, single film fed and double film fed, starved and flooded and found that the upstream and downstream boundaries are always connected by a zone of lubrication flow. Rigid forward roll coating was described with finite element methods also by Mmbaga et al. (2005) with comparison to measured pressure pulses in the nip and exit fluid shapes.

The predictions and measurements of the roll rubber deformation in contact have been characterized without fluid present. Johnson (1985) proposed that the constant in the one-dimensional elastic model is a function of elastic modulus, Poisson's ratio and the layer thickness. Batra (1980) used a Moonsey-Rivilin constitutive equation, a two dimensional finite deformation model to analyze the deformation of a rubber covered roll indented by a rigid roll. Later, Bapat and Batra (1984) extended the same approach for the non-linear viscoelastic constitutive equation. Poranen (2001) developed experimental techniques to measure the pressure profiles in the rolling nip; roll cover temperature and strain of the roll cover in the meter sized press process and reported the influence of various parameters on the measure pressure profiles.

The analysis of deformable roll coating flows involves the solution of the fluid and solid mechanics at the same time. Pranckh and Coyle (1997) provide a review of elasto-hydrodynamic coating systems. An early example of elasto-hydrodynamic lubrication was been given by Dowson and Higginson (1966); they adopted a simple elastic deformation model, called the constrained column model, in which the deformation of rubber cover at each point is a function of pressure only at that point. The deformed gap profiles for a lubricated elasto-hydrodynamic contact with a fixed external load were measured by Crook (1961). Cohu and Mangin (1997) measured the flow rate of Newtonian liquids during forward roll coating for fixed external loads and accounted for the viscoelastic behavior of the roll cover material. They showed that the use of thin cover material reduces the coating film thickness. Dobbels and Mewis (1978) modeled the hydrodynamics of fluid flowing between rotating viscoelastic rolls. In their model, they imposed an orthogonal collocation for the roll deformation in the nip and also specified that the roll deflection at the inlet region as independent variable. Coyle (1988) developed a one dimensional elasto-hydrodynamic model of forward roll coating with deformable rolls. This model, which assumes that the local deformation is directly proportional to the local pressure, predicts the flow rate, pressures and roll surface deflections as a function of either a dimensionless gap setting or load between rolls. Carvalho and Scriven (1994) took up Coyle's analysis and proposed a 'non-linear elastic model' (Neo-Hookean Model) which better describes the response of rubber when deformation is appreciable. They also went on to model the relation of roll cover deflection to pressure distribution in the liquid by means of a 'two-dimensional plane strain Hookean model'. They found that both the models predict the same trends and the flow rates differed by no more than 10% for the cases they examined. The important conclusion of their comparison is that the one-dimensional model predicts the overall performance of forward roll coating well although it is easier to solve. Recently, Lecuyer et al. (2009) model the flow of a deformable roll cover for non-Newtonian fluids using finite element methods for both the fluid and the rubber: results compared well to pressure pulses for an industrial coating formulation.

Carvalho and Scriven (1997a) studied the three-dimensional stability limit of a film split flow between a deformable roll and rigid roll using the one-dimensional spring model coupled with the complete Navier–Stokes formulations for free surface flows and linear stability analysis. Their results agree qualitatively with the experimental evidence on the effect of rubber covered rolls on the behavior of the coating gap. Carvalho and Scriven (1997b) also analyzed the flow between deformable rotating rolls using lubrication theory and coupled with a one-dimensional elastic model of the deformable cover and viscocapillary model to describe the film split region. They reported the critical capillary number for the onset of ribbing and the wavelengths of the ribbing patterns.

Carvalho and Scriven (1997c) also report on the flow between a rigid roll and deformable roll by solving the complete Navier–Stokes system coupled with a non-linear plane-strain model of the rubber cover deformation, in which the rubber cover was represented by an array of radially-oriented Hookean springs. Their theoretical predictions showed how the flow rate and forces on the rolls vary with roll cover deformation and illustrated the use of the deformable rolls to obtain thin film thickness with less sensivity to roll run outs.

A few models have been proposed to describe the penetration of fluids during coating of porous webs. Chen and Scriven (1990) developed a model to predict the liquid penetration into the deformable porous substrate for blade coating: the penetration into the porous substrate was calculated using an approximate pressure distribution of a blade coating flow field. They also accounted the deformable nature of the substrate as well as the