Prediction of roll coating with counter-rotating deformable rolls by analytical methods

Bettina Willinger and Antonio Delgado
Institute of Fluid Mechanics, Department of Chemical and Bioengineering, Friedrich-Alexander University Erlangen-Nuremberg (Germany)

Corresponding author: Bettina.willinger@lstm.uni-erlangen.de

In the present work a new analytical approach for the prediction of the film thickness in roll coating with deformable rolls and negative gaps is developed. This method is based on the fluid dynamic theory of lubrication approximation. The film thickness is calculated in dependency on the geometry of the rolls (including the elasticity of the rubber), the fluid properties of the applied film and the roll velocities. This is gained by using boundary conditions for pressure and - different to former literature - for force.

The quality of the predicted results is validated by experiments with an industrial five roll system and data from literature. The comparison shows good agreement and thus the derived analytical model offers new possibilities for predicting the film thickness and thus industrial process control.

1. Introduction

Roll coating is a common technique for continuous coating of papers and foils but also used discontinuously for example for coating of plates. The application field ranges from adhesive labels via composites to optical active coatings. Nowadays roll coaters with deformable rolls are widely spread, due to their higher coating stability and the possibility of creating thin film thicknesses. The prediction of film thickness is of importance for the properties of the final coating layer as well as for the economic efficiency of the process. Since roll coating processes are self-metered and possess, especially with deformable rolls, a lot of influence parameters, analytical prediction is difficult and mostly numerical methods are used today, e.g. [1].

In the presented work a new analytical approach for the prediction of the film thickness in roll coating with deformable rolls and negative gap is developed. In difference to former approaches calculating the resulting gap geometry [2] a fixed shape was assumed to enable the analytical solution. Moreover different boundary conditions have been used.

2. Model set-up and Governing equations

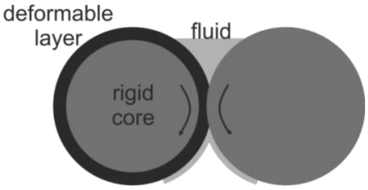

Figure 1: Sketch of deformable roll coating

For prediction of the resulting volume flow through the gap of a deformable roll coater a set-up like shown in Figure 1 is used. The roll pair consists of a rigid roll and a deformable roll. The latter normally is a steel roll wrapped with an elastic rubber layer. For the feed system a flooded inlet with constant filling level is assumed.

In the presented work the situation of a negative gap was investigated, i.e. in case of non-moving rolls both rolls are pressed and the elastic layer is deformed.

For the calculation, the set-up was modified using a plate-roll model with an average roll Radius R and an approximation for the roll curvature (see Equations (1) and (2)).

$$\frac{1}{R} = \frac{1}{2R_1} + \frac{1}{2R_2} \quad (1)$$

$$h(x) = h_0 + \frac{x^2}{2R} (2)$$

Within the equations, R_1 and R_2 are the roll radi of roll 1 respectively roll 2, h is the describing function of the undeformed roll surface with a negative minimum gap width h_0. Furthermore the calculation area was divided in three parts, inflow, deformed region and outflow, as shown in Figure 2.

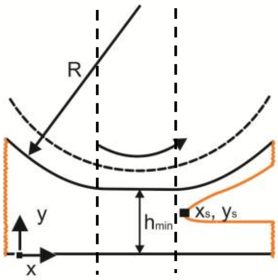

Figure 2: Used model for the prediction by analytical method

Due to preexisting flow conditions the fluid flows between the pressed rotating rolls creates a thin lubricating film. In difference to existing literature, the emerging gap was assumed to have a nearly constant height h_{min} to enable the analytical prediction.

Based on the geometry simplifications calculations are done with thin film theory, a simplification of the Navier-Stokes Equations. For description of the elastic behavior of the rubber layer the rubbers are classified in thin and thick rubber layers according to their thickness in relation to the radius of the inner steel roll and consequently different equations are used for the prediction.

According to literature ambient pressure boundary condition has been used at inflow side and at the outflow side Capillary pressure was introduced as boundary condition. In difference to this in the deformable region pressing force is used as boundary condition to close the analytical prediction for volume flow through the gap. Finally for film splitting the correlation (3) with the empirical parameters α and β was used following Benkreira et al. [3] and Benjamin et al. [4]. Within the equation q_1 and q_2 are the volume flows per unit width after film splitting on roll 1 and 2 and u_1 and u_2 are the corresponding roll velocities.

$$\frac{q_1}{q_2} = \alpha \left(\frac{u_1}{u_2}\right)^{\beta} \quad (3)$$

3. Calculation result and comparison with experimental data

The resulting analytical equation is a function of the roll geometry, the fluid properties and the roll velocities, including also parameters describing the elasticity behavior of the deformable roll. The calculation is validated with experimental results of a two-roll coater from Cohu and Magnin [5] (see Figure 3).

The calculated result agree within a uncertainty of 25 % good with the experimental data of Cohu and Magnin, who stated the uncertainty of their experiments with up to 25 %.

Finally the derived analytical equations were used to predict the film thickness of an industrial five roll coater with two deformable rolls using fluids with negligible surface tensions. Figure 4 shows the predicted and measured values for dimensionless film thickness in dependency of dimensionless roll velocity u2 and the general agreement between measured and calculated results for varying roll velocities, foot print and fluid viscosities.

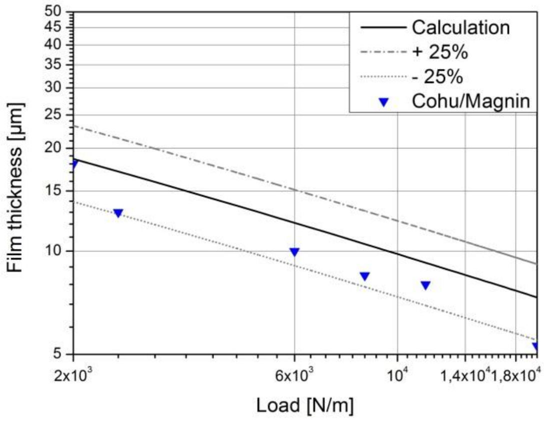

Figure 3: Comparison between analytical calculation and experimental data [5]

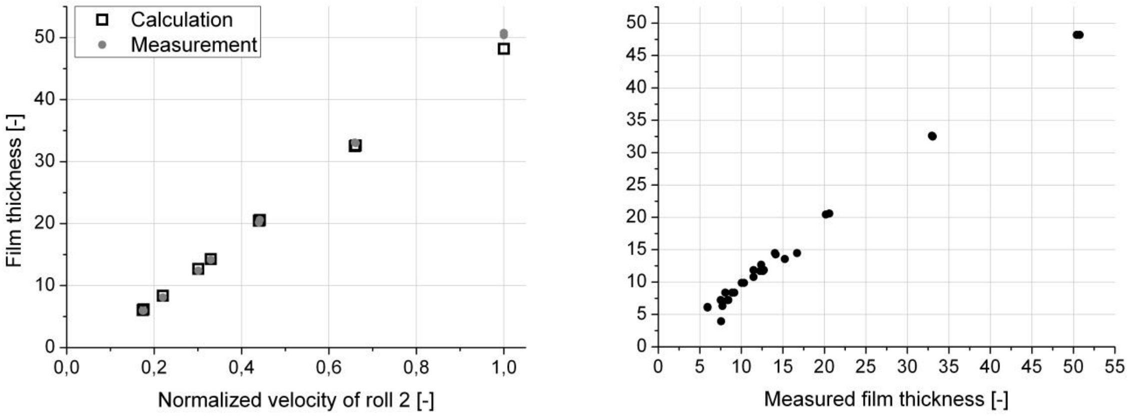

Figure 4: Dependency of normalized velocity of roll 2 for calculated results and experimental data from an industrial five roll coater (left) and agreement between measured and calculated data for different setups (right)

The roll velocity of roll 2 is one of the main influence factors and film thickness can be predicted well even for high velocities of roll two. Furthermore for different conditions, including three different fluids and seven foot print adjustments between roll one and two the final coating film thickness is forecasted very well. The derived calculation offers thus the possibility of an improved process understanding and its main influence factors. Moreover it enables thus process control of deformable roll coaters.

References:

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