# Numerical investigation of the onset of air entrainment in forward roll coating

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## Abstract

A numerical investigation is performed to predict the onset of air entrainment in forward roll coating. Different configurations for the two-dimensional simulation have been tested. The results of the simulation are compared with experimental data from literature and achieve a good agreement. In a parametric study, the influence of viscosity and surface tension is investigated. It can be demonstrated that only for fluids with a low Capillary number a significant influence of the Capillary number on the critical speed for the onset of air entrainment is given.

## 1. Introduction

Roll coating is a common technique for applying thin films on continuous substrates, e.g. papers and foils. The product quality of the films is mainly limited by the coating speed. In general, at low speeds a uniform film is formed, but when a critical speed is exceeded, wetting failures occur and air can be entrained between the feeding coating films or at the three phase contact point. The air entrainment may result in defects of the coating film and has an impact on the product quality.

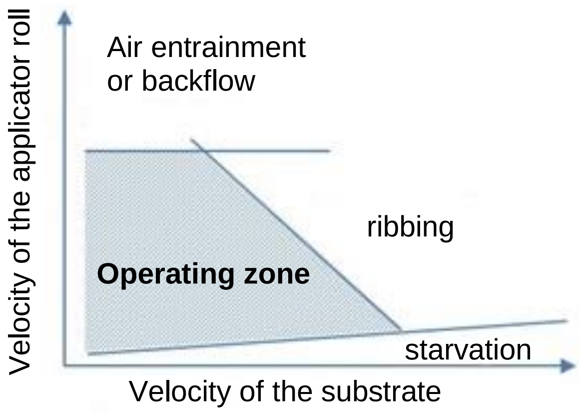

**Figure 1: Operation zone for two rolls and different velocities [1]**

Figure 1 schematically shows the operation zone, which is limited by instabilities. The type of instability depends on the velocity ratio of the two rolls respectively of the applicator roll to the substrate [1].

## 2. Material & Methods

For the simulation the program FLOW-3D (Flow Science, Inc.) was chosen, which uses the Finite-Difference Method (FDM). FLOW-3D is specialized for numerical simulations of time-dependent problems with free surfaces. The free surfaces are modelled with the Volume of Fluid (VOF) technique [2].

The used model in the simulation is based on the configuration used in the experimental study of Benkreira [3]. Two inelastic rolls (R = 0.1 m) are vertical arranged with a gap of 500 µm. For the validation a lubricating oil with a viscosity of 0.204 Pas, a surface tension of 0.035 N/m and a density of 965 kg/m$^3$ is used [3]. For the parameter analysis of the influencing parameters another set of fluid data is chosen (see Table 2). The density is kept constant to 1234 kg/m$^3$ [4]. For the modelling of the air bubbles different possibilities are offered in the code. A model with constant pressure in the bubble is optimal for channel flows. But during the roll coating process compression occurs due to the inclined geometry in the gap. For such cases the description with an isentropic change of state is advantageous [2]. As geometry change in the gap is small both models are tested. The inflow condition of a single-feed film with height of 650 µm was realized in two configurations, with a baffle (see Figure 2) or a splitted mesh (see Figure 3). In the latter case two boundary conditions can be set at the left mesh boundary. The cell size is 50 µm. The total number of the cells in both mesh configurations is approximately 210,000.

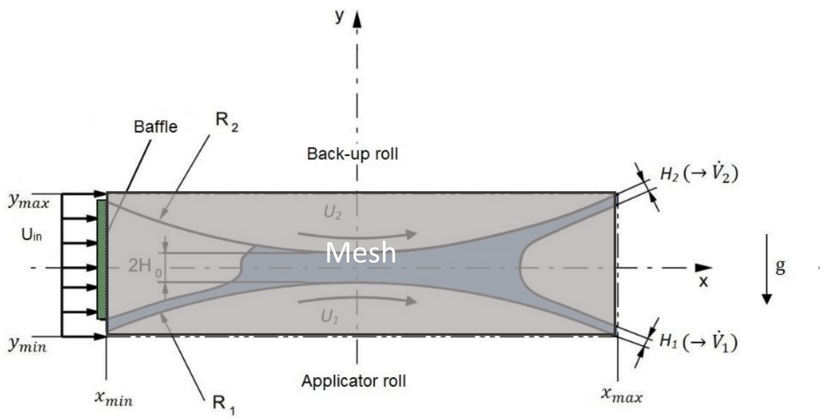


**Figure 2: Restriction of the inlet flow by a baffle**

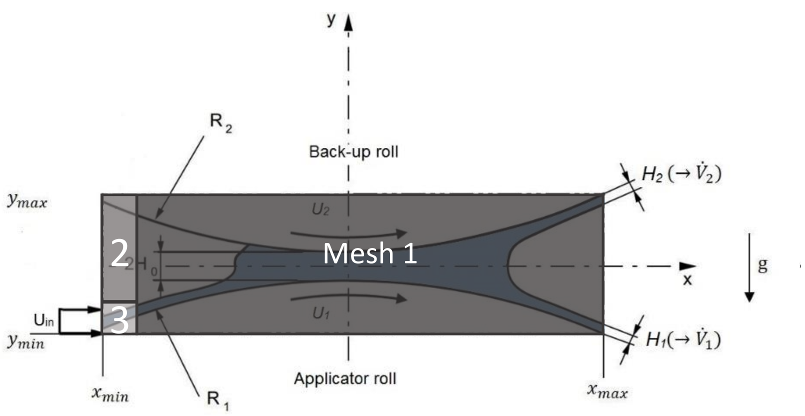


**Figure 3: Restriction of the inlet flow by a splitted mesh**

In all simulations a fixed applicator roll speed of 0.15 m/s is used and the back-up roll speed was gradually increased until air entrainment occurs.

## 3. Results and Discussion

### 3.1. Validation

For the validation of the simulation the results of the numerical calculations are compared to experimental data for the critical speed for the onset of air entrainment of Benkreira [3]. Additionally the physical correctness of the simulation is checked by an analysis of flow variables.

The tested mesh configurations are shown in Table 1.

**Table 1: Mesh configurations**

| Mesh configuration | Inflow restriction | Modelling of the air bubbles |
|---|---|---|
| **1** | Baffle | Adiabatic change of state |
| **2** | Baffle | Constant pressure |
| **3** | Splitted mesh | Adiabatic change of state |
| **4** | Splitted mesh | Constant pressure |

Except the configuration with a baffle as inflow restriction and adiabatic change of state, all other simulations result in a quite similar and realistic pressure distribution within the gap.

But generally the adiabatic model seems to be able to represent the movement of the entrapped air more realistic compared to the model with a constant pressure in the bubble. This configuration should be preferred in general to investigate numerical the air entrainment. However, the simulation with this boundary conditions takes significantly more time than the configurations with a constant pressure. As a result of the study, it is stated that for the determination of the critical speed for the onset of air entrainment the setup with a constant pressure and a baffle as inlet restriction fast delivers results. The pressure as well as the velocity profile is in agreement with the simulation with a splitted mesh. But especially when the movement of the bubbles should be considered the simulation with splitted mesh and the adiabatic bubble model has to be preferred and is used in further simulations. The simulation with this configurations predicts a critical speed for the onset of air entrainment of 0.137 m/s. Benkreira determined a critical speed of 0.146 m/s. The discrepancies between individual and averaged speed data were found to be < ± 9 % [3]. Consequently both results agree quite well.

### 3.2. Parameter study

The influence of viscosity and surface tension is investigated using the validated CFD-model. The parameters are often summed in the Capillary number. The results of the calculations are shown in Table 2.

**Table 2: Simulation results**

| Simulation | Dynamic viscosity μ [mPas] | Surface tension σ [mN/m] | $v_{crit, simulation}$ [m/s] | Ca [-] |
|---|---|---|---|---|
| 1 | 207 | 67 | 0.1275 | 0.46 |
| 2 | 414 | 67 | 0.1275 | 0.93 |
| 3 | 100 | 67 | 0.1325 | 0.22 |
| 4 | 207 | 33.5 | 0.1275 | 0.93 |
| 5 | 207 | 134 | 0.1350 | 0.23 |

The simulation results show that a decrease of the viscosity from 207 mPas to 100 mPas has an influence on the critical speed. For an increased viscosity no change of the critical speed is detectable. In contrast the surface tension has only a detectable influence, if it is increased. The experimental results of Cohu and Benkreira for the critical speed of dip coating flows show a similar behavior. In their results a decreased viscosity respectively an increased surface tension is much more important for the air entrainment at lower Capillary numbers [4].

## 4. Conclusion

It can be concluded, that the simulation model is able to predict the onset of air entrainment. The adiabatic bubble model should be preferred to illustrate realistically the movement of the air bubbles. The simulation offers the possibility to investigate influencing parameters. Future work should cover also flows with higher and very low Capillary numbers to investigate differences between the critical speeds due to different fluid parameters in a broader range.

## References:


[1] S. F. Kistler, P. M. Schweizer, Liquid Film Coating – Scientific principles and their technological implications, Chapman & Hall, London, 1997

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