High speed very thin films with reverse roll coating at near zero gaps

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Extended Abstract

Reverse roll coating is a well established coating system to achieve thin films at high speed. Typically, up to 1m/s, this coating operation is stable and with the lowest tolerable (to avoid roll clash) gaps of order 100 microns can lead to films of order 30-50 microns. This performance is supported by a lot of research, both theoretical and experimental [1-3]. However, except for the limited initial work by Coyle et al [3], no comprehensive data is available to assess if very thin films, 20 microns and less (particularly lower limits in the region of 5 microns) can be achieved at high speeds, of 2 or more metres per second. This study is concerned with this aim of interest to modern applications in electronics and solar cells manufacture for example.

The experimental rig used in this study is a replicate of industrial set-up: two rollers arranged vertically with the bottom roller partially immersed in a trough and feeding the nip. The film of interest is h_M the one formed on the metering roller at exit. The film thickness data collected are presented in Figure 1 as H_M $(=h_M/ho)$ vs. r_S at fixed $Ca(=\mu V_a/\sigma)$ for comparison with the only other available data of this kind, those due to Coyle et al. [3]. The first observation is the qualitative agreement regarding the form of the curve, a linear lubrication approximation region followed by an upturn above a critical speed ratio, r_S^*. The second observation is the added value of the present work: it provides complementary data in the interesting region where the film thickness drops significantly below 0.45 down to as low as 0.05.

When we probe the comparison further (see Figure 2), we observe that our measured minimum film thicknesses are lower than those of Coyle et al. [3] by about 30% as the Ca number is lower than about 1. Interestingly, when we compare both sets of data with the theoretical predictions made by Coyle et al. [3], we find a closer fit with our data (see Figure 3). Remarkably, in both sets of data and in the theoretical predictions, for a given capillary number, the critical speed ratios where the minimum film thickness occurs are similar (see Figure 3 and Figure 4). As our data were obtained from a *typical* reverse roll coating configuration, the discrepancy, albeit minor but significant, suggests that the *half submerged* configuration stated by Coyle et al. [3] as being "a good representation of the flow in a reverse roll coater" is strictly not accurate. This is not surprising as the critical speed ratio and the minimum film thickness are critically related to the flow near the minimum gap position. The film thicknesses measured by Coyle et al. [3] in an actual coater, similar to our arrangement, under starved feeding demonstrate clearly that the feeding conditions have an effect on the thickness of the films formed.

In conclusion, the better fit between our data and the theoretical predictions reinforces our suggestion that the half submerged configuration is not an accurate representation of the actual reverse roll coating flow. This makes the data presented here all the more important for more accurate design and operation of actual reverse roll coating. An experimental correlation on how the minimum film thickness varies with Ca and r_S can also be developed to guide operation. This correlation derives from the data given in Figure 3 and can be expressed as:

$$H_M = h_M/h_o = 0.08 \ln(Ca) + 0.36$$

Also, as the critical speed ratio r_S^* where the upturn in film thickness occurs is an important indicator of stability and a limit for a lubrication approximation analysis (linearity of H_M with r_S), we correlated it with *Ca* and compared our findings with those of Kang and Liu [4]. Figure 4 shows the comparison and suggests a more appropriate correlation covering the wide range of *Ca* tested as:

$$r_s^* = -0.17 \ln (Ca) + 0.55$$

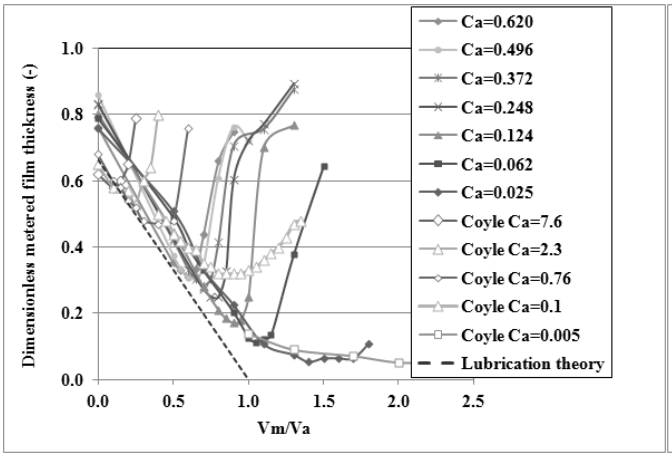

Figure 1: Film thickness measured in this study and comparison with data of Coyle et al. [3]

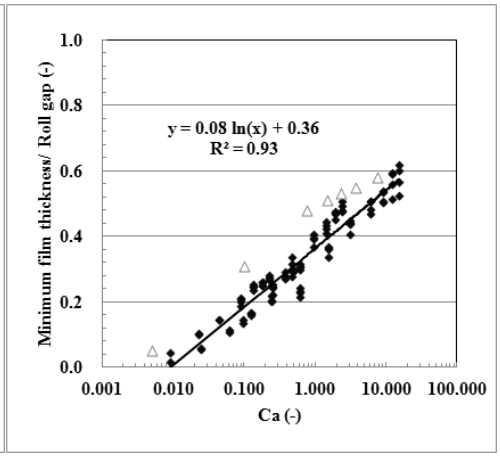

Figure 2: Minimum Film thickness measured in this study (♦) and comparison with data of Coyle et al. [3] (Δ)

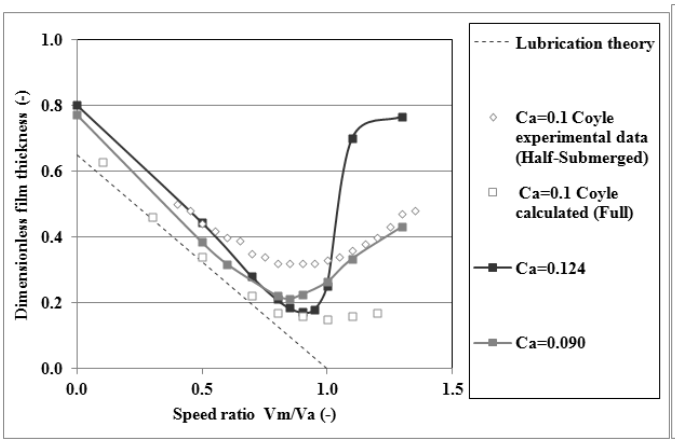

Figure 3: H_M measured in this study compared with H_M measured and predicted by Coyle et al. [3]

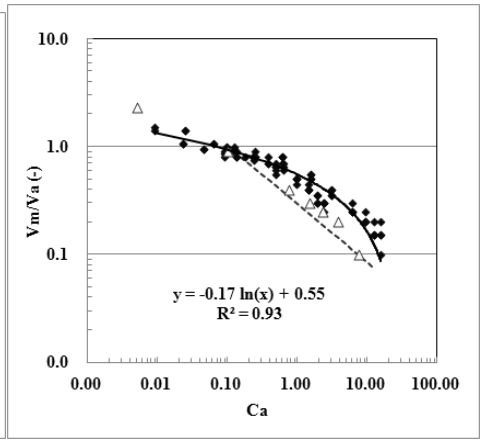

Figure 4: Critical speed ratio vs. Ca: data from this study (♦) and comparison with Coyle et al. [2] data (Δ) and Kang and Liu [4] correlation (-------).

Another important point to note with these data is that they provide guidelines with regard to producing very thin films at high speeds. To illustrate this, we need to present the data in dimensional form as in Figure 5 which gives a typical set of data obtained at the lowest permissible positive gap of 25 μm with a coating of viscosity 6.6 mPa.s and surface tension of 26.8 mN/m. A minimum film thickness of 7.5 μm is obtained here at speeds of 2.5m/s. This shows clearly the potential of reverse roll coating at producing very thin films when operated at near zero gaps.

Films thinner than 7.5 μm are permissible if the applicator speed is lowered and an appropriate speed ratio (below the critical value) is used. Now the question is: are these films uniform, i.e. is the flow stable at these conditions?

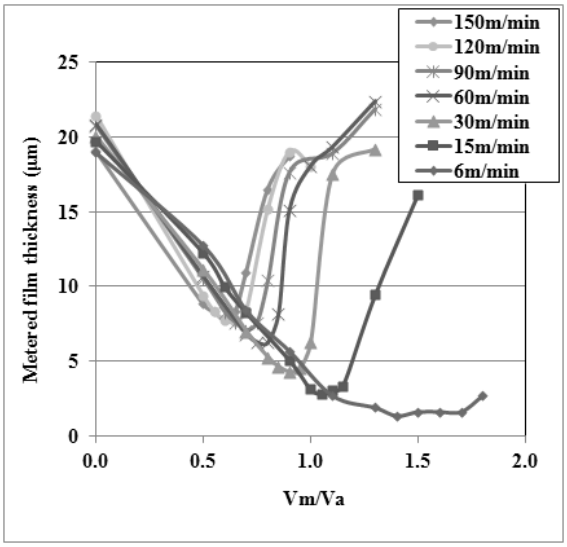

Figure 5: Feasibility of producing thin films with reverse roll coating (h_0 = 25 μm ; μ = 6.6 mPa.s and σ = 26.8 mN/m).

Two forms of surface instabilities arise in coating flows: ribbing which is common to all coating flows and cascade which is specific to reverse roll coating. Prior to the paper of Coyle et al. [3], none of these instabilities had been reported with reverse roll coating so we use their findings as a first basis of comparison. These show that the parameters controlling the stable coating window, situated between regions of ribbing and cascade, are the capillary number $Ca\ (=\mu V_a/\sigma)$, the speed ratio, $r_S\ (=V_m/V_a)$ and the dimensionless metering gap h_0/R. Our data at gaps 200, 100, 50 and 25 μm and viscosities 27 and 176 mPa.s shows this behavior to hold. However when we consider lower viscosity (~7mPa.s), a different picture emerges. Interestingly, we observe that the propensity for ribbing instabilities is reduced as the gap size is decreased rather than being exacerbated as in the case of the high viscosity fluids.

Clearly, ribbing with very low viscosity fluids is being controlled in a way different. After further analysis we find that in this situation, the other forces at play- inertia forces- are the destabilizing factor. As in all cases, surface tension stabilizes the flow, the Weber number, We $(=\rho V_a^2 h_o/\sigma)$ is the appropriate parameter to consider as an alternative to Ca. To test this hypothesis, we processed the data under all conditions (i.e. including low and large viscosities) with respect to *Ca* in Figure 6 and We in Figure 7. The better fit with We proves indeed that it is the case that in reverse roll coating it is the We number and not the Ca number that is the control parameter of ribbing instabilities. The best fit correlation of all the data describing the onset of instability is given by:

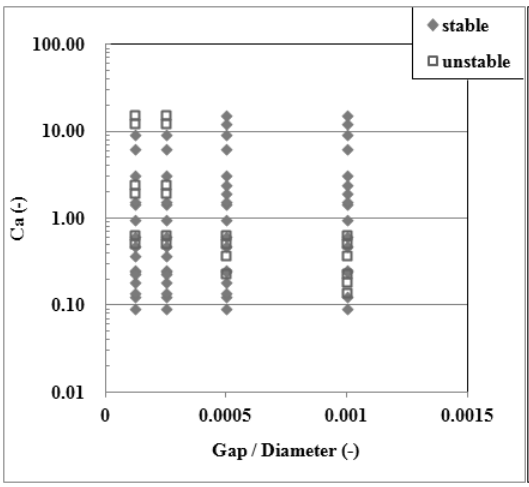

Figure 6: Ribbing instabilities as correlated using Ca: poor fit.

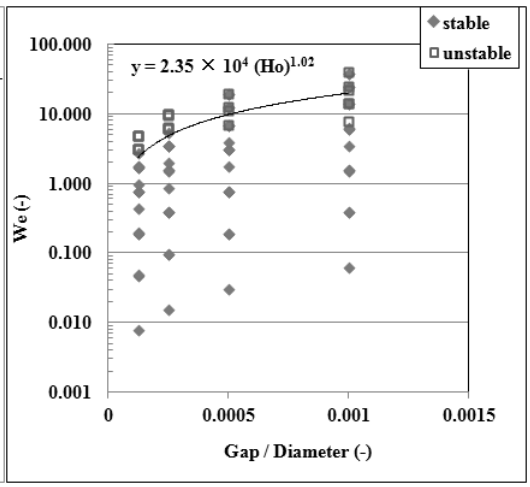

Figure 7: Ribbing instabilities as correlated using We: good fit.

References

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3. Coyle, D. J., C. W. Macosko, and L. E. Scriven, "The Fluid Dynamics of Reverse Roll Coating," *AIChE J.*, **36**(2)**,** 161 (1990).
4. Kang, Y. T., and T. J. Liu, "Minimum Film Thickness for Reverse Roll Coating," *Chem. Eng. Sci*., 46, 2958 (1991).