

Supplementary Material: Delaying the onset of dynamic wetting failure through meniscus confinement

ERIC VANDRE¹, MARCIO S. CARVALHO² †
AND SATISH KUMAR¹ ‡

¹Department of Chemical Engineering and Materials Science, University of Minnesota,
Minneapolis, MN 55455, USA

²Department of Mechanical Engineering, Pontificia Universidade Católica do Rio de Janeiro,
Rio de Janeiro, RJ, 22451-041, Brazil

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This document examines some of the procedures and observations that are mentioned, but not fully developed, within the primary article (“Delaying the onset of wetting dynamic wetting failure through meniscus confinement”). Section 1 provides a detailed description of our experimental procedure. Sections 2 and 3 discuss how our wetting-failure data is influenced by liquid viscosity and feed flow rate, respectively, and comparisons are made with similar studies found within the literature. Section 4 illustrates mesh-independence within our two-dimensional (2D) flow model using the finite element method (FEM).

1. Experimental Procedure

Our experimental procedure follows a tiered structure in which an experimental series is composed of multiple runs that are defined by the same governing steps. This process

† Email address for correspondence: msc@puc-rio.br

‡ Email address for correspondence: kumar030@umn.edu

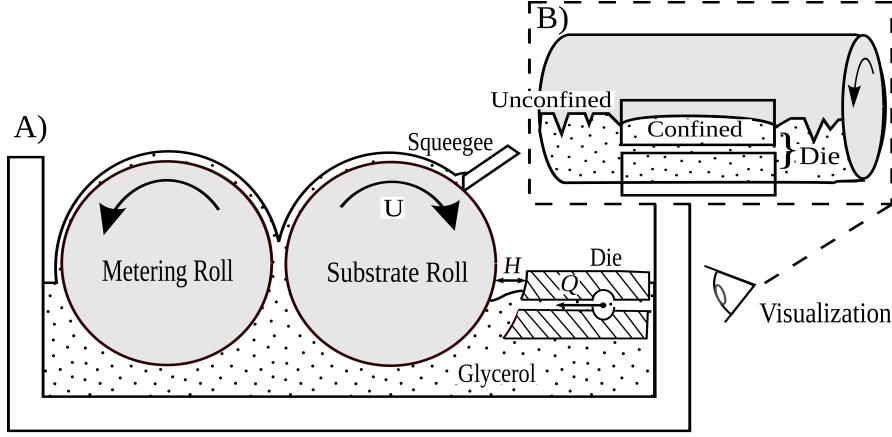


FIGURE 1. Schematic of the experimental apparatus. The side view (A) shows the substrate roll dried by the metering roll and squeegee as it rotates at speed U into the glycerol bath. A coating die provides a confinement gap H and feed flow rate Q along a portion of the substrate length. The visualization field (B) simultaneously includes the confined and unconfined wetting regions.

is designed to minimize errors that may accrue from some of the crude aspects of the system design (refer to figure 1 and the primary article for discussion of the experimental apparatus). The following outline highlights some of the key components of our procedure:

- **Experimental series:** Shims are used to find parallel alignment between the stationary die base and the substrate roll. Clamps are applied to fix the base position and the shims are removed. Approximately 15 confinement runs (one per confinement gap) are conducted before resetting the die alignment.

- **Confinement run:**

- (i) A confinement gap is chosen at random from 15 possibilities spanning $H \in [0.1 \text{ mm}, 10 \text{ mm}]$. The gap is measured between the upper die block and the substrate surface using shims for $H < 2 \text{ mm}$ and a ruler for larger gaps. Clamps hold the upper block in position and prevent the gap from widening during operation.
- (ii) Glycerol is added to the reservoir until the die is submerged (approximately 16 L).

The glycerol is mixed for approximately 30 minutes within the tank to eliminate any density gradients within the reservoir.

- (iii) Data acquisition begins at low roll speed ($\approx 13 \text{ cm s}^{-1}$). Feed flow from the die is adjusted to place the confined meniscus at a desired position between the roll and the upper die block. After observing steady-state for at least 3 minutes, the roll speed is incremented in 1 cm s^{-1} steps. The die flow rate is increased in parallel with roll speed to maintain a constant meniscus position. While waiting for steady-state, the confined and unconfined wetting lines are observed simultaneously for the characteristic air veees associated with wetting failure.
- (iv) The critical speed U^{crit} is recorded once the wetting line spontaneously forms a sawtooth meniscus. This critical point is observed at distinct speeds for both the unconfined and confined wetting regions, yielding two critical capillary numbers (Ca_u^{crit} and Ca_c^{crit} , respectively) recorded for each run. Following wetting failure, the roll speed is reduced to a sub-critical value and then slowly ramped toward wetting failure to test for hysteresis and repeatability of the critical speed. Less than 1% uncertainty is reported for values of Ca_c^{crit} during each run.

The experimental series was repeated three times to obtain a suitable sample of critical speeds at the various confinements.

2. Unconfined Wetting Failure: Viscosity Effect

Values of Ca_u^{crit} vary from day to day due to imperfect control of liquid viscosity, μ_{liq} , and ambient conditions (e.g., temperature and humidity). During our confinement runs, we adjust the glycerol composition to tolerate 10% uncertainty for μ_{liq} , which generates a narrow distribution of fluid properties tested over the entirety of the study. In Figure 2, our recorded critical speeds are well described by a power-law correlation found in Blake

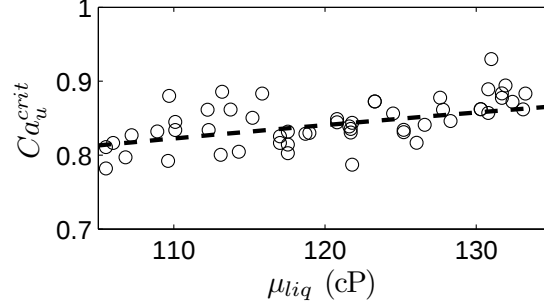


FIGURE 2. The dependence of Ca_u^{crit} on glycerol viscosity, μ_{liq} . Each symbol represents a critical speed recorded during a distinct run. The dashed line is fitted from a power-law correlation, $Ca^{crit} \sim \mu_{liq}^b$ (Blake & Ruschak 1997), using $b = \frac{1}{4}$ and matching the mean critical capillary number ($Ca_u^{crit} = 0.84$) at $\mu_{liq} = 120$ cP.

& Ruschak (1997). This agreement suggests that the slight variability in μ_{liq} is primarily responsible for any run-to-run variation seen in critical speed. Note that any effects from variable fluid properties are effectively removed from our analysis because comparisons are made only between confined and unconfined data observed during the *same* run.

3. Confined Wetting Failure: Feed Flow Effect

In addition to confining a local region of the wetting meniscus, the coating die also provides a feed flow (Q) to aid in positioning the confined wetting meniscus between the roll and the upper die block. The flow within the small gap generates large drag forces that pull the meniscus in the direction of the substrate motion (Carvalho & Kheshgi 2000). It is found that Q must increase proportionally with Ca to counteract the increasing drag generated by the moving substrate and hold the meniscus at a steady position. Figure 3 demonstrates the linear correlation between flow rate and Ca while holding a constant meniscus position.

Pressurized fiber coating uses narrow gaps ($H \sim 100 \mu\text{m}$) between the coating die walls and the fiber substrate to delay wetting failure to high speeds (Jacqmin 2002). Reports

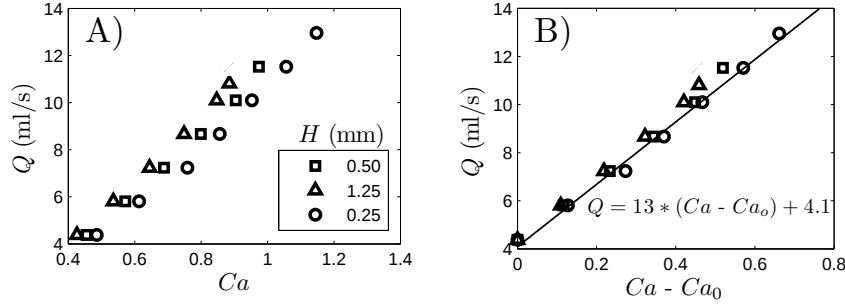


FIGURE 3. Feed flow rate as a function of Ca needed to maintain steady a meniscus position (approximately 1 cm above the feed slot). Plot (A) shows the raw data, while (B) shifts the data along the horizontal axis by Ca_o , the capillary number corresponding to $Q \approx 4.1$ for each data set. The inset equation provides the linear fit of the shifted data.

claim that wetting failure can be resisted to $Ca \sim 1000$ so long as the liquid pressure is increased to stabilize the wetting meniscus against the drag from the moving fiber (Simpkins & Kuck 2003). Our experimental system shows a similar result (figure 3), where the feed flow rate must be increased proportionally with substrate speed to maintain a steady meniscus position, which can be explained by a simple Couette flow argument ($Q \propto UH$). Despite this relationship between feed rate and steady-wetting speed, we observe the onset of wetting failure for each confinement gap to be *independent* of the feed rate. Thus, we must conclude that, at least within our system, the confinement parameter plays a more significant role in delaying wetting failure than any local pressurization from the feed flow. Furthermore, because our experimental design allows direct, real-time comparison between confined and unconfined wetting exposed to the same substrate and fluids, we can be confident that any relative increase in critical speed is due only to confinement.

4. Mesh-Independent FEM Solutions

Wetting-line resolution presents the primary hurdle to numerical analysis of 2D wetting flows. Recent works (Wilson *et al.* 2006; Sprittles & Shikhmurzaev 2011*a,b*) have identified some factors which hinder FEM simulations of wetting systems from converging to mesh-independent solutions. For instance, strongly imposed boundary conditions at the wetting line (i.e., slip velocity and contact angle) appear to cause larger global errors than the weak form of these conditions (see Sprittles & Shikhmurzaev (2011*a*) for further discussion). Our FEM study is vulnerable to these errors because we strongly impose velocity and mesh boundary conditions along the interface and substrate. To ensure that we acquire mesh-independent solutions, we have extensively studied the effect of mesh refinement on our reported FEM results.

In this section, we demonstrate the convergence to a mesh-independent solution for our air-glycerol system with $\lambda = 0.1$. We focus on the effect of wetting-line resolution achieved by concentrating the mesh while holding the total number of elements constant ($N_{ele} = 4000$). Resolution is characterized by the element height (Δy_{cl}) at the wetting line. We include one case with a 300% increase in N_{ele} to show the insensitivity of our solution to the global element count. The selected studies are listed in Table 1 with relevant mesh parameters and resulting Ca^{crit} values.

Solution families are plotted for each mesh study in Figure 4. The plot shows that computations with a coarser mesh converge to the refined result at low Ca , but then deviate at some finite capillary number, $\widetilde{Ca}^{crit}$. Unfortunately, artificial turning points are produced at $\widetilde{Ca}^{crit}$ as a consequence of poor mesh quality. Therefore, one cannot simply rely on the presence of a “critical point” to identify the true Ca^{crit} , but must successively refine the computational mesh until converging to a single value for $\widetilde{Ca}^{crit}$.

As we illustrate in Figure 5, failure to sufficiently resolve the wetting line can lead to

Mesh	N_{ele}	Δy_{cl}	$\widetilde{Ca}^{crit}$	Error %
A	4000	7.7×10^{-3}	1.81	57
B	4000	3.3×10^{-3}	2.09	50
C	4000	1.2×10^{-3}	2.50	40
D	4000	3.3×10^{-4}	3.27	21
E	4000	1.7×10^{-4}	4.08	1.7
F	4000	1.6×10^{-5}	4.14	0.2
G	16000	7.7×10^{-6}	4.13	–

TABLE 1. FEM mesh studies for the air-glycerol system ($\chi = 1.5 \times 10^{-4}$, $\theta_{mic,R} = 70^\circ$, $\theta_{mic,L} = 90^\circ$) with $\lambda = 0.1$. Error percents are determined by comparing $\widetilde{Ca}^{crit}$ values to the true critical capillary number found with Mesh G ($Ca^{crit} = 4.13$).

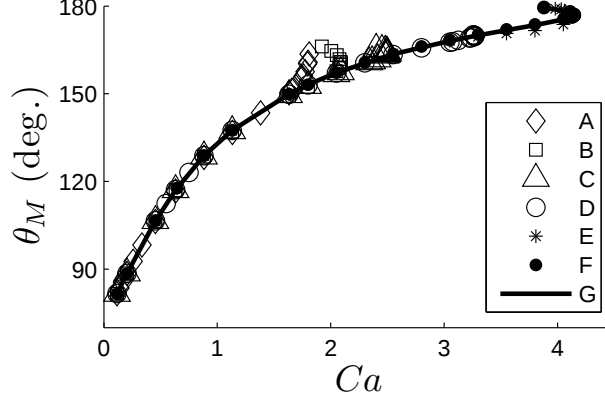


FIGURE 4. Solution families for the FEM mesh studies listed in Table 1.

grossly inaccurate estimates for Ca^{crit} . For example, even a 10-fold refinement of the slip length ($\Delta y_{cl} = \lambda \times 10^{-1}$) yields over 50 % error in Ca^{crit} . For the parameters of interest to our air-glycerol system we have achieved mesh independence when the wetting line is resolved three orders of magnitude below the length scale ratio ($\Delta y_{cl} = \lambda \times 10^{-3}$). This heuristic seems to remain valid for the entire range of λ examined within this study ($\lambda \in [2 \times 10^{-6}, 10^{-1}]$). However, the necessary mesh conditions for a general wetting

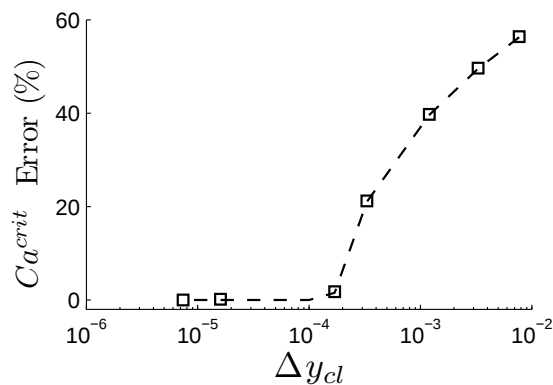


FIGURE 5. The convergence of Ca^{crit} with increasing mesh resolution near the wetting line.

system likely depend on θ_{mic} and factors set by the macroscopic flow field. This issue remains under investigation.

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