Study of Wet Scroll

How paper curls and uncurls

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Background Information

When a piece of semi-transparent sulfuric acid paper (Tracing Paper) is gently placed on the surface of water, it may quickly curl up into a roll and then slowly unfold. It is made by immersing high-quality uncut ordinary paper in sulfuric acid for a few seconds, during which some of the cellulose in the paper is converted to starch-like protein by the acid

- specially processed
- increased light transmittance and hydrophobicity
- hereinafter referred to as paper for simplicity

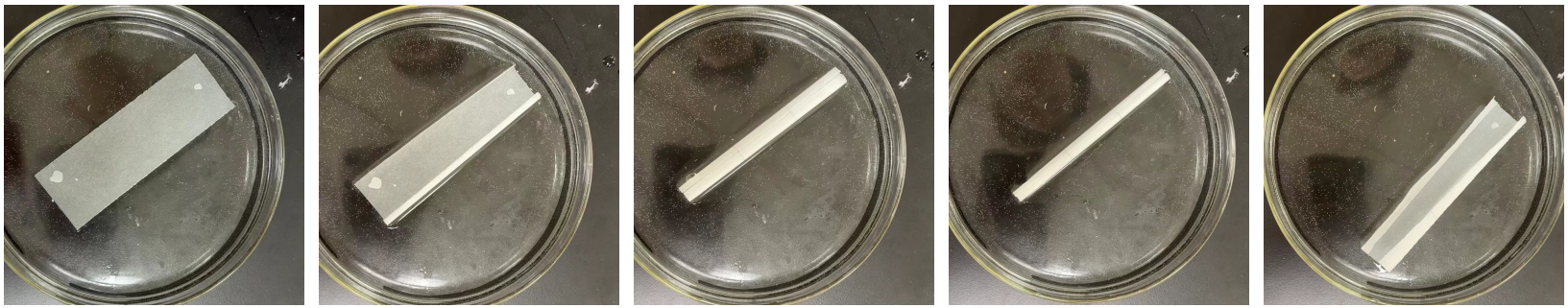


Figure 1: Changes of paper strips over time

Research Gaps

paper's microstructure, its interaction with liquids, and the elastic and plastic characteristics of paper as a solid

- studied the basic properties of paper (Alava and Niskanen, 2006) and (Van der Reyden et al., 1993)
- explained the diffusion of water in paper (Dano and Bourque, 2009)
- explained the change in curvature of paper (Reyssat and Mahadevan, 2011)

proposed a different model and used it to explain the change in curvature of sulfuric acid paper over time

- GAP1: no simple and effective experimental approach
- GAP2: surface tension has not been considered

Theoretical Modeling

- transport problem of water in paper
  - Fick's second law of diffusion
  - second-order differential equation and boundary conditions
  - linear relationship between paper width and water content
- mechanical analysis
  - consider paper as a homogeneous elastic material
  - gravity can be neglected
  - torque balance equation and force balance equation
- assume that paper strip cannot roll into a cylinder

Experimental Measuring

- place a paper strip on water surface
- use a camera to record the changes
- use Tracker software to measure the width of paper strips

First, water was filled into a glass dish. Then, the paper strip was gently placed on the water surface, and a camera was simultaneously turned on to record the changes in the paper strip. The recording was stopped after the paper strip completed one curling-uncurling cycle. We used Tracker software to analyze and read the changes in the width of the paper strip over time.

Comparison: experimental and theoretical results show similar variation tendency.

The variation tendency of experimental and theoretical curves is similar, butthe theoretical curve exhibits an overall shift compared to the experimental curve.

Initially, the width of the paper decreases as paper curls, then it increases as paper uncurls, and finally, the width becomes slightly larger than the initial width, which is a result from expanding after absorbing water.

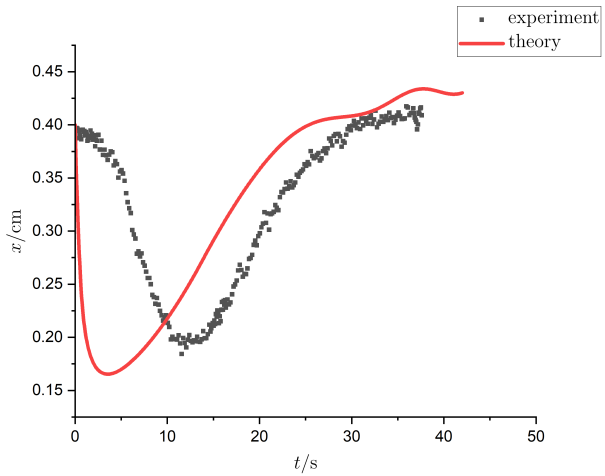
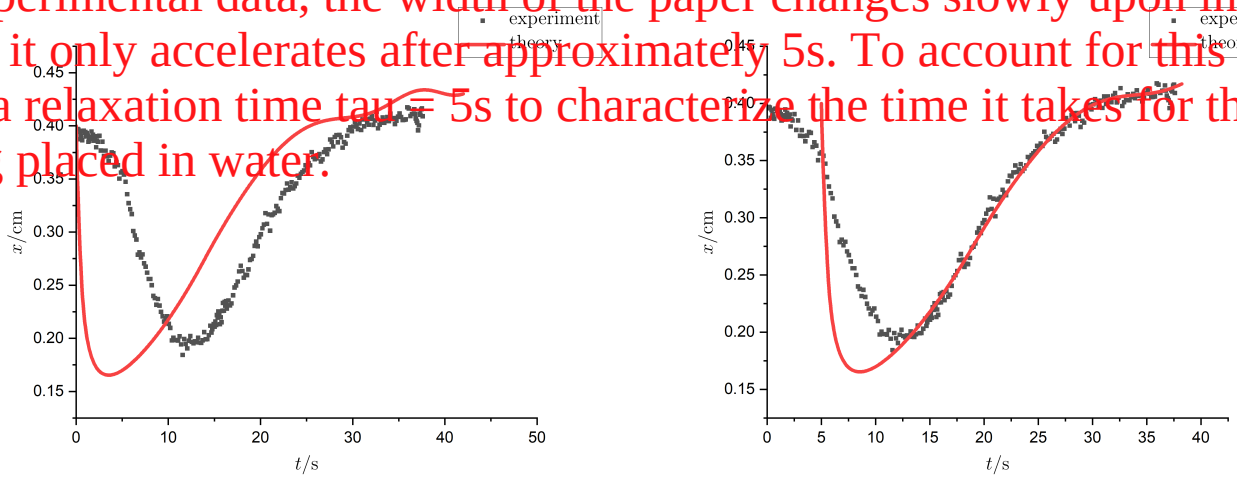


Figure 2: Changes in paper width(x) over time(t) in water

Introducing relaxation time τ: the second half of curves fit very well.

After introducing a relaxation time $\tau = 5$seconds, the second half of experimental and theoretical curves, but there are still differences in the short period after the paper strip is placed on the water surface.

For the experimental data, the width of the paper changes slowly upon initial contact with water, and it only accelerates after approximately 5s. To account for this behavior, we introduce a relaxation time tau = 5s to characterize the time it takes for the paper to curl after being placed in water.



(a) original (b) modified

Figure 3: Figure(b) is obtained by shifting the theoretical curve in Figure(a) to the right by $\tau = 5$s.

Conclusion

What's in this presentation:

- a new method to measure the motion of paper strips
- improvements to Reyssat and Mahadevan (2011)'s theory
- comparison between the experimental and theoretical results
- introduction of relaxation time τ

Some problems remain:

- relaxation time needs explanation
- another case remains unsolved: the case where paper strips can roll into a cylinder

References

Alava, M. and Niskanen, K. (2006). The physics of paper. *Reports on progress in physics*, 69(3):669.

Dano, M.-L. and Bourque, J.-P. (2009). Deformation behaviour of paper and board subjected to moisture diffusion. *International Journal of Solids and Structures*, 46(6):1305–1316.

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Thanks!