FROM RESEARCH TO INDUSTRY

cea tech

CAPILLARY FLOWS:
DYNAMICS & GEOMETRY EFFECTS

COMSOL conference
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10/15/2015

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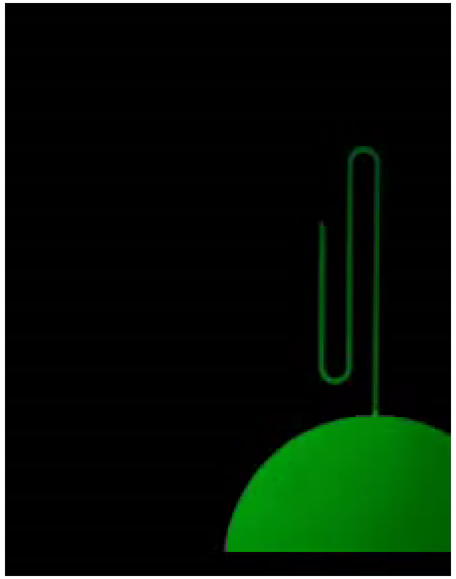
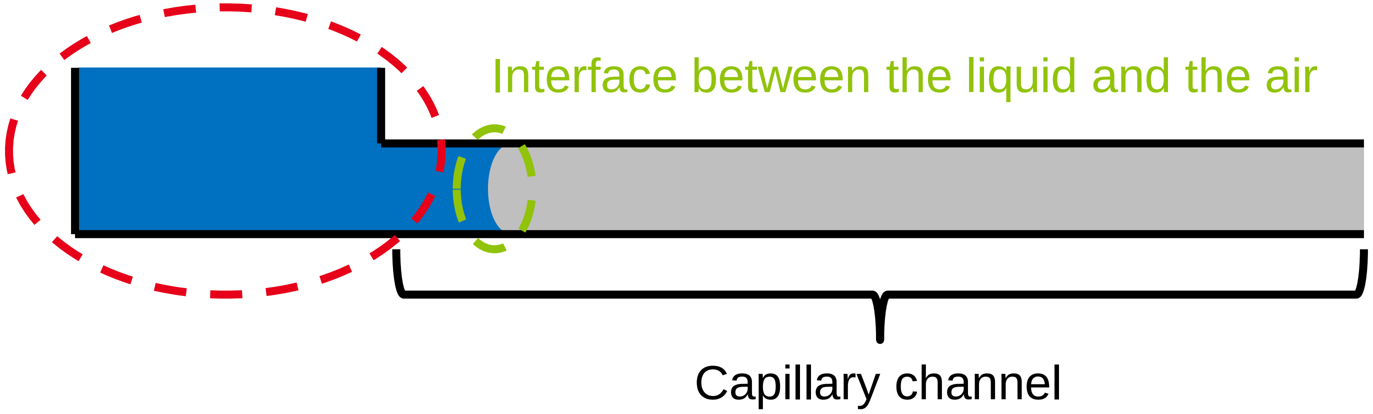
WHAT IS A SPONTANEOUS CAPILLARY FLOW ?

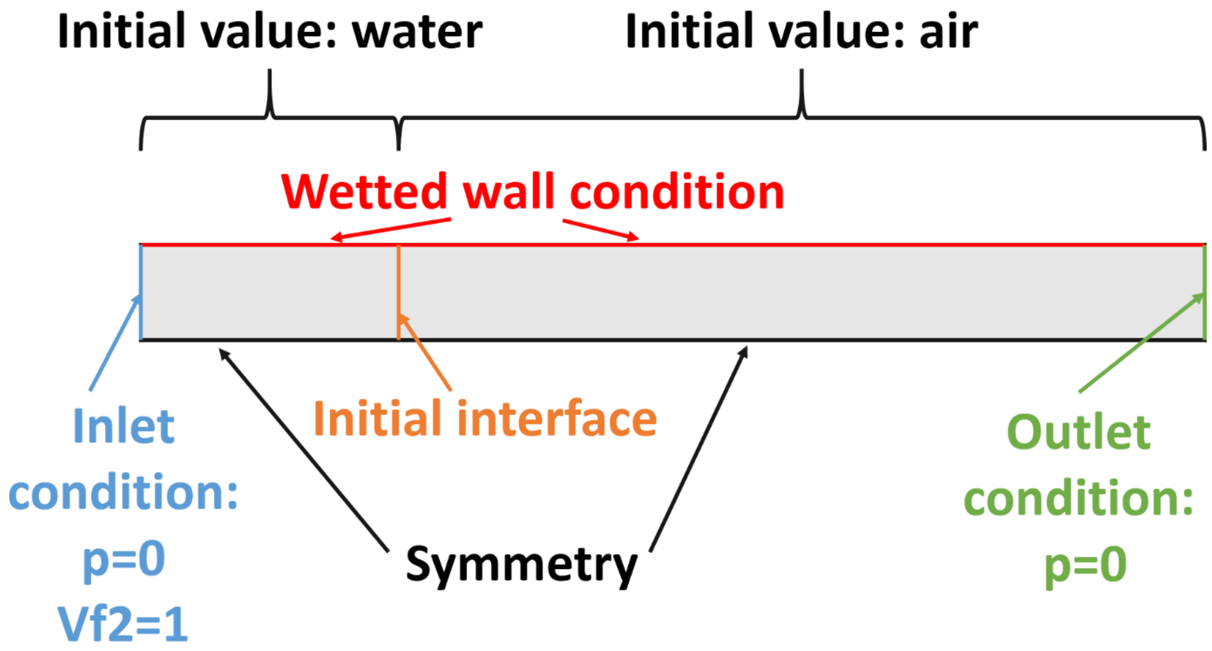




Cross-section of a typical capillary device.

- The reservoir is large enough to assume a zero Laplace pressure at the interface.
- The flow is driven by the capillary pressure at the front interface.

2D GEOMETRY, CONDITIONS & POSTPROCESSING



Filling distance : Integration of the level set function along the symmetry axis.

Filling velocity: Average of the velocity over the initial interface.

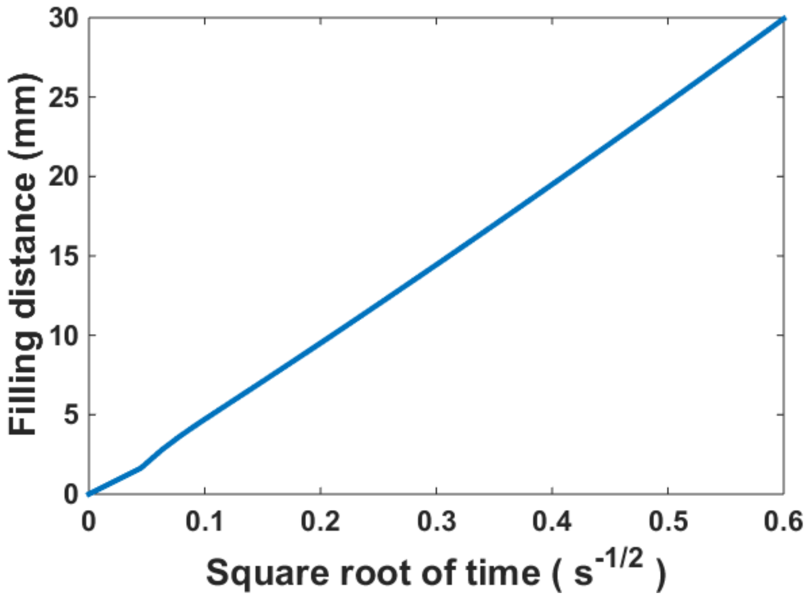
FROM RESEARCH TO INDUSTRY

DYNAMICS

THE LUCAS-WASHBURN-RIDEAL LAW (UNIFORM CHANNELS)

The filling distance increases according to the square root of time.

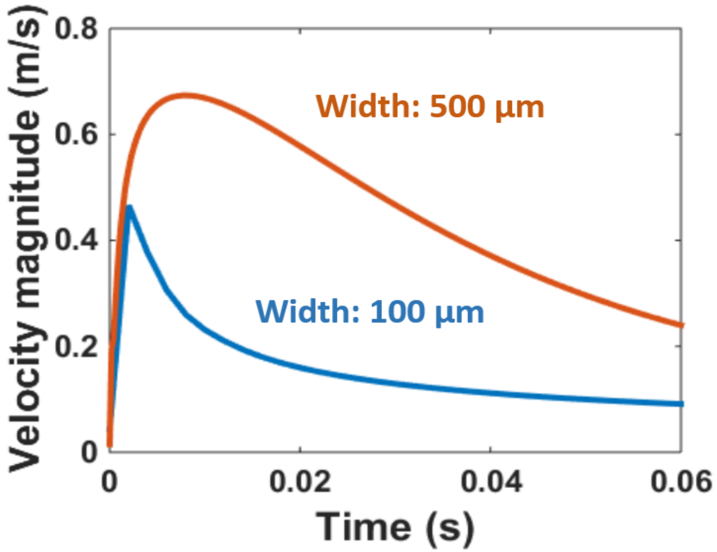
$$z = \sqrt{\frac{r\,\gamma\,\cos(\theta)}{2\,\mu}}\sqrt{t}$$



Data extracted from a COMSOL simulation

The larger the channel is, the higher the velocity is.

$$\boldsymbol{u} = \sqrt{\frac{r\,\gamma\,\cos(\theta)}{8\,\mu}}\,\frac{1}{\sqrt{t}}$$



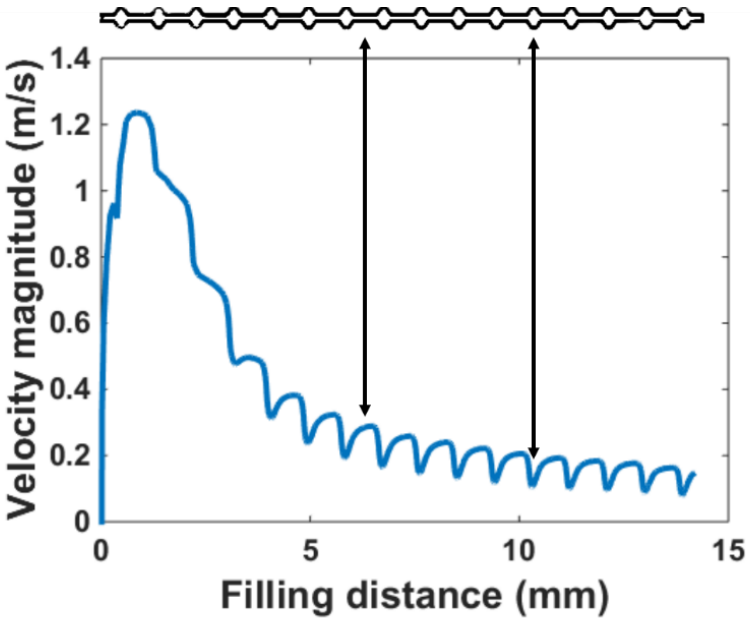
Data extracted from a COMSOL simulation

Washburn & al, Phys. Rev. **17**(3), p 273, (1921)

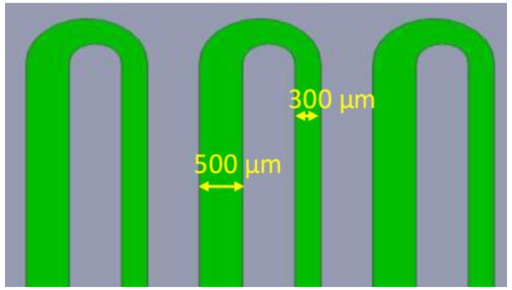
CAPILLARY FLOWS DYNAMICS

NON-UNIFORM CHANNELS

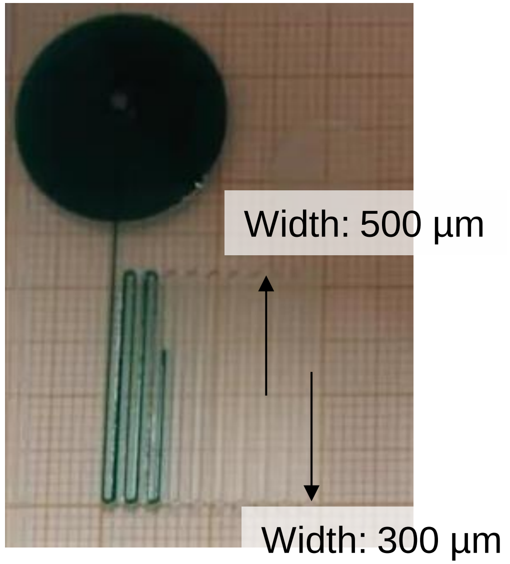
The capillary filling is slower within the larger regions of the channel.



Data extracted from a COMSOL simulation



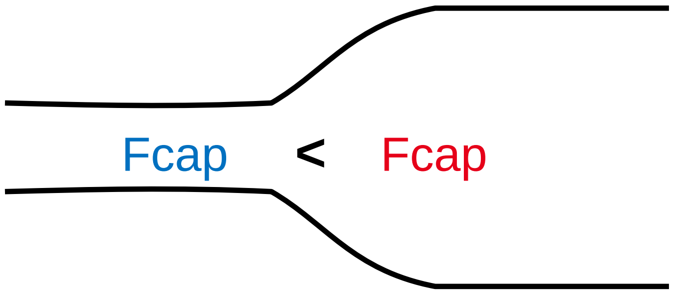
Schematic of the channel used.



Capillary flow filmed with a camera.

At an enlargement:

Why does the velocity decrease whereas the capillary force increases ?



Fcap < Fcap

But V > V ?

NON-UNIFORM CHANNELS

There is a balance between the capillary force and the drag force.

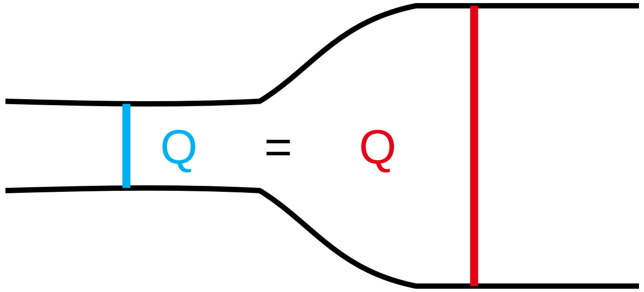
$$F_{drag} = F_{cap}$$

$$F_{drag} = k \; * V$$

$$F_{cap} = 2\,\pi\,R\cos(\theta)$$

Because of the mass conservation, $VR^2 = cst$

The capillary force evolves according to R.



$$V = R^2/R^2 \; * V$$

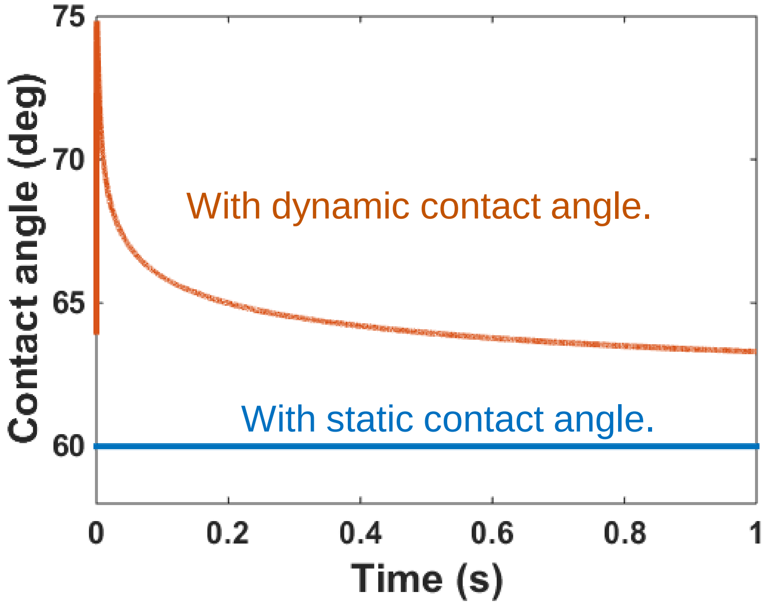
If the velocity increases in the large region, the velocity in the narrow region would increase as R^2 , and so the drag force.

-> This can not compensate the increase of the drag force.

-> The velocity must decrease when the flow reaches a larger region.

DYNAMIC CONTACT ANGLE

- At the beginning of the capillary flow, the velocity is high and the dynamic contact angle tends to 90°.
- As the liquid flows, the velocity decreases and the dynamic contact angle decreases towards the static contact angle.



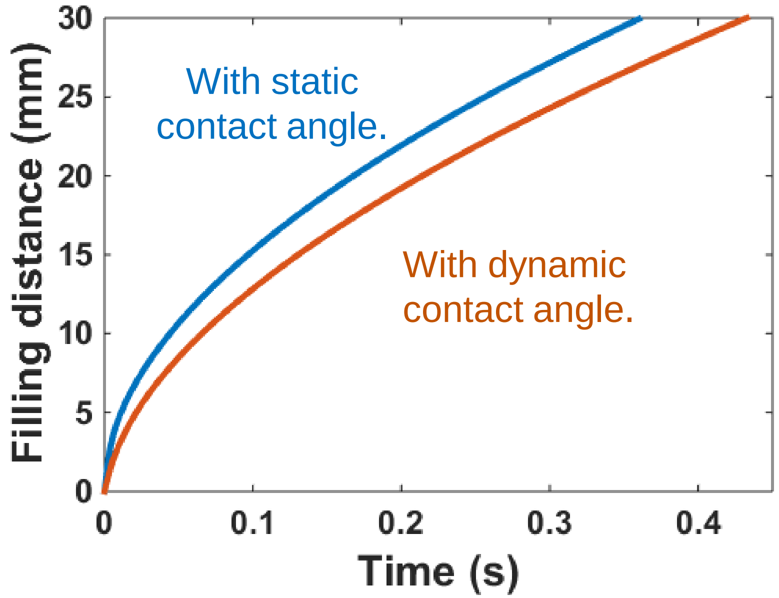
Data extracted from a COMSOL simulation

Bracke formula:

$$\cos(\theta_d) = \cos(\theta_s) - 2(1 + \cos(\theta_s)) * \sqrt{Ca}$$

$$Ca = \frac{\mu V}{\gamma}$$

Because the dynamic contact angle is higher than the static contact angle, the capillary filling is slowed down.



Data extracted from a COMSOL simulation

*Bracke & al, Progress in Colloid Polymer Science, **79**, p 142-149 (1989)*

*Berthier & al, Sensors and Transducers, **191**(8), p 40-45 (2015)*

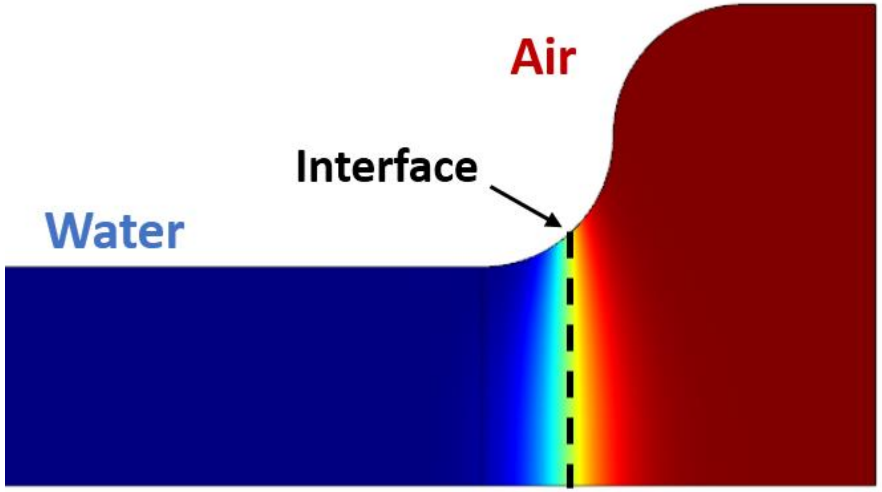
GEOMETRY EFFECTS

CAPILLARY FLOWS
GEOMETRIC EFFECTS

STOP VALVE

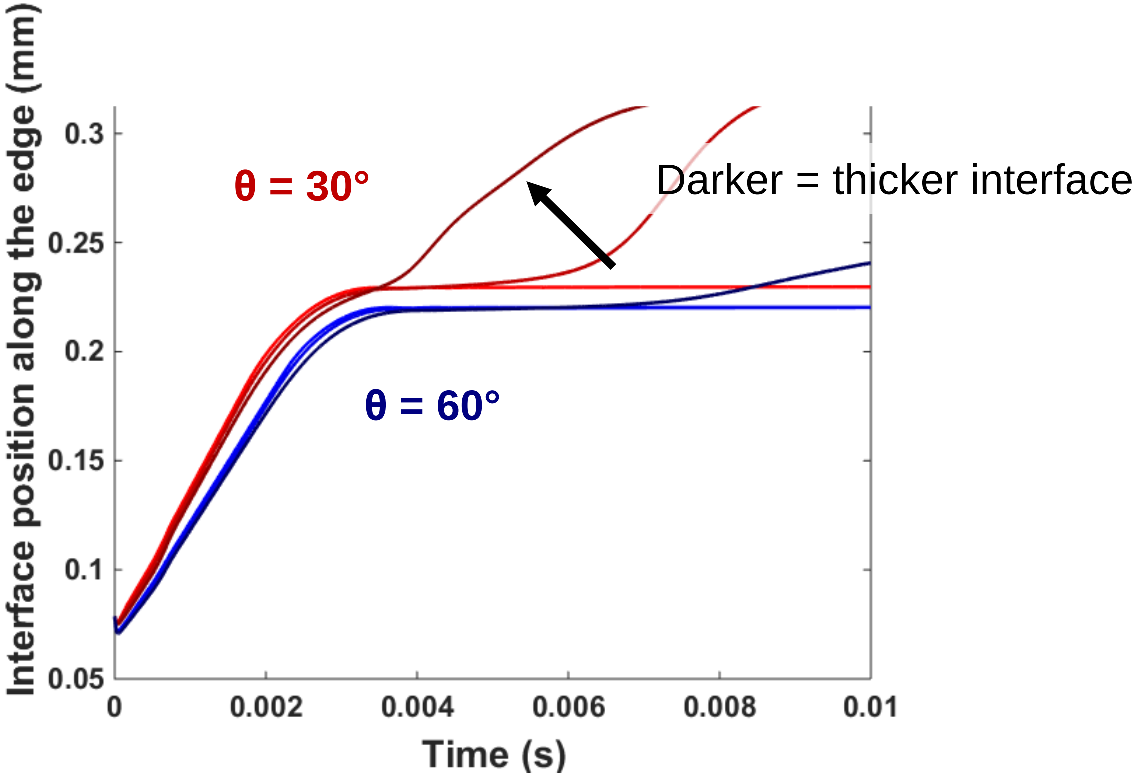
The equilibrium position.

The capillary flow stops when the interface is flat (zero Laplace pressure) .



COMSOL simulation: Volumic fraction of water.

The role of the interface thickness.

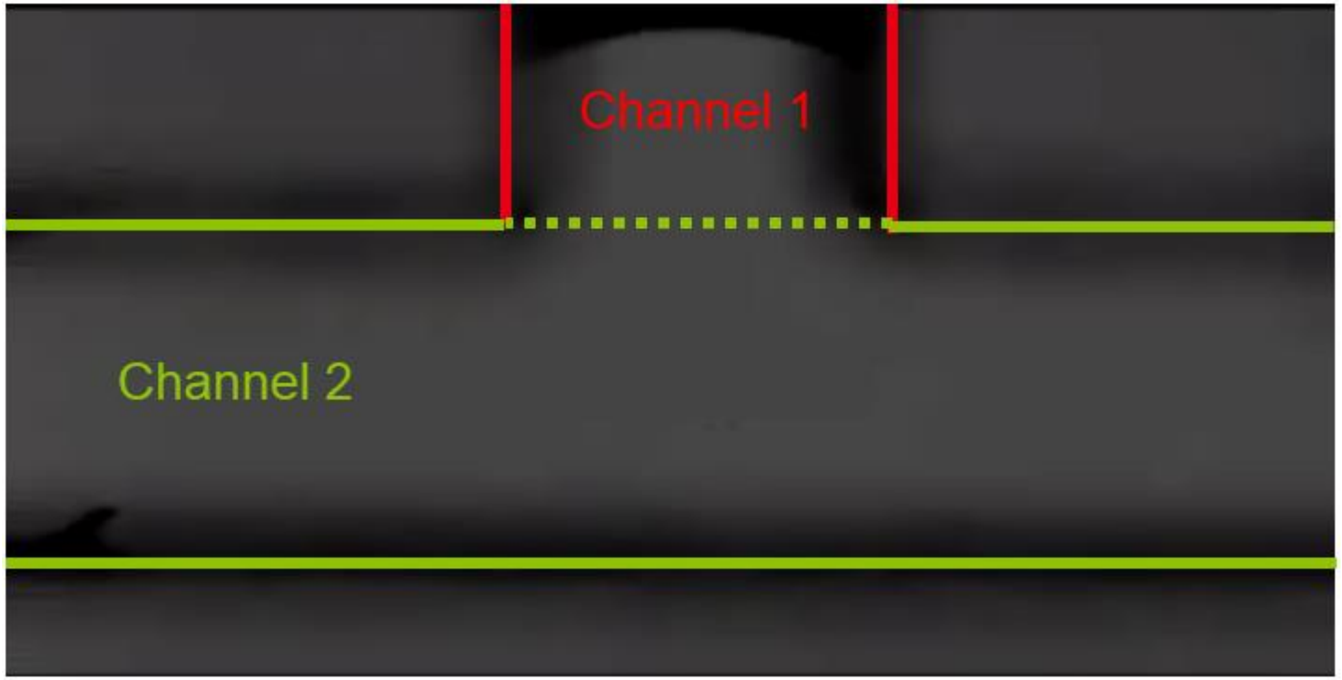


Data extracted from a COMSOL simulation

The thicker the interface, the easier the interface passes through the stop valve.

TRIGGER VALVE

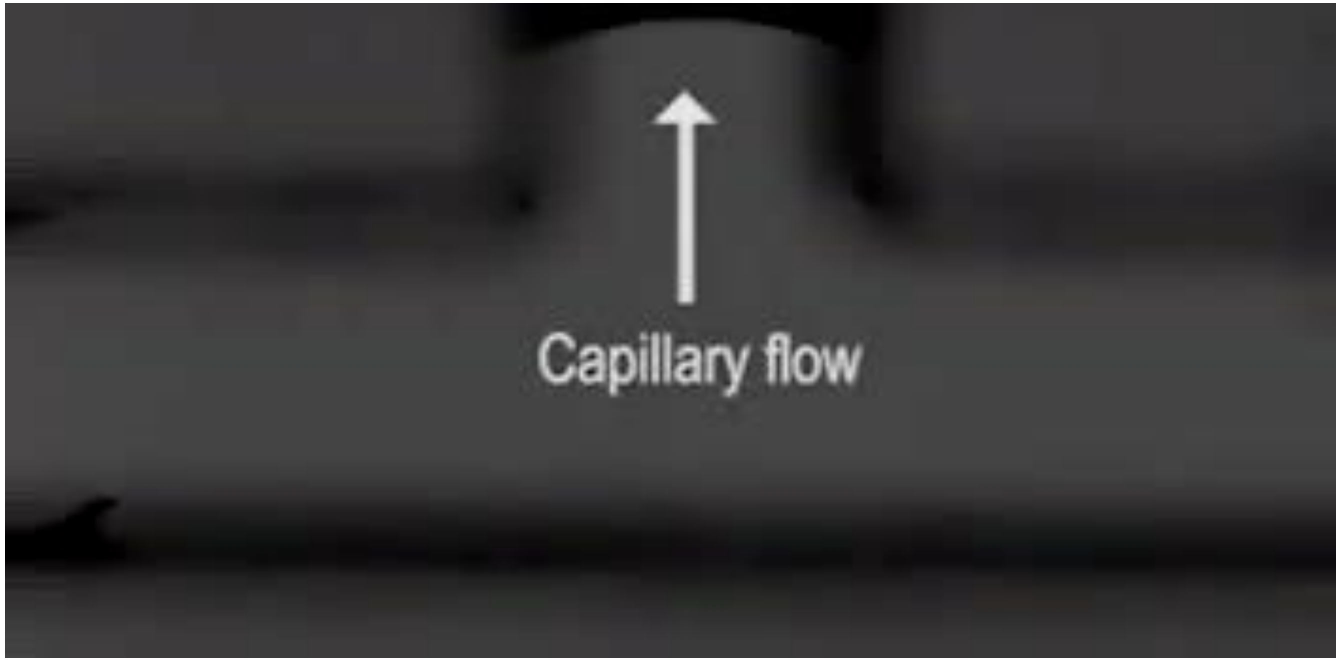
How does it work ?



Video sequence realised with a high speed camera.
Time is slowed down 40 times.

TRIGGER VALVE

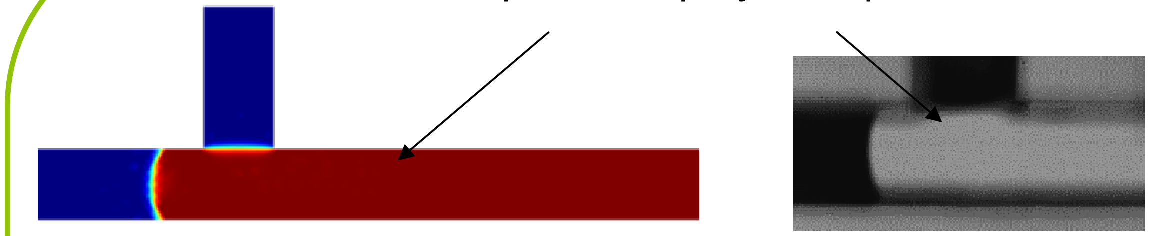
How does it work ?



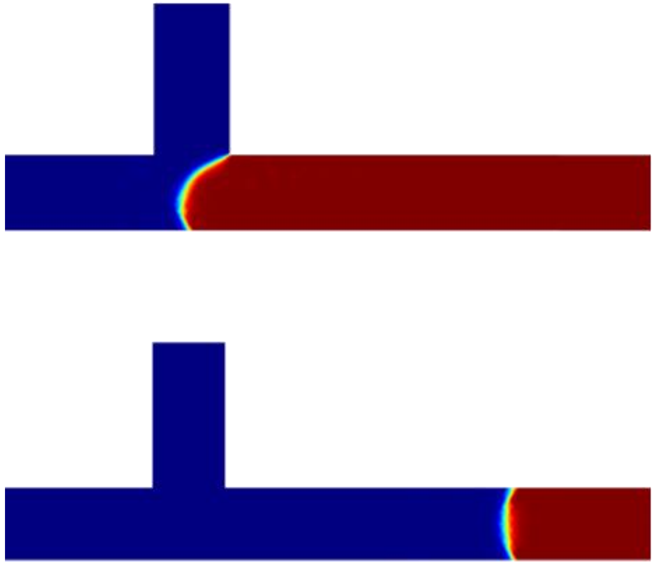
Video sequence realised with a high speed camera.
Time is slowed down 40 times.

TRIGGER VALVE

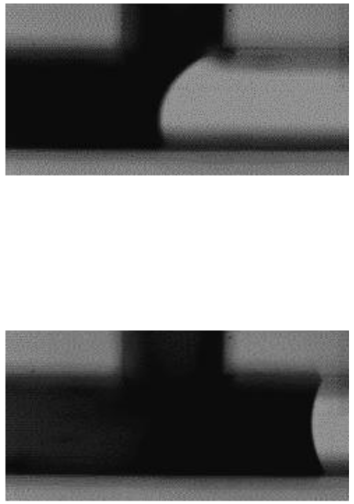
The liquid is stop by a stop valve



When the second liquid reaches the stop valve, it triggers the flow.

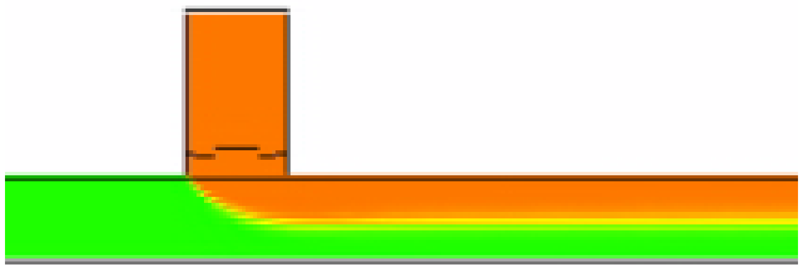


COMSOL simulations.

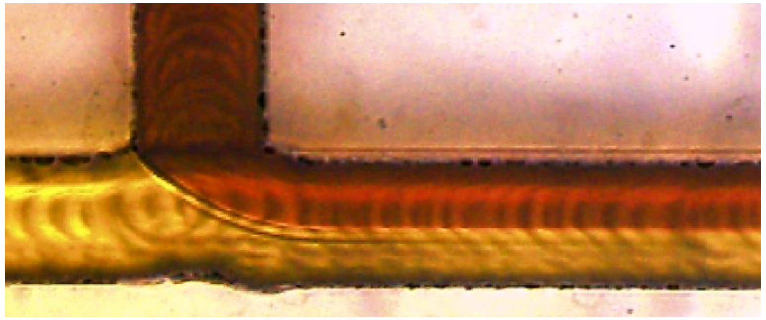


High speed camera pictures.

By adding a chemical species to one of the liquid, one can confirm that this trigger is followed with the usual laminar flow.



Comsol simulation

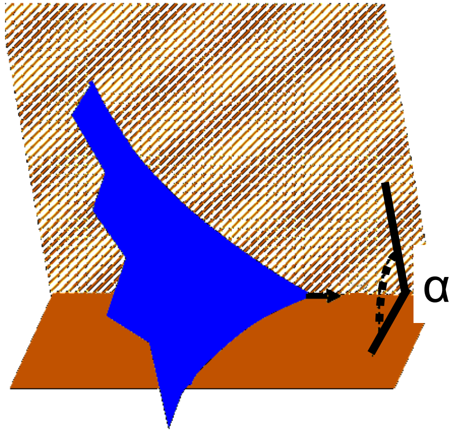


Picture taken under a microscope.

CONCUS-FINN FILAMENTS

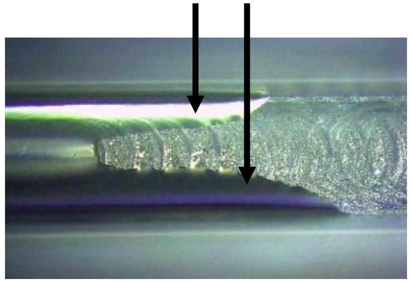
Concus-Finn condition:

There is a filament in an inner corner if: $\theta < \frac{\pi}{2} - \frac{\alpha}{2}$



3D view of a Concus-Finn filament. Evolver simulation.

Concus-Finn filaments.

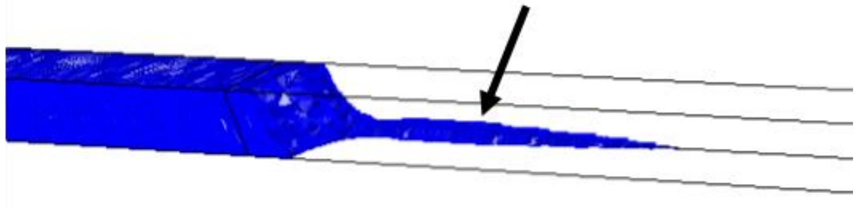


Top view of a capillary filling with Concus-Finn filaments.

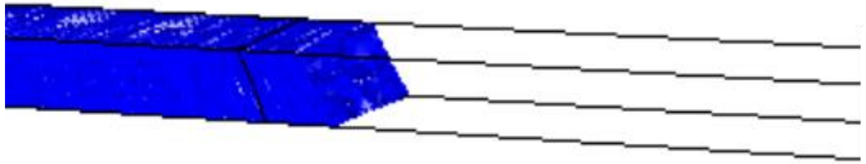
COMSOL simulation of a capillary flow within a rectangular duct.

The concus-Finn condition writes: $\theta < 45°$

Simulation with a contact angle of 30°:



Simulation with a contact angle of 60° :

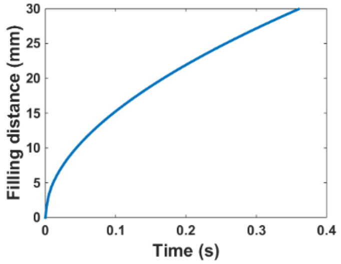


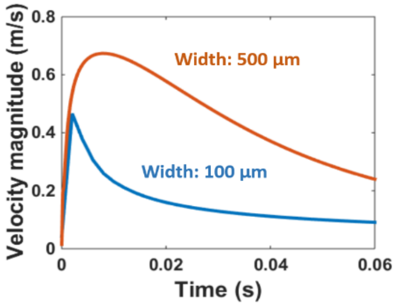
COMSOL simulations.

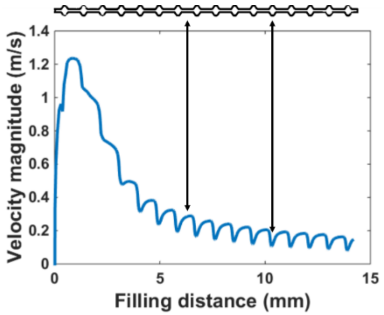
*Concus & al, PNAS, **63**(2), p 292 (1969)*

CONCLUSION

- Simulations of the dynamics of capillary flow done with COMSOL Multiphysics are qualitatively in agreement with the theory.

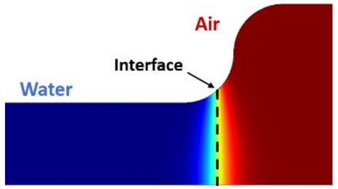


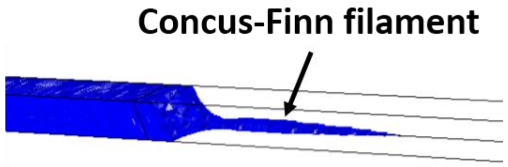




- Dynamic contact angle have been implemented.

- Geometry effects occuring during a capillary flow can be simulated with COMSOL Multiphysics.





Perspectives:

- Simulations with 3D geometries.
- Simulations with non-Newtonian fluids.

Thank you for your attention