11. Chalk on the water

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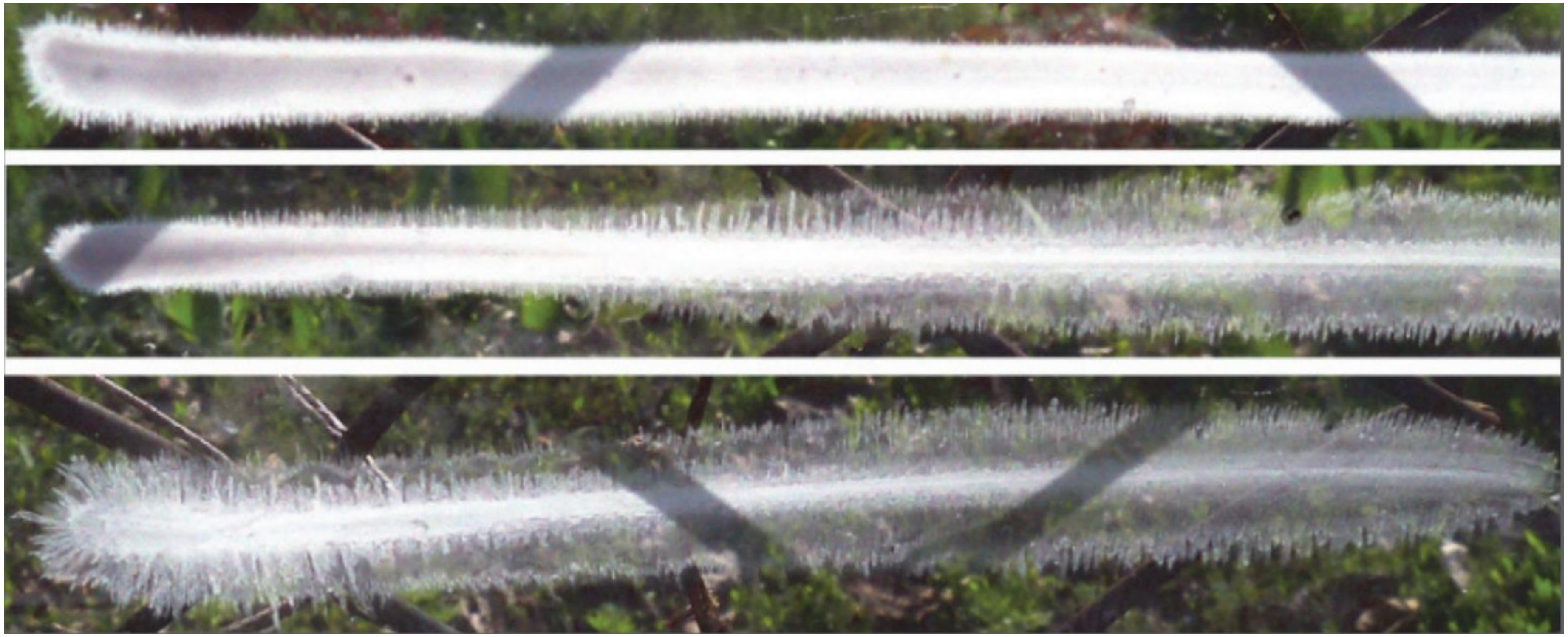
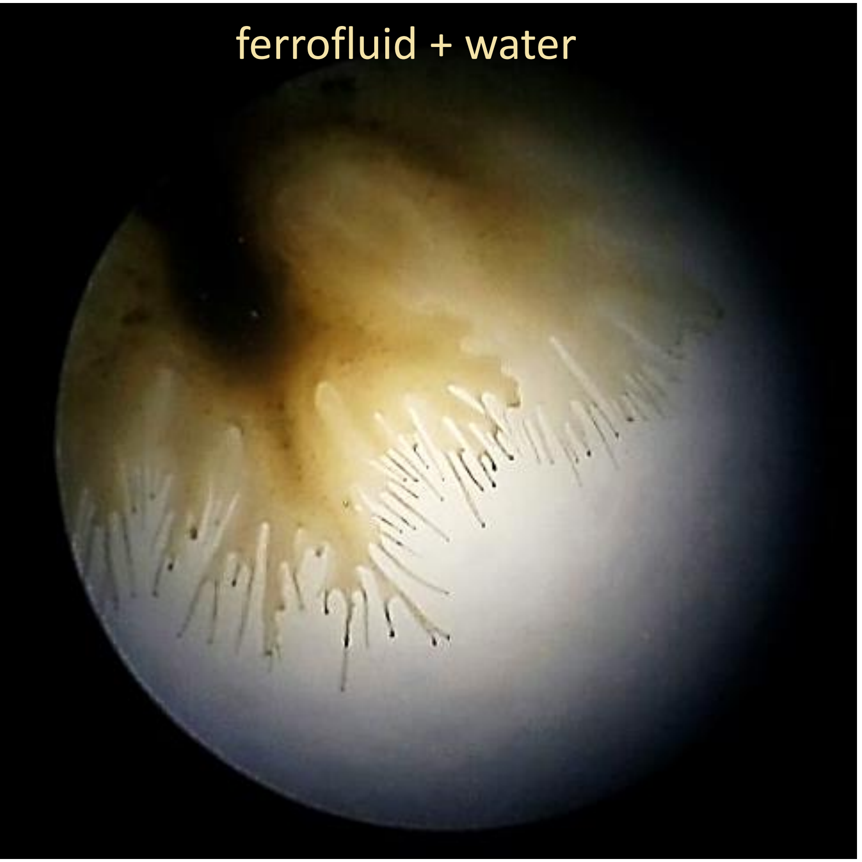
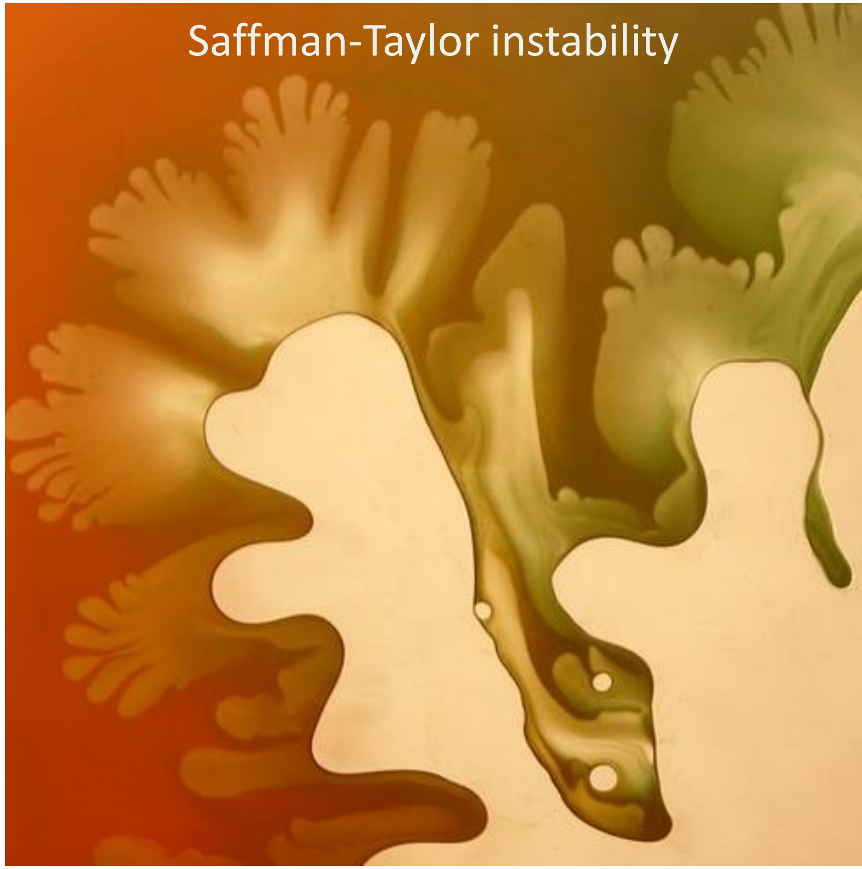
Problem statement

If you draw a line on a glass surface covered with a thin layer of water using chalk, the line will blur in offshoots distributed in the lengthwise direction. What are the statistical properties of this distribution and how do they depend on the important parameters?



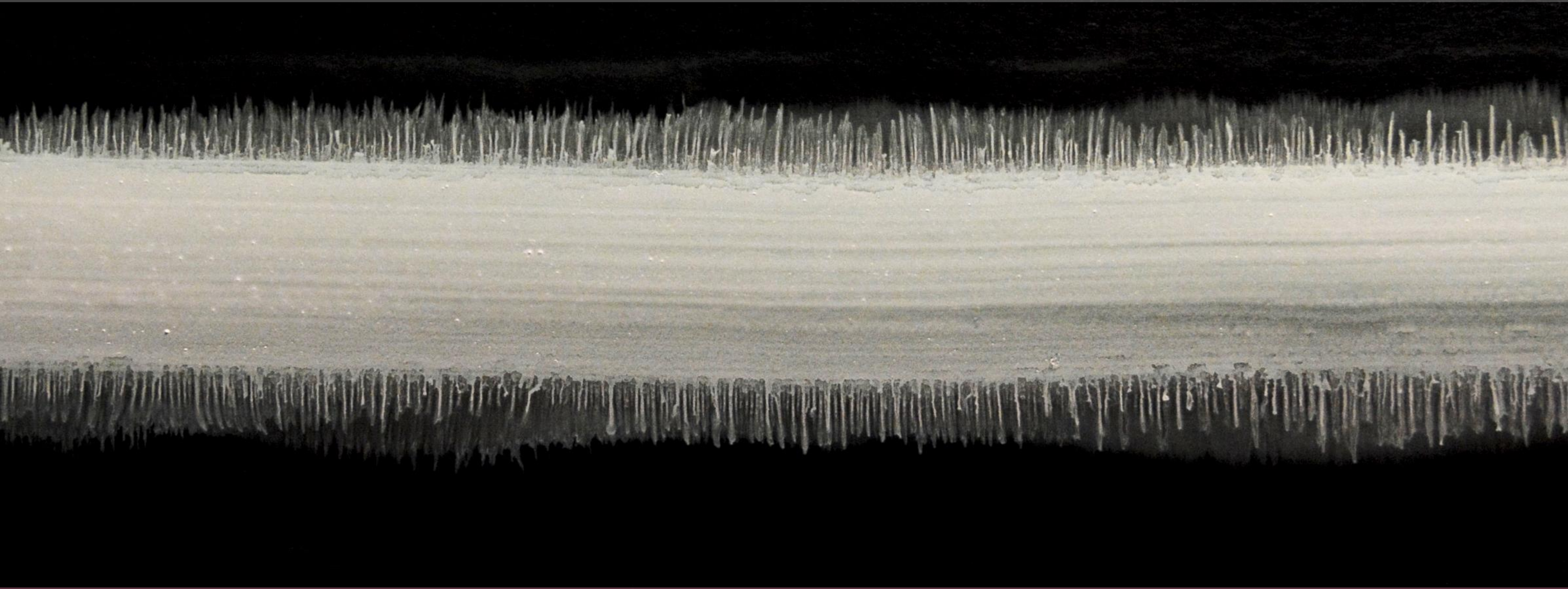
Fingering instability






Experiment with chalk
The effect wasn't reproduced!
4

Reproducing the effect from the condition



Chalk marker

The composition of the chalk marker

Provide the effect

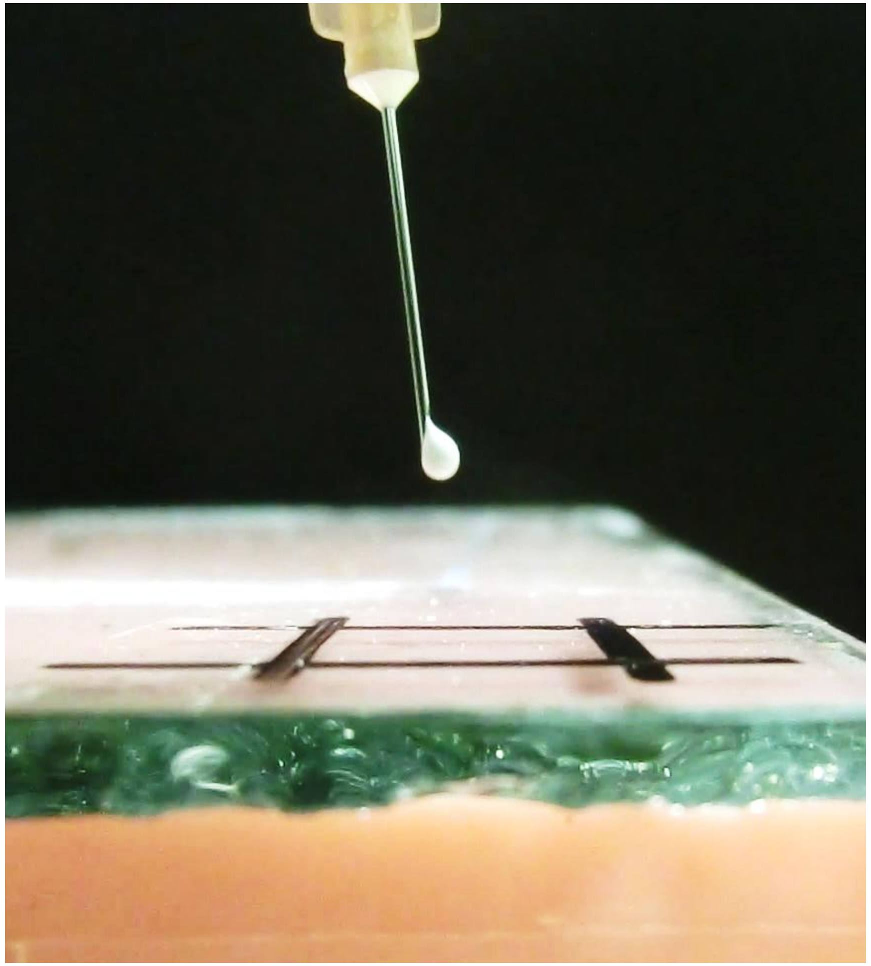
- Dispersing agent
- Titanium dioxide
- Isopropyl alcohol
- Water
- Pigment (white)

From the composition we can highlight the following conclusions:

1) No chalk!
2) A small surface energy, which leads to the liquid "sticking" to the glass
3) Evaporation rapidity

Needle formation

Surface tension measurement (marker liquid)



1 ml of marker liquid
was injected into the syringe

The marker liquid was dripped

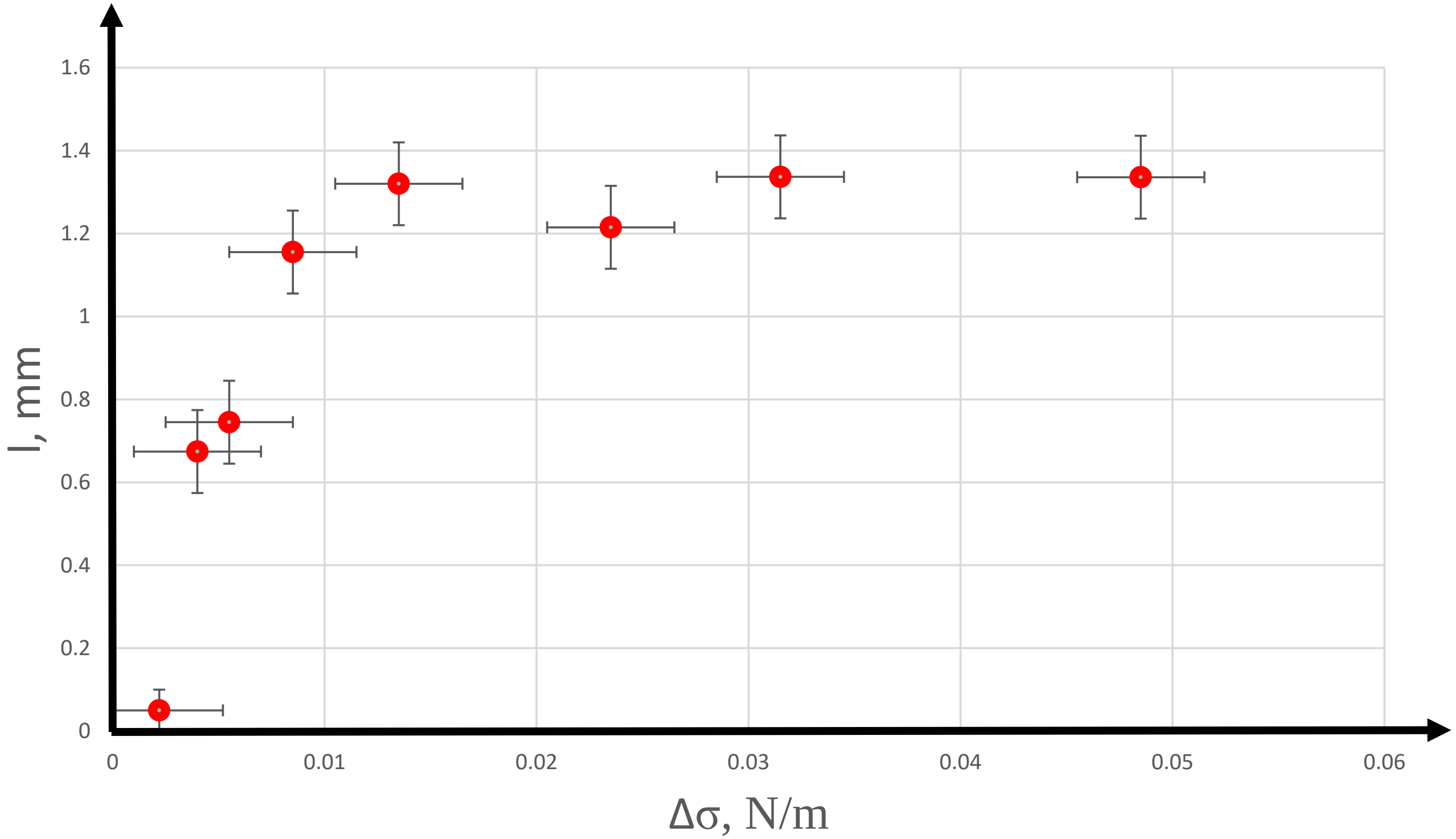
$$\sigma = \frac{mg}{\pi N d}$$

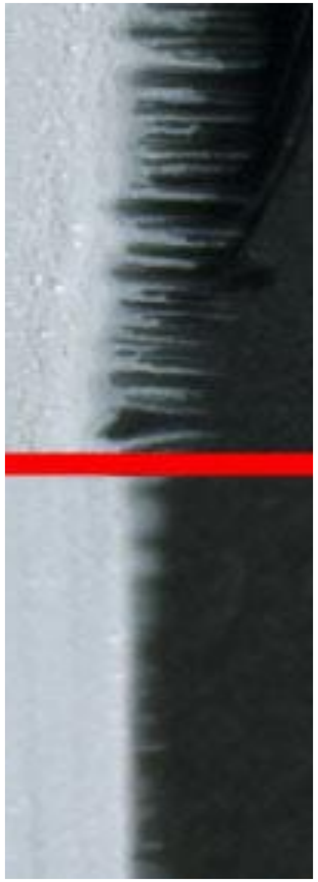
d – diameter of needle bevel

N – number of drops

$$\sigma_{marker} = 24{,}5 \cdot 10^{-3}\, N/m$$

Needles length VS difference between surface tension of marker and outer liquid





0% of alcohol

50% of alcohol

The difference in surface tensions leads to the needles appearence

Needle formation mechanism

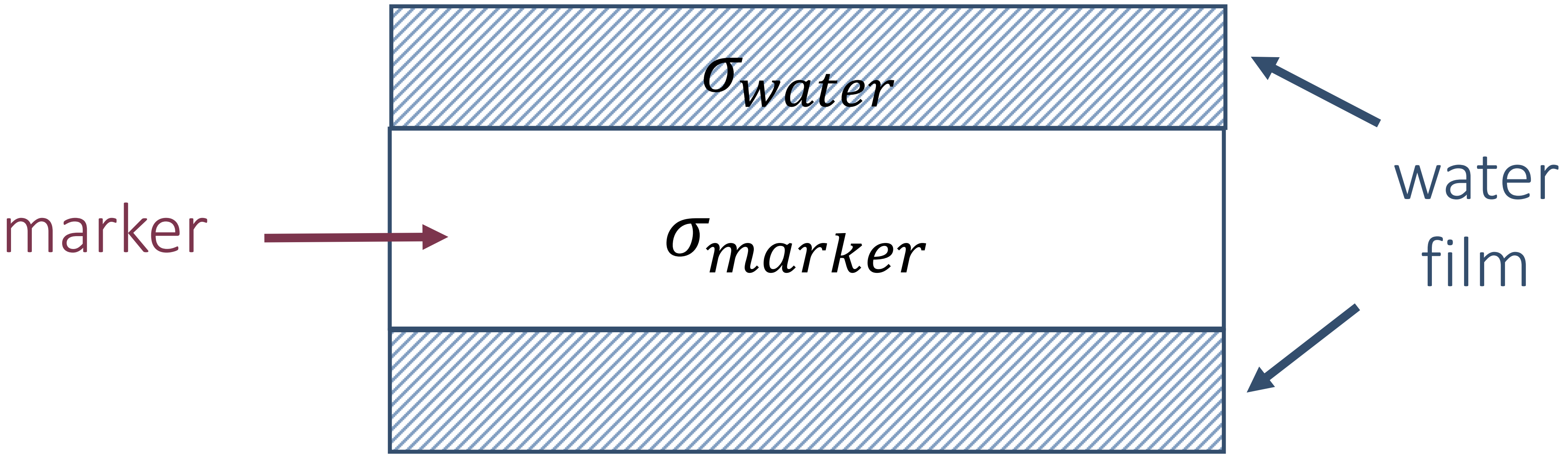
1 stage

2 stage

3 stage

Marangoni effect

$$\sigma_{marker} < \sigma_{water}$$



$$\sigma_{water} = 72{,}86 \cdot 10^{-3}\, {}^{H}\!/_{m} \qquad \sigma_{marker} = 24{,}5 \cdot 10^{-3}\, {}^{H}\!/_{m}$$

Marangoni effect

The flow comes from a region with a low surface tension to the region with a higher surface tension.

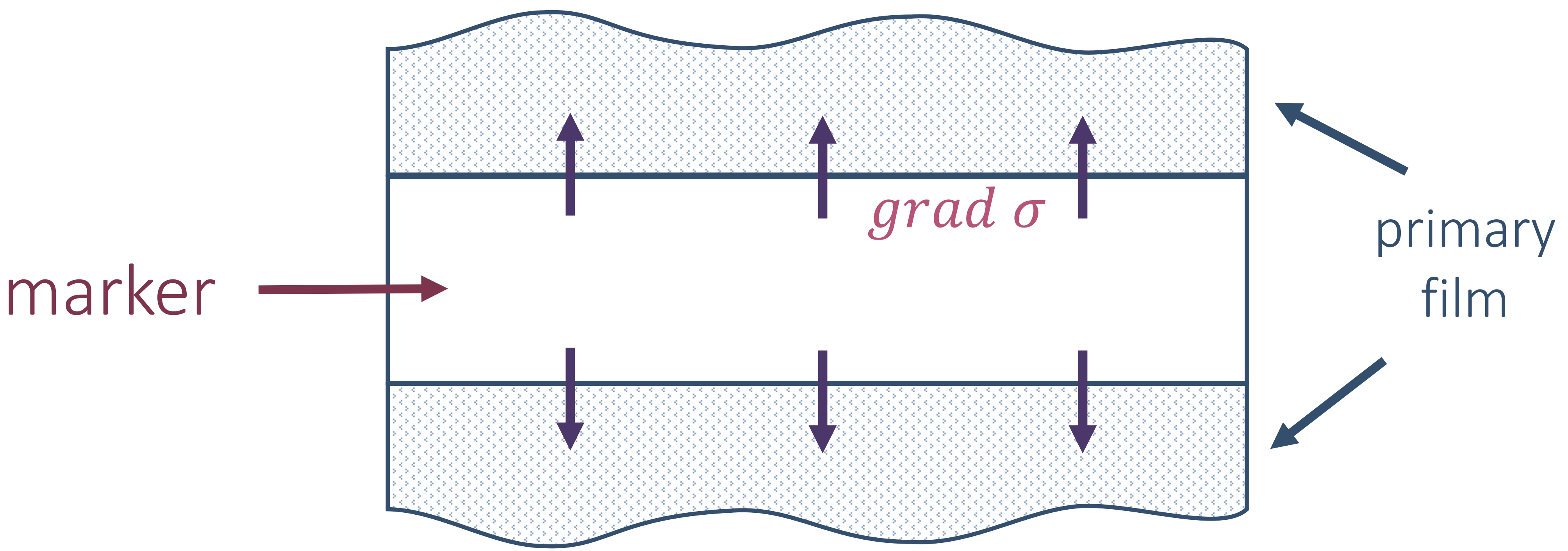
Needle formation mechanism

Primary film formation

1 stage

2 stage

3 stage



The greater the difference is in surface tension, the greater is the velocity of the fluid.

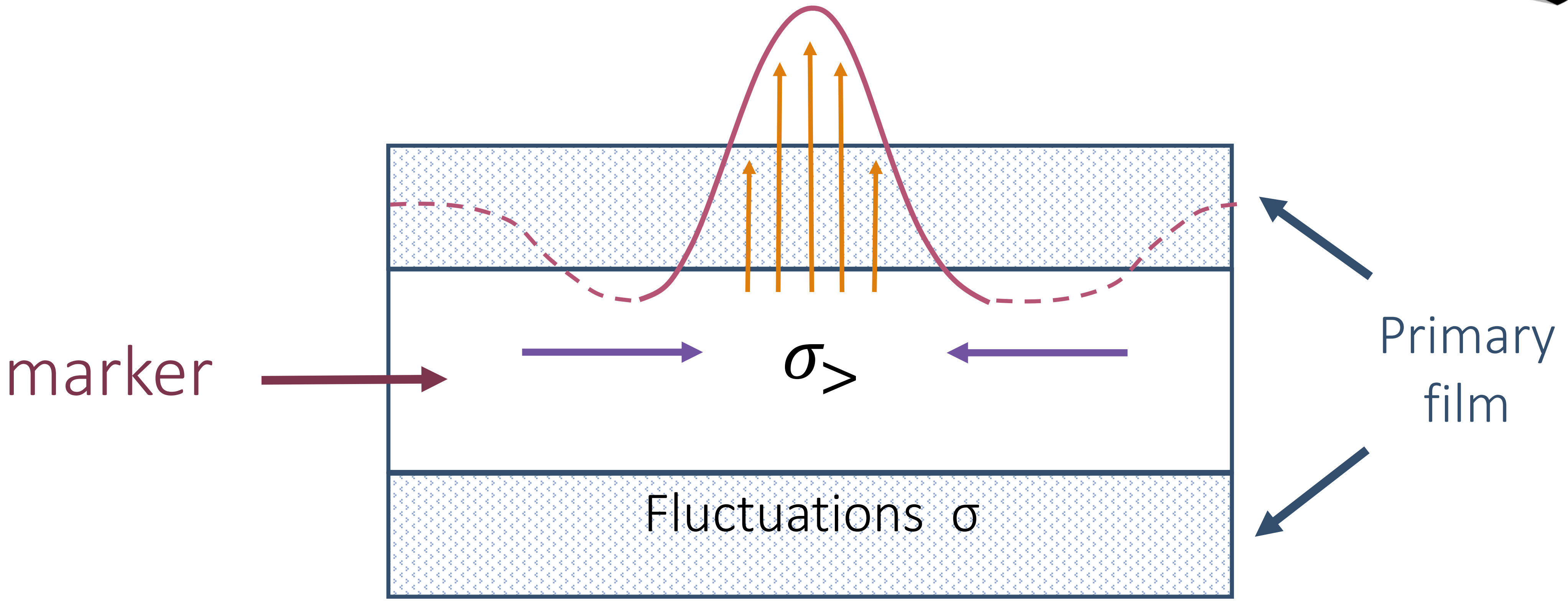
Primary film formation

Needle formation mechanism

1 stage

2 stage

3 stage



The greater the layer thickness is, the greater is the velocity of the marker fluid movement

The speed of the needle is greater than the speed of the rest of the fluid movement

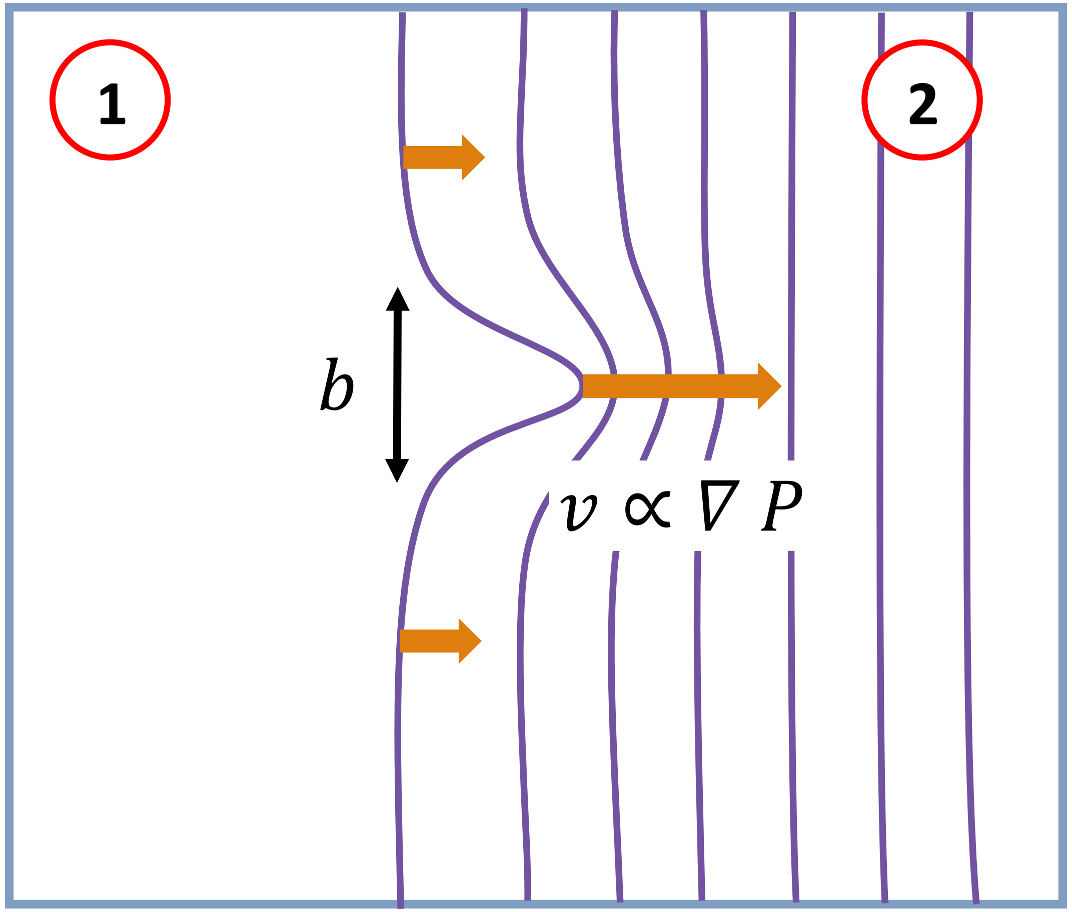
The role of diffusion

Peclet number

$$Pe = \frac{\Delta\sigma\, H}{\mu\, D_s} \approx 5 \cdot 10^6$$

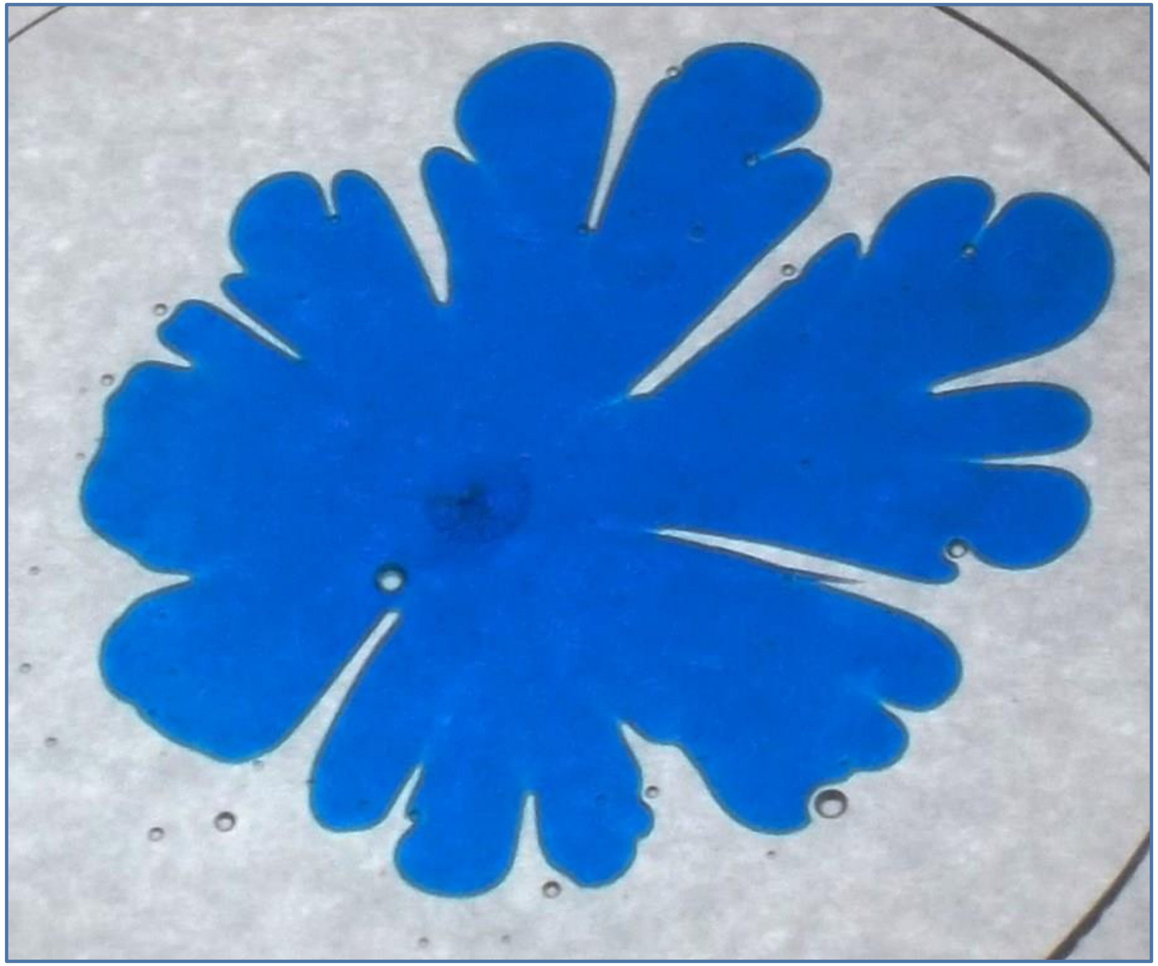
Diffusion is happening much slower in comparison with needles growth

Saffman – Taylor instability



$\mu_1 \ll \mu_2$

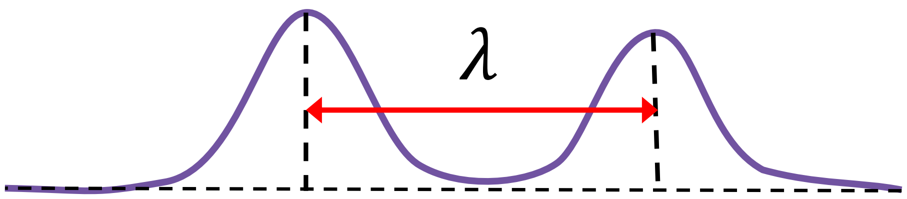
1, 2 – liquids of different viscosities



Analogy with the Saffman-Taylor instability

Wave-length instability λ:

$$\lambda = \frac{\pi H}{\sqrt{C_a}}$$



Capillary number $C_a = \mu \frac{U}{\sigma}$

Velocity (Marangoni effect) $U = \frac{H}{\mu} \, grad \, \sigma$

where μ – dynamic viscosity

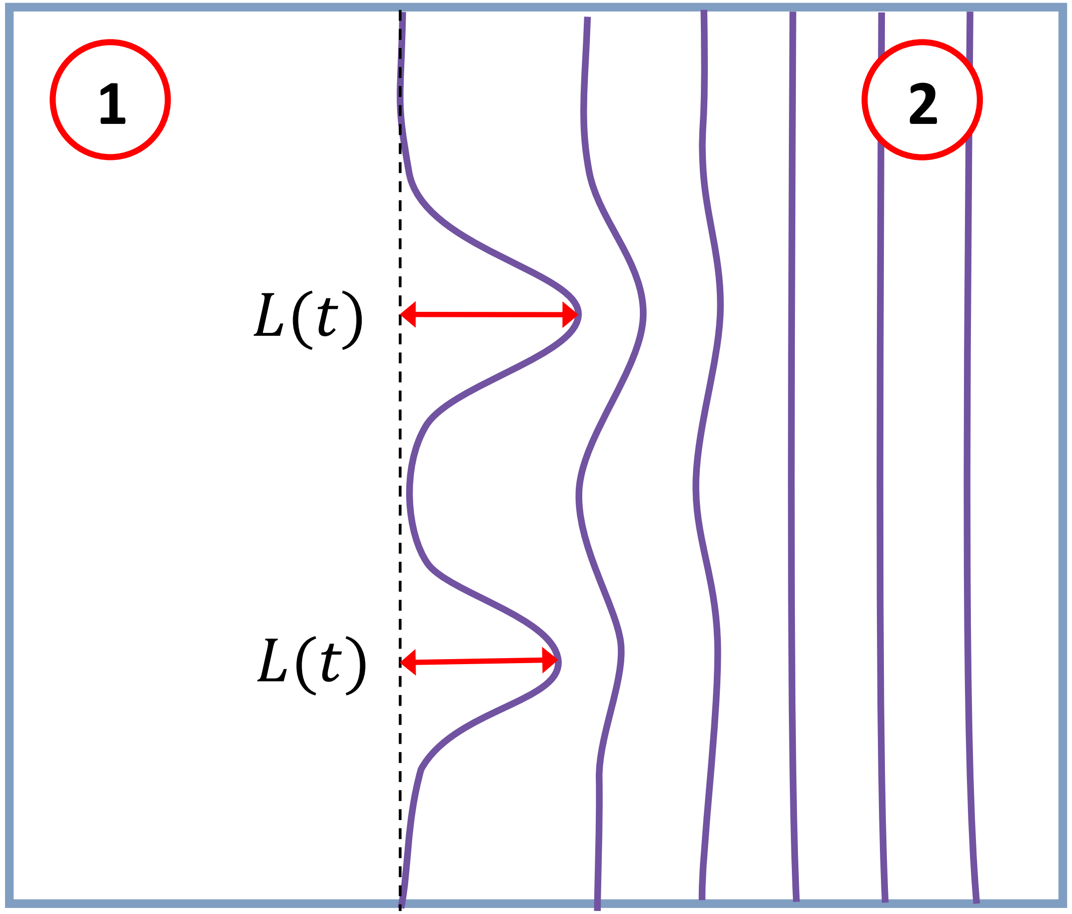
What does wavelength depend on?

H – water layer thickness

σ – surface tension coefficient

$$\lambda = \pi \sqrt{\frac{H \sigma}{grad \, \sigma}}$$

Front propagation speed for thick and thin films



$L(t)$ – the needle length as a function of time

$$\frac{H_{marker}}{H_{water}} \gtrsim 2$$ → Thick film

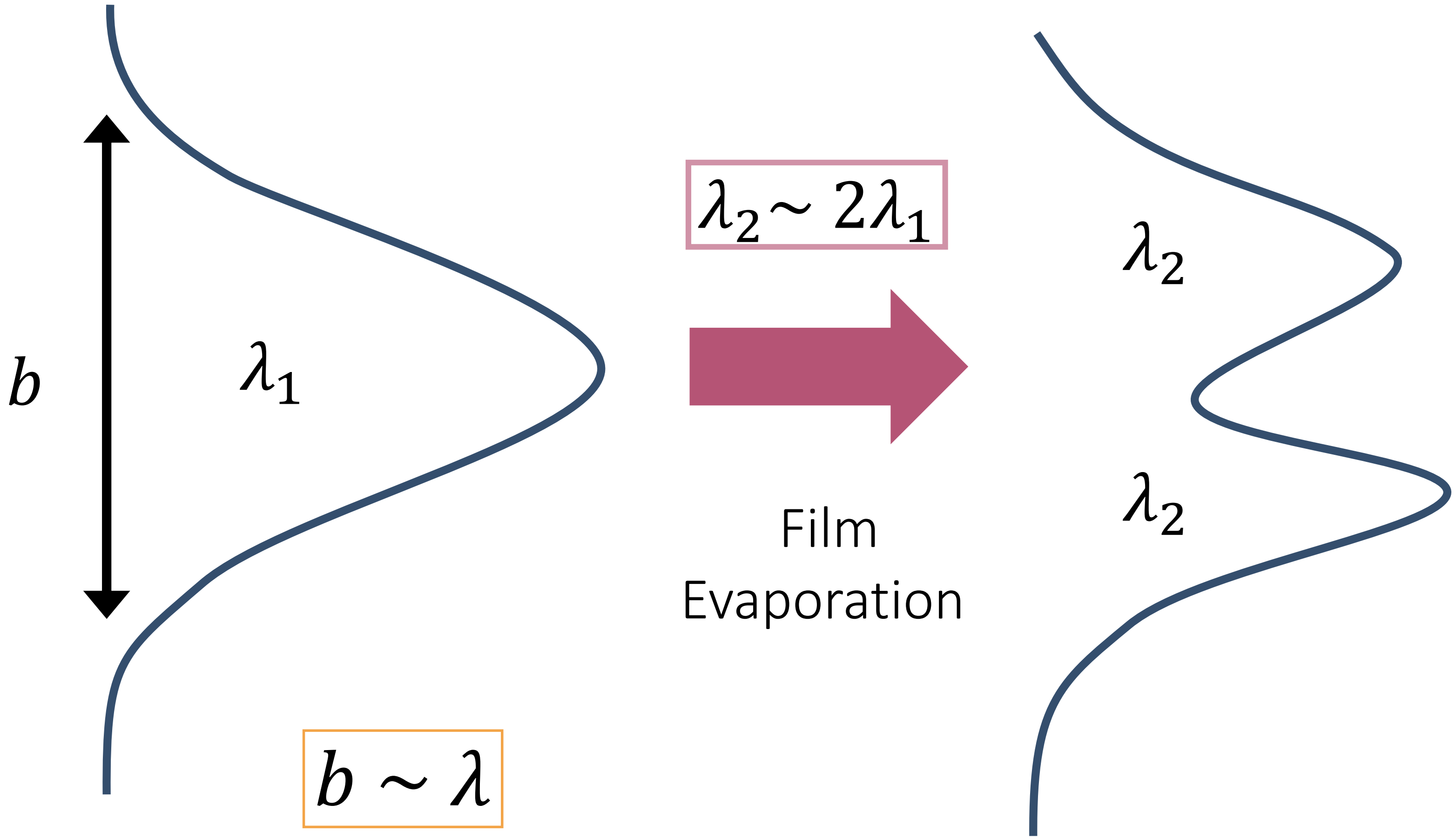
$$L(t) \sim \frac{\sqrt{\sigma}}{(\mu\,\rho)^{1/4}} t^{3/4}$$ [1]

$$\frac{H_{marker}}{H_{water}} \lesssim 2$$ → Thin film

$$L(t) \sim \frac{\sigma^{1/3}}{(\mu\,\rho)^{1/6}} t^{1/2}$$ [1]

[1] Abia B. Afsar-Siddiqui, Paul F. Luckham, Omar K. Matar; The spreading of surfactant on thin liquid films

Mechanism of needle division for thin film



$$\lambda = \pi \sqrt{\frac{H\,\sigma}{grad\,\sigma}}$$

$$H(t) = H_0 - q \cdot t$$

H_0 – thickness of initial water film

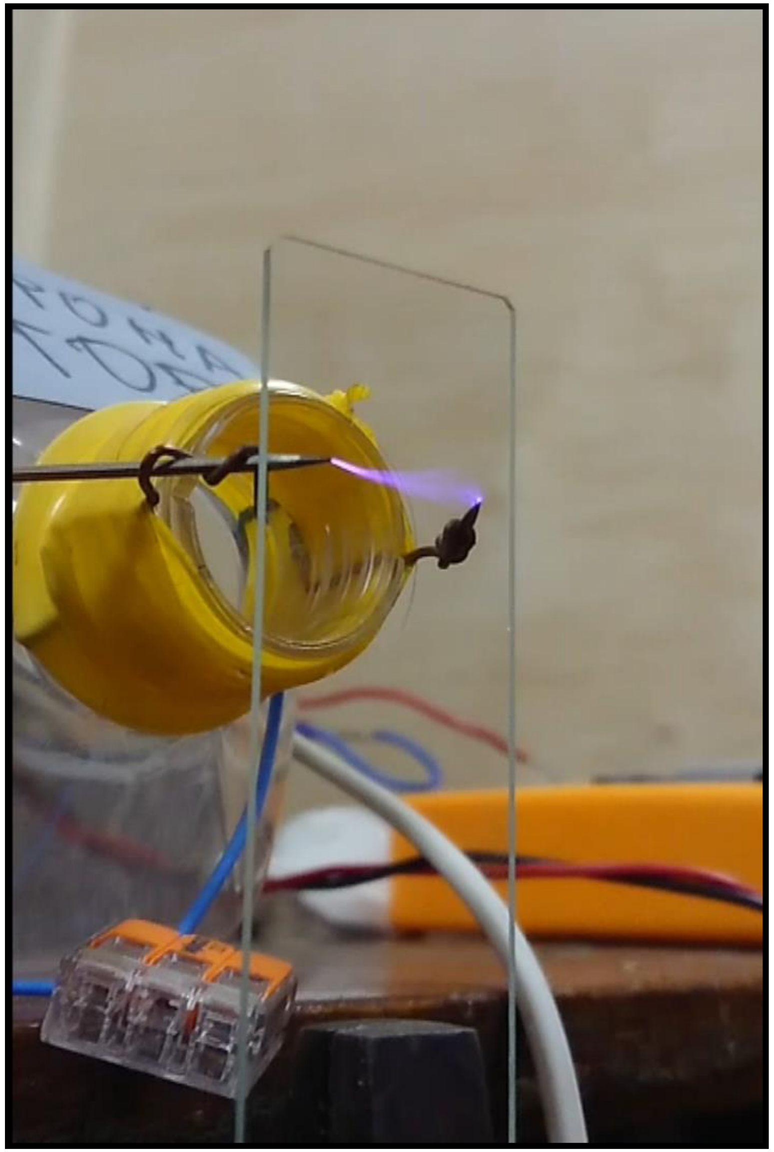
q – evaporation rate

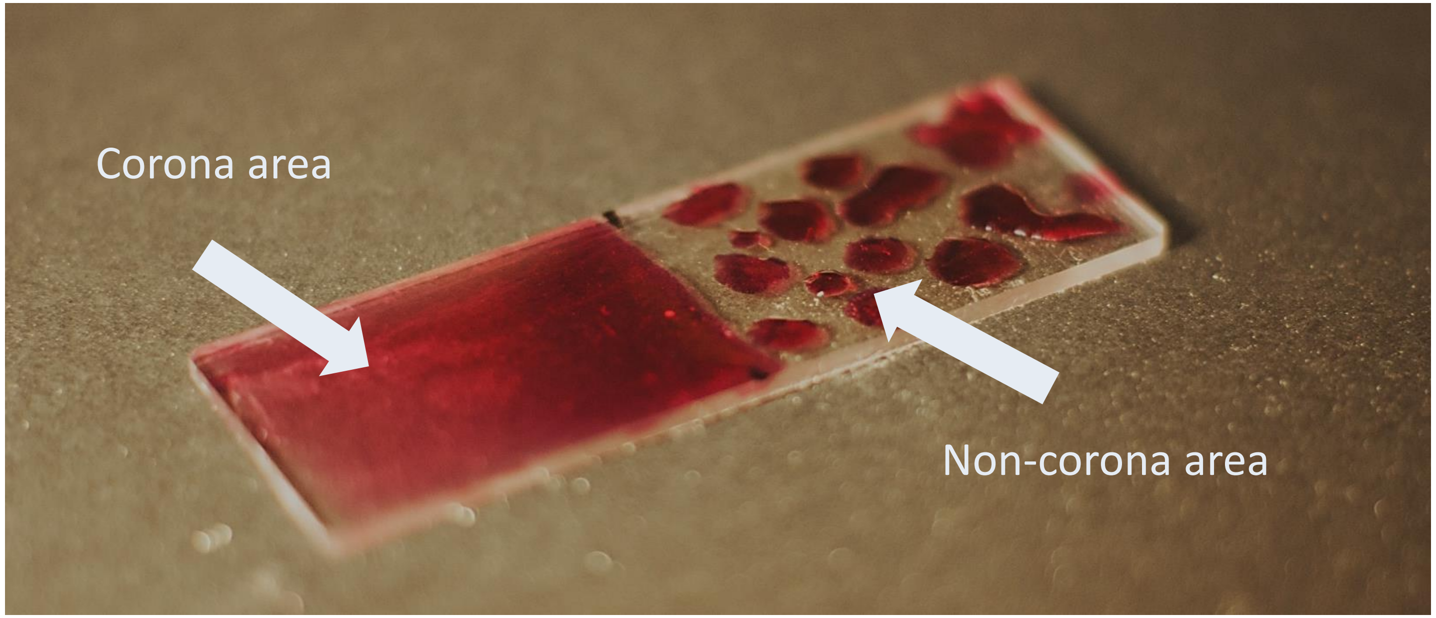
$$t = \frac{3\,H}{q}$$

t – the time through which the needle will share

The thinner the film is, than more often the needles split

Corona discharge of glass before experiment



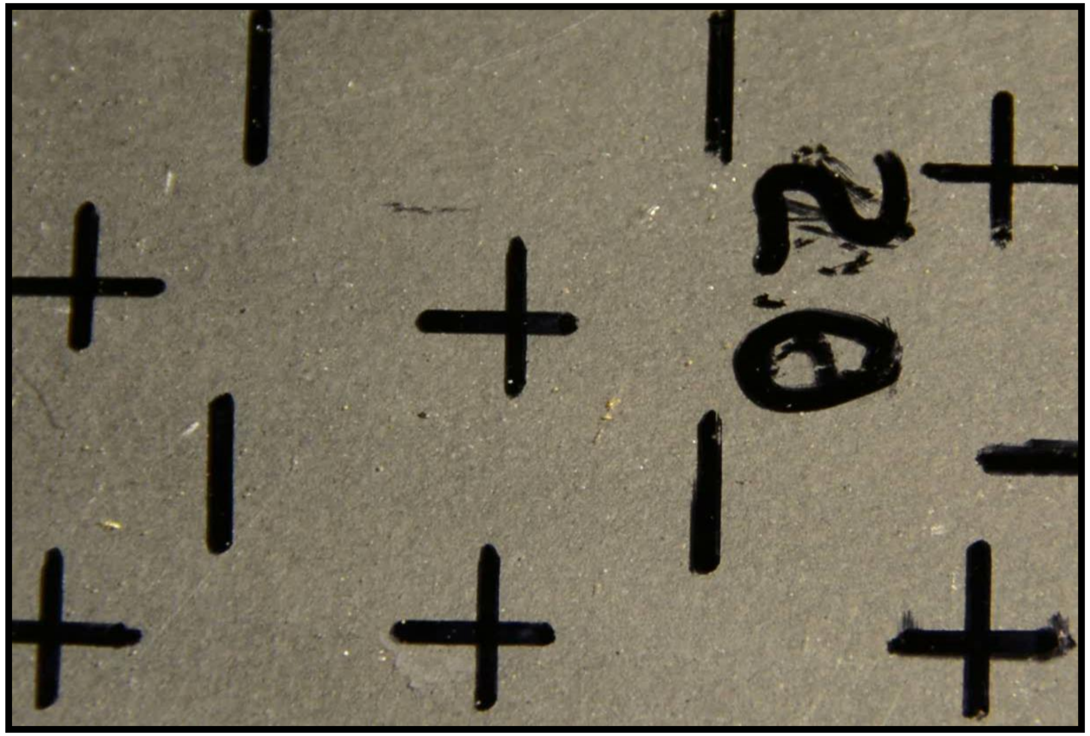


Corona discharge increased the surface energy

Ensured the uniformity of the applied layer

Film thickness measurement

Control the water film thickness by evaporation



Applied the fixed volume of the drop 1/40 ml

Rubbed on the area of $80\ cm^2$

Got films of different thicknesses,

depending on the evaporation time

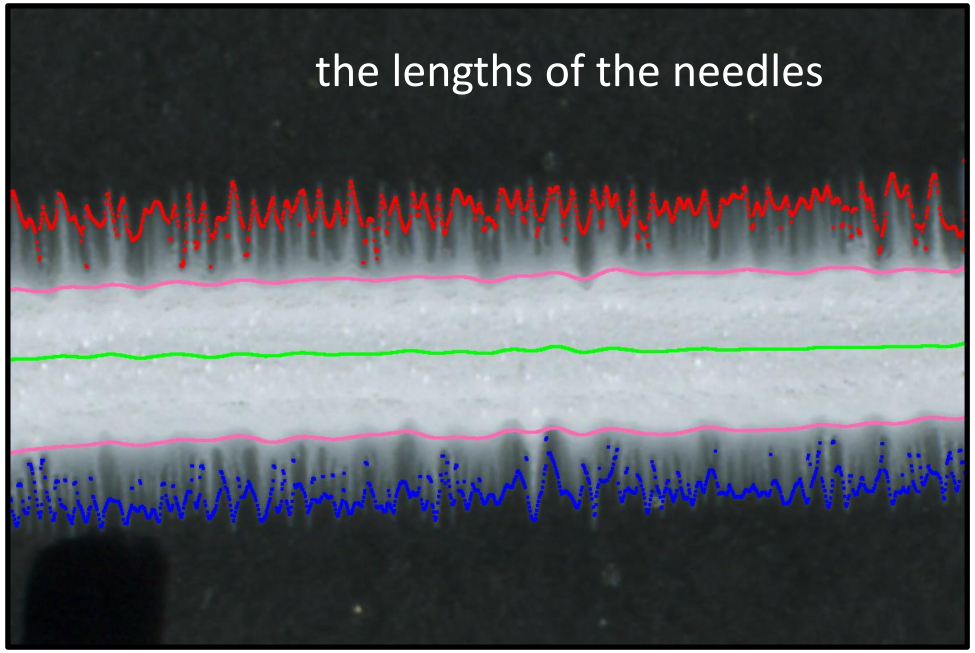
Standardization: controlling time for full film drying of various thickness.

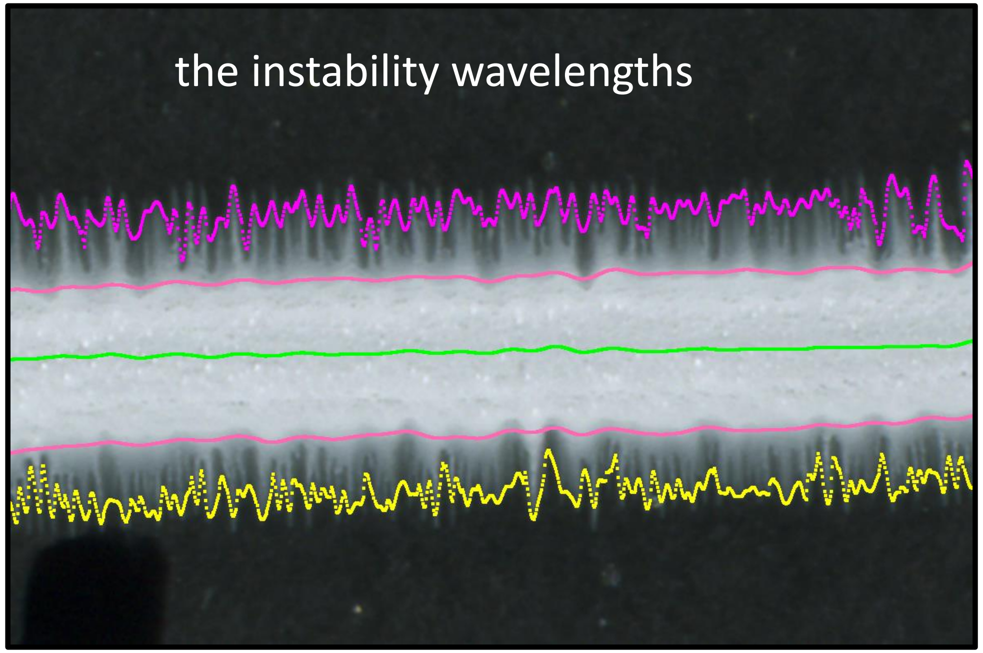
Marker layer thickness $\sim 6\ \mu m$

Experiment processing

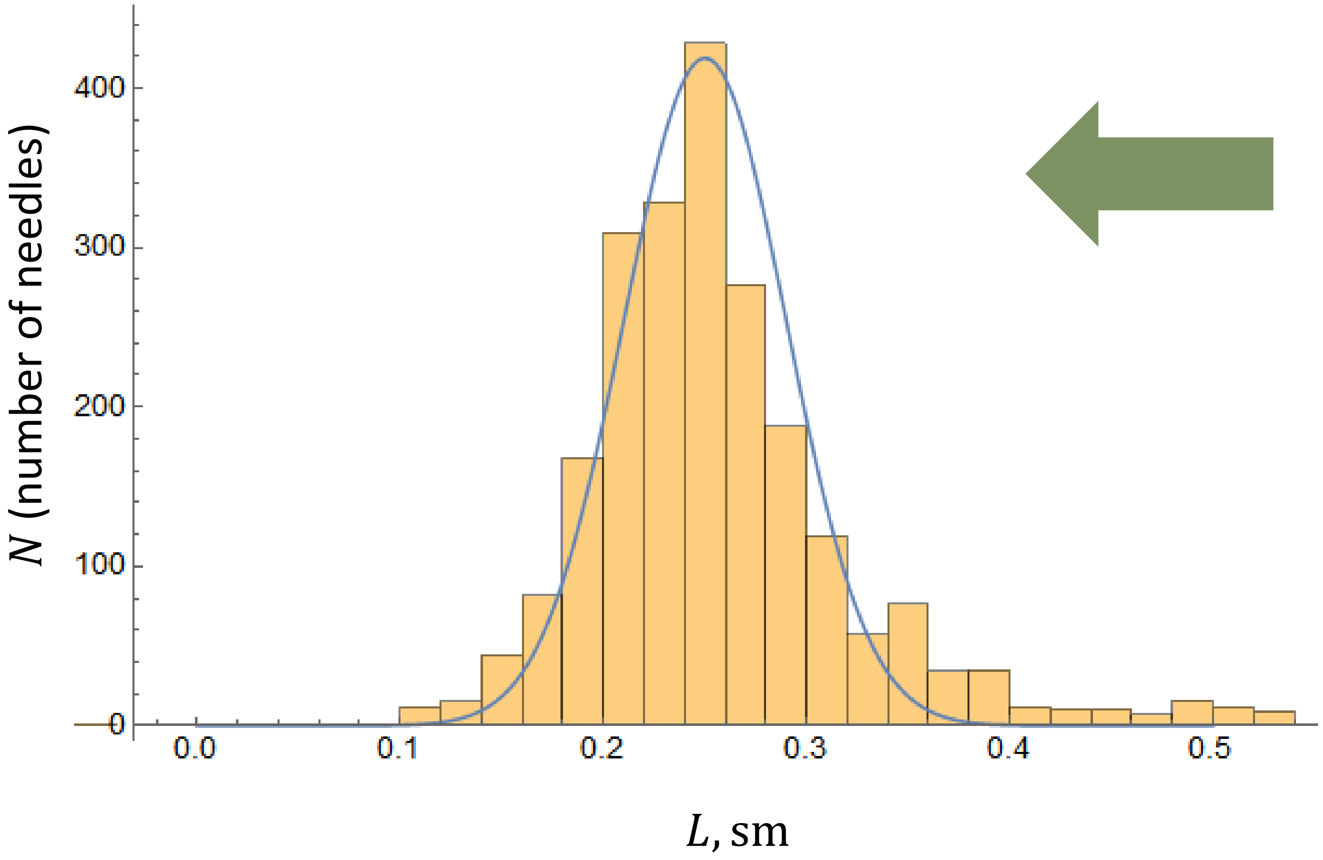
We scanned the results

We got the lengths of the needles and the instability wavelengths through our written program

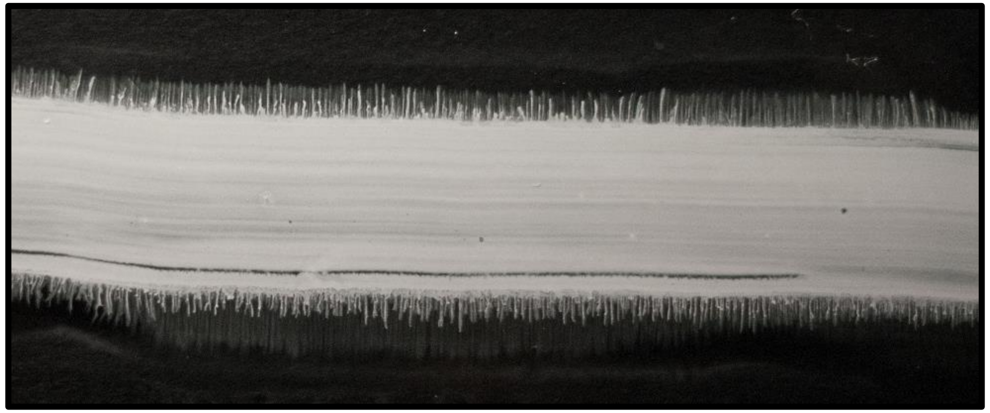




Distribution of needles length



Normal distribution

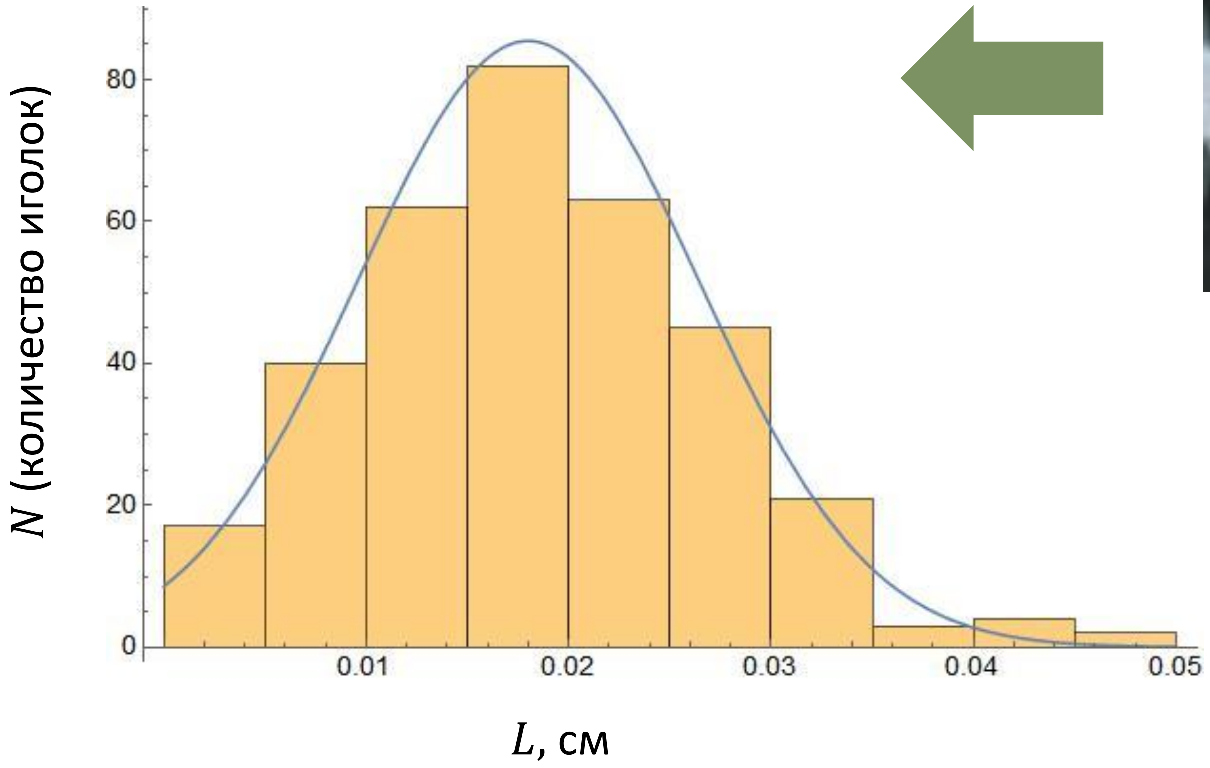


Gaussian function:

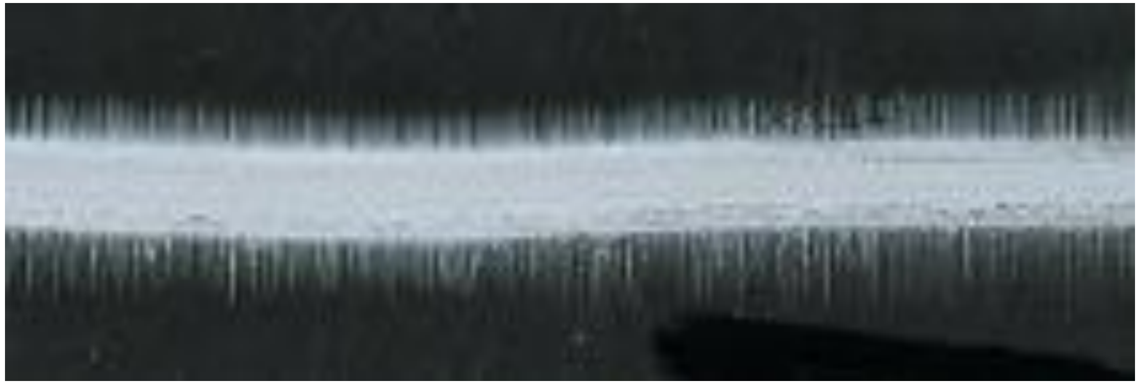
$\mu\ (mean) = 2{,}5$ mm

$\delta\ (standard\ deviation) = 0{,}4$ mm

Distribution of long wave instability



Normal distribution

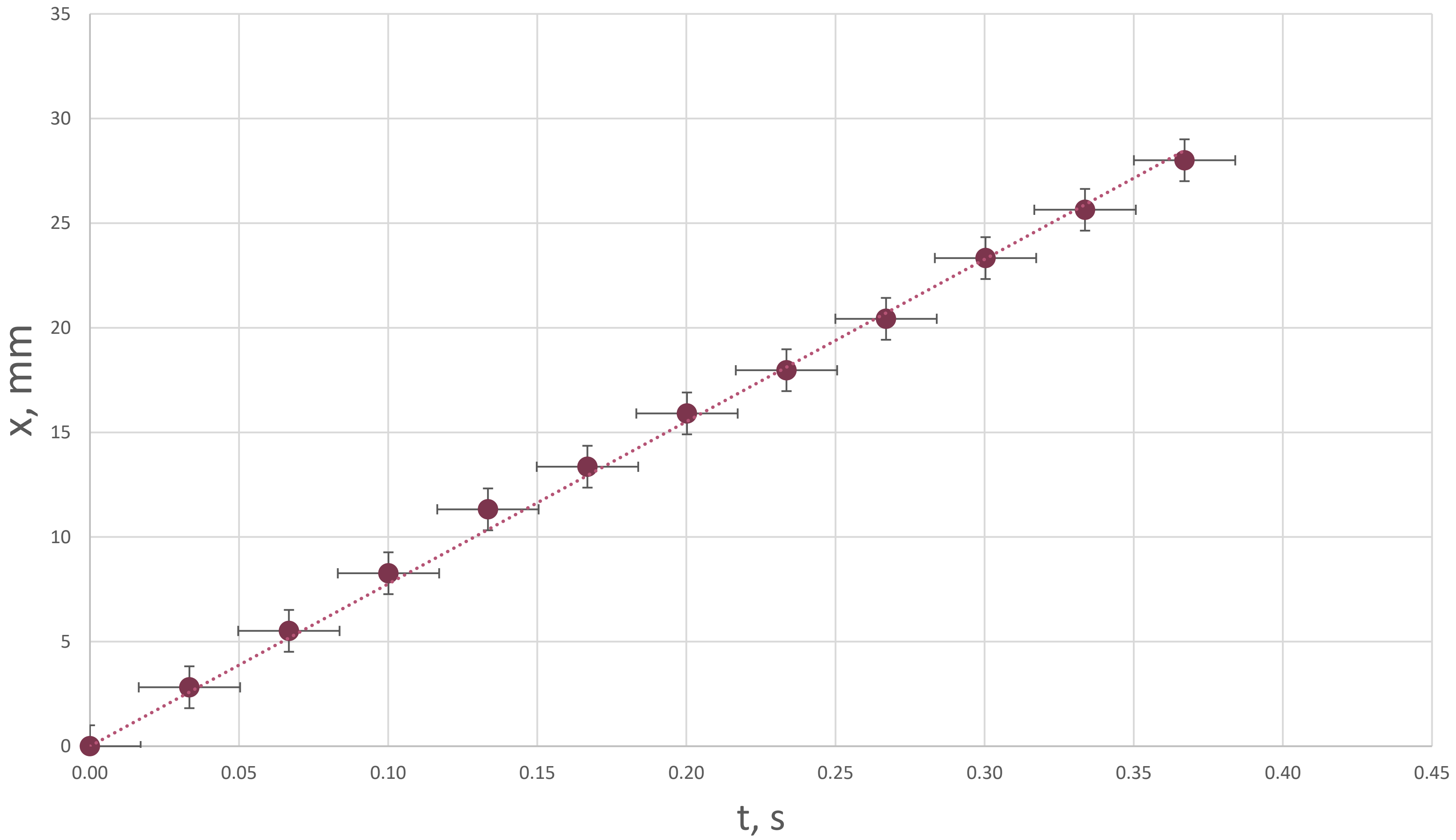


Gaussian function:

$\mu\ (mean)$ =0,18 мм

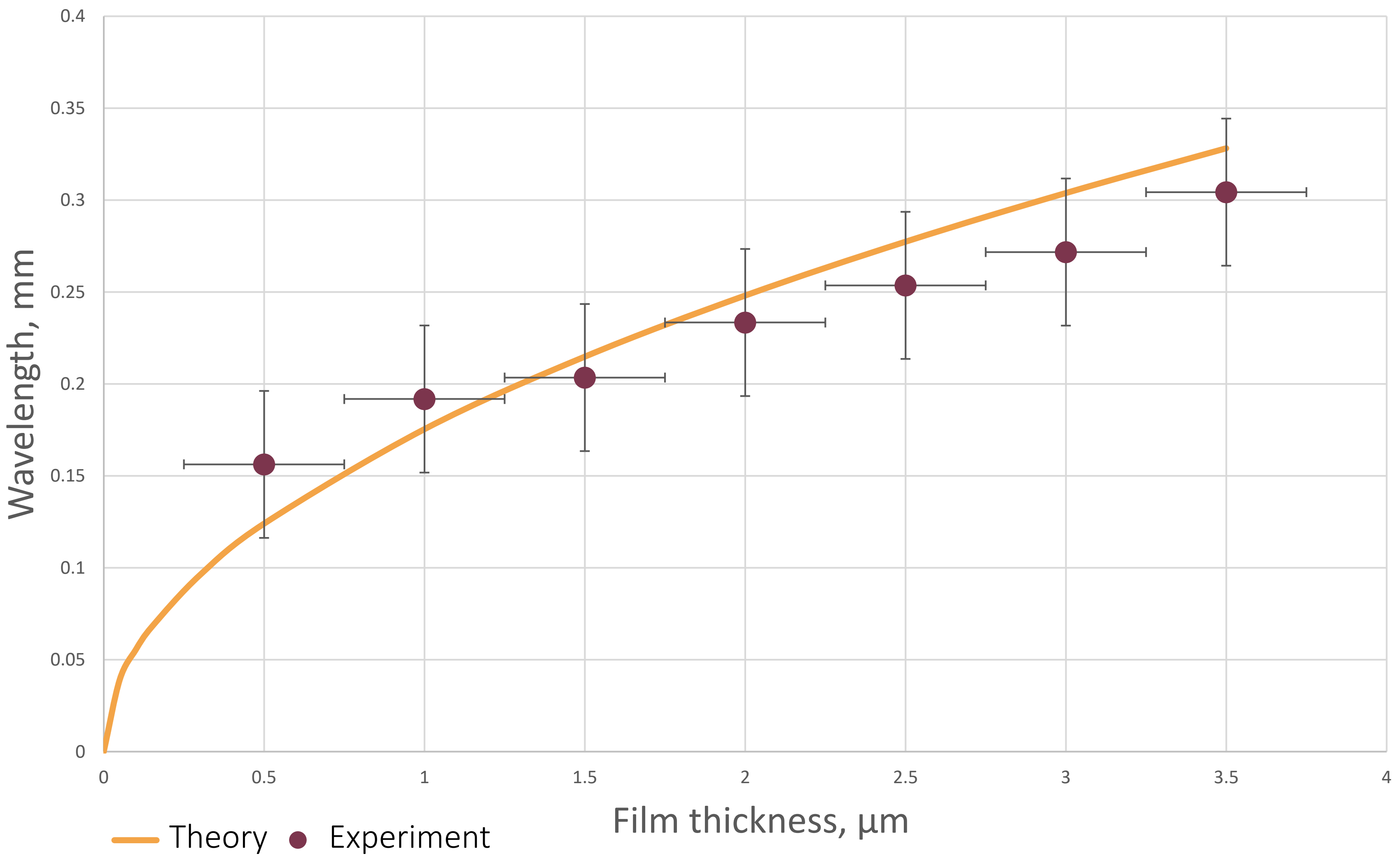
$\delta\ (standart\ deviation) =$ 0,08 мм

The speed of marker

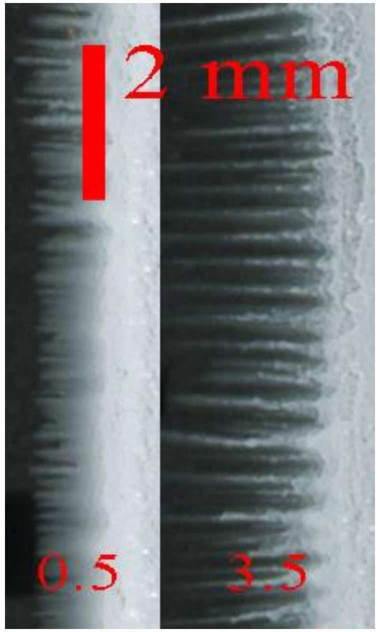


We chose experiments where the speed of marker was $v = 7{,}7 \pm 0{,}7\ {}^{cm}/_{s}$

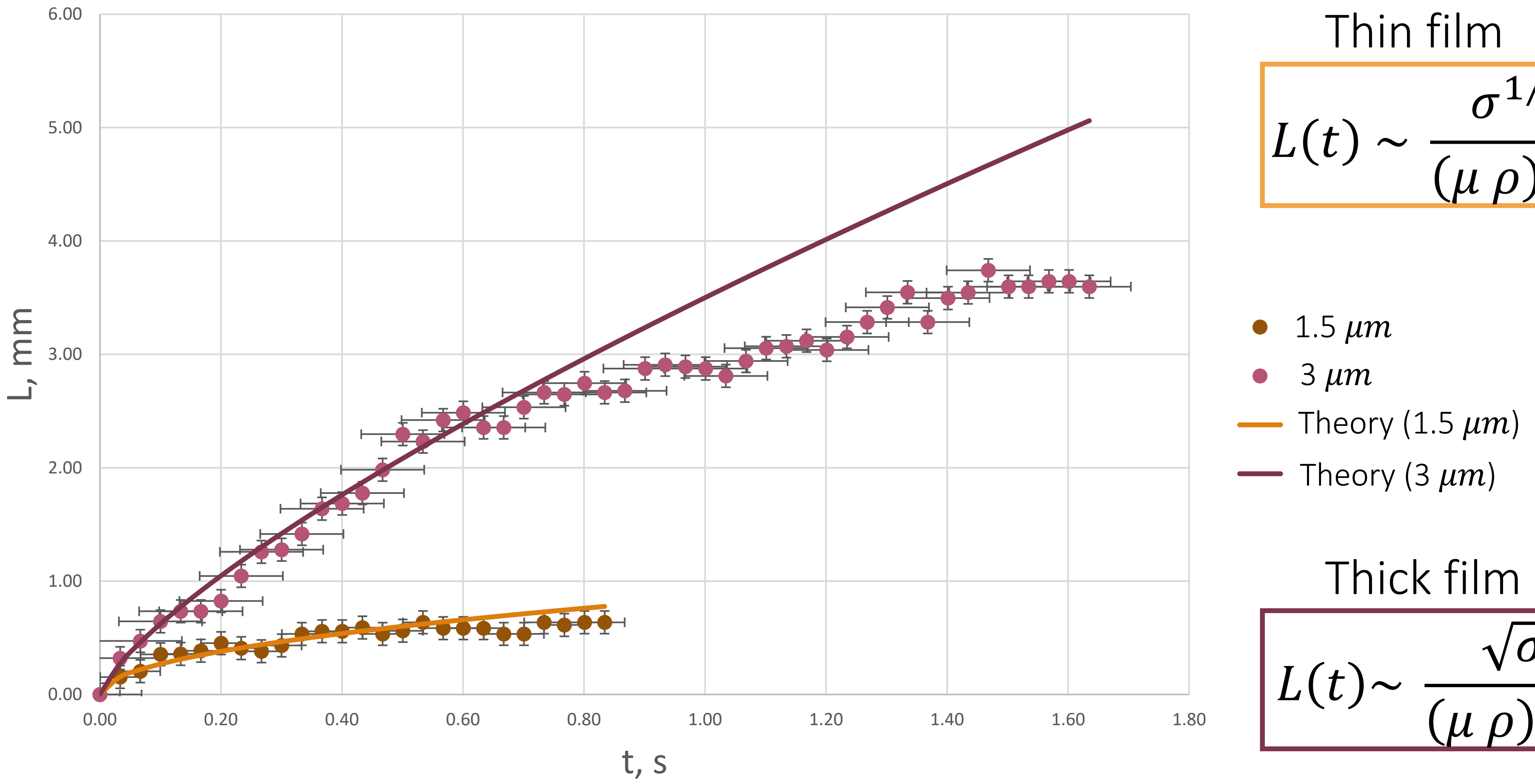
Experiment with the dependence of the wavelength on the film thickness



$$\lambda = \pi \sqrt{\frac{H\,\sigma}{grad\,\sigma}}$$



The dependence of the needle length to time at different film thicknesses



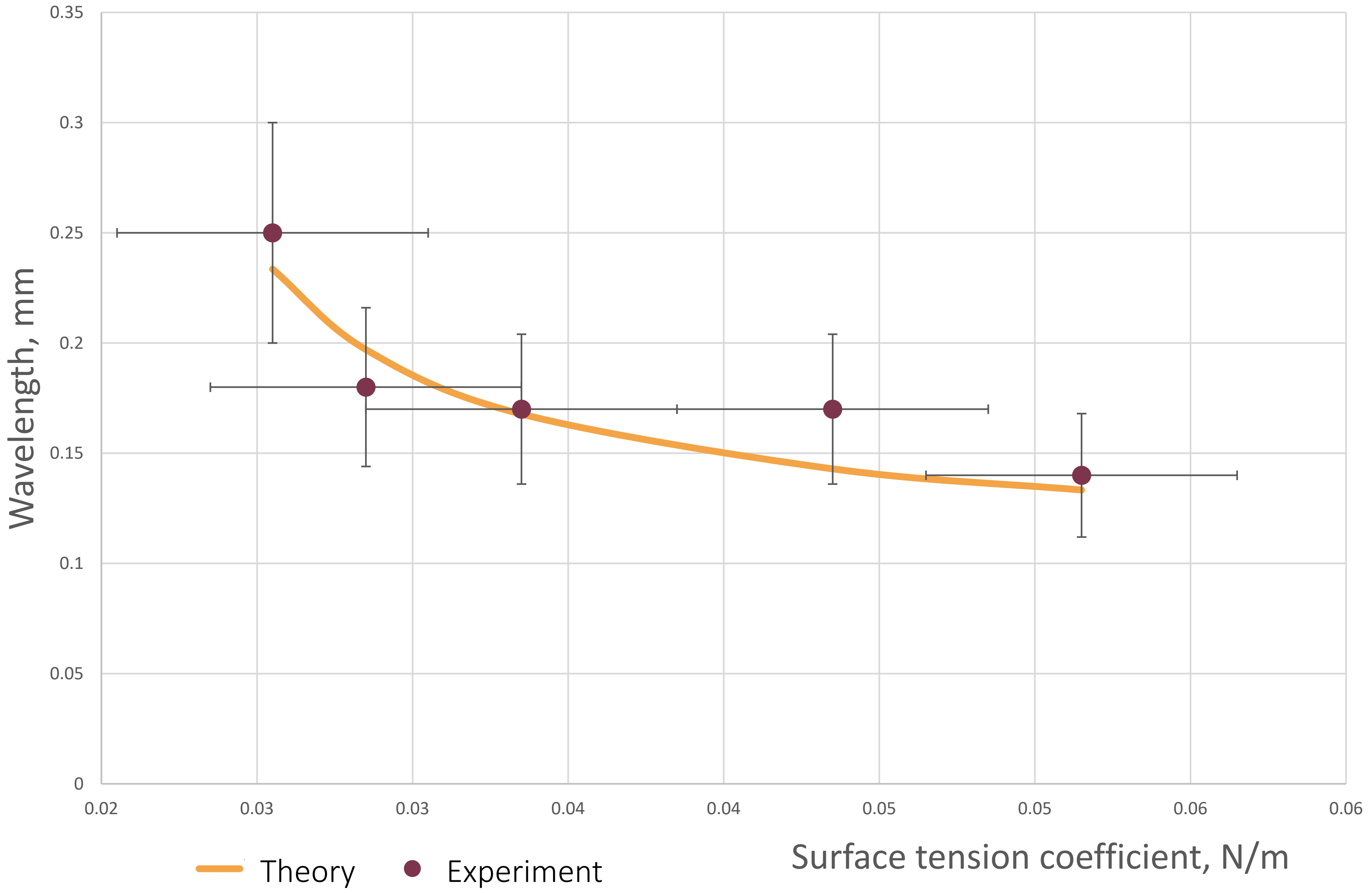
Thin film

$$L(t) \sim \frac{\sigma^{1/3}}{(\mu\,\rho)^{1/6}}\, t^{1/2}$$

Thick film

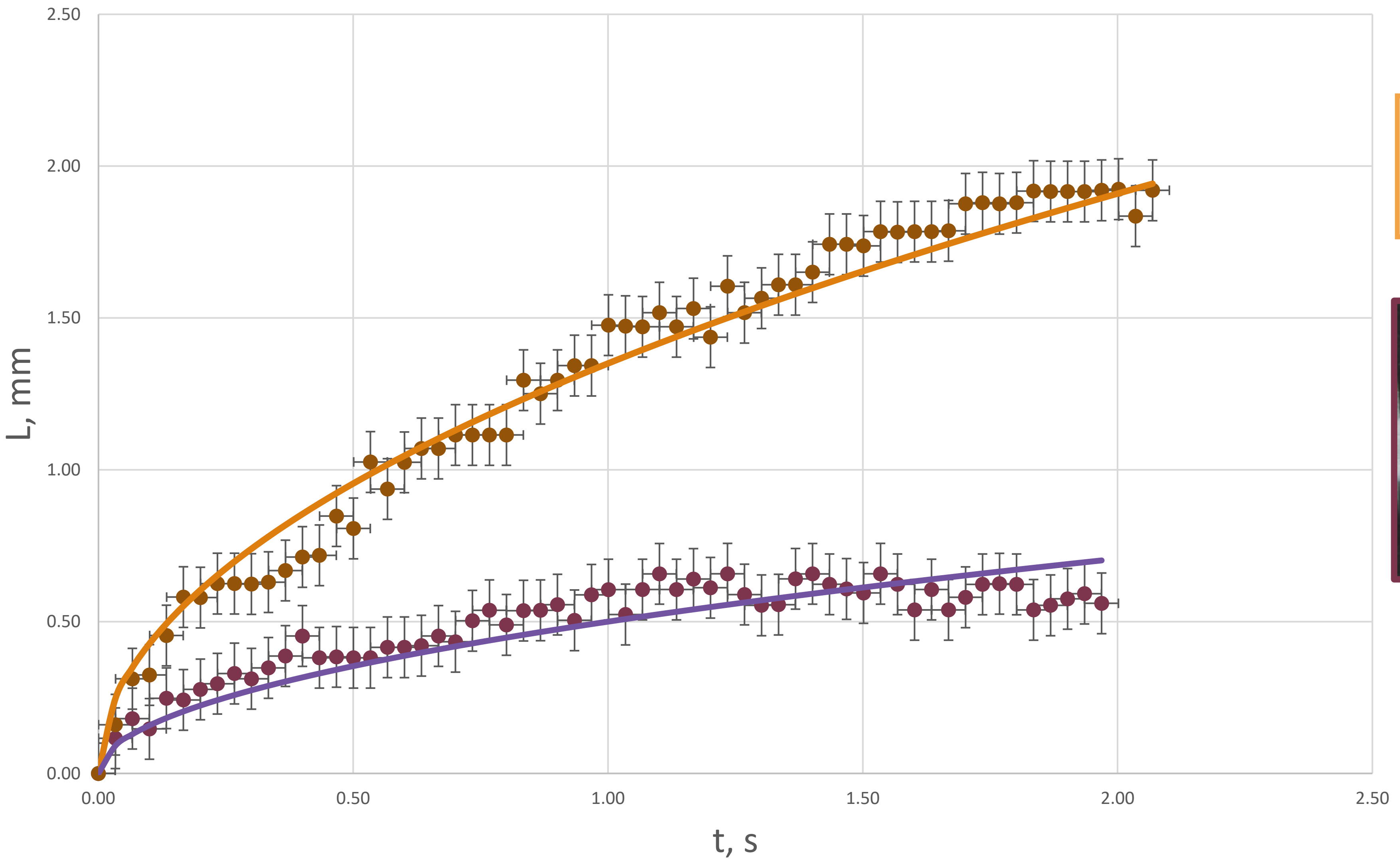
$$L(t) \sim \frac{\sqrt{\sigma}}{(\mu\,\rho)^{1/4}}\, t^{3/4}$$

The dependence of wavelength on surface tension (with water-alcohol film)

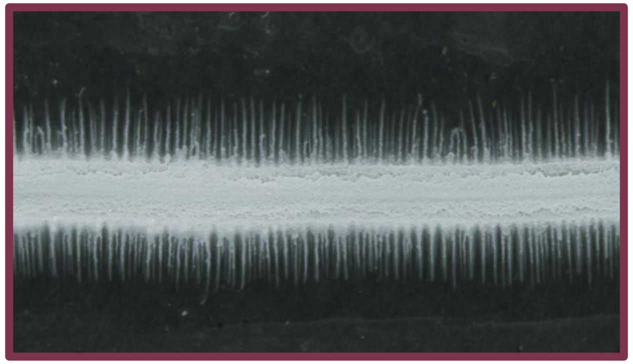


$$\lambda = \pi\sqrt{\frac{H\,\sigma}{grad\,\sigma}}$$

The dependence of the needle length on surface tension (with water-alcohol film)

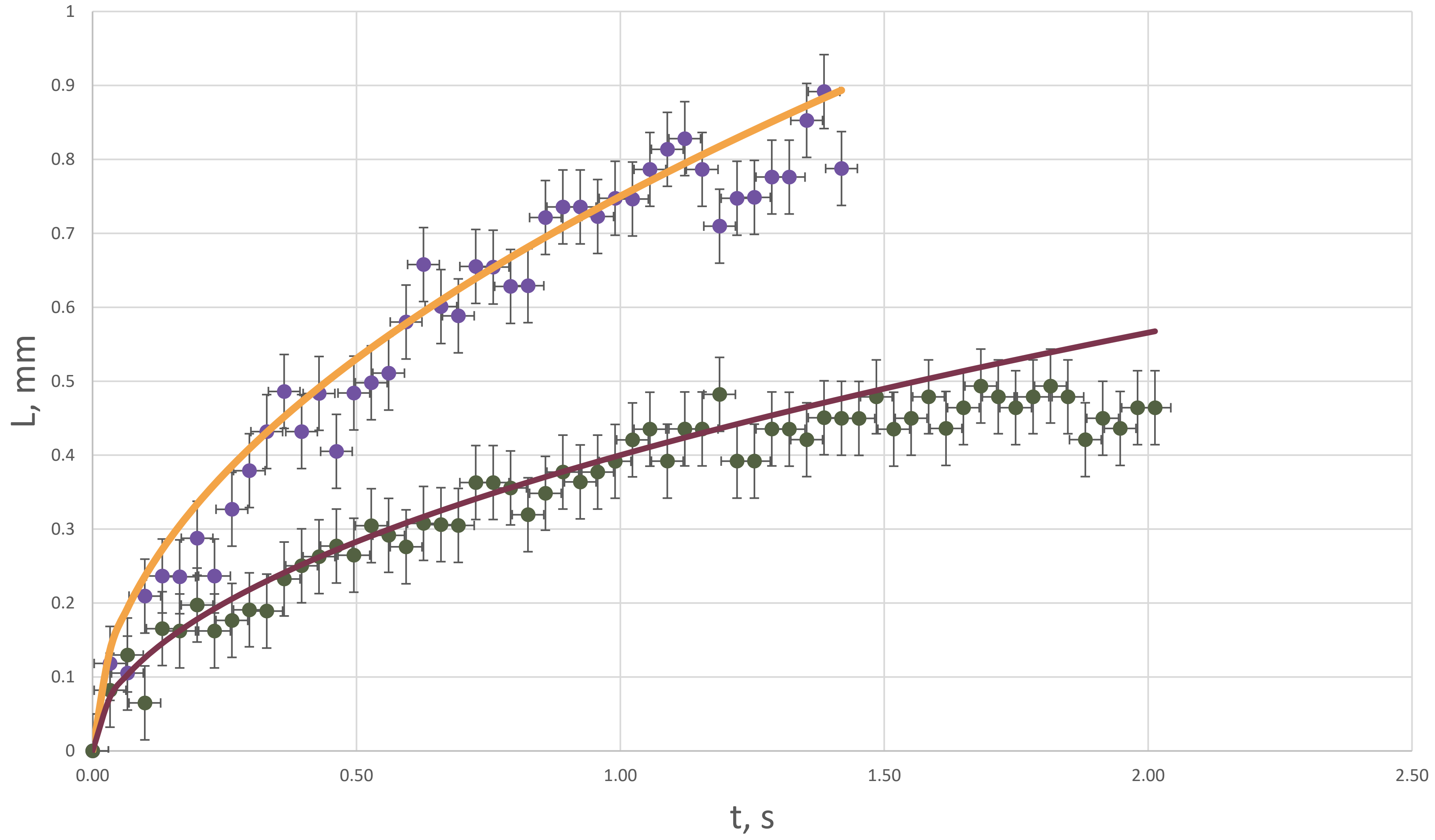


$$L(t) \sim \frac{\sigma^{1/3}}{(\mu\,\rho)^{1/6}}\, t^{1/2}$$



- 40% alcohol
- 20% alcohol
- Theory (20% alcohol)
- Theory (40% alcohol)

The dependence of the needle length to time at different viscosity



$$L(t) \sim \frac{\sigma^{1/3}}{(\mu\,\rho)^{1/6}}\, t^{1/2}$$

Conclusion

- Explained the needles occurrence mechanism (Marangoni effect)

- Normal lengths of the needles illumination and the wavelength instability

- The position of the maximum illumination from the aqueous film thickness, the viscosity, and the surface tension coefficient were studied

Thank you for attention!