
***Problem # 09***

One can make small water droplets rotate over a hydrophobic surface by making various hydrophilic patterns over them.

What properties of the liquid (not necessarily water) can we extract from this type of experiment?

Optimize the setup to maximize the rotational speed of the droplets.

# Outline

1. Theory
2. Experimental set up
3. Results, Treatment and discussion
4. Conclusion

# THEORY

1) Surface Tension
2) Superhydrophobic VS Hydrophilic
3) Droplets’ spin : Momentum and Forces
4) Parameters ?

# Surface tension

**Surface Energy = energy cost at the interface [1]**

For a water droplet:

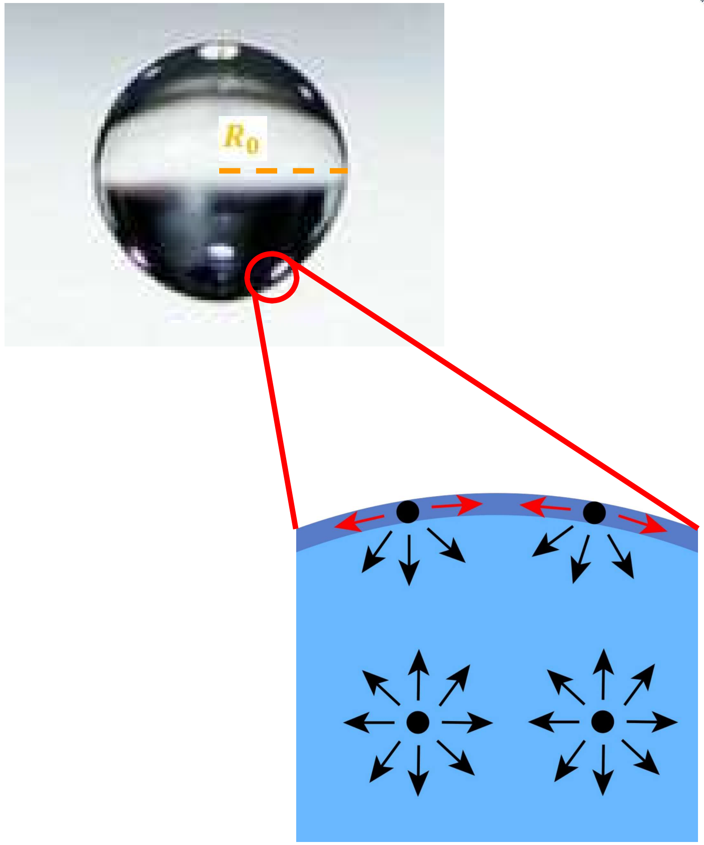
$$E_s \sim \gamma R_0^2$$

$\gamma$ is the surface tension of the fluid (N/m)

Between liquid and vapor : $\gamma = \gamma_{LV}$

Between liquid and solid : $\gamma = \gamma_{LS}$

Between solid and vapor : $\gamma = \gamma_{SV}$




***Driving force phenomenon behind the spinning droplet***

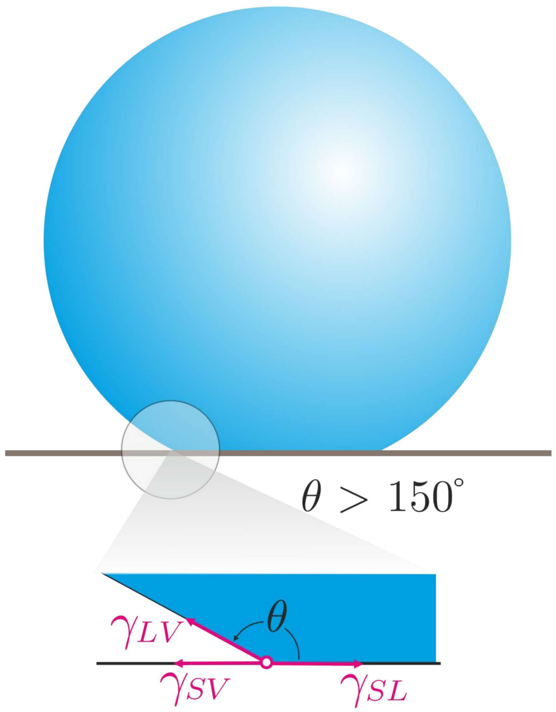
# Superhydrophobic VS Hydrophilic

Young equation : $\cos\theta = \frac{\gamma_{SV} - \gamma_{SL}}{\gamma_{LV}}$ [1]

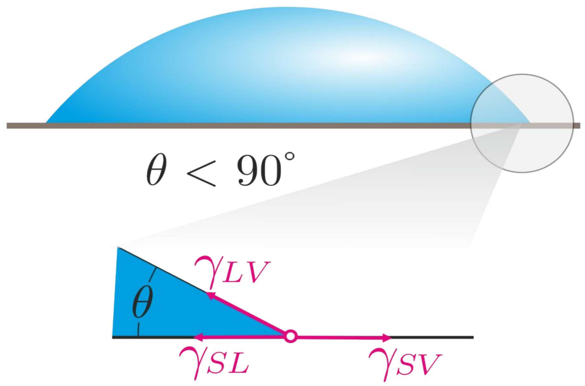
Static contact angle : $\theta$

- $\theta < 90°$ : hydrophilic
- $\theta > 90°$ : hydrophobic
- $\theta > 150°$ : superhydrophobic

**EXAMPLE OF A SUPERHYDROPHOBIC SURFACE**



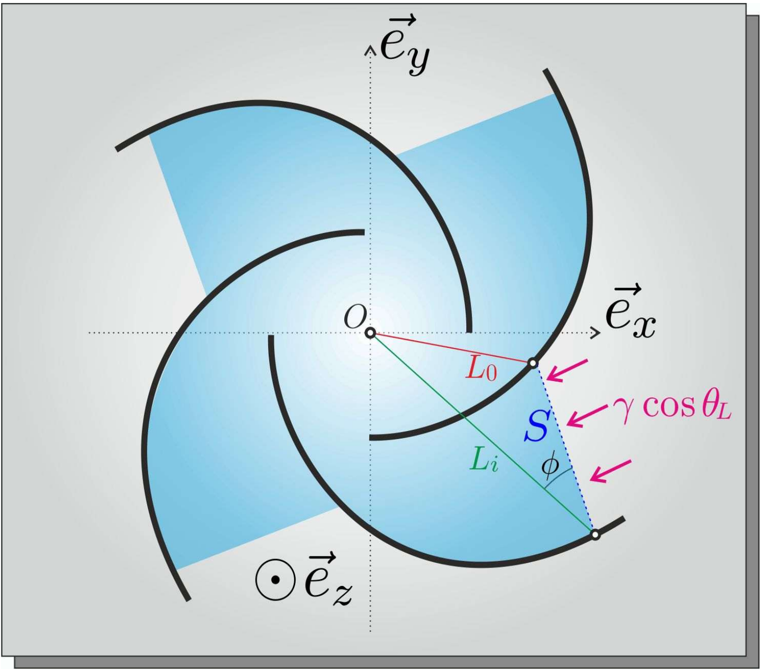

**EXAMPLE OF A HYDROPHILIC SURFACE**



# Droplets' spin : Momentum and Force

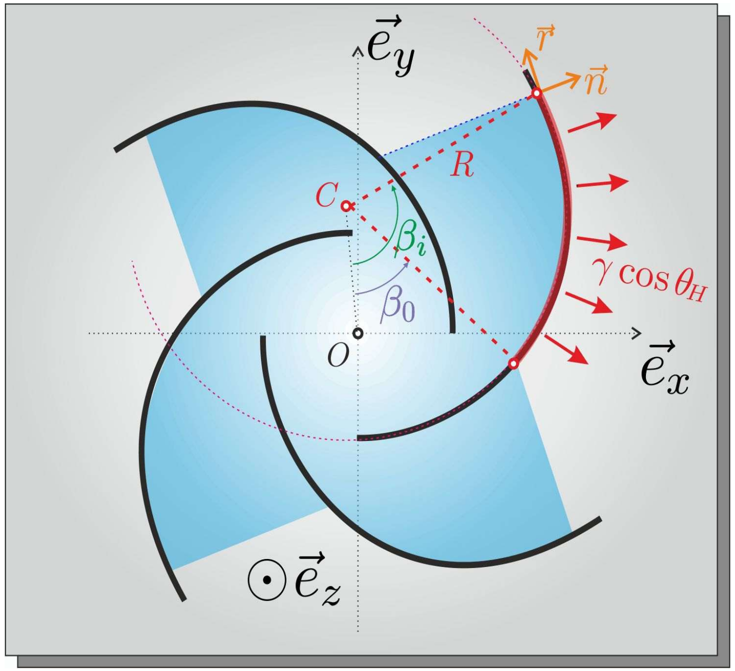
## Why is the droplet spinning when a hydrophilic pattern is added on a superhydrophobic surface ? [2]

**Force applied by the superhydrophobic surface**



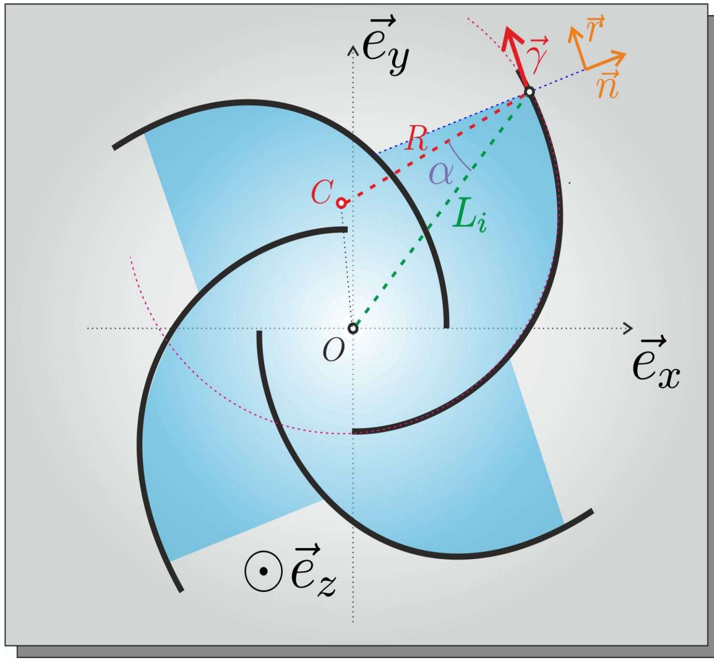

$$M_L=\gamma\cos\theta_L S(L_i\cos\varphi-\frac{S}{2})$$

**Force applied by the hydrophilic pattern**




$$M_H=\int_{\beta_0}^{\beta_i}\gamma\cos\theta_H RC\sin\beta d\beta$$

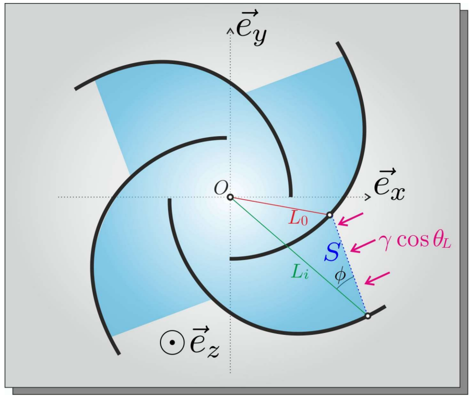
**Resistance Force**




$$M_R=\gamma W L_i\cos\alpha$$

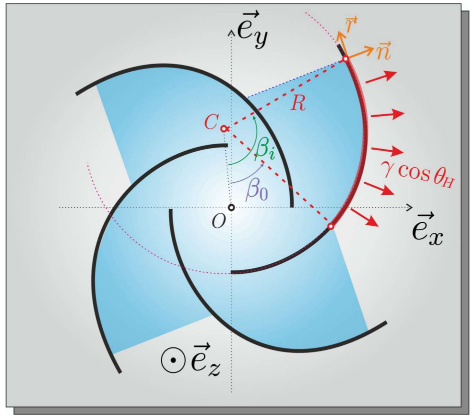
# Parameters?

**Force applied by the superhydrophobic surface**




**+**

**Force applied by the hydrophilic pattern**




## Rotational Speed of the droplet [2]

$$T \approx \frac{N\gamma}{6}(\cos\theta_H - \cos\theta_L)D^2\Delta\tau$$

N : Number of spirals

$\gamma$ : surface tension

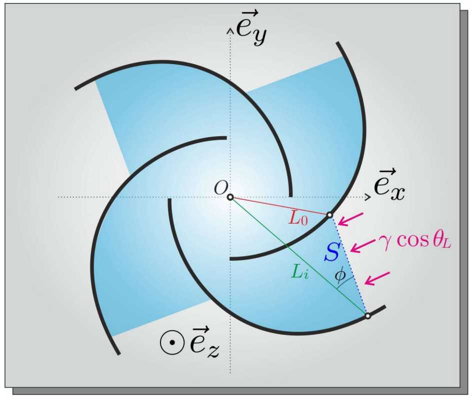
D : diameter of the splash

$\Delta\tau$ : Difference between the time when the water stops being in contact with the spiral from the outside and the time when the water stops being in contact with the spiral from the inside

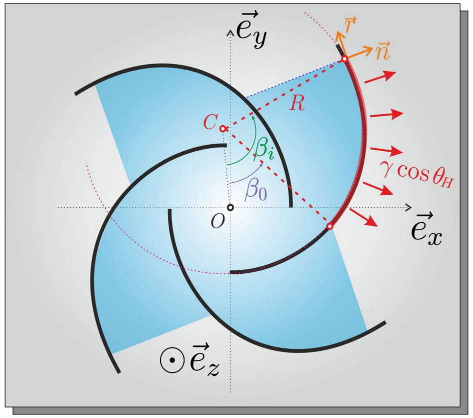
## Parameters?

| | |
|---|---|
| N | number of spirals |
| $\gamma$ | surface tension |

**Force applied by the superhydrophobic surface**




**Force applied by the hydrophilic pattern**

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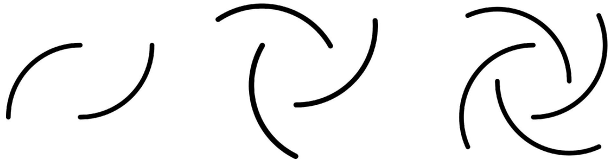
## Parameters?

| | |
|---|---|
| N | number of spirals |
| $\gamma$ | surface tension |

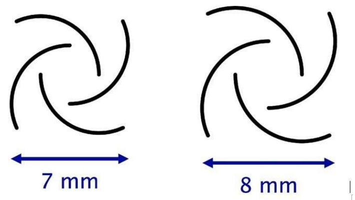
# Study of the different parameters

**PARAMETERS :**

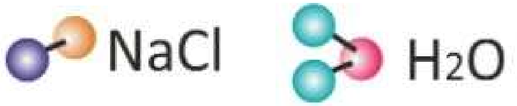
- different spiral numbers N : 2, 3, 4



- radius of the pattern R : 3.5 mm, 4 mm




- surface tension $\gamma$



# Outline

1. Superhydrophobic surface
2. Experimental set up
3. Results and discussion
4. Conclusion

# Experimental Set Up

**VIDEO PREPARATION**

- Preparation Superhydrophobic surface
- Verification Surface Static Angle
- Hydrophilic Pattern Design
- Video set up (40000 fpm)

**VIDEO**

- **> 100 videos**
- **> 9000 pictures per video**

**TREATMENT PROCESS**

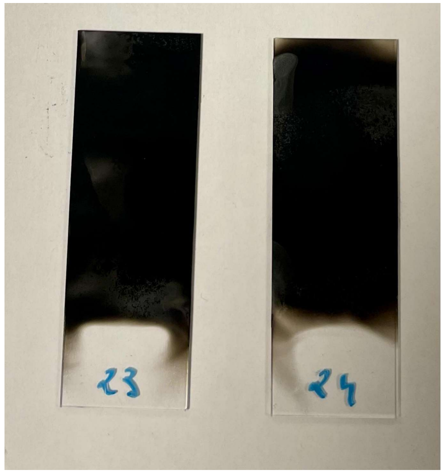
- Video Selection
- MATLAB
- PIV (Particle Image Velocimetry)
- MATLAB

**AVERAGE SPEED**

# Step 1 : Preparation of hydrophobic surfaces

Different methods :

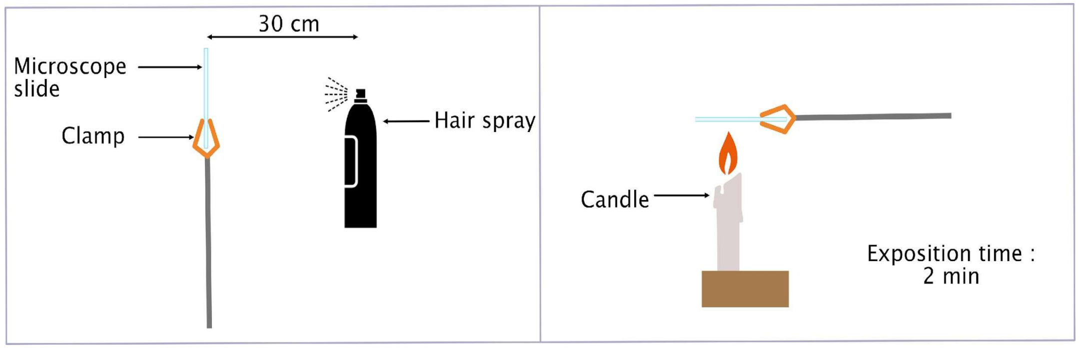
- Candle soot
- Isopropanol soot
- surface treatment with silanes
- Candle soot after surface treatment with hair spray




Substrate : microscope slides (75 by 26 mm)

Selection requirements :

- Robustness
- Higher surface static angle possible

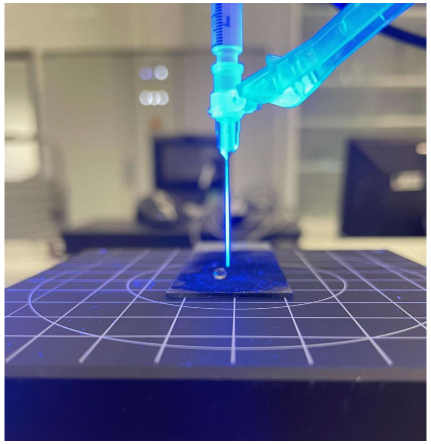


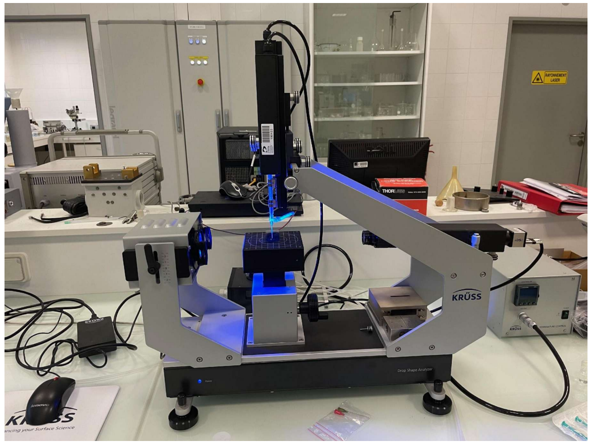
# Step 2 : Verification of the surface static Angle

Surface static angle measures

| Surface treatment | Surface static angle |
|---|---|
| Silanes | 93 ° |
| Candle soot | 133° |
| Isopropanol soot | 134 ° |
| Hair spray and candle soot | 120 ° |


A picture of the surface static angle of our hydrophobic surface





Final surfaces :

- Not superhydrophobic but high static angle
- Resistant : stay hydrophobic indefinitely and can be reused for ten droplets

# Step 3 : Hydrophilic pattern design

**SET UP**

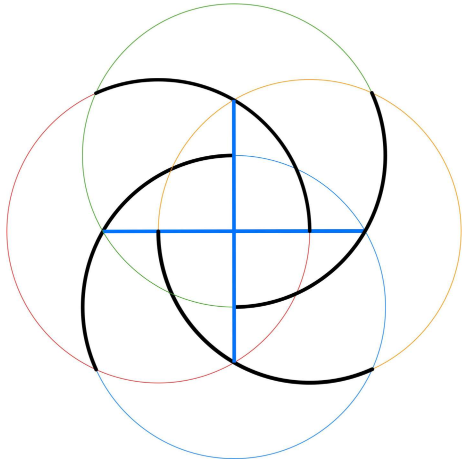
Cutting machine

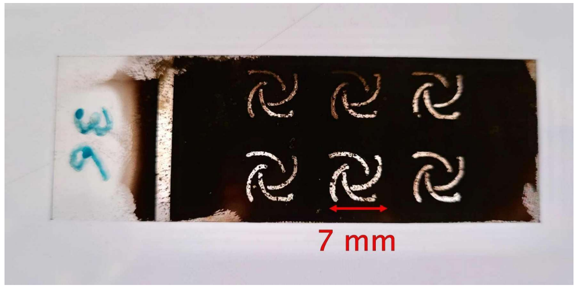
Pen BIC®

Hydrophobic slide

Vectorial design

**PATTERN DESIGN**





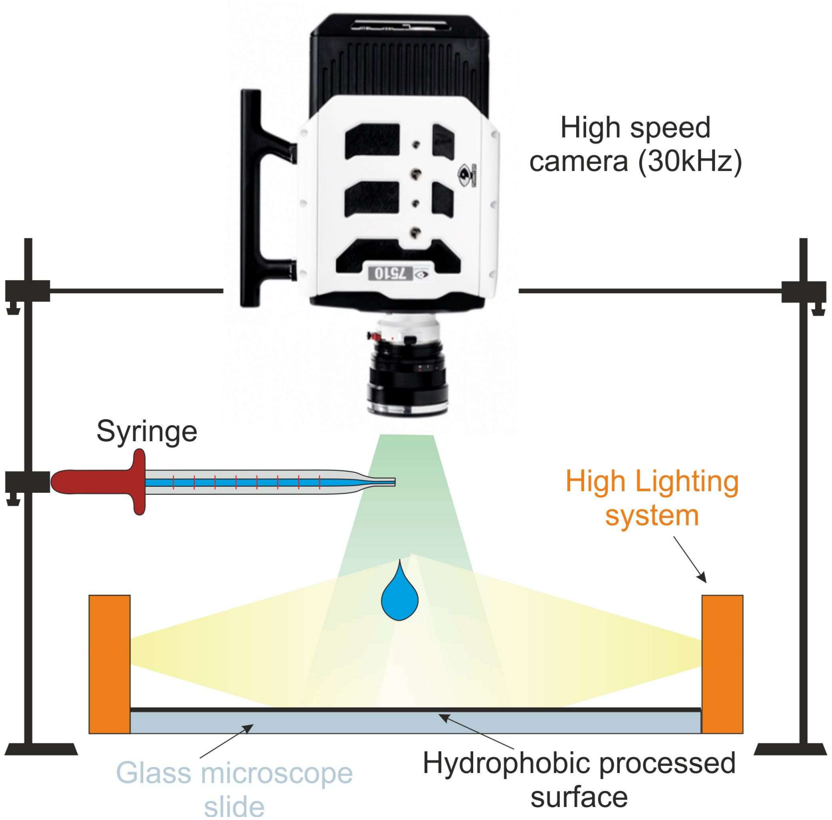
# Step 4 : Video set up

High-speed camera with a macroscopic lens

Syringe

Continuous light lamp

Hydrophobic slide with pattern



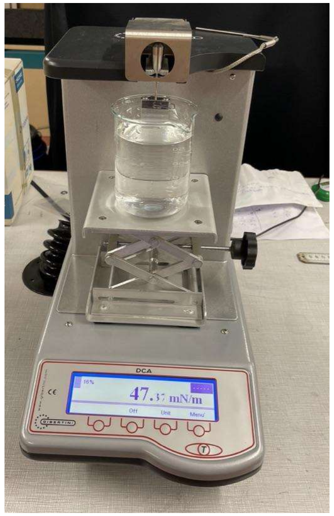
# Impact of the tension surface

Theorically : $$T \approx \frac{N\gamma}{6}(\cos\theta_H - \cos\theta_L)D^2\Delta\tau$$

=> Rotational speed proportional to $\gamma$

Liquids with different surface tension :

- Pure water
- Cold water (T = 2°C) => actually surface tension equivalent to ambient temperature water
- Solution of NaCl :
    - Objective : higher surface tension according to scientific article [3]
    - Actually, according to our measures, lower surface tension observed



# Outline

1. Superhydrophobic surface
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# RESULTS, TREATMENT, DISCUSSION

1) Our results
2) Treatment and Verification using PIV
3) Impact of the different Parameters

   a- Impact of the parameter N

   b- Impact of the parameter D

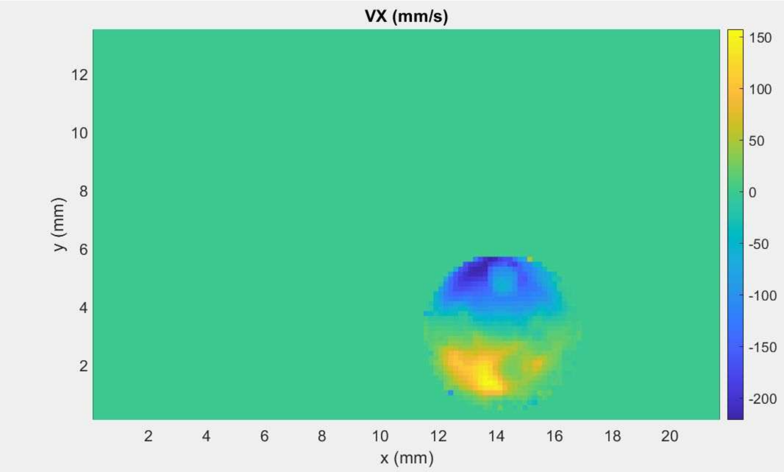
   c- Impact of the parameter $\gamma$

# Results

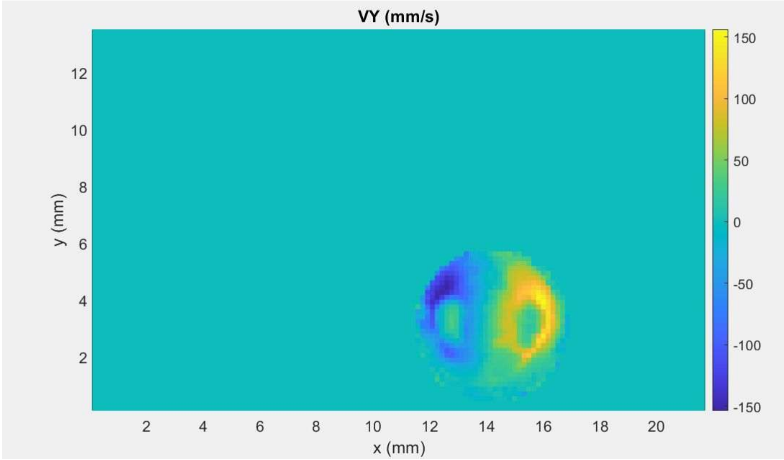
Video for a droplet radius : R = 1,96 ± 0,07 mm


# Verification of the rotational speed (PIV)

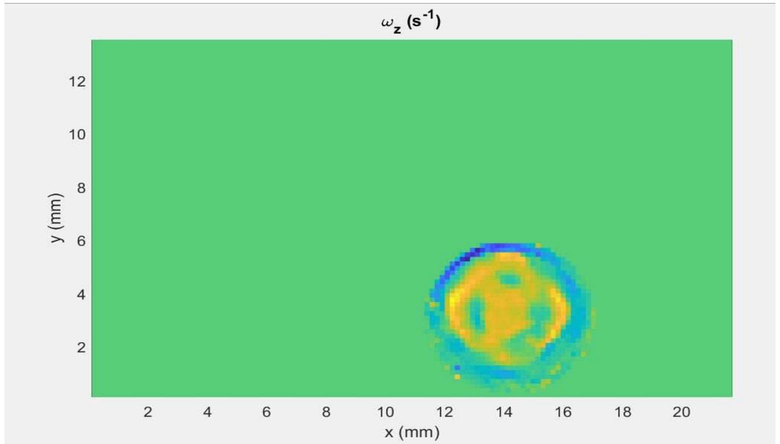
the x component of the velocity



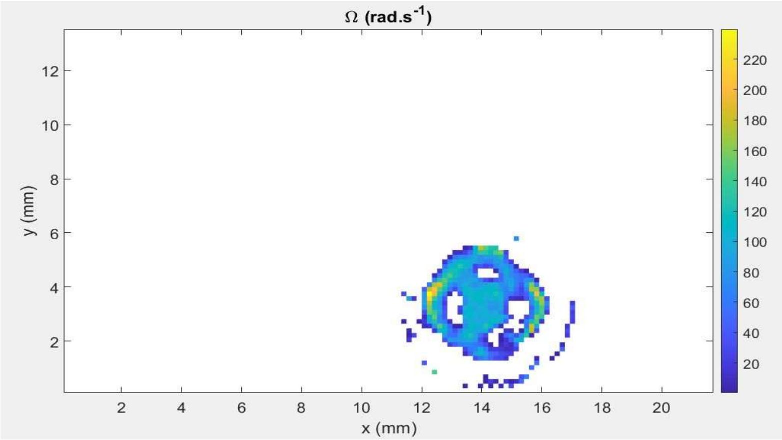

the y component of the velocity



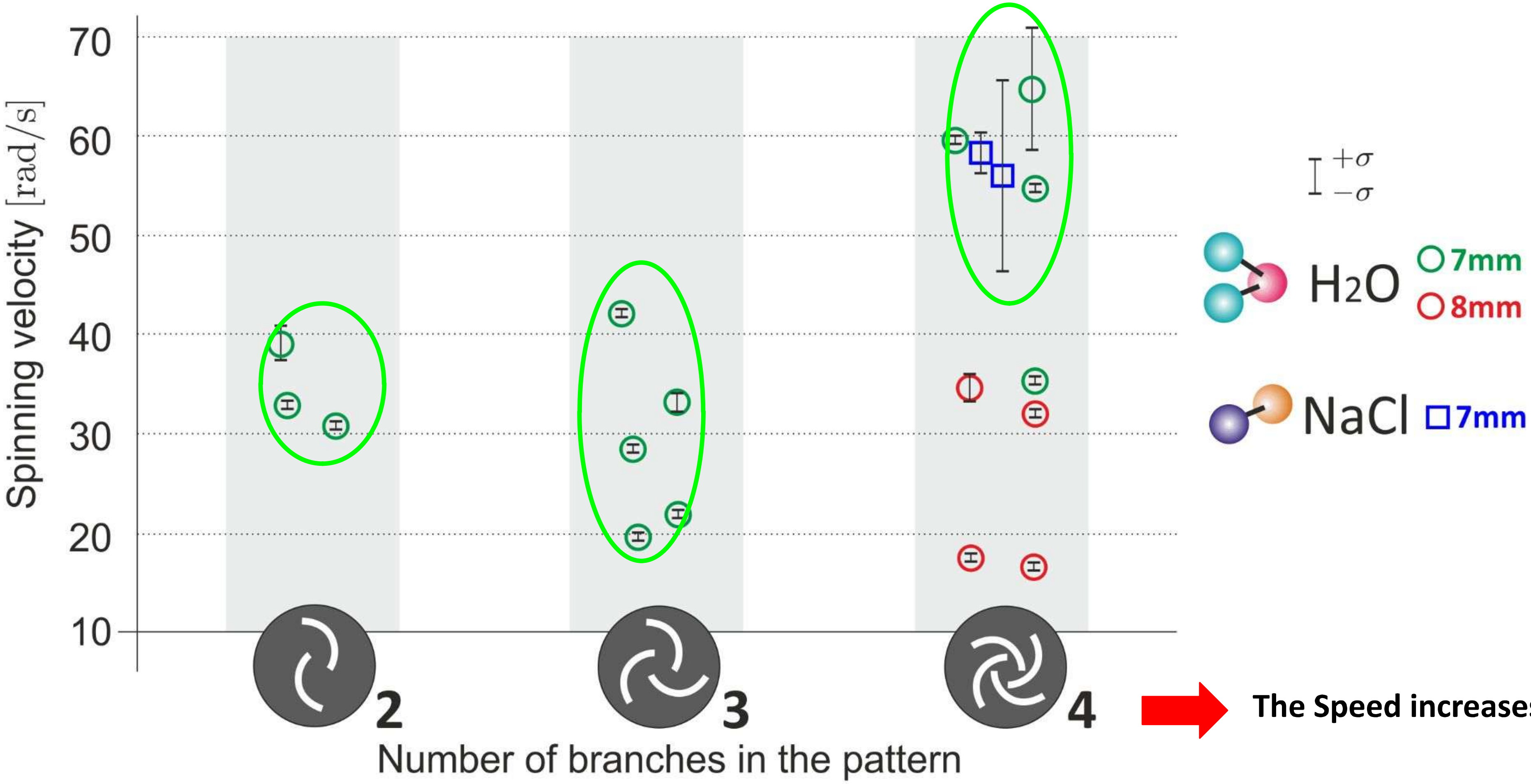

the z component of the vorticity




the intensity of the velocity

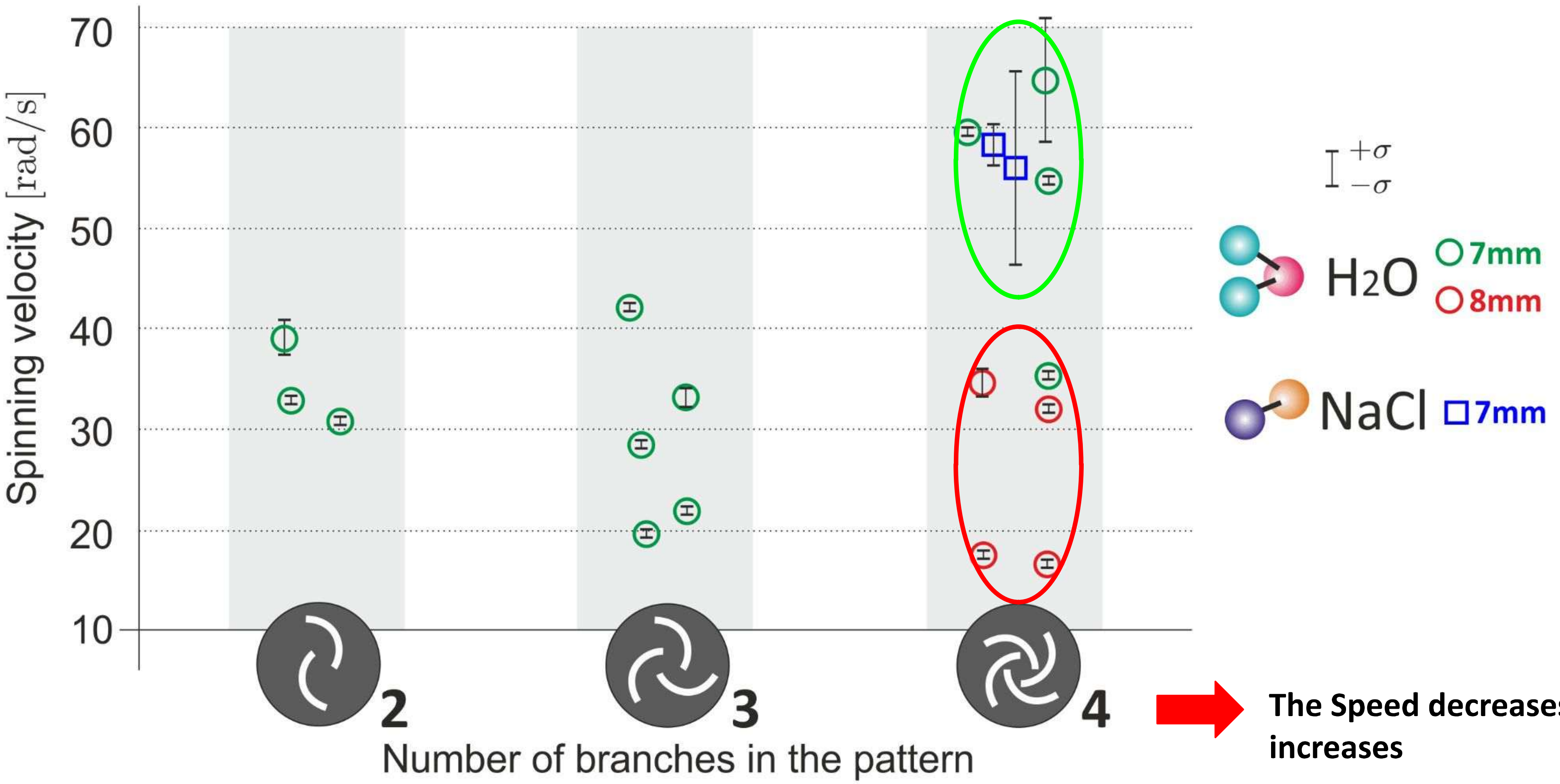


# Impact of the parameter N



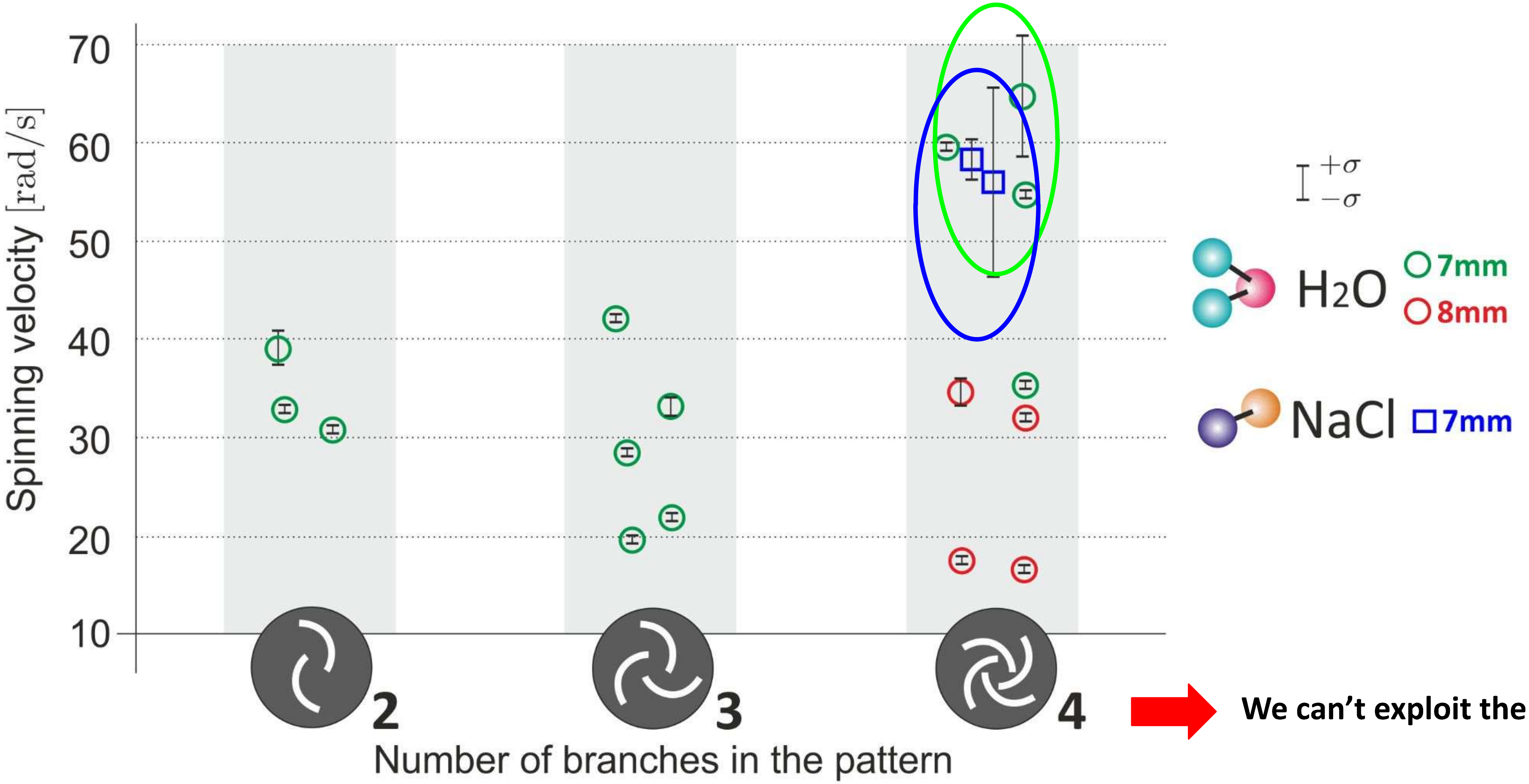

The Speed increases with N

# Impact of the parameter D




The Speed decreases if D increases

# Impact of the parameter $\gamma$




**We can't exploit the data**

# Summary of the experiments

Impact of the different parameters :

- spiral numbers N : speed increases when N increases
- radius of the pattern R : speed increases when R decreases
- surface tension $\gamma$ : we can’t say anything for sure

# Conclusion


1) To optimize the set up : high number of spirals and small radius of the pattern
2) Property that can be deduced : surface tension. It was proven theoretically but not experimentally

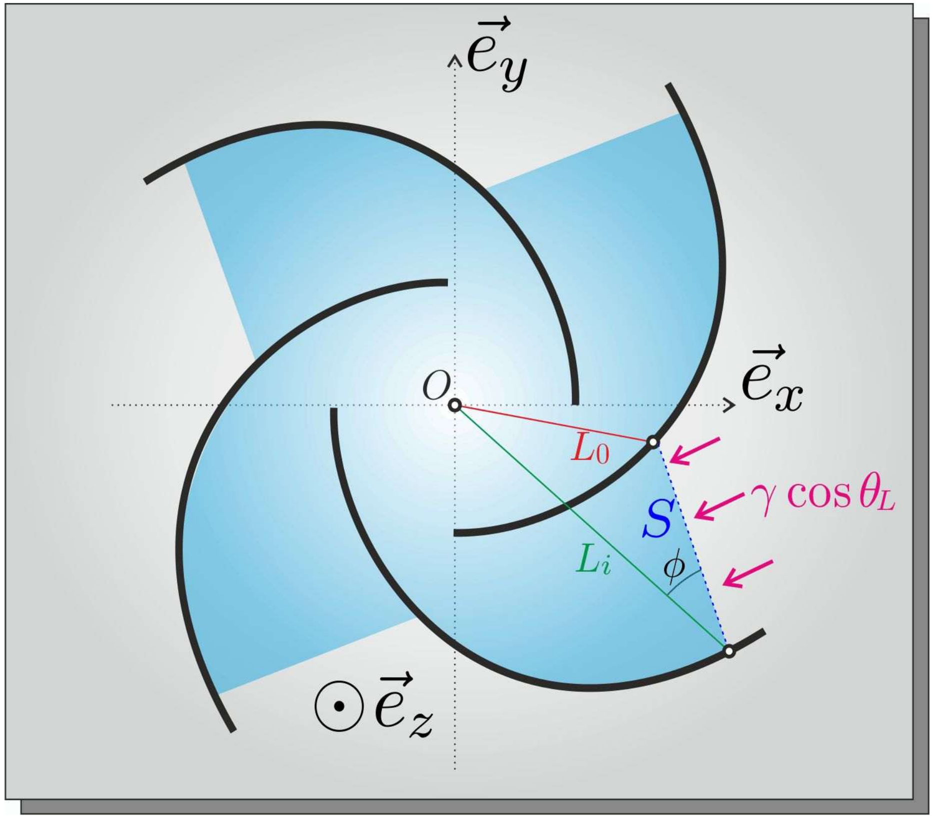
# Appendices

# Bibliography


1. Raphaële Thévenin. *Superhydrophobie Active*, https://pastel.archives-ouvertes.fr/pastel-01074498, HAL, 2014
2. *Spontaneous droplets gyrating via asymmetric self-splitting on heterogeneous surfaces*, https://doi.org/10.1038/s41467-019-08919-2, Nature Communications, 2019
3. *Chloride: from Dilute to Highly Supersaturated Solutions and Molten Salt*, https://doi.org/10.5194/acp-2017-1013, Manuscript under review for journal Atmos. Chem. Phys., 2017

# Explanation of the momentum and the forces

**Force applied by the superhydrophobic surface**



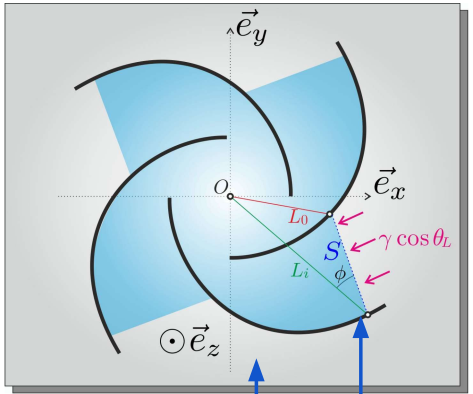

$$\vec{F}_L = \gamma * cos\theta_L * S\vec{n}$$

$$\vec{OM}.\vec{t} = L_i * cos(\Phi) - S/2$$

$$M_L = \gamma \cos\theta_L S(L_i \cos\varphi - \frac{S}{2})$$

**Force appliquée par la surface superhydrophobe**

**Force appliquée par le motif hydrophile**




surface superhydrophobe

motif hydrophile

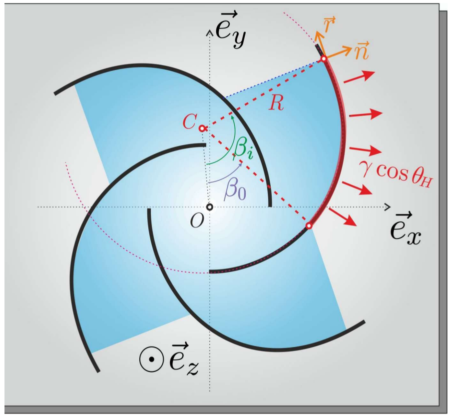
## Moment de rotation de la goutte

$$\boxed{T \approx \frac{N\gamma}{6}(\cos\theta_{\mathrm{H}} - \cos\theta_{\mathrm{L}})D^2\Delta\tau}$$

N : nombre de spirales

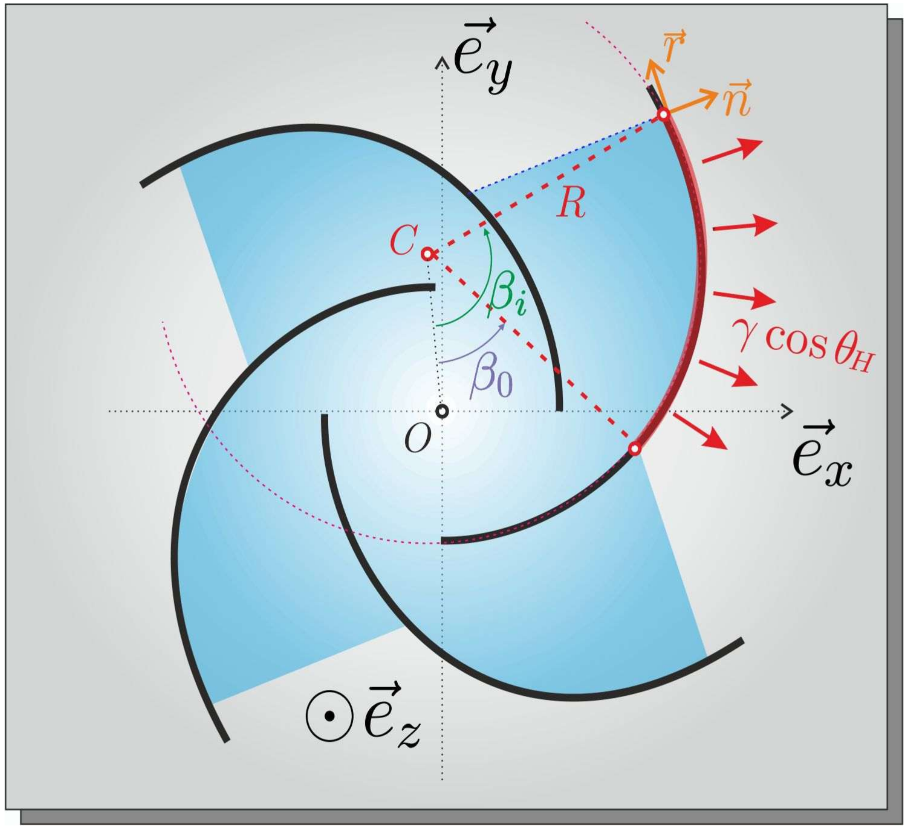
D : diamètre maximal de la goutte étalée

γ : tension de surface



# Explanation of the momentum and the forces

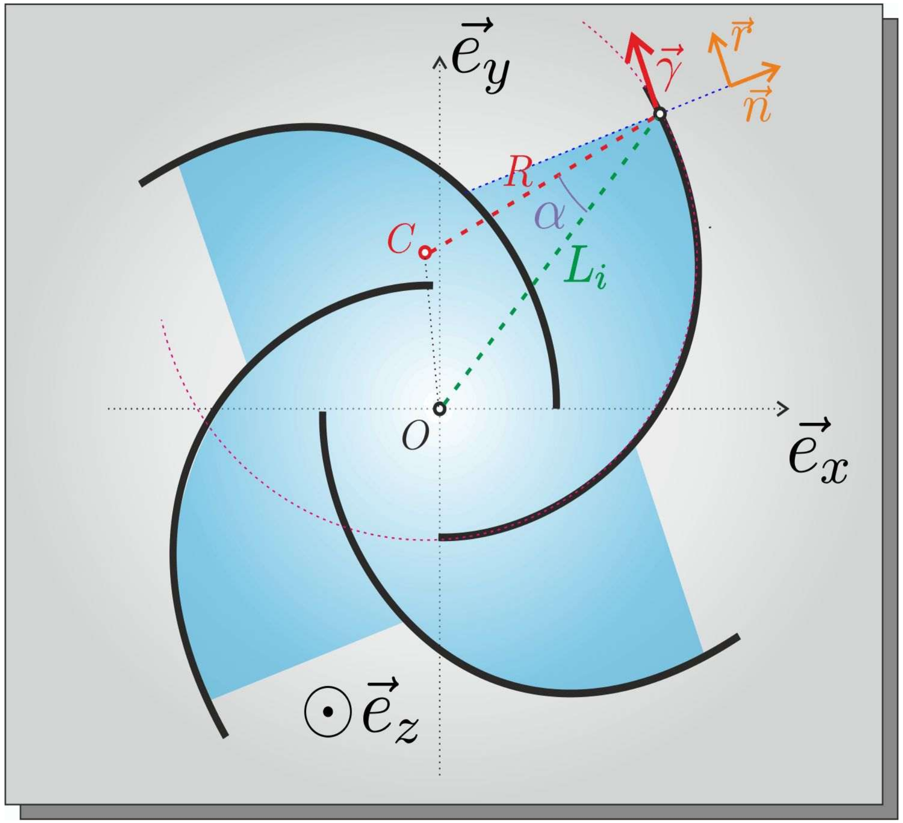
**Force applied by the hydrophilic pattern**




$$M_H = \int_{\beta_0}^{\beta_1} \gamma \cos \theta_H R C \sin \beta \, d\beta$$

# Explanation of the momentum and the forces

**Resistance Force**




$$M_R = \gamma W L_1 \cos\alpha$$

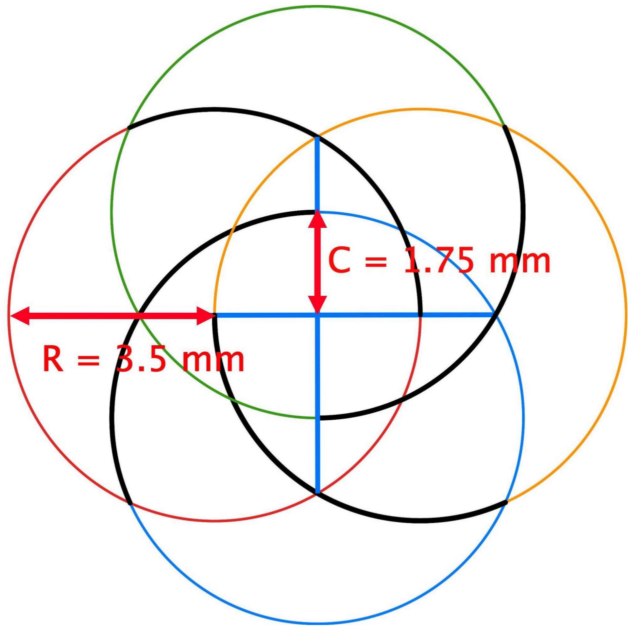
# Supplementary information about the experiment

Radius of the droplets : R = 1,96 ± 0,07

Radius of the maximum spreading : R = 4,6 ± 0,1

Parameters of the spirals :

- radius of the spirals R = 3.5 mm or R = 4 mm
- center to center distance C = R/2
- spiral width W = 0.1 mm
- Spiral number N = 2, N = 3, N = 4



# Measure of the rotational speed

PIV software : Particle Image Velocimetry

$T_0$ : reference time when the spreading of the droplet is maximum

$T_i$ : Beginning of the speed measure

$\Delta t = T_i - T_0 = 2{,}875$ ms