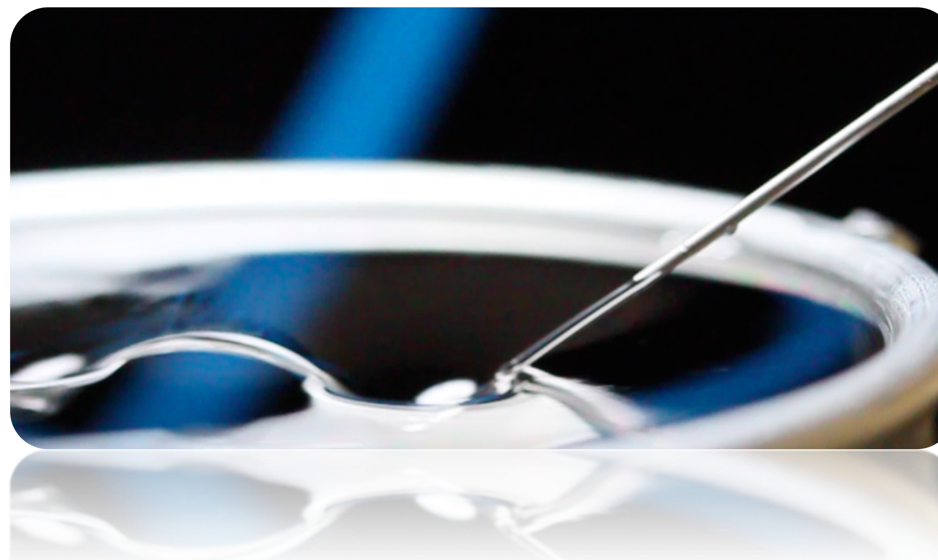
Team of Brazil

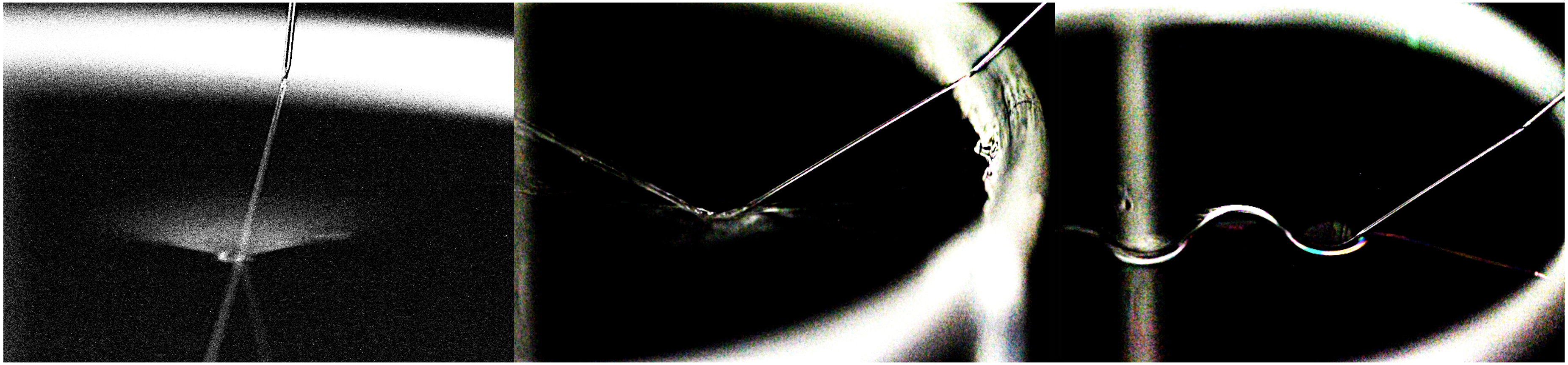
Problem 8
Jet and film



reporter: Liara Guinsberg

Problem 8

A thin liquid jet impacts on a soap film. Depending on relevant parameters, the jet can either penetrate through the film or merge with it, producing interesting shapes. Explain and investigate this interaction and the resulting shapes.



Examples of the phenomena

Introduction

Theoretical formulation

- Weber number
- Optical analogy
- Fluid properties
  - Capillarity
  - Viscosity
- Kaye effect

Experiments

- Experimental set up
- Materials
- Analysis of the data

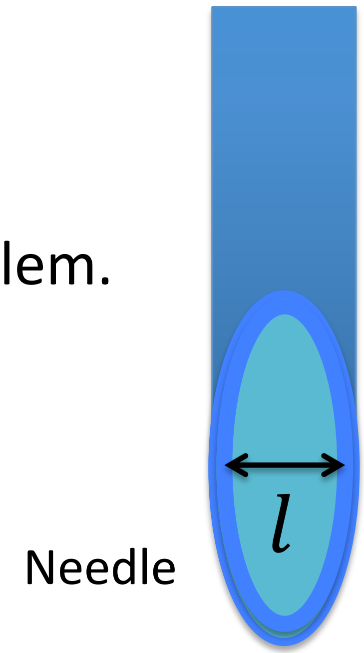
Comparison between the theory and the experiments

Weber number

- It's a non-dimensional number
- It's mainly used in the study of interfaces between fluids

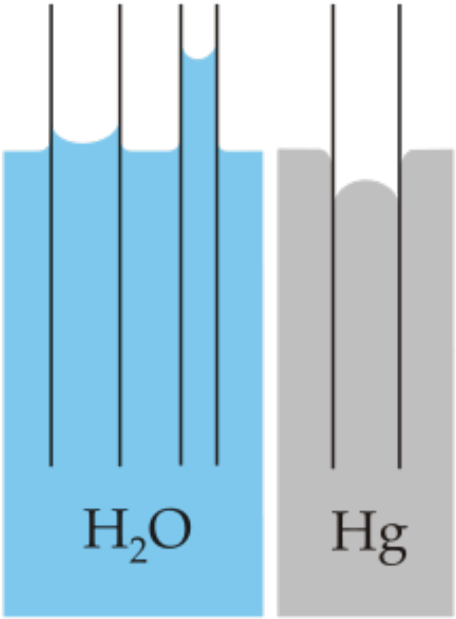
$$W_e = \frac{\rho v^2 l}{\gamma}$$

- It's a very important parameter in our problem.



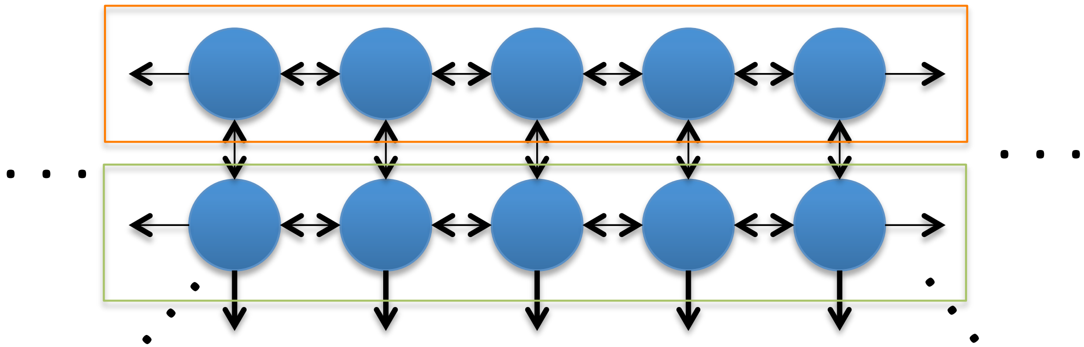
Capillarity

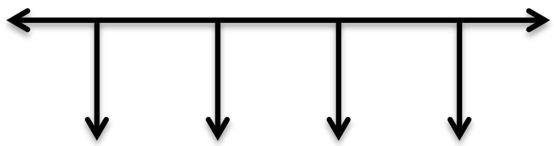
- It's the ability of a fluid to flow in narrow spaces.
- It's caused by the combination of the adhesive and cohesive forces inside the liquid and between the surrounding solid and the fluid molecules, respectively.
- We can see it's effect on the interface between the jet and the film



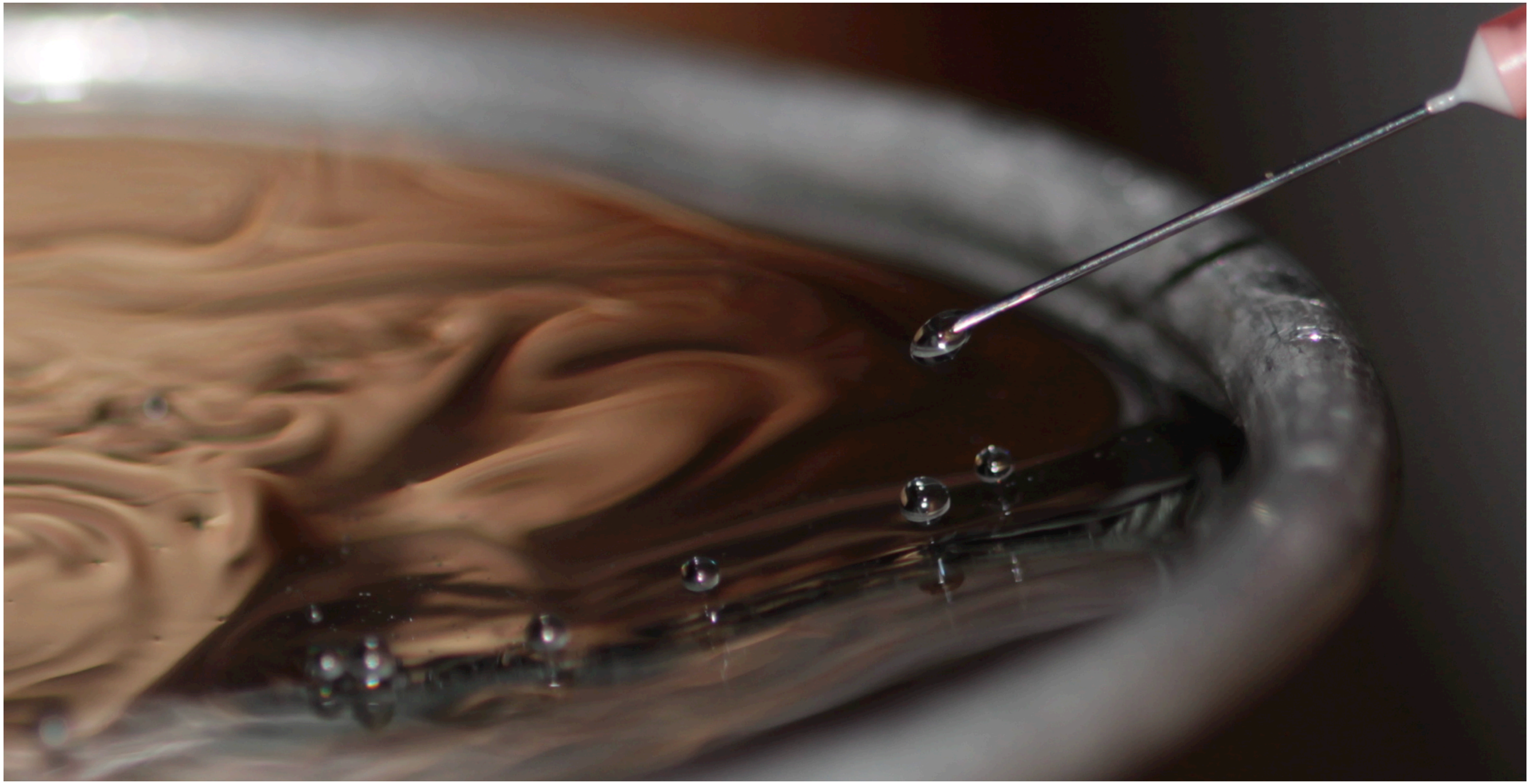
Surface tension

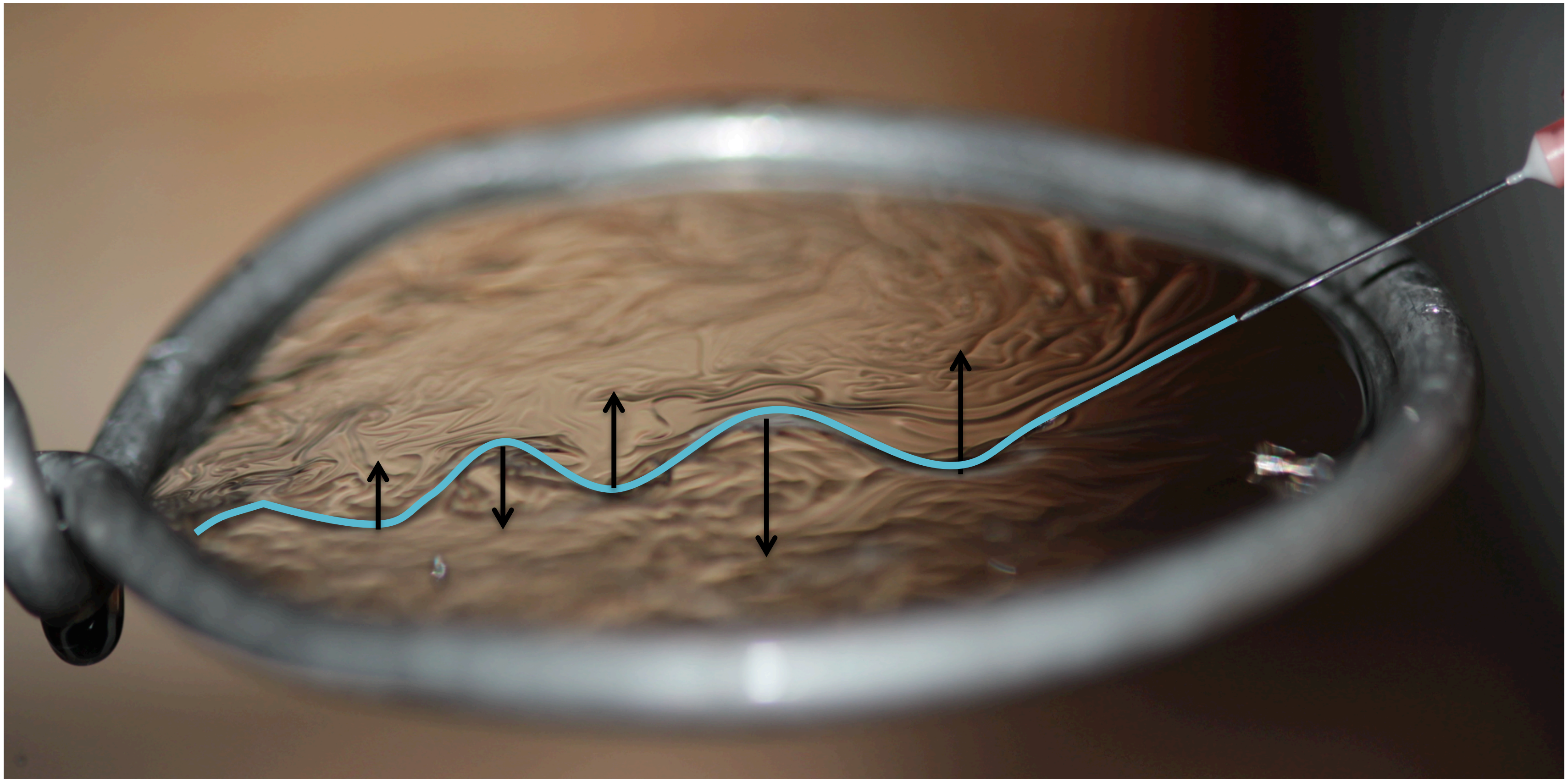
- The boundary molecules have a higher energy.
- The number of higher energy molecules must be minimized.
- Minimizing the quantity of boundary molecules we minimize surface area.





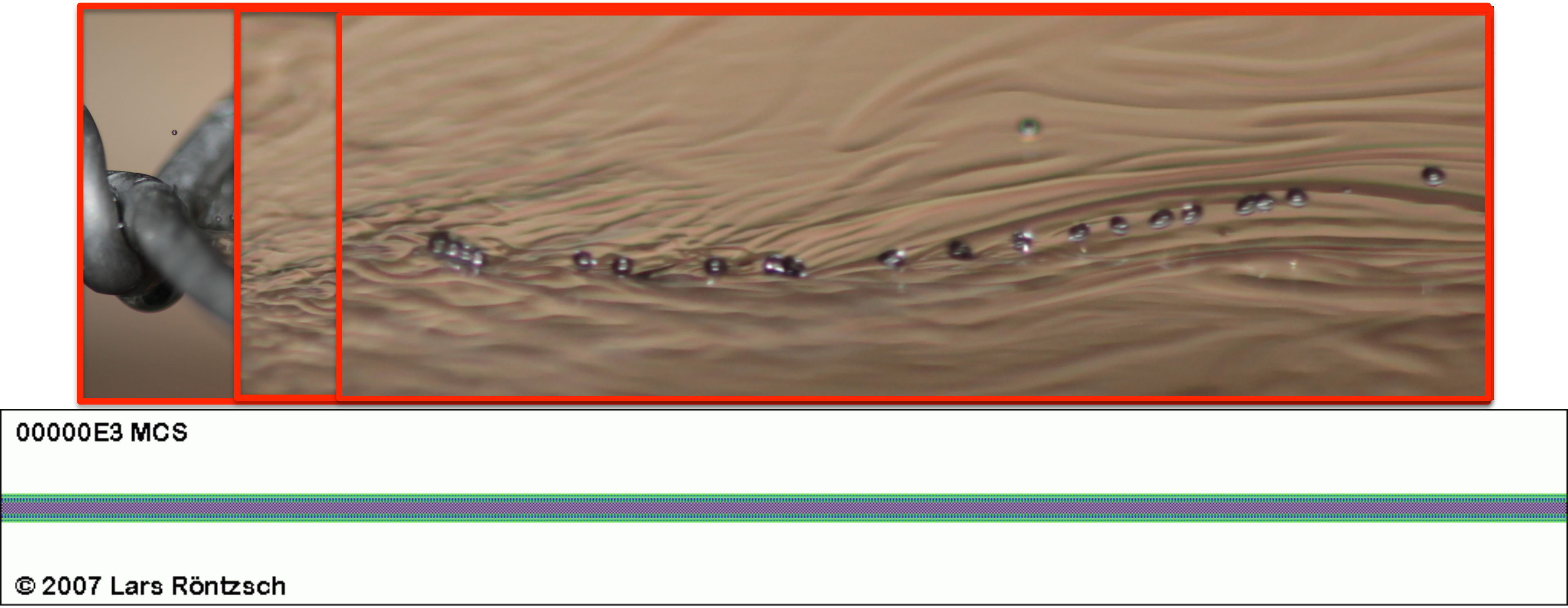
Example in the phenomena





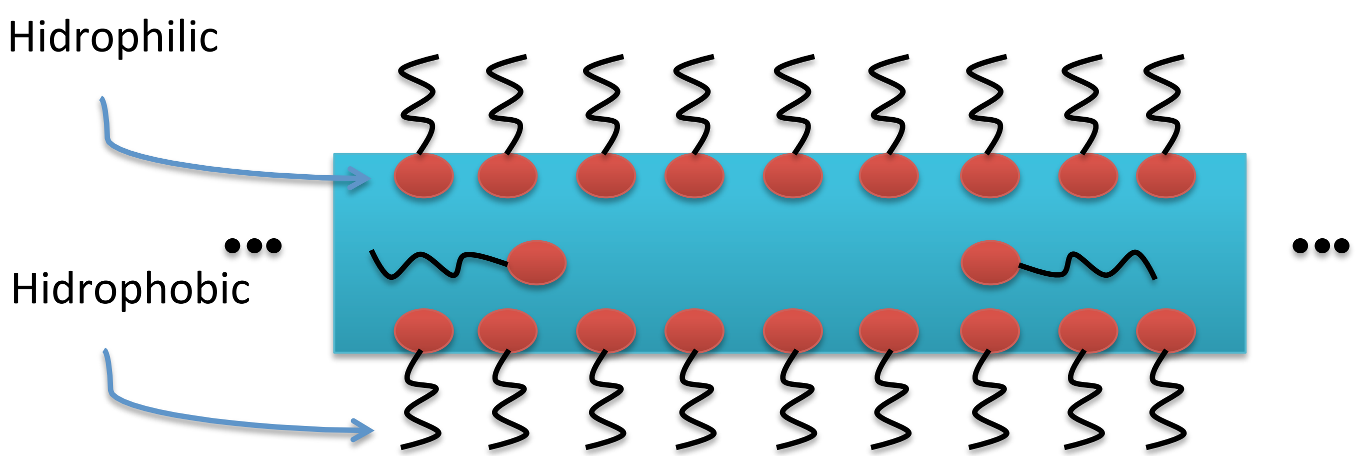
Plateau-Rayleigh instability

- The surface tension causes some oscillations in the jet, sometimes breaking it into droplets, to minimize surface area.



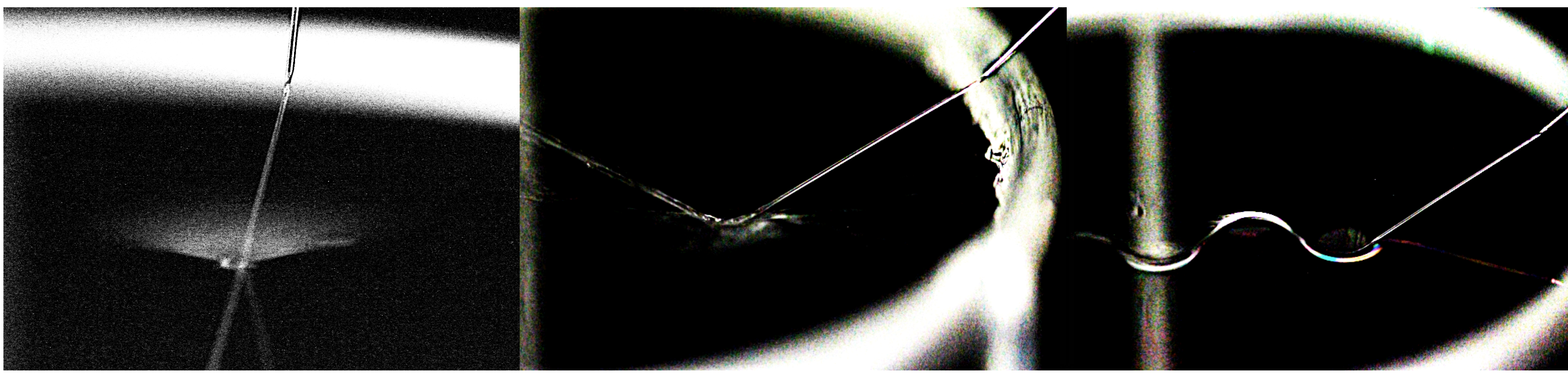
Dynamics of a soap film

- A thin layer of water gets stuck between the anphiphilic molocules
- The stability is given by the surface tension



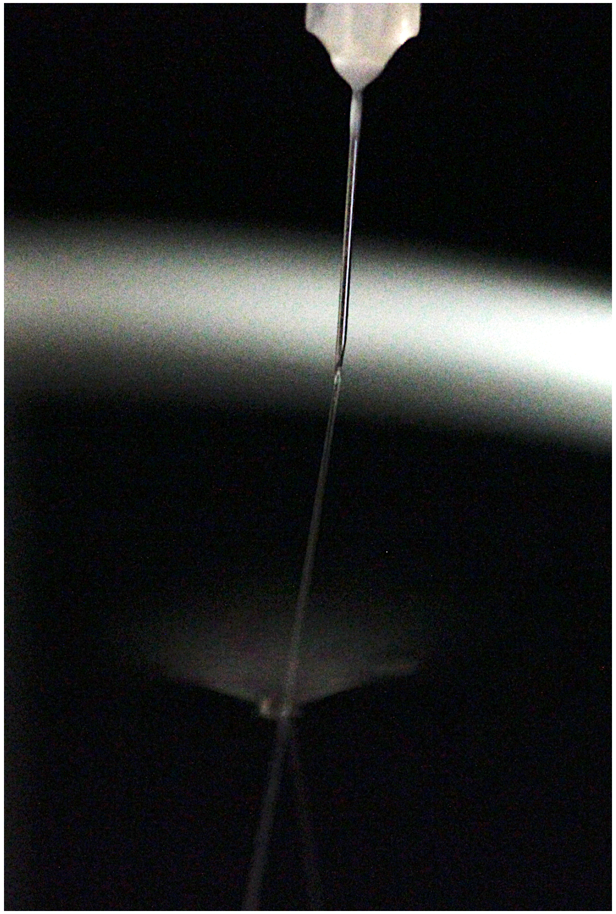
Phases

- First, we can divide the problem in distinct three phases:
  - Refraction
  - Jump
  - Absortion

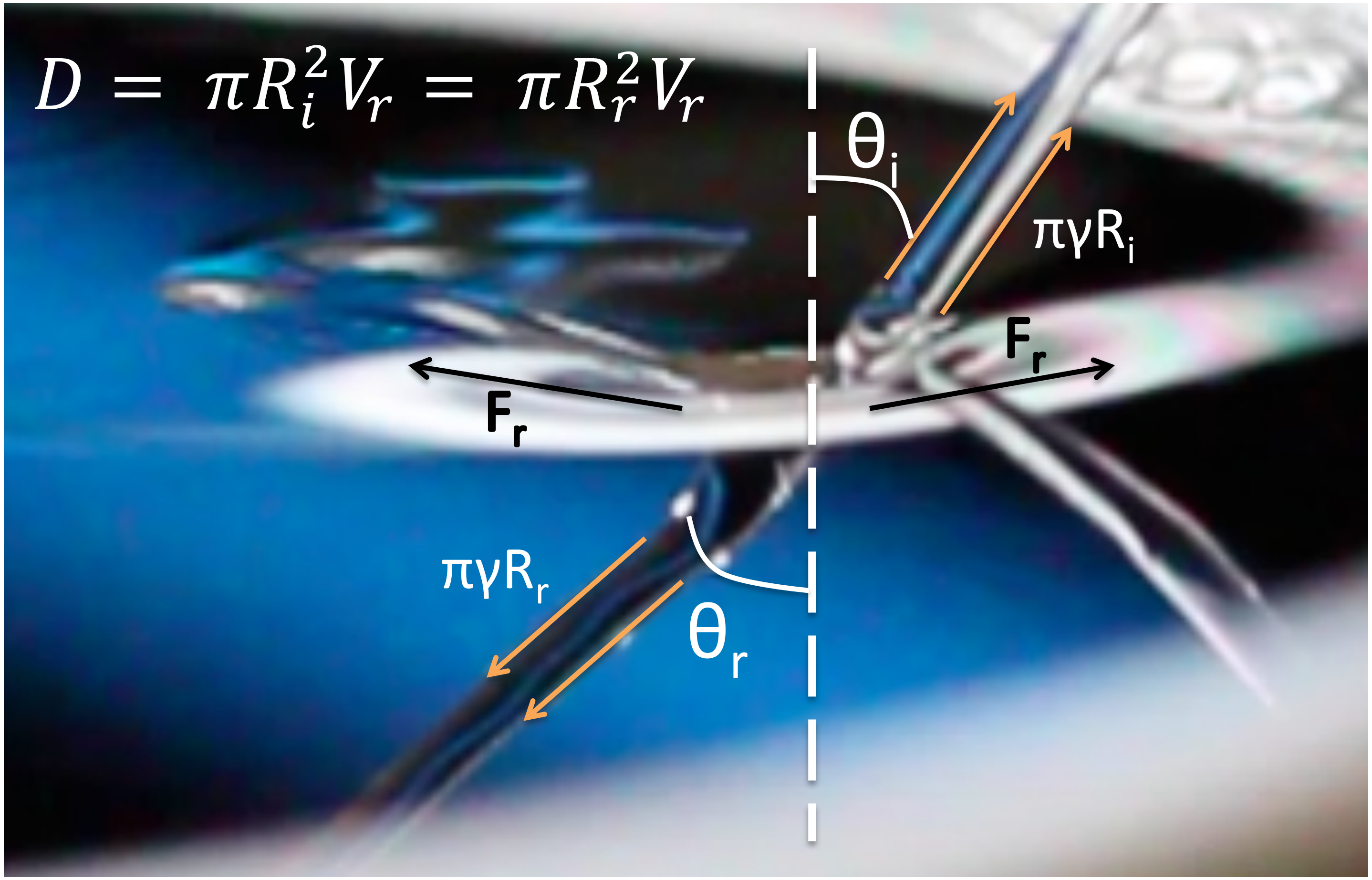


Refraction

- High Weber numbers
- Small incidence angles
- Condition of total wetting



Fluid diagram



Absorption phase formulaion

- After some algebraic work, we can find the refraction index coefficient, depending on the Weber number:

$$F_R \sim 4\pi\gamma R_i$$
Membrane union

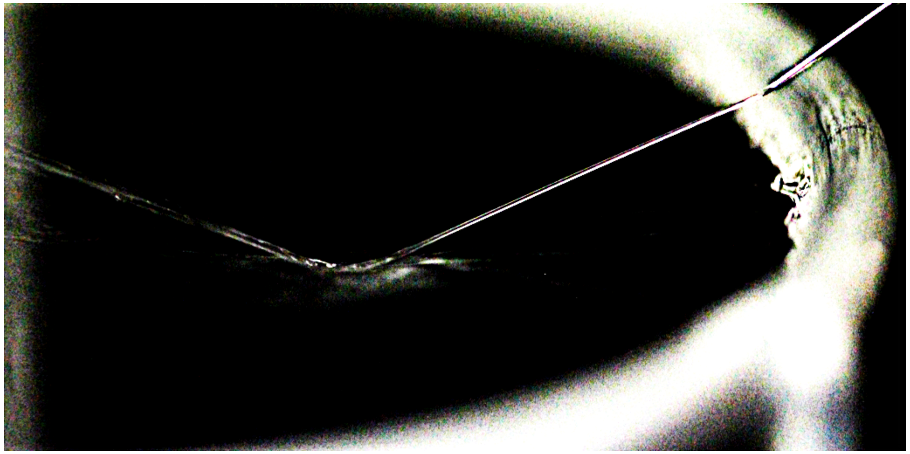
$$\sin\theta_i \sim \theta_i$$
$$\theta_i \ll 1$$

$$\sin\theta_r \sim n\theta_i$$
Refraction condition

$$n = \frac{W_e - 1}{W_e - 5}$$

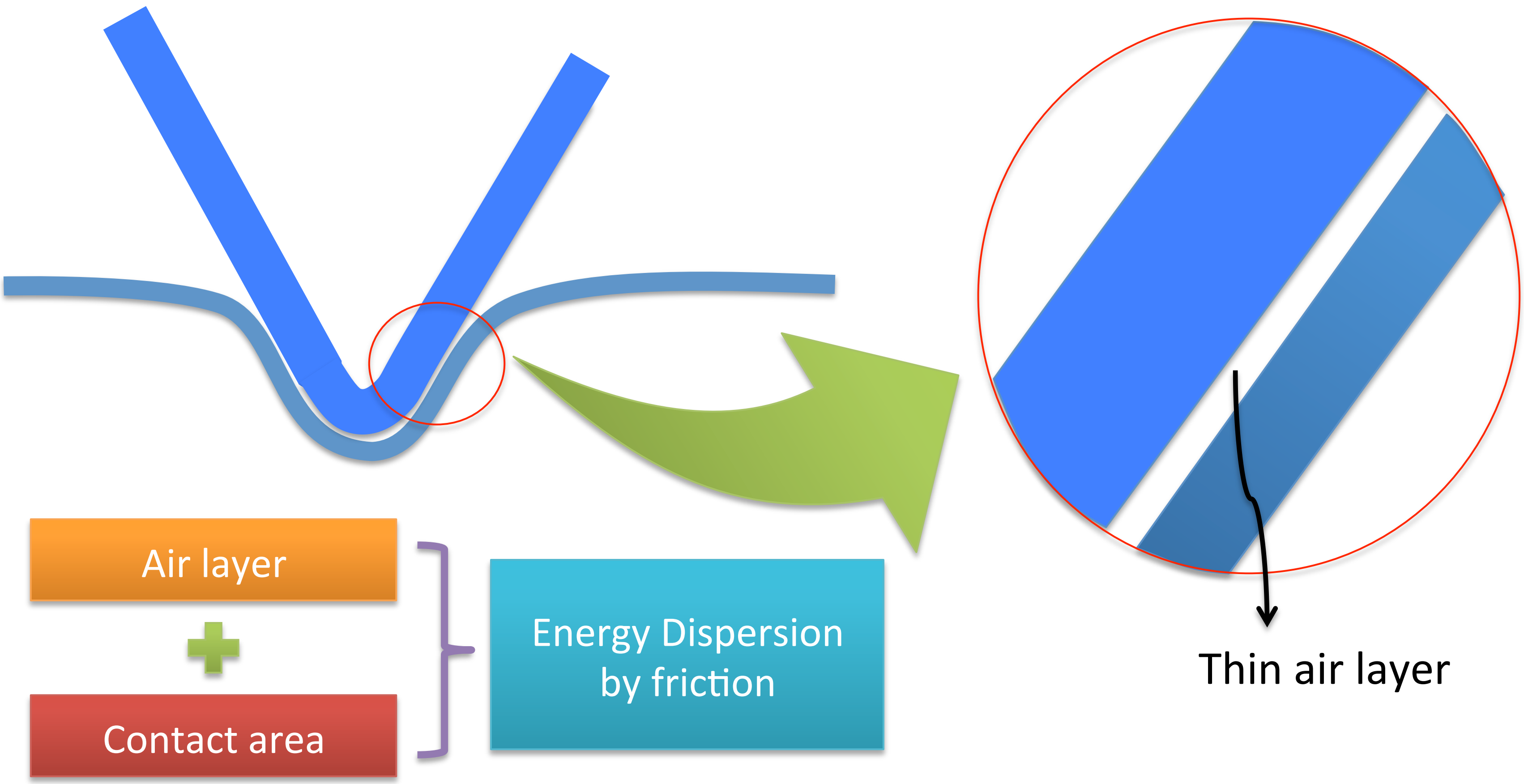
Jump

- It's the known Kaye effect
- It's hard to quantify
- The membranes don't join
- There's shear tinning, the diminution of the viscosity with the applied stress.



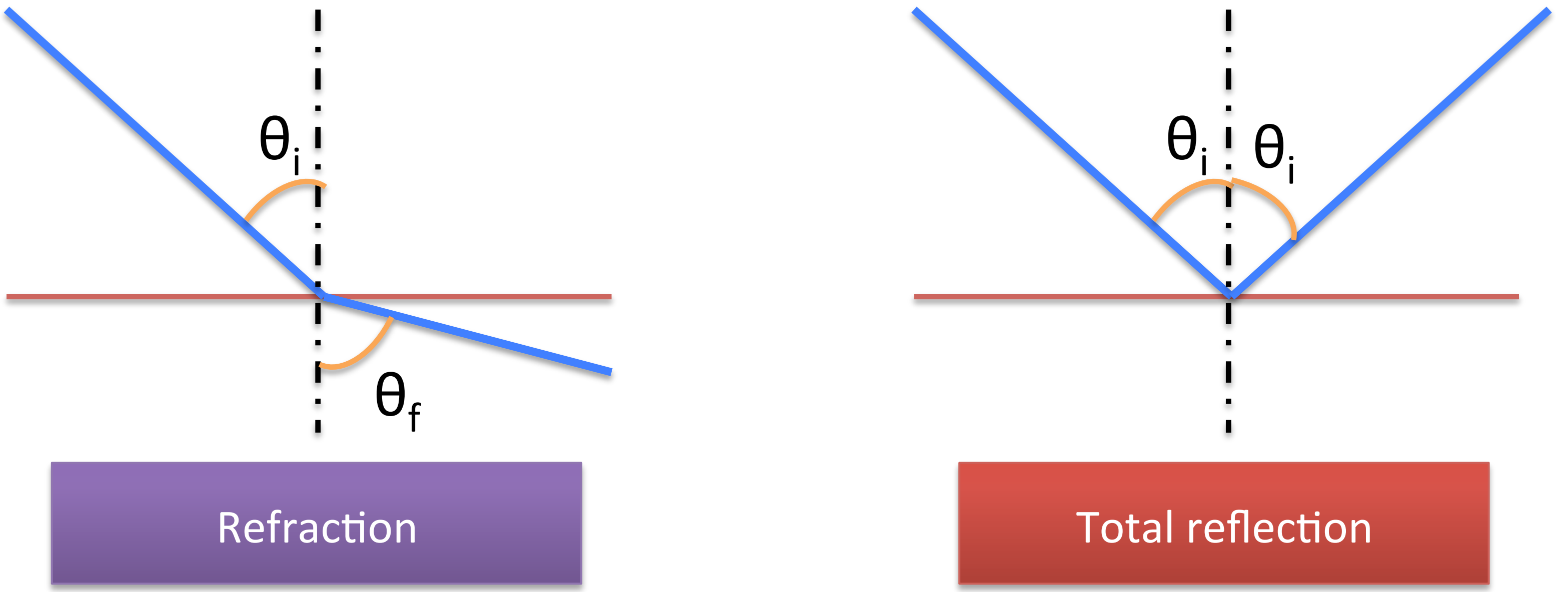
Jump formation

Jump analysis



Optics analogy

- By optics analogy, we can define a limit angle, when the refraction angle would be 90° and the total reflection happens.



Formulation

- For the transition, we can still use the same formulation for the refraction index:

$$n = \frac{W_e - 1}{W_e - 5}$$

Refraction formulation

$$n = \frac{1}{\sin \theta_i}$$

Total reflection results

Absortion

- Low weber Weber
- Higher angles

- Capillary forces > Normal forces

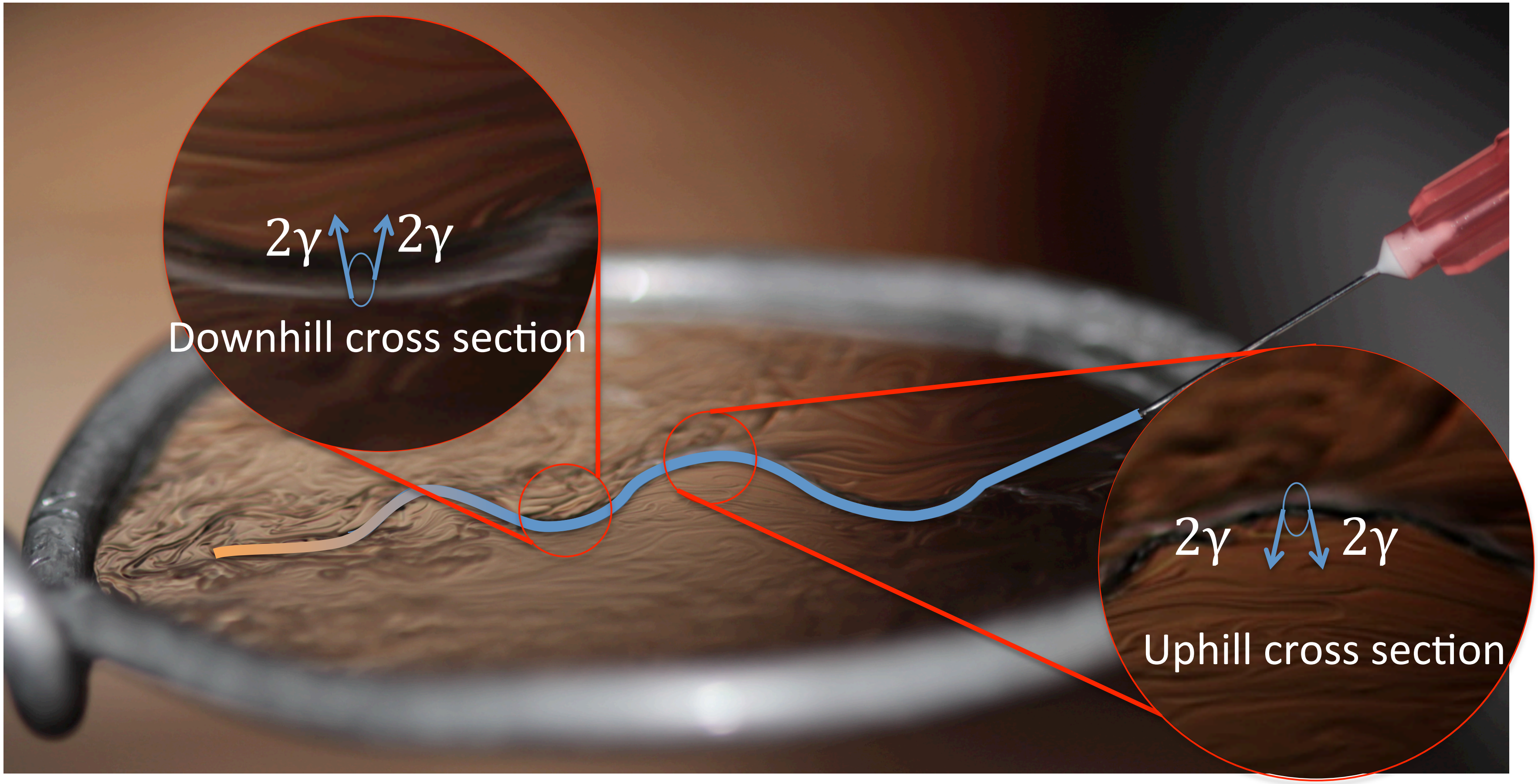
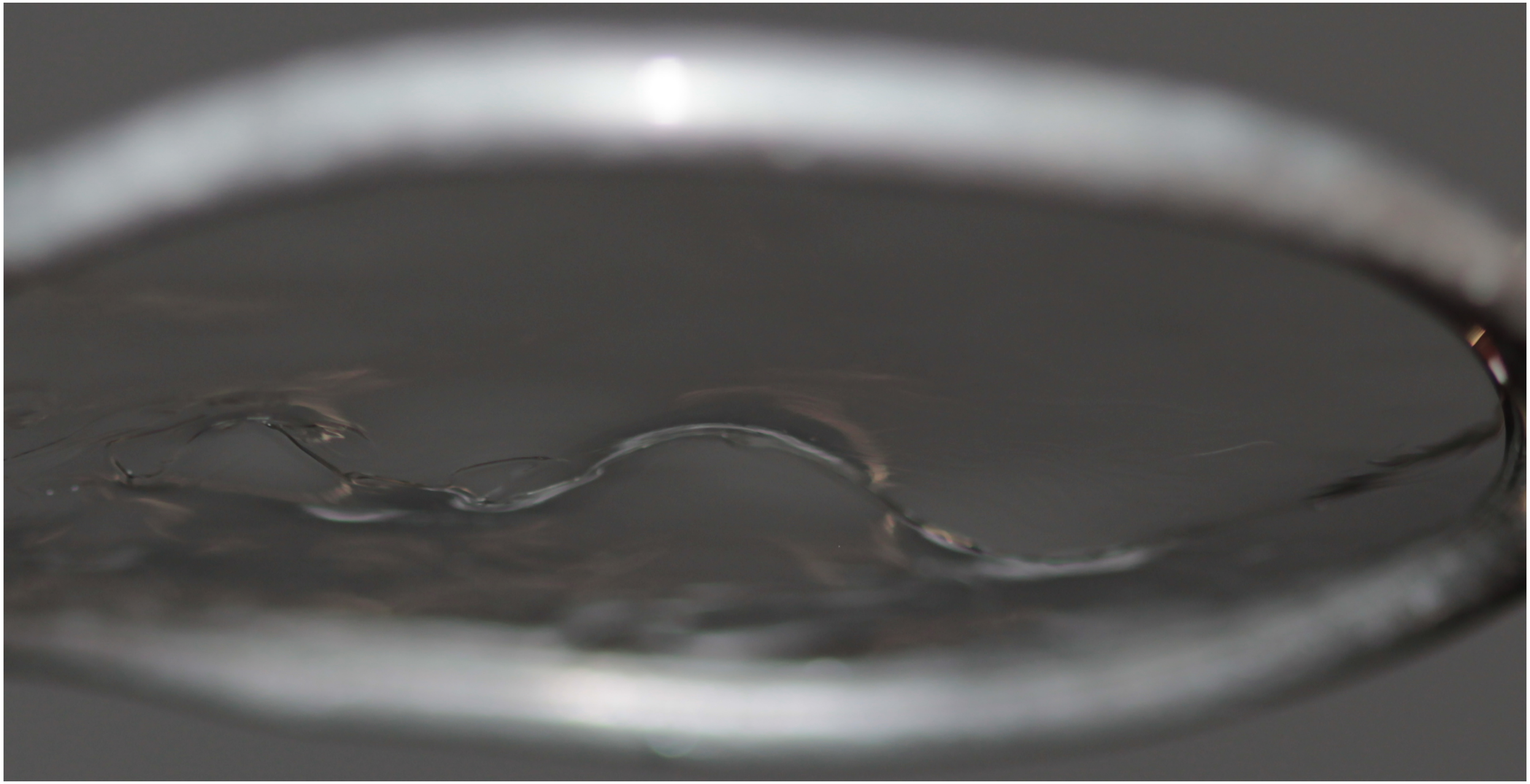
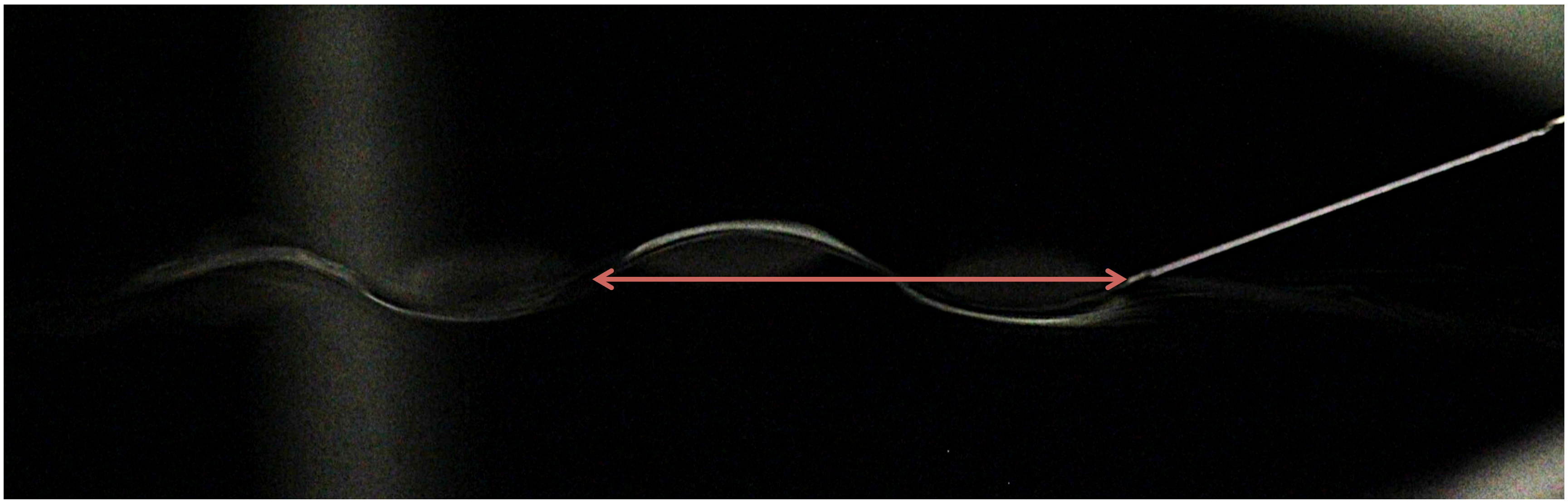

2γ 2γ
Downhill cross section
2γ 2γ
Uphill cross section

Photo from under the film

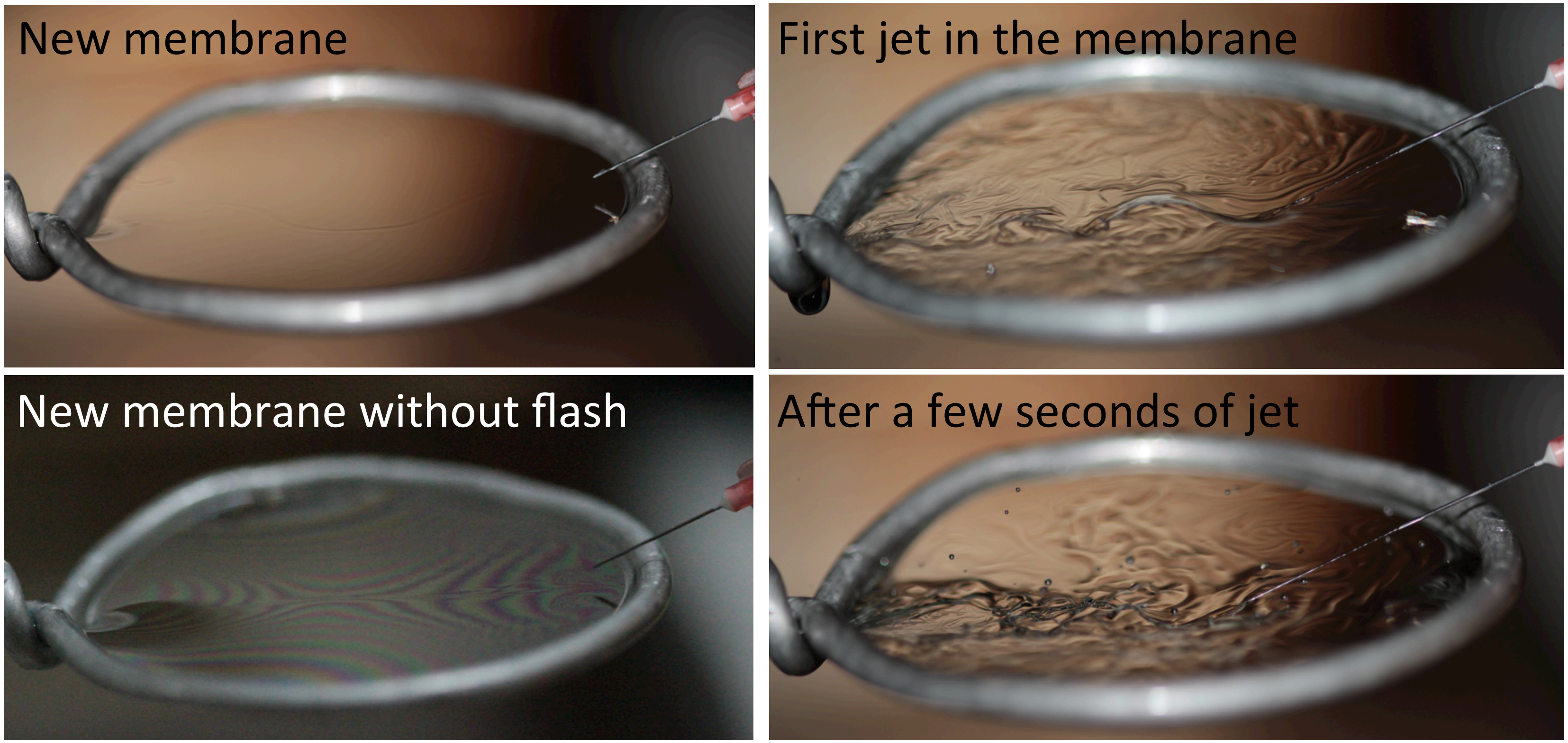


Formulation

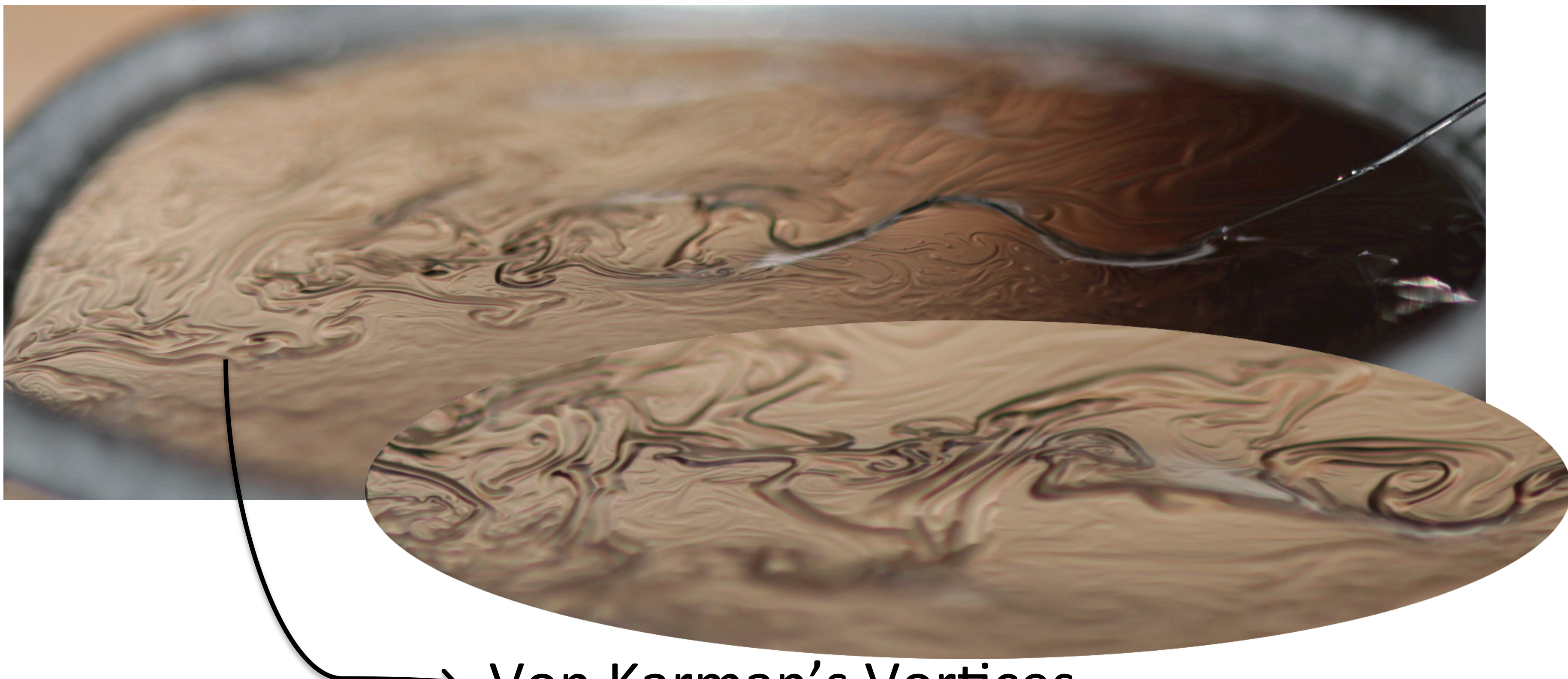


$$\lambda = \frac{2\pi}{\tilde{f}} R_i (W_e - 1) \cos \theta_i$$

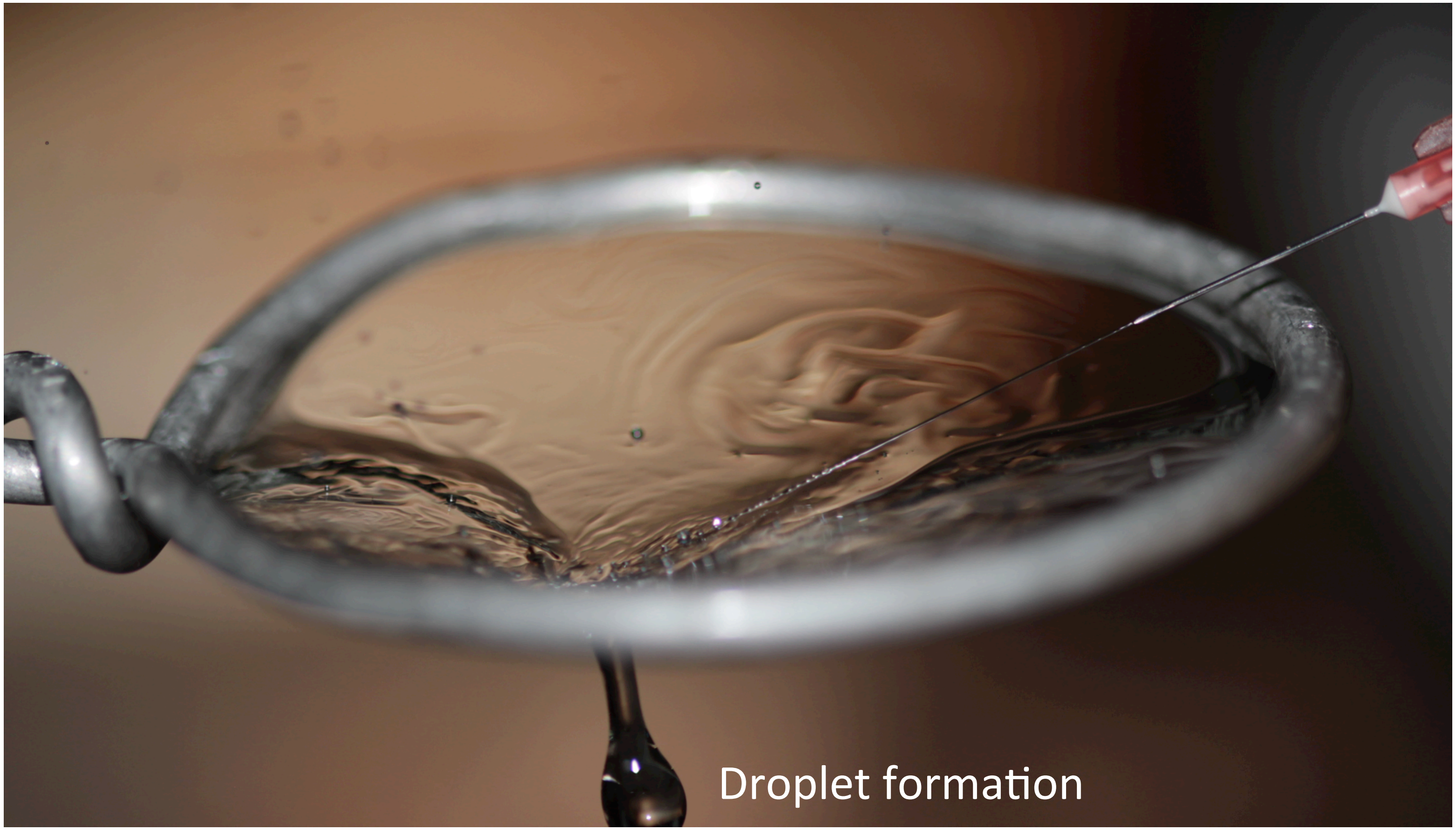
Membrane dynamics



Von Karman's Vortex



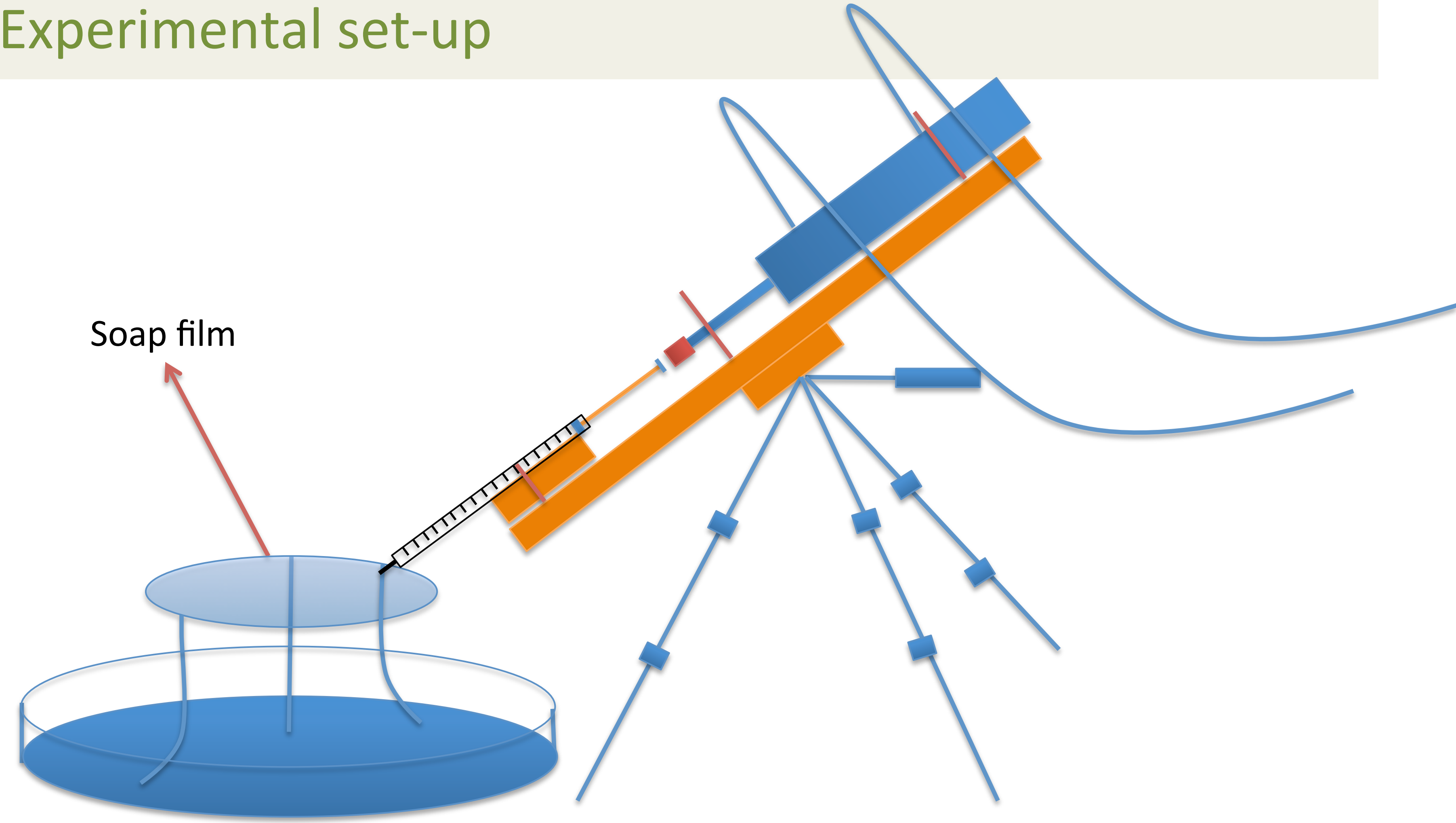
Von Karman's Vortices

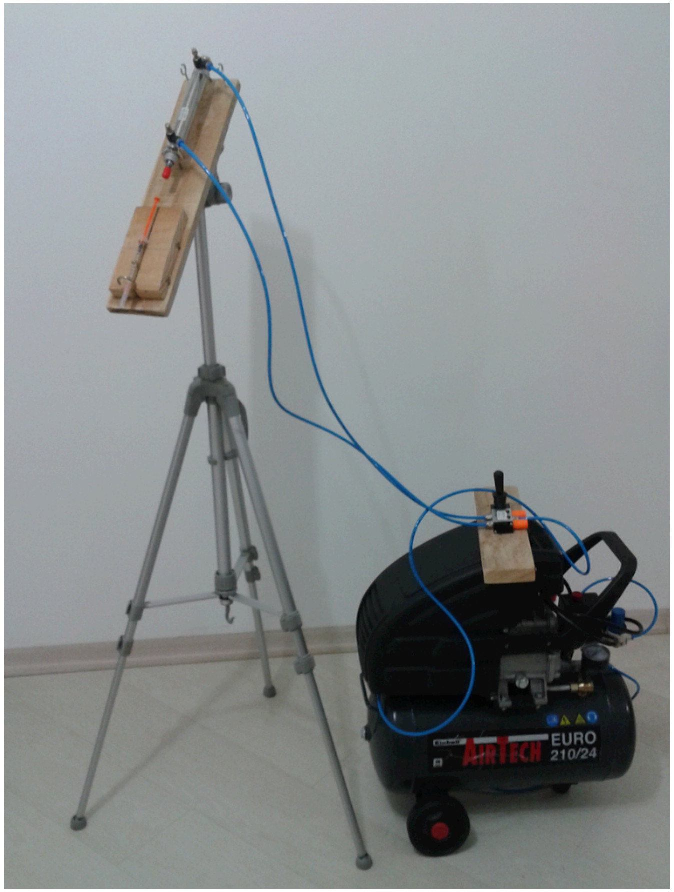

Droplet formation

Experimental analyzis

- Materials
  - Needles
    - 0.30mm, 0.40mm, 0.45mm, 0.75mm.
  - Detergent solution
  - Hoop for the film
  - Camera

Experimental set-up




AIRTECH
EURO
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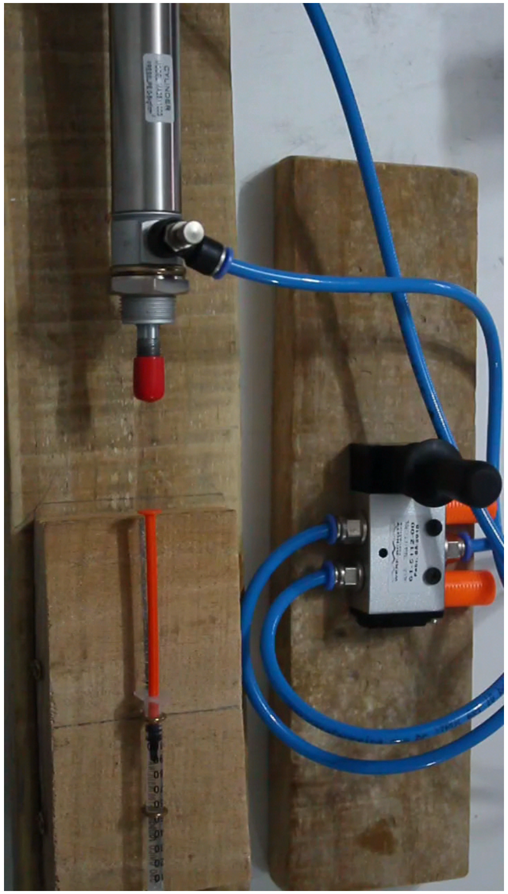
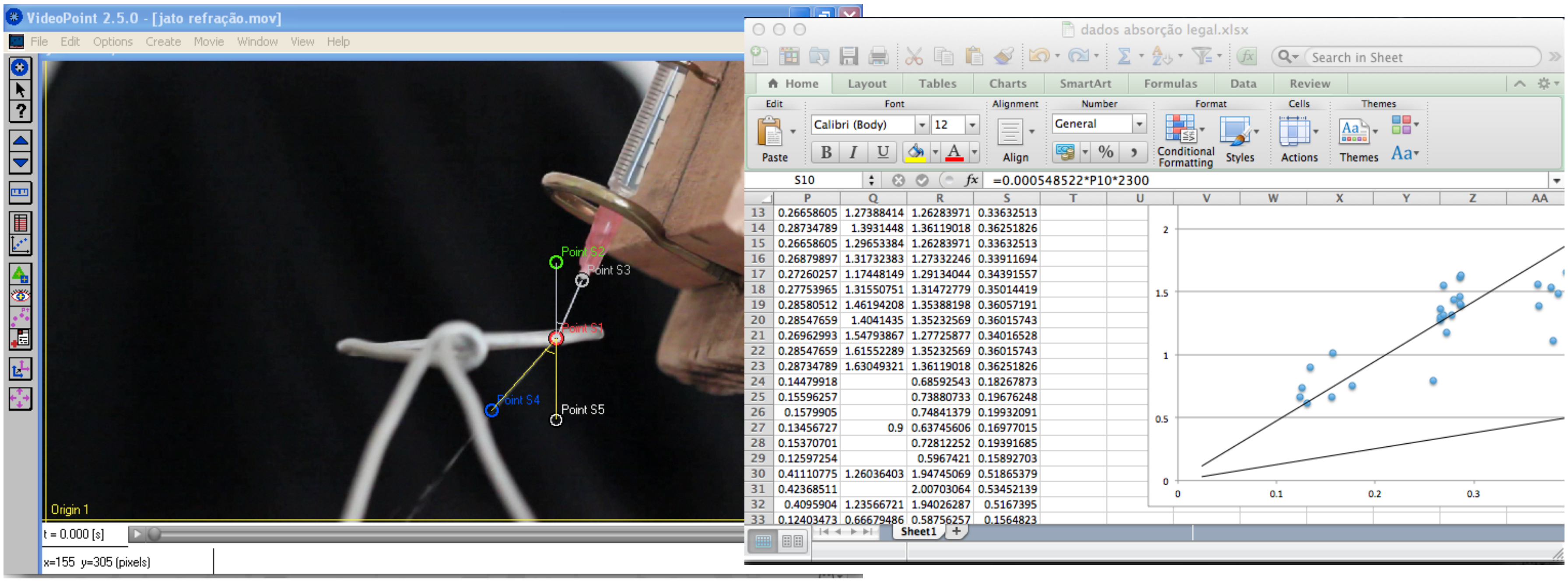
Minuano
ALTA PERFORMANCE



CYLINDER

Data

- We used Video Point to get the angles and the lambda values
- We plotted the graphs using Excel

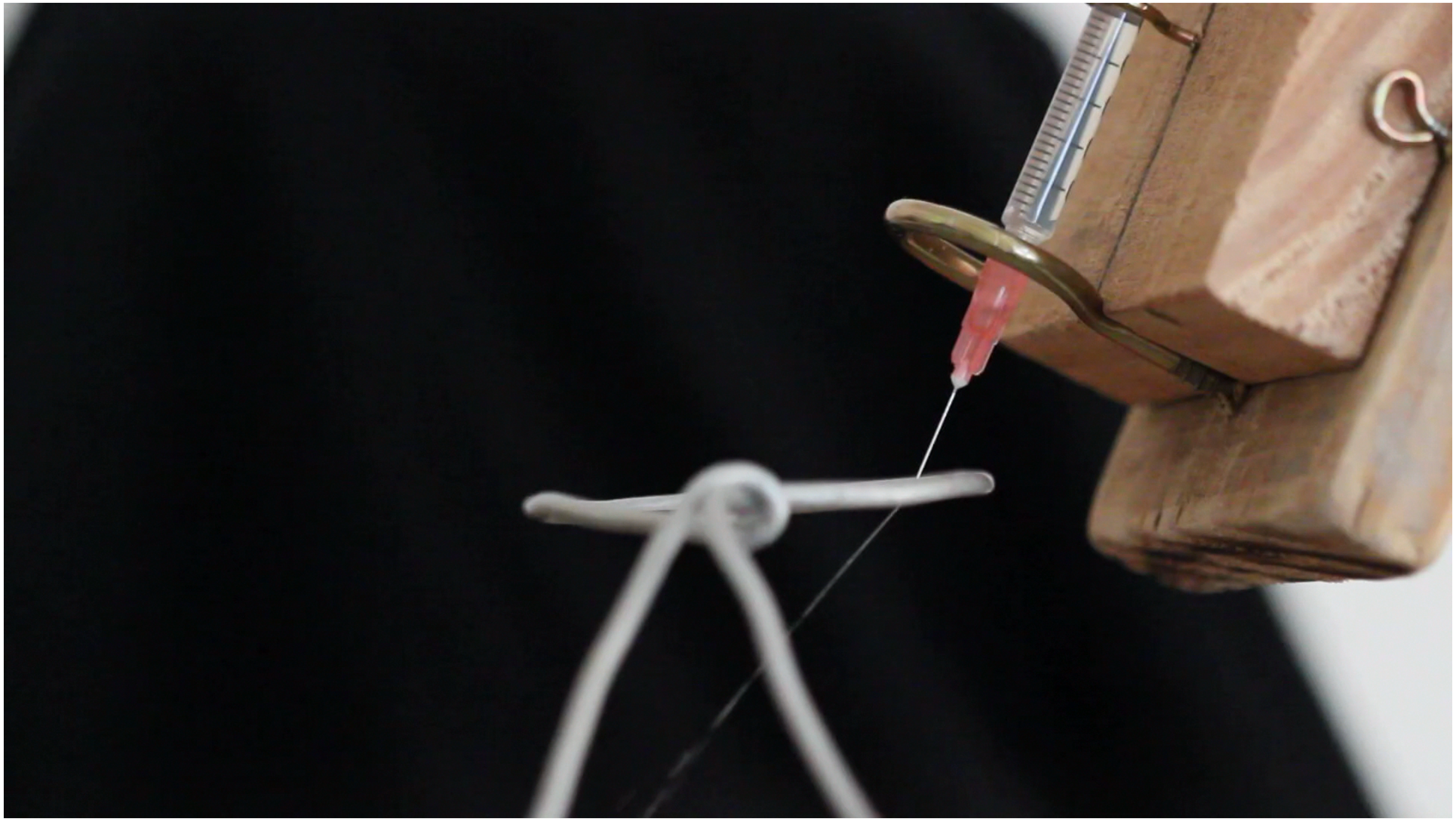


	P	Q	R	S
13	0.26658605	1.27388414	1.26283971	0.33632513
14	0.28734789	1.3931448	1.36119018	0.36251826
15	0.26658605	1.29653384	1.26283971	0.33632513
16	0.26879897	1.31732383	1.27332246	0.33911694
17	0.27260257	1.17448149	1.29134044	0.34391557
18	0.27753965	1.31550751	1.31472779	0.35014419
19	0.28580512	1.46194208	1.35388198	0.36057191
20	0.28547659	1.4041435	1.35232569	0.36015743
21	0.26962993	1.54793867	1.27725877	0.34016528
22	0.28547659	1.61552289	1.35232569	0.36015743
23	0.28734789	1.63049321	1.36119018	0.36251826
24	0.14479918		0.68592543	0.18267873
25	0.15596257		0.73880733	0.19676248
26	0.1579905		0.74841379	0.19932091
27	0.13456727	0.9	0.63745606	0.16977015
28	0.15370701		0.72812252	0.19391685
29	0.12597254		0.5967421	0.15892703
30	0.41110775	1.26036403	1.94745069	0.51865379
31	0.42368511		2.00703064	0.53452139
32	0.4095904	1.23566721	1.94026287	0.5167395
33	0.12403473	0.66679486	0.58756257	0.1564823

Variations

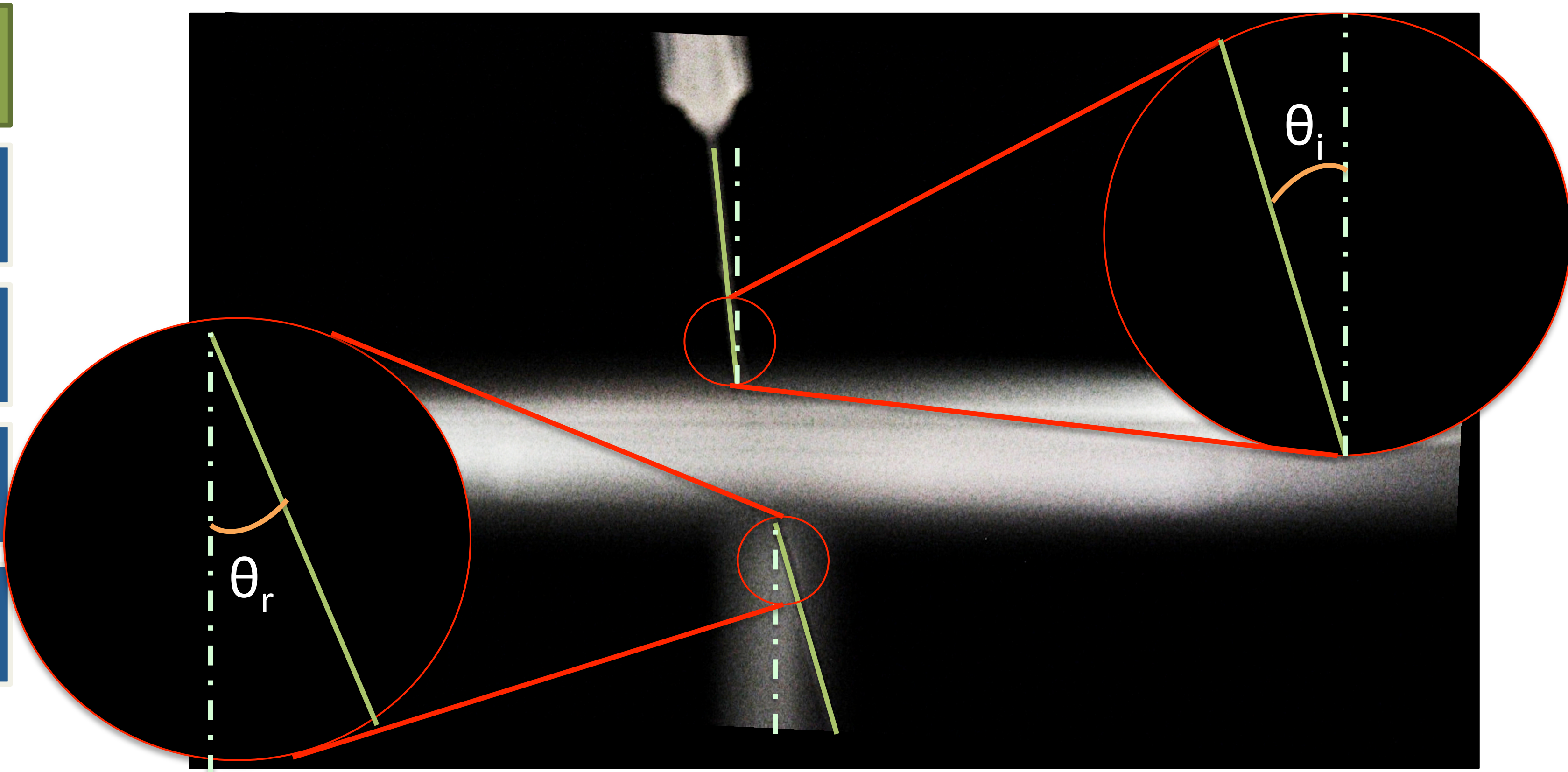
Needle radius	Jet velocity	Percentage of detergent in solution
0.30 mm	0.7 m/s	5%
0.38 mm	1.1 m/s	10%
0.45 mm	1.5 m/s	15%
1.10 mm	7 m/s	

- Refraction
- Diameter variation
- Transition
- Jump
- Absortion

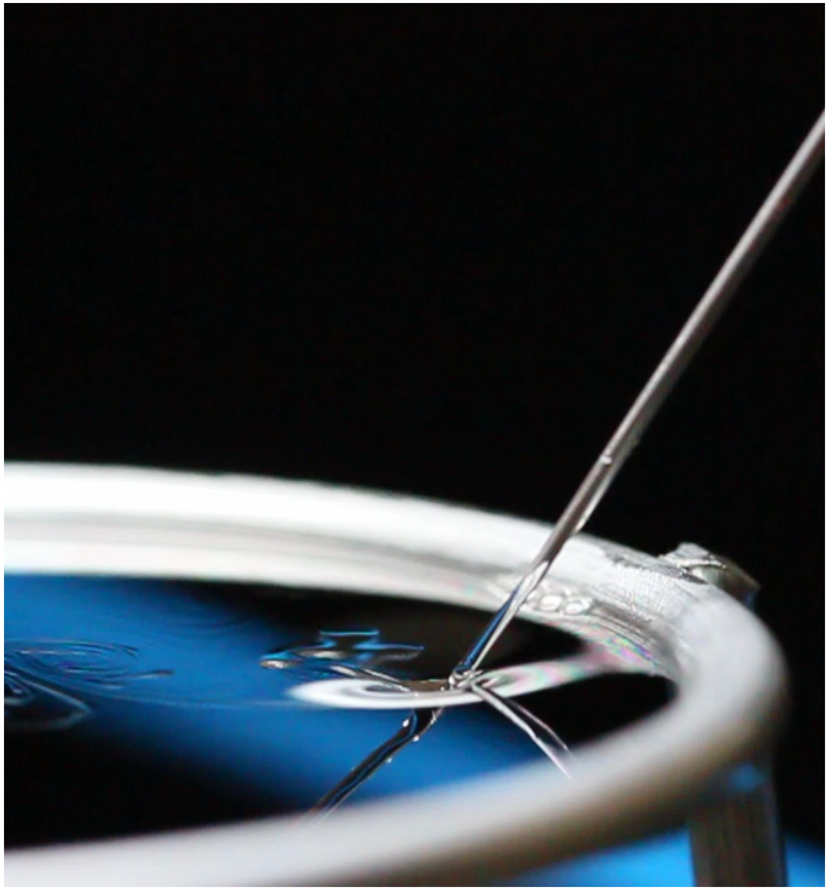


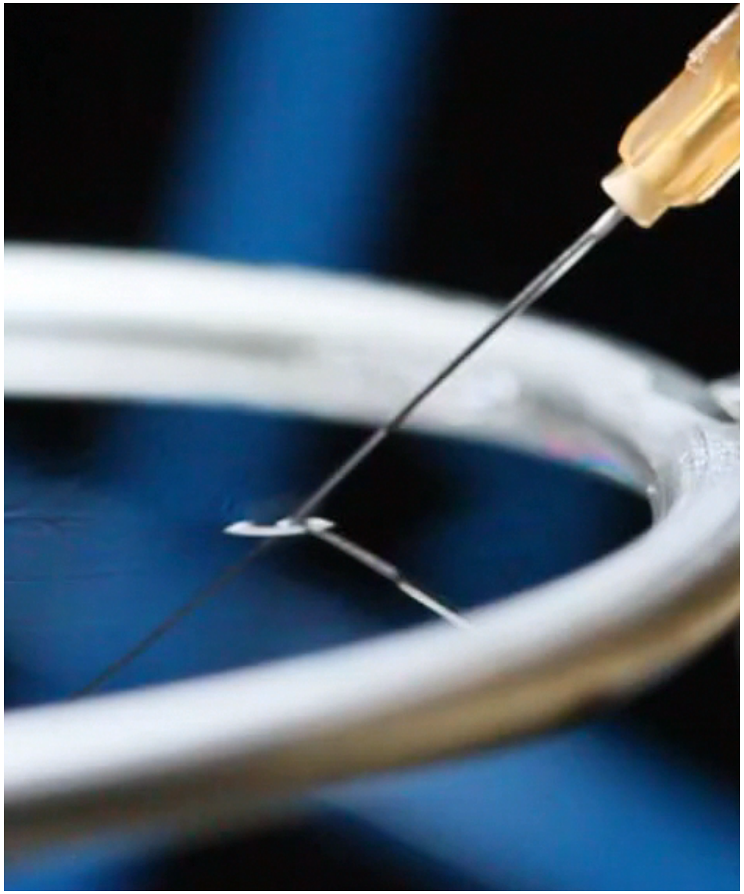
Refraction

- **Refraction**
- Diameter variation
- Transition
- Jump
- Absorption



- **Refraction**
- Diameter variation
- Transition
- Jump
- Absorption





Graph – 0.30 mm

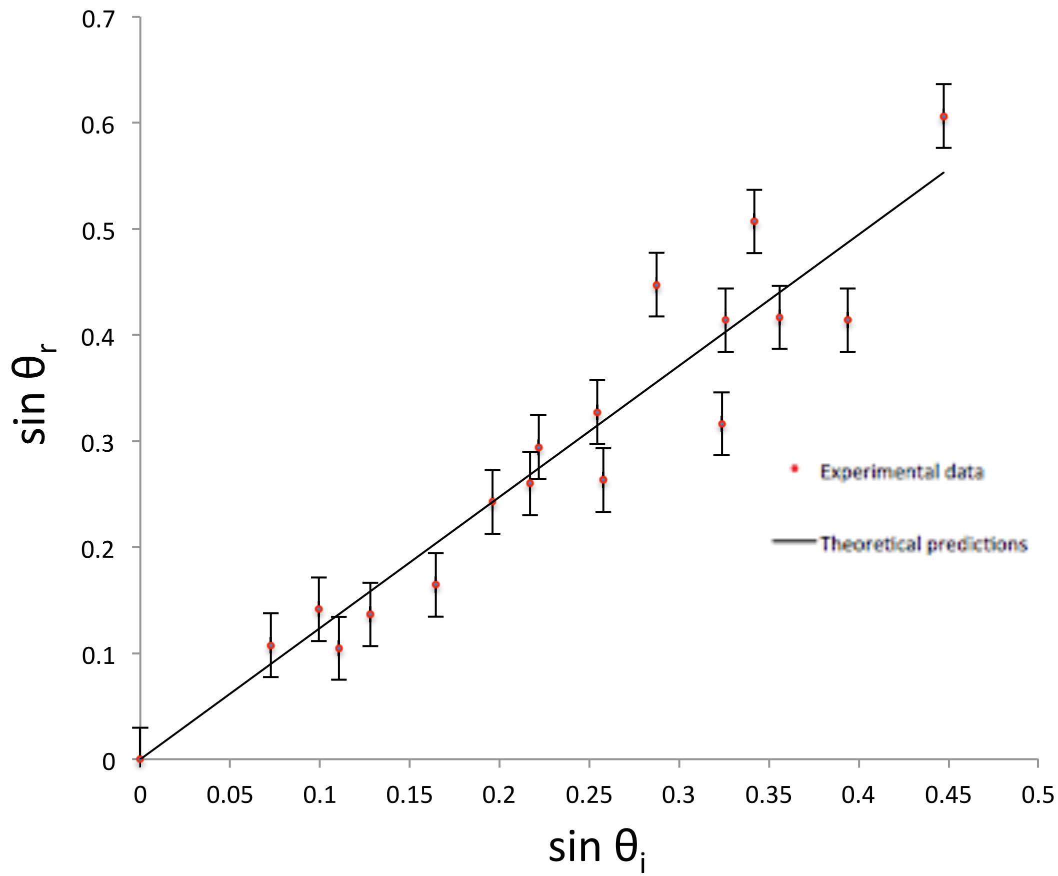
- Refraction
- Diameter variation
- Transition
- Jump
- Absorption

$R_i = 0.30mm$

$W_e = 23.0$

$V_i = 1.5$ m/s

$n = 1.124$



Graph – 0.38 mm

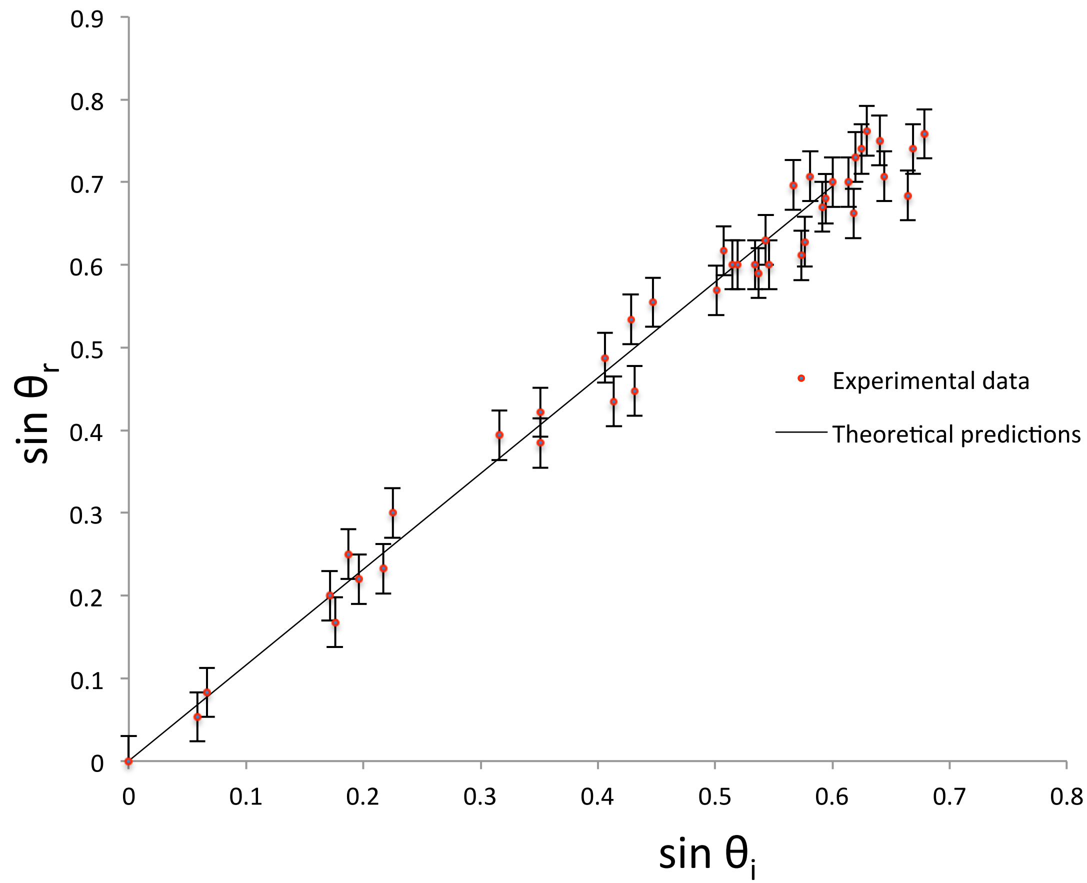
- Refraction
- Diameter variation
- Transition
- Jump
- Absortion

$R_i = 0.38mm$

$W_e = 29.0$

$V_i = 1.1\ m/s$

$n = 1.157$



Graph – 0.45 mm

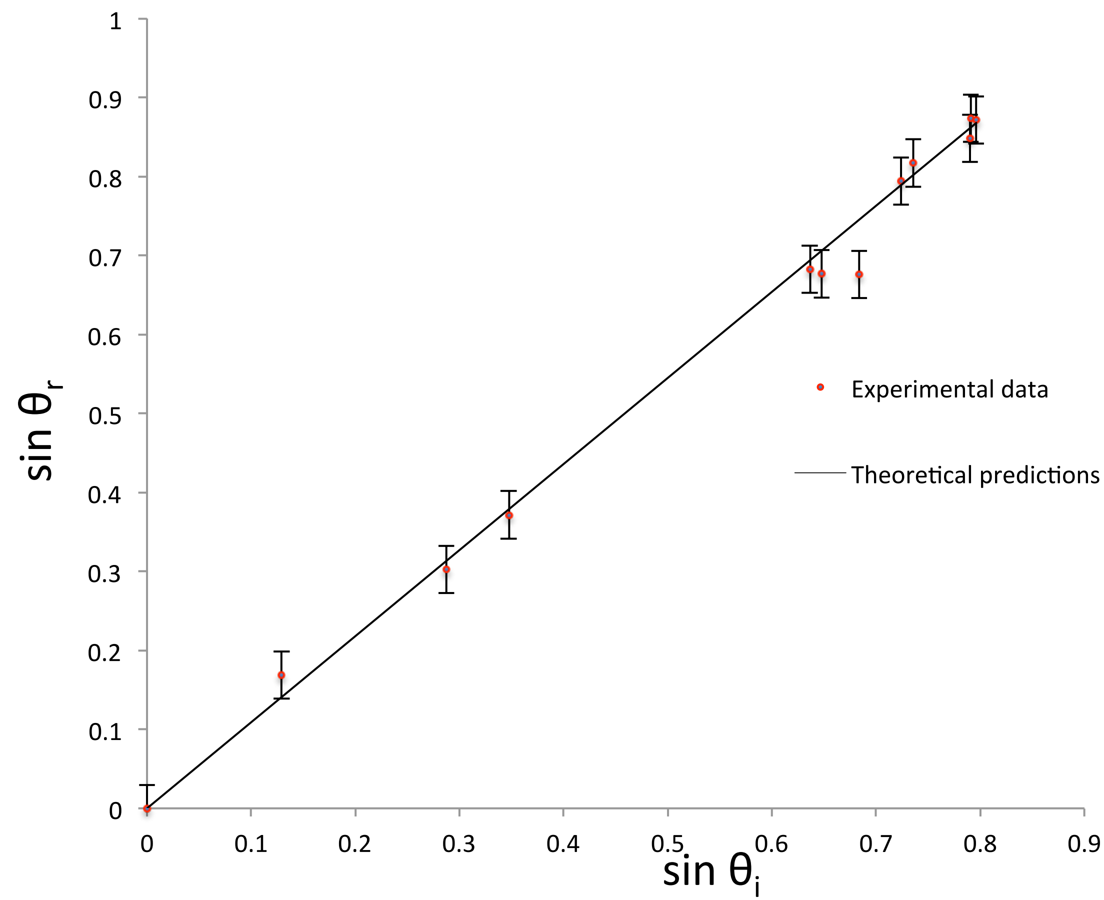
- Refraction
- Diameter variation
- Transition
- Jump
- Absorption

$R_i = 0.45mm$

$W_e = 49.5$

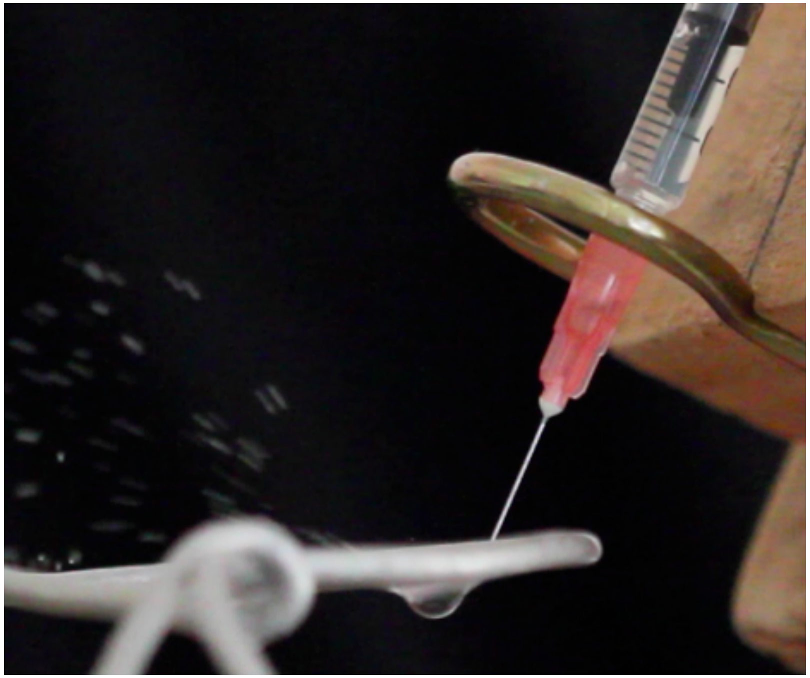
$V_i = 1.8 \text{ m/s}$

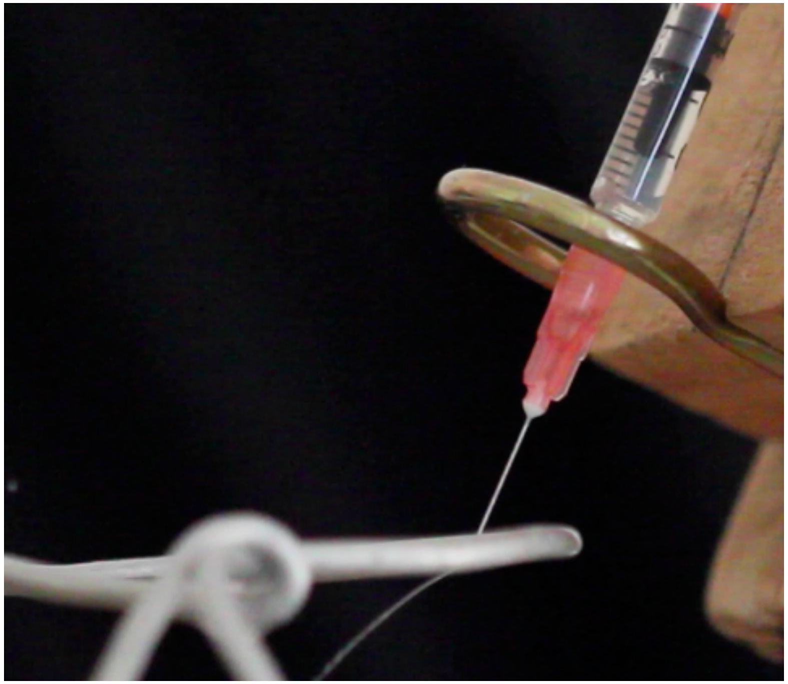
$n = 1.09$



Transition between refraction and jet

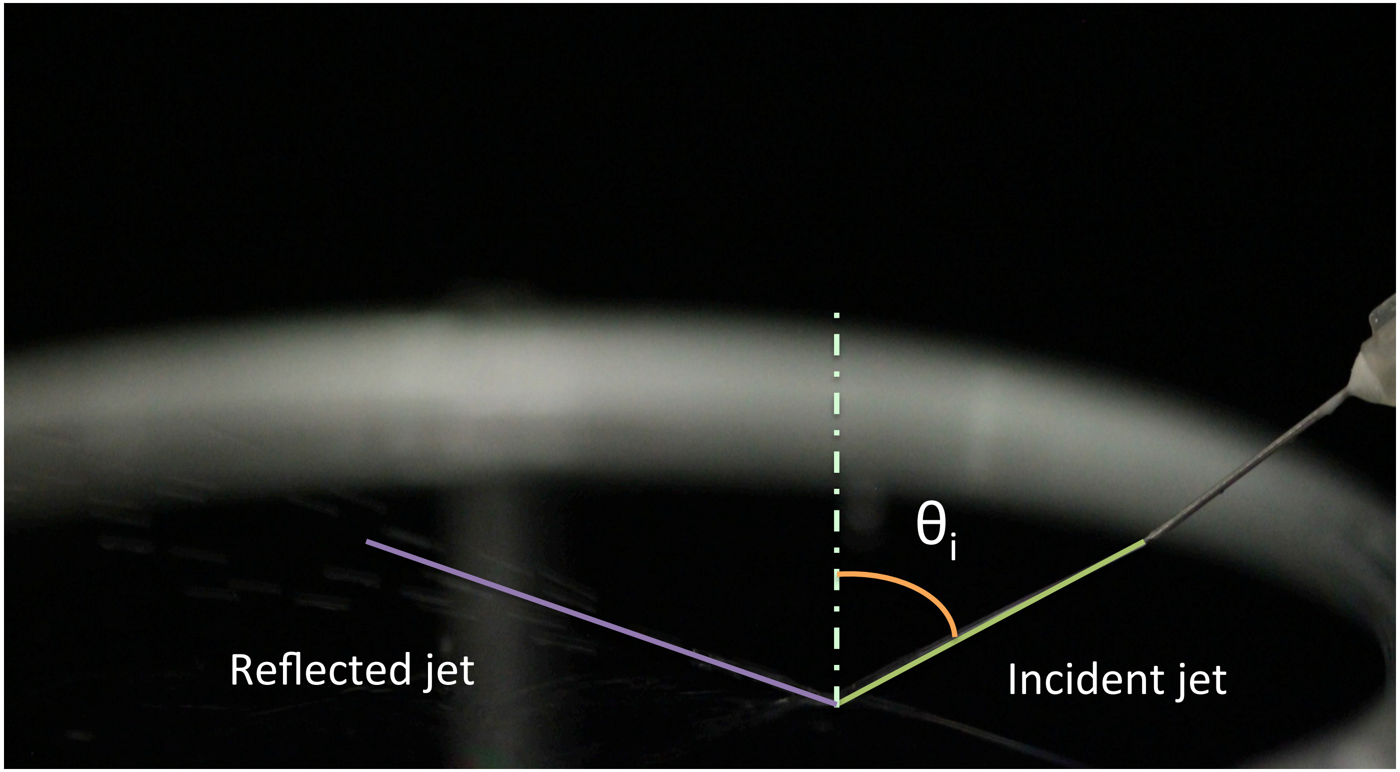
- Refraction
- Diameter variation
- **Transition**
- Jump
- Absorption





Slow motion:
0.5 of real
velocity

- Refraction
- Diameter variation
- Transition
- **Jump**
- Absorption



Comparison

Refraction
Diameter variation
Transition
Jump
Absorption

Needle radius	Experimental data $n = \frac{1}{\sin \theta_i}$	Theoretical predictions $n = \frac{W_e - 1}{W_e - 5}$	Error
0.30 mm	n = 1.24	n = 1.30	5.1%
0.38 mm	n = 1.16	n = 1.20	3.7%
0.45 mm	n = 1.15	n = 1.09	5.2%
1.10 mm	n = 1.28	n = 1.20	6.2%

Refraction

Diameter variation

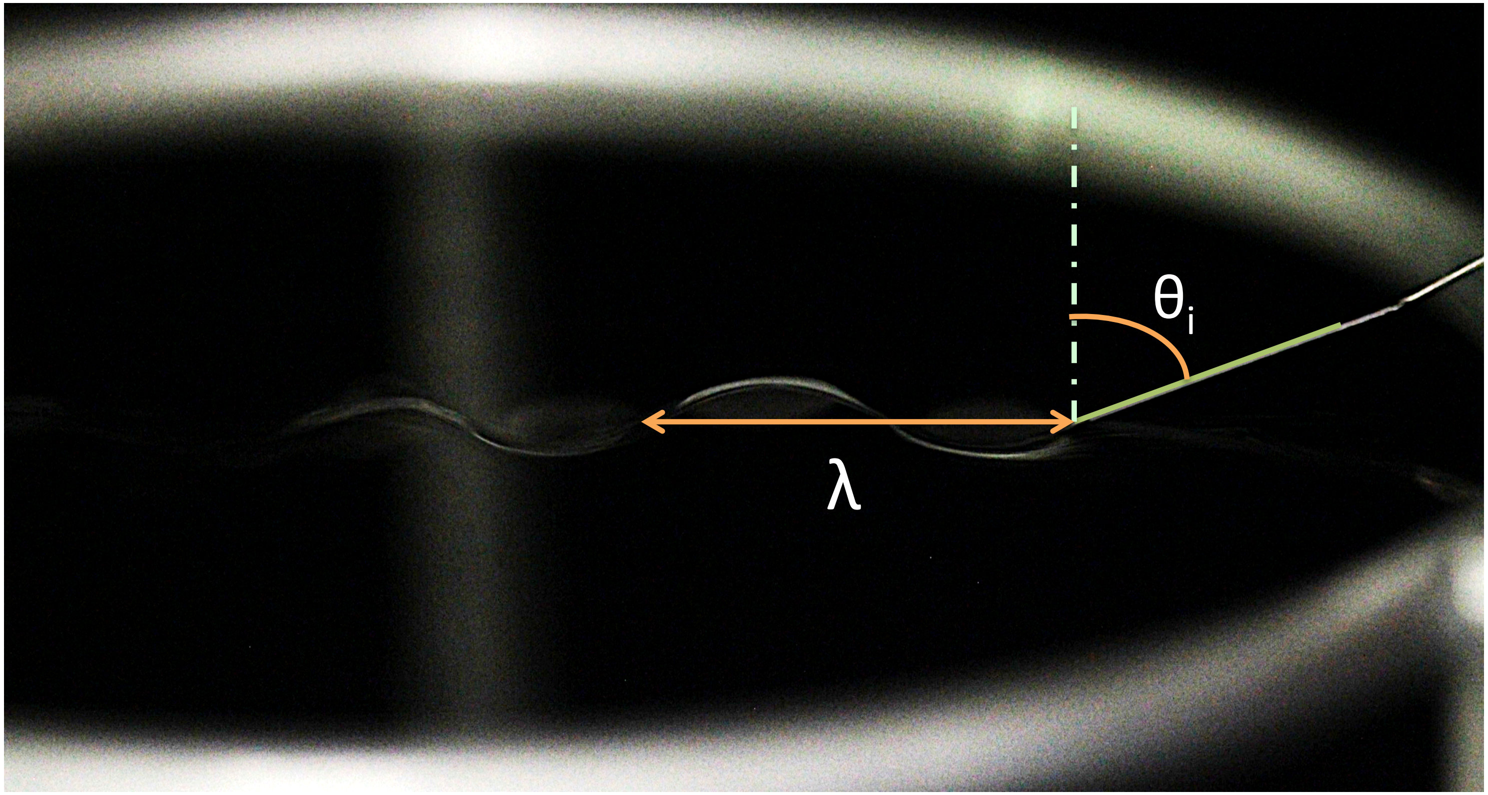
Transition

Jump

Absorption

Absorption regime

- Refraction
- Diameter variation
- Transition
- Jump
- **Absorption**



Graphs

Refraction

Diameter variation

Transition

Jump

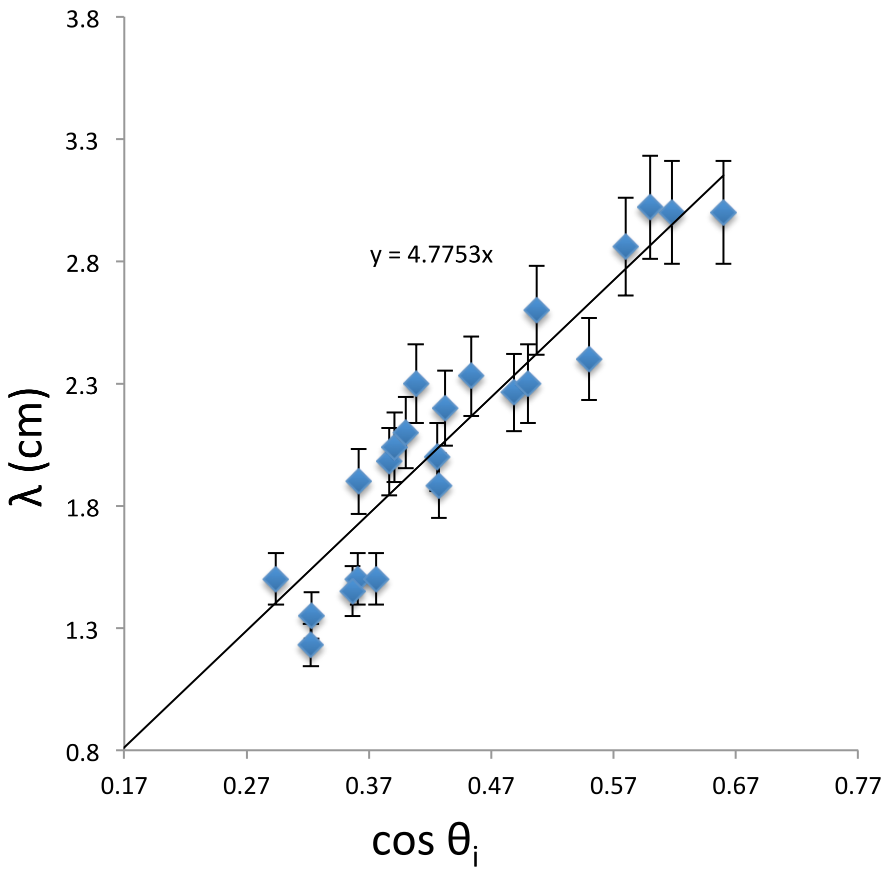
Absorption

$R_i = 0.38mm$

$W_e = 30$

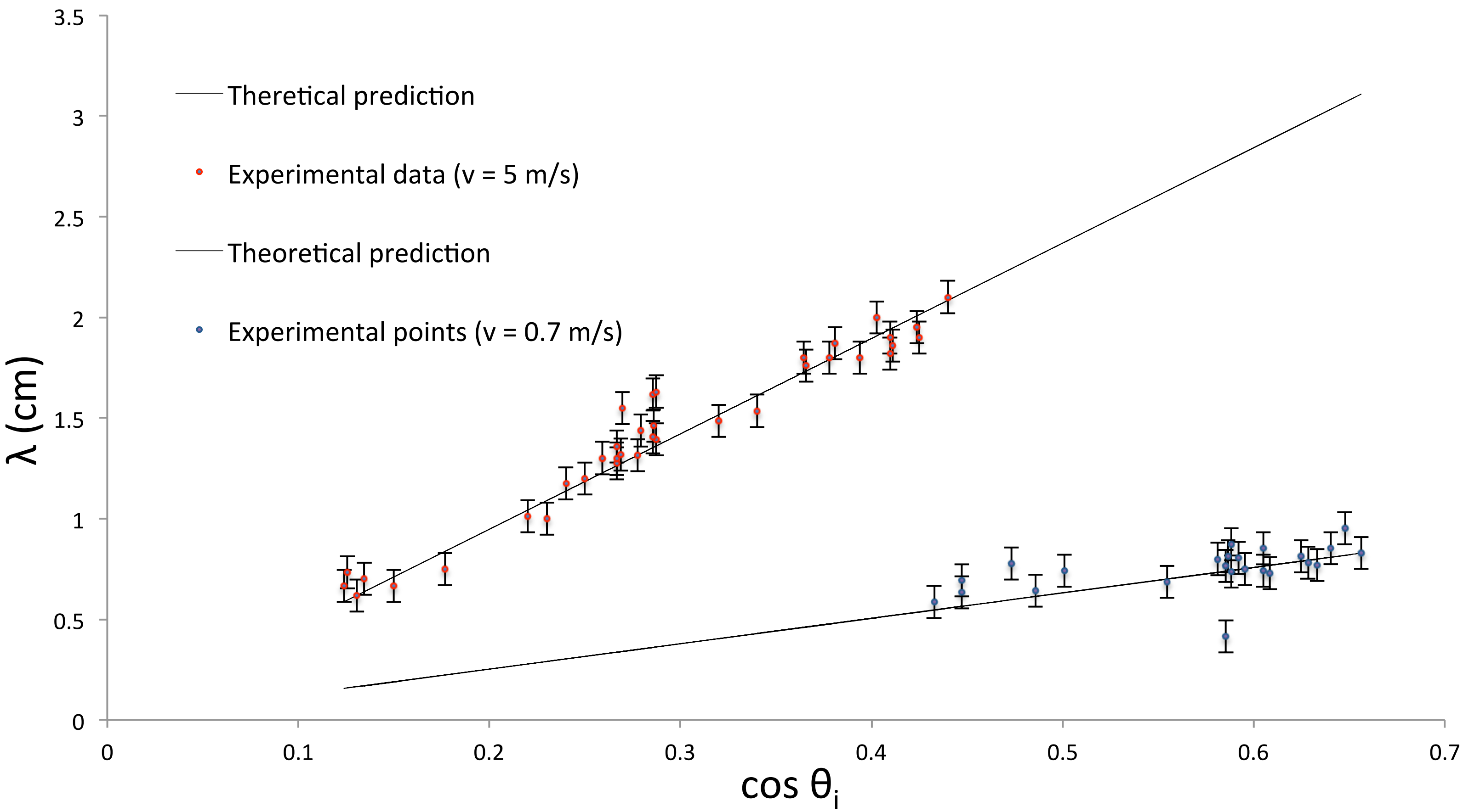
$V_i = 1.1$ m/s

$\tilde{f} = 0.68$



Velocity variation

- Refraction
- Diameter variation
- Transition
- Jump
- Absorption



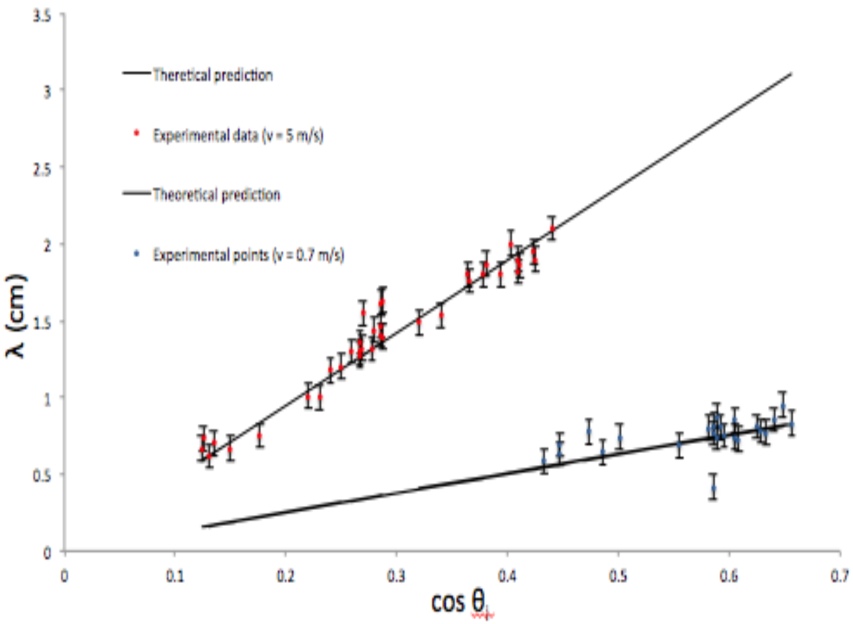
Conclusion

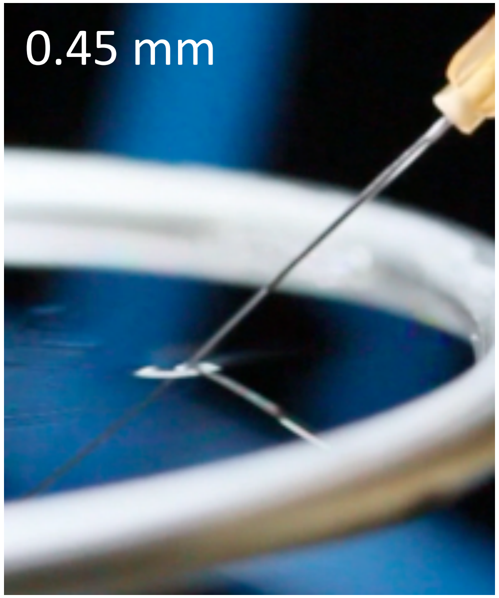
- We divided our problem in 3 phases, depending on the angle of incidence of the jet.

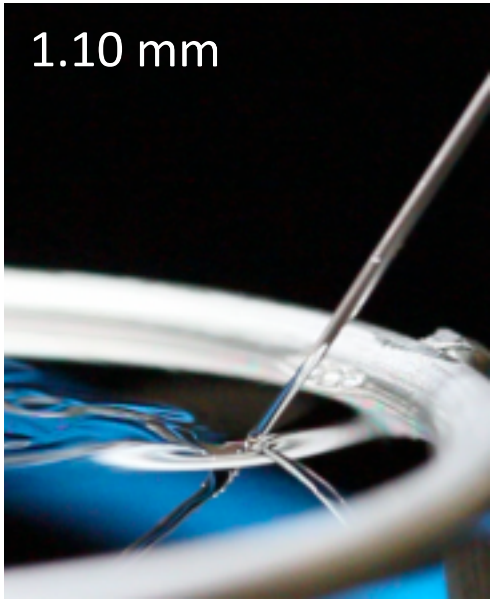


Conclusion

- The fluid's velocity and needle's diameter are very relevant parameters for the regimes:







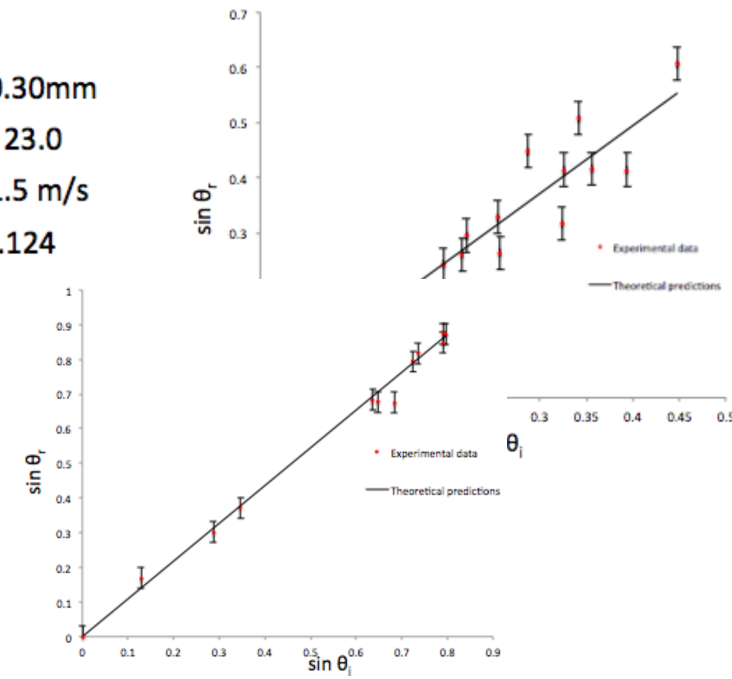
Conclusion

- We can study the problem in a quantitative way, predicting the refraction index and the parameter dependency of each regime.

Needle radius	Experimental data	Theoretical predictions	Error
0.30 mm	n = 1.24	n = 1.30	5.1%
0.38 mm	n = 1.16	n = 1.20	3.7%
0.45 mm	n = 1.15	n = 1.09	5.2%
1.10 mm	n = 1.28	n = 1.20	6.2%

R_i = 0.30mm
W_e = 23.0
V_i = 1.5 m/s
n = 1.124

R_i = 0.45mm
W_e = 49.5
V_i = 1.8 m/s
n = 1.09



References

- Geoffroy Kirstetter, Christophe Raufaste, and Franck Celestini. Jet impact on a soap film. Phys. Rev. E 86, 3, 036303 (2012)
- Stable Kaye effect on a thin soap film (Devaraj van der Meer, Univ. of Twente)

Thank you!

Theoretical formulation

- Weber number
- Capillarity
- Dynamics of a soap film
- Optic analogy
- Surface tension
- Kaye effect

Kaye effect

- The **Kaye Effect** is a property of complex liquids which was first described by the British engineer Alan Kaye in 1963.[1]
- While pouring one viscous mixture of an organic liquid onto a surface, the surface suddenly spouted an upcoming jet of liquid which merged with the downgoing one.
- This phenomenon has since been discovered to be common in all shear-thinning liquids (liquids which thin under shear stress). Common household liquids with this property are liquid hand soaps, shampoos and non-drip paint. The effect usually goes unnoticed, however, because it seldom lasts more than about 300 milliseconds. The effect can be sustained by pouring the liquid onto a slanted surface, preventing the outgoing jet from intersecting the downward one (which tends to end the effect).
- It is thought to occur when the downgoing stream "slips" off the pile it is forming, and due to a thin layer of shear-thinned liquid acting as a lubricant, does not combine with the pile. When the slipping stream reaches a dimple in the pile, it will shoot off it like a ramp, creating the effect.

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Shear thinning

- **Shear thinning** is an effect where a fluid's viscosity—the measure of a fluid's resistance to flow—decreases with an increasing rate of shear stress. Another name for a shear thinning fluid is a **pseudoplastic**. This property is found in certain complex solutions, such as lava, ketchup, whipped cream, blood, paint, and nail polish. It is also a common property of polymer solutions and molten polymers. Pseudoplasticity can be demonstrated by the manner in which squeezing a bottle of ketchup, a Bingham plastic, causes the contents to undergo a change in viscosity. The force causes it to go from being thick like honey to flowing like water. The study of such phenomena is called rheology.
- All materials that are shear thinning are thixotropic, in that they will always take a finite time to bring about the rearrangements needed in the microstructural elements that result in shear thinning.

How to measure the fluid velocity at the needle

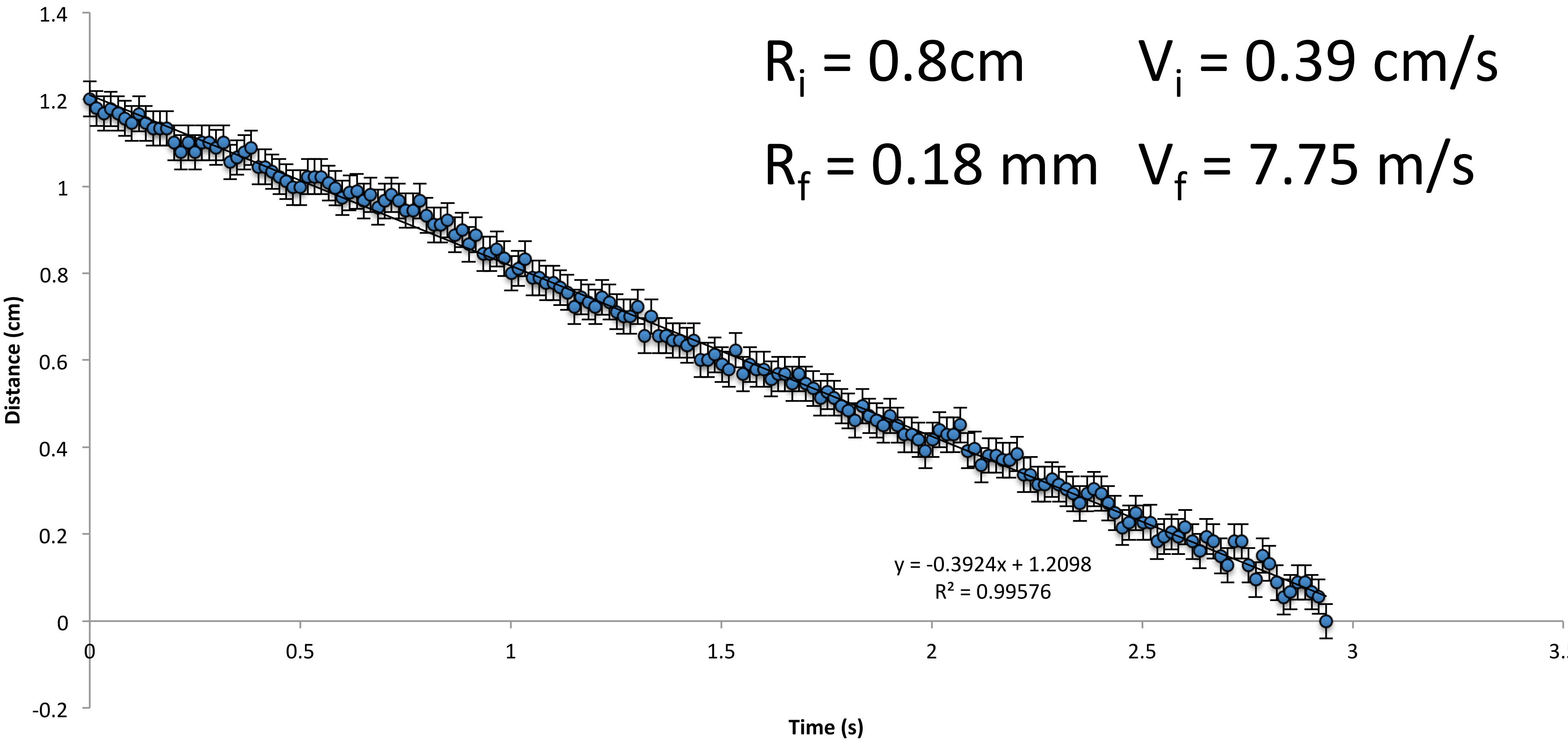
- Film the syringe with the fluid
- Analyze the video in video point
- Calculate the velocity by the approximation:

$$R_i^2 \cdot v_i = R_f^2 \cdot v_f$$

Chart

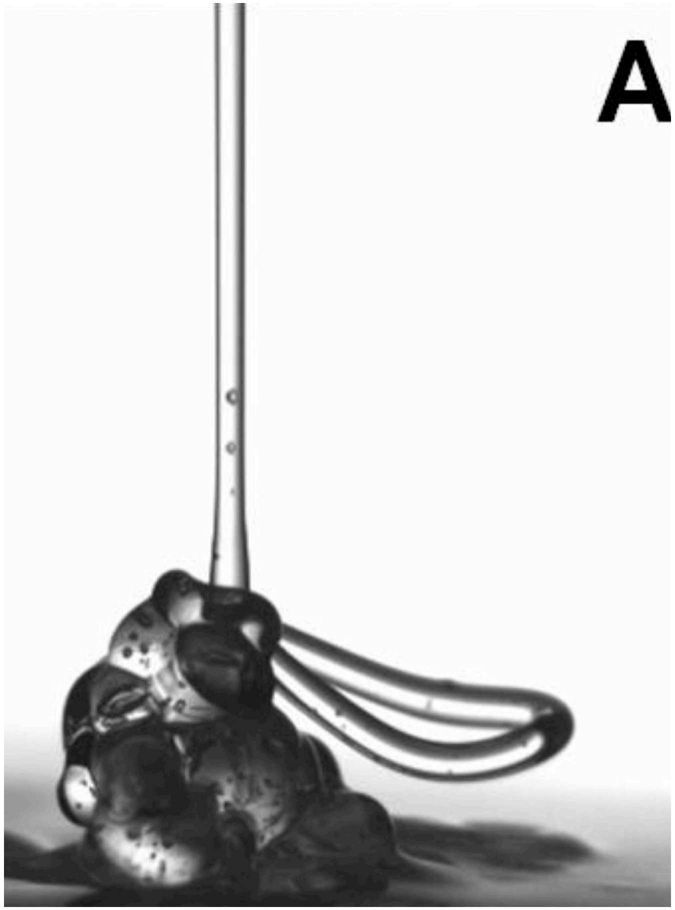
$R_i = 0.8cm$ $V_i = 0.39$ cm/s

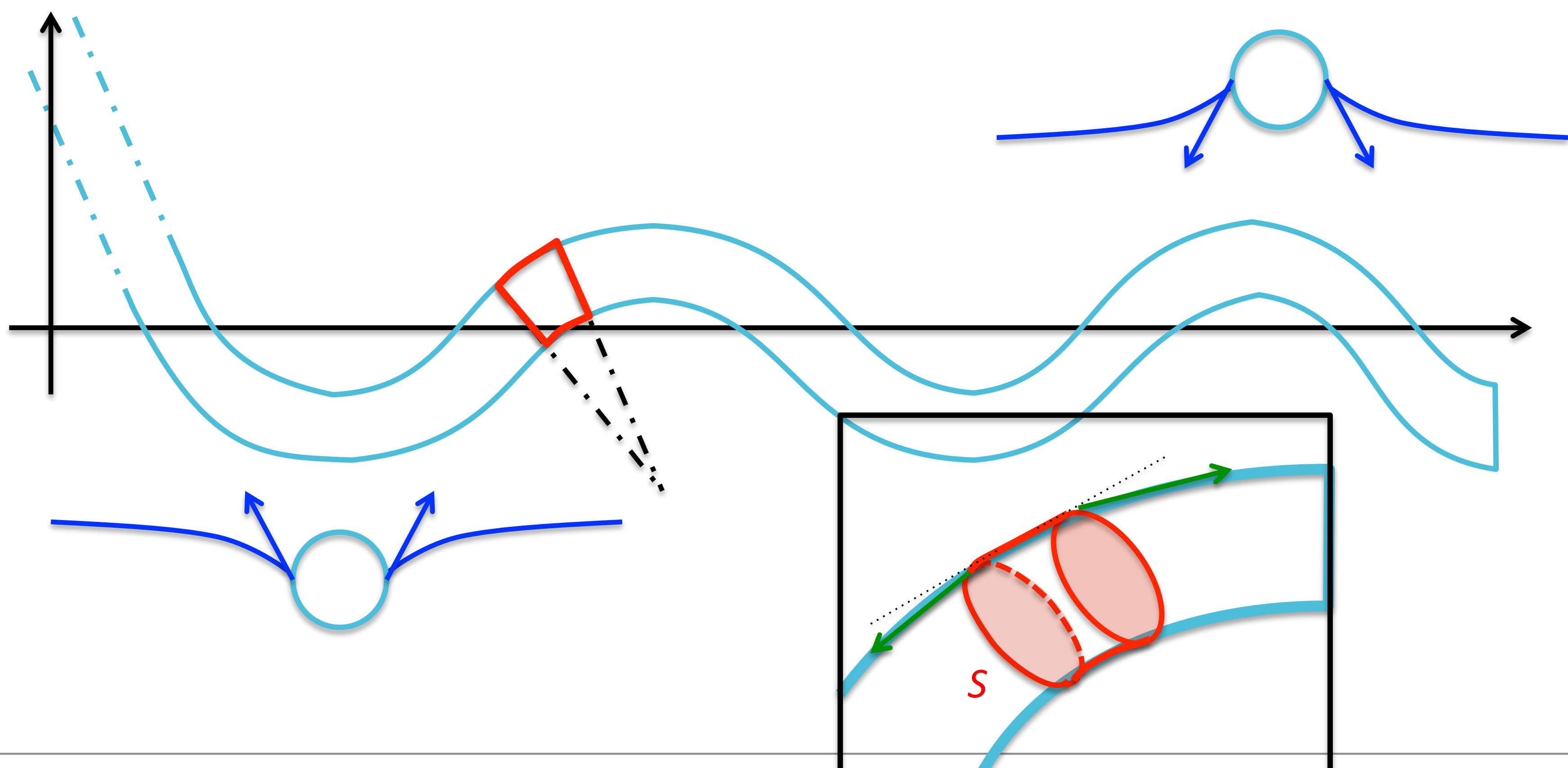
$R_f = 0.18$ mm $V_f = 7.75$ m/s



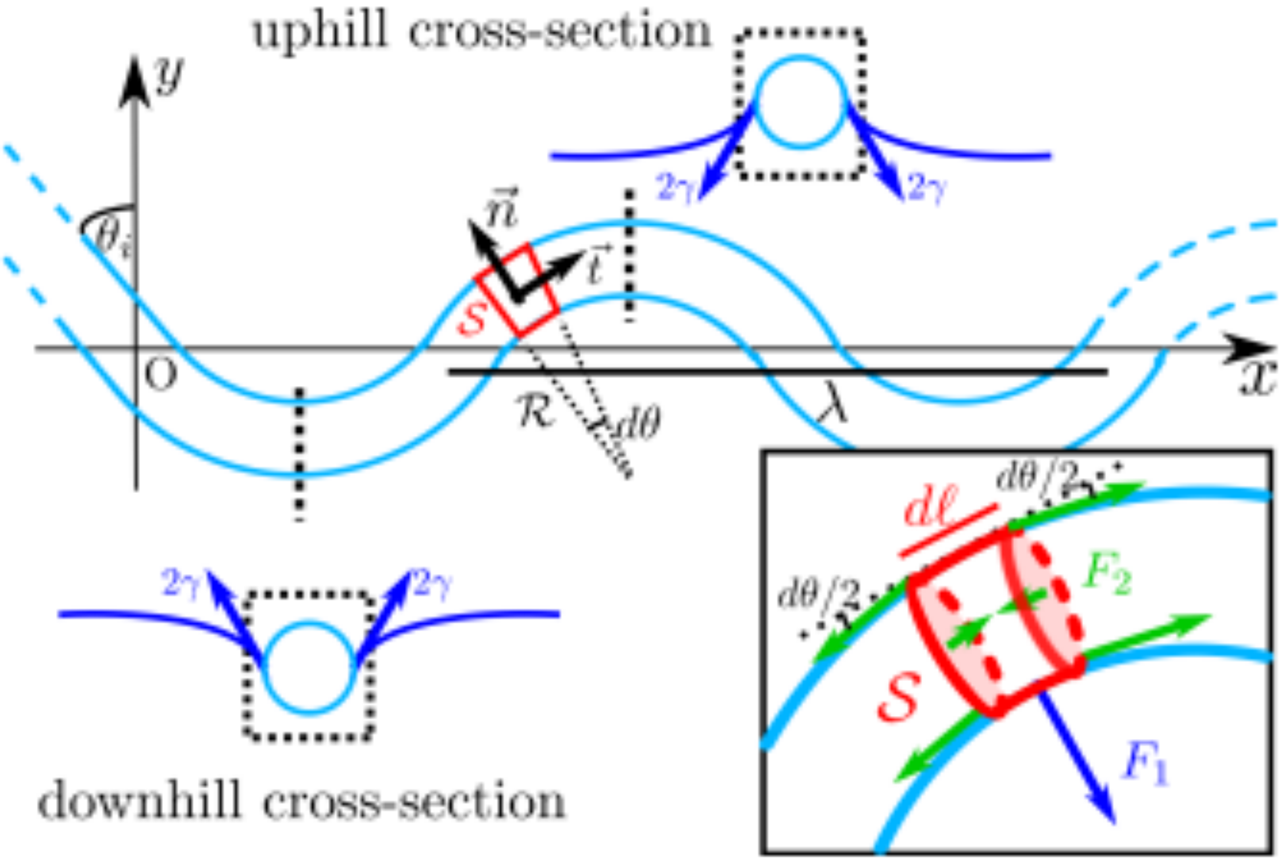
Kaye effect

- It’s caused by the shear-thinning behavior of some non Newtonian fluids
- There’s a thin air layer between the two fluids



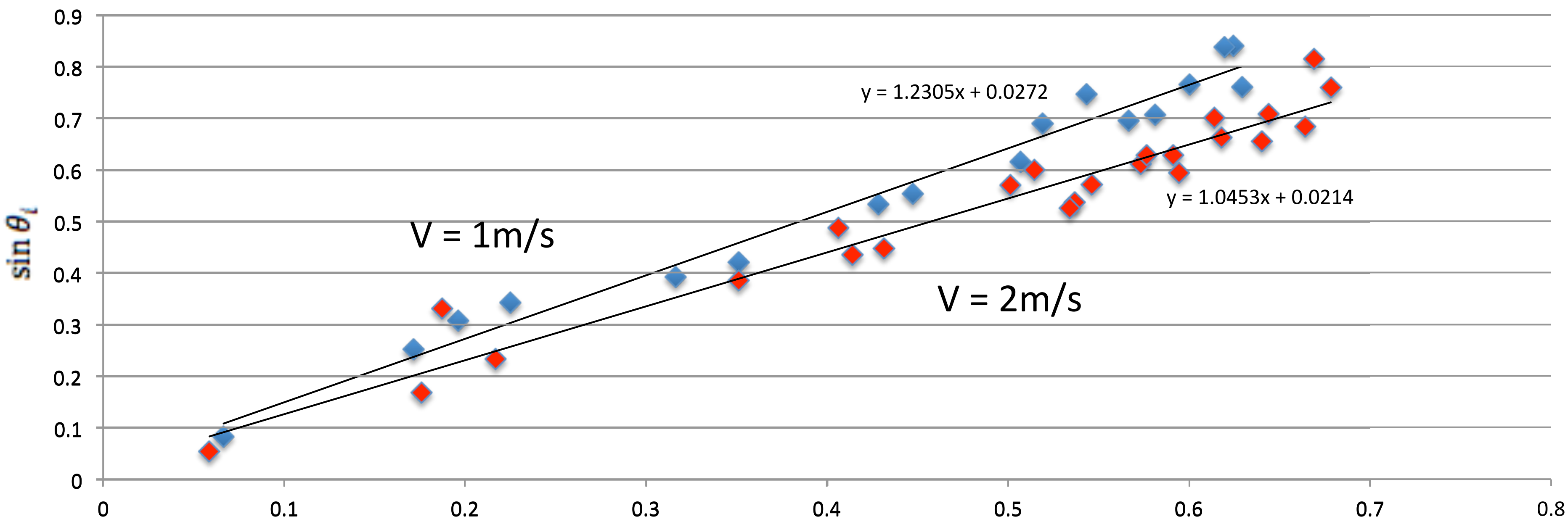

S

Scheme


uphill cross-section
y
x
O
θ_i
$\vec{n}$
$\vec{t}$
S
$\mathcal{R}$
$d\theta$
λ
2γ
2γ
2γ
2γ
downhill cross-section
$d\ell$
$d\theta/2$
$d\theta/2$
F_2
S
F_1

Gráficos

- Refração



Materials

- Detergent solution(5%)
  - $\gamma = 26.2 \pm 0.2$ mNm^{-1}
  - $\rho = 10^3$kg/m^3
  - V_i between 1m/s and 2m/s

Absorption phase formulaion

- After some algebric work:

$$(W_e - 1)\sin(\theta_r - \theta_i) = \frac{F_R}{\pi\gamma R_i}\sin\theta_r$$

- We can do some approximations:

$$F_R \sim 4\pi\gamma R_i$$
$$Membrane\ union$$

$$\sin\theta_i \sim \theta_i$$
$$\theta_i \ll 1$$

$$\sin\theta_r \sim n\theta_i$$
$$Refraction\ condition$$

$$n = \frac{W_e - 1}{W_e - 5}$$

Formulation

- Mass consevation:

$$D = \pi R_i^2 V_r = \pi R_r^2 V_r$$

- Decomposition of the forces acting on the film:

$$D(\rho V_r \sin\theta_r - \rho V_i \sin\theta_i) = \pi\gamma(R_r \sin\theta_r - R_i \sin\theta_i)$$

$$D(\rho V_r \cos\theta_r - \rho V_i \cos\theta_i) = \pi\gamma(R_r \cos\theta_r - R_i \cos\theta_i) - F_r$$

Formulation

$$\rho d\ell \frac{\pi R_i^2 V_i^2}{\mathcal{R}} = 2\gamma \tilde{f} d\ell \epsilon + \pi R_i \gamma d\theta \epsilon$$

Convexity

Radius of curvature

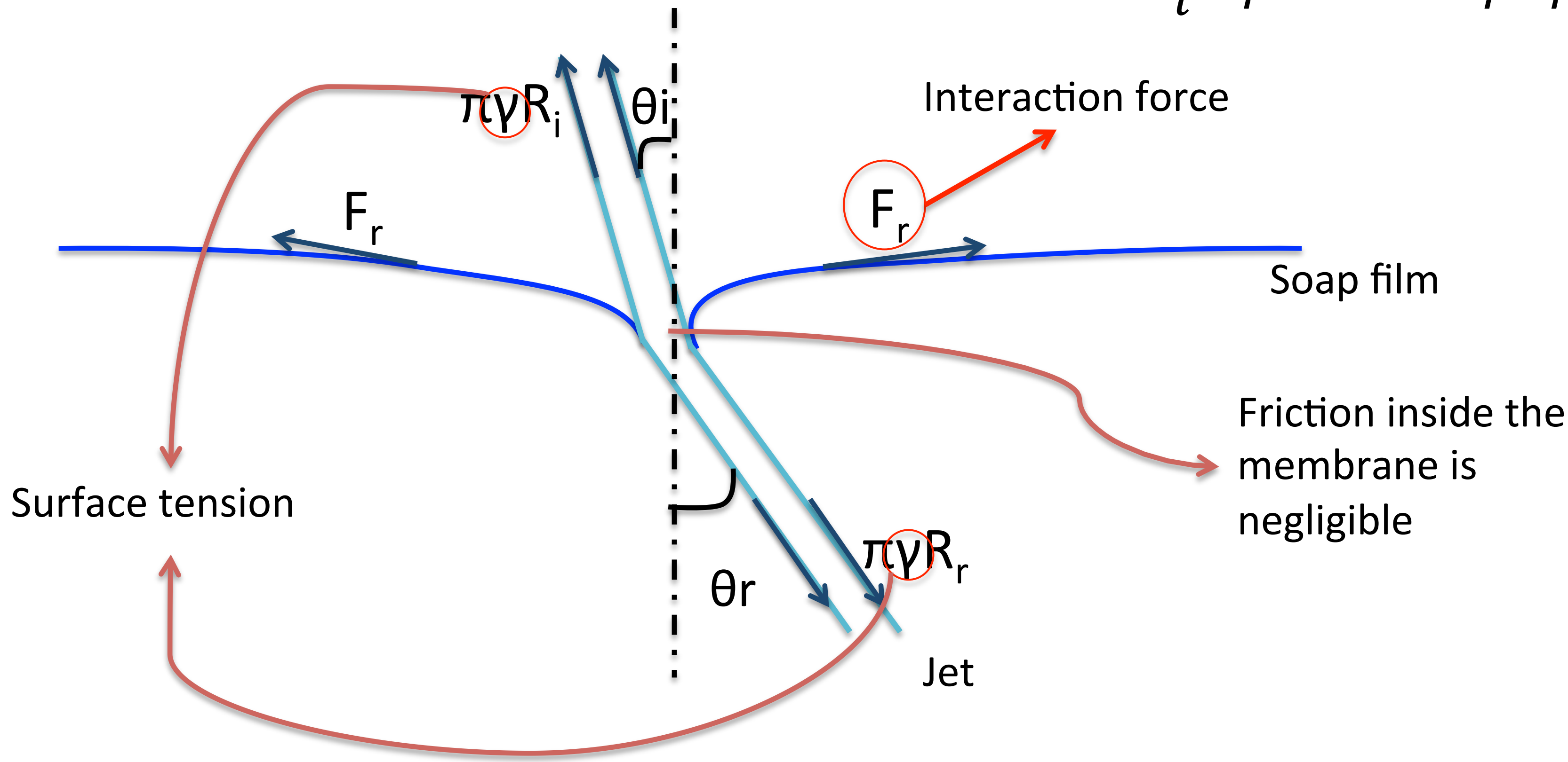
$$d\ell = |\mathcal{R}| d\theta$$

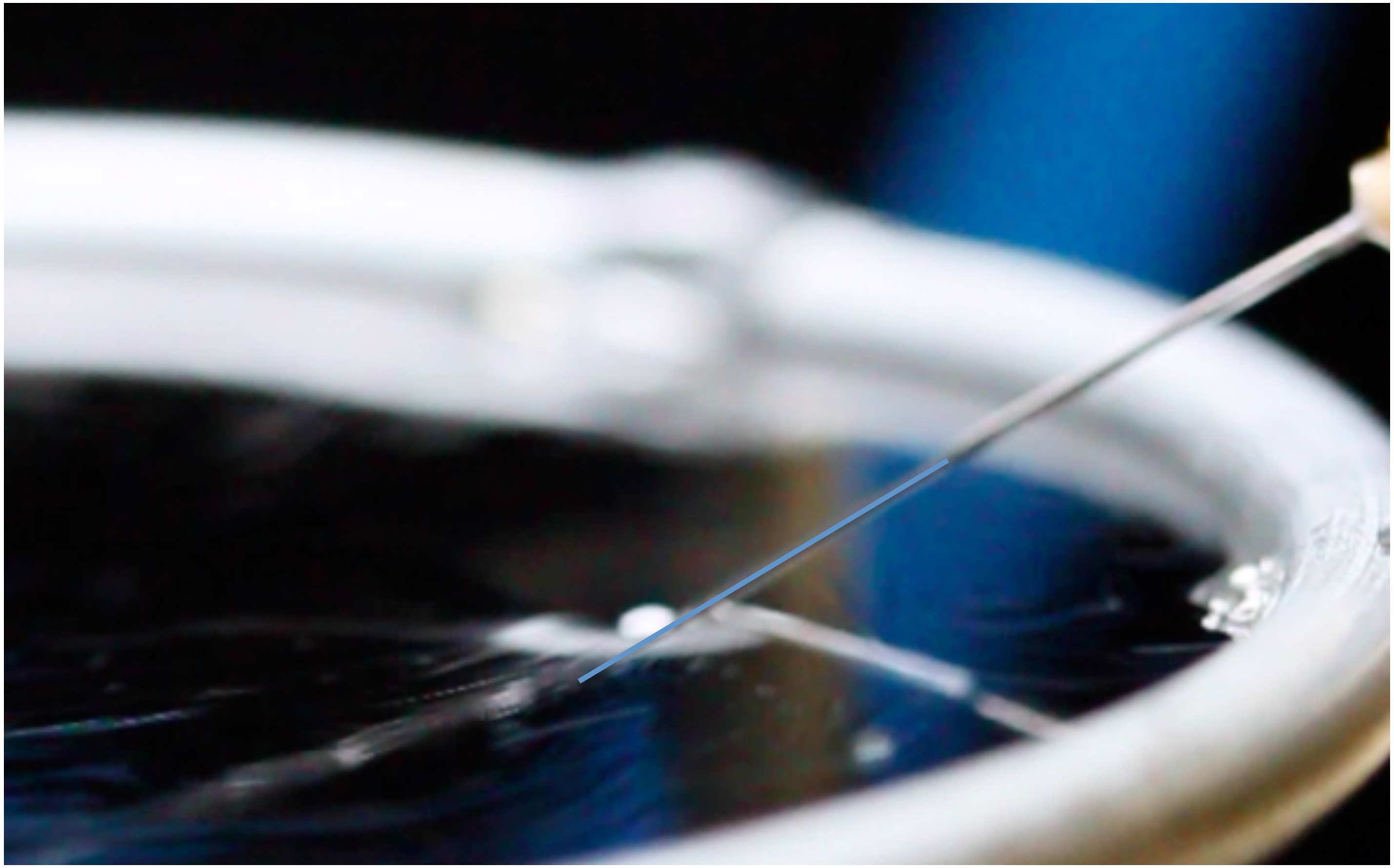
$$\mathcal{R} = \frac{\epsilon R_i \pi (W_e - 1)}{2\tilde{f}}$$

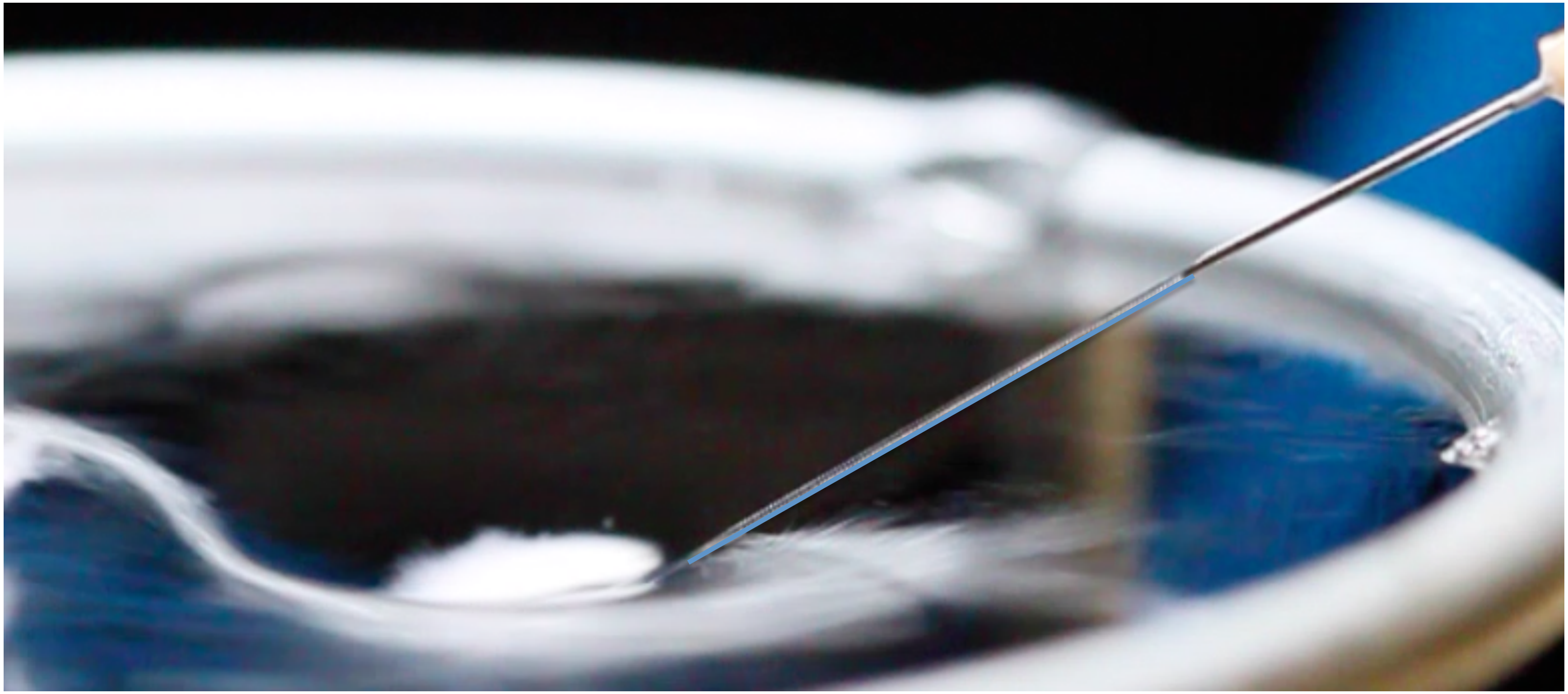
$$\lambda = \frac{2\pi}{\tilde{f}} R_i (W_e - 1) \cos\theta_i$$

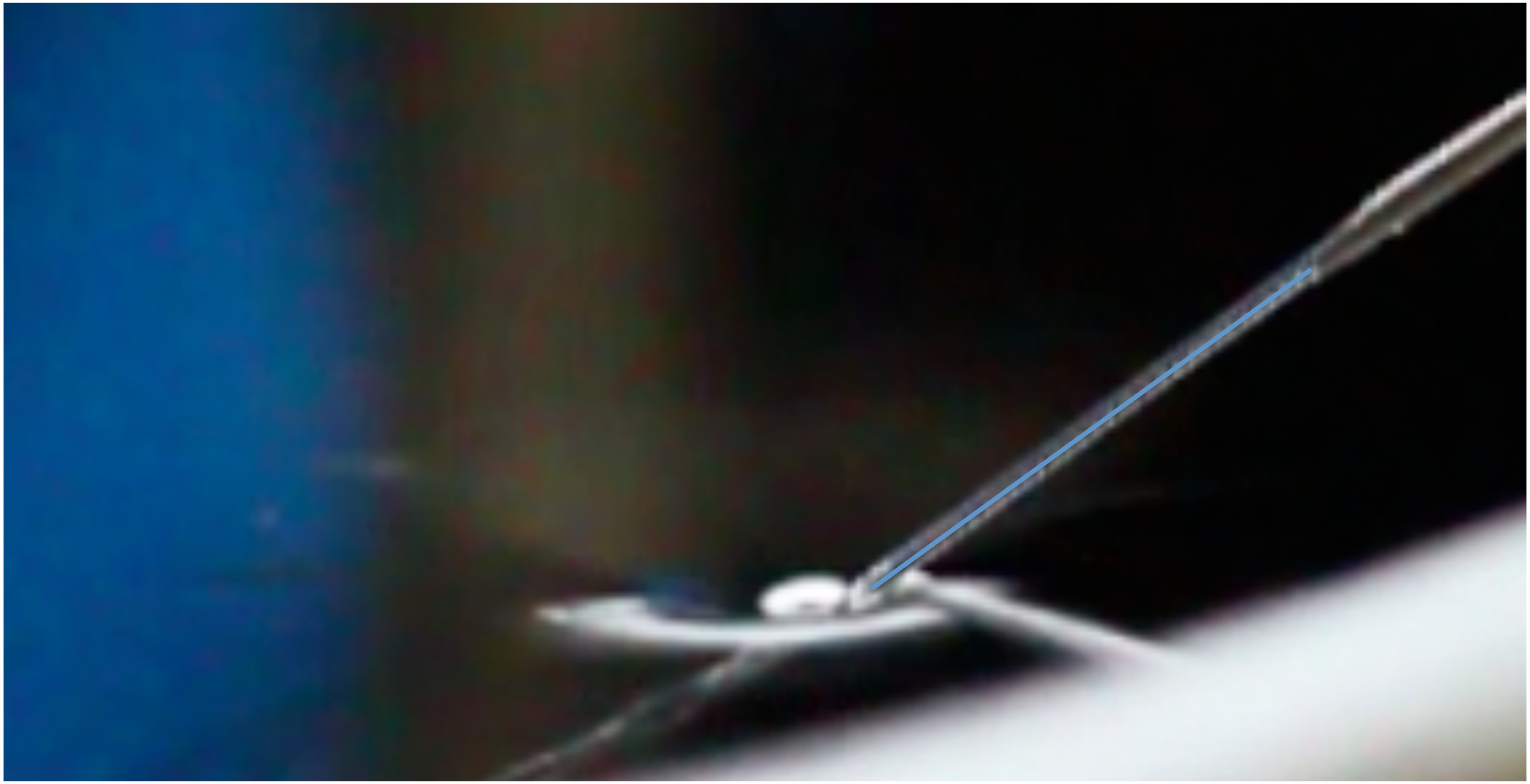
Fluid diagram

$$D = \pi R_i^2 V_r = \pi R_r^2 V_r$$

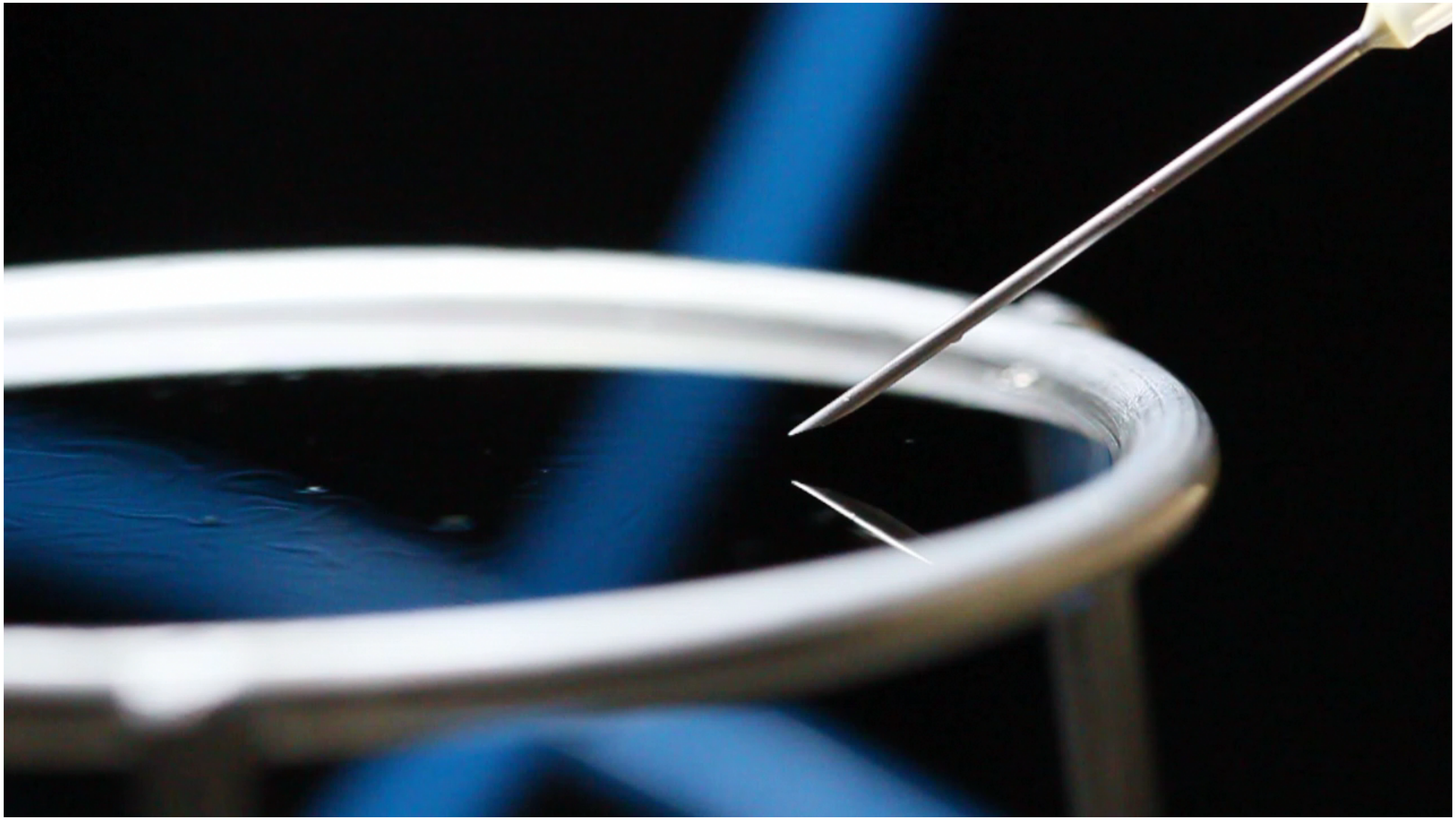


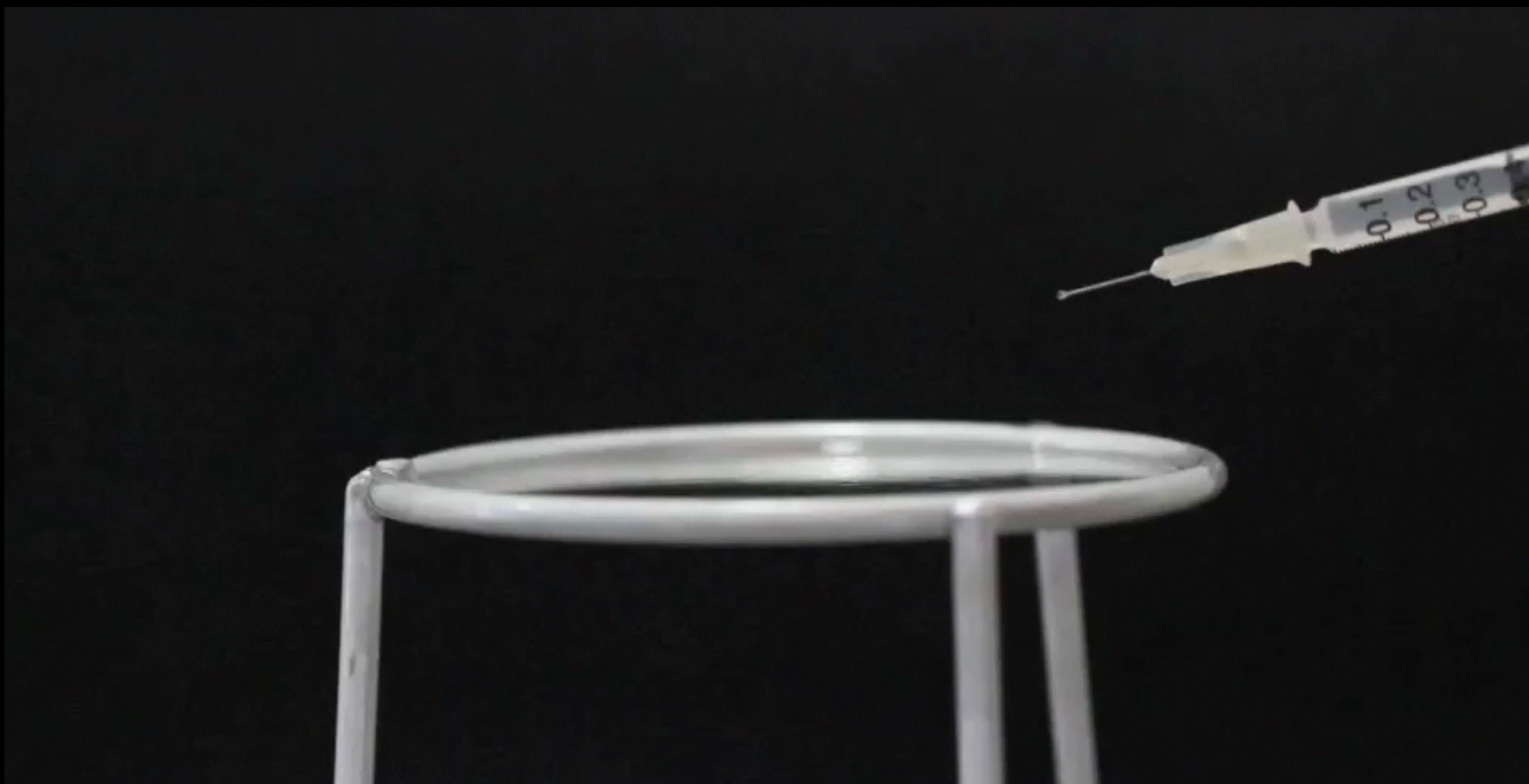






Effect of very low velocity of the jet




0.1
0.2
0.3

- Refraction R = 0.18mm

$W_e = 209.42$

$V_i = 5.5$ m/s

n = 1.1

Errors

- Refraction
- Diameter variation
- Transition
- Jump
- Absorption

ror: 3.7%

- 0.38mm
- γ = 26.2 ± 0.2 mN/m
- 10^3 kg/m^3
- = 30

n xpected = 1.20

btained = 1.157

$$n = \frac{W_e - 1}{W_e - 5}$$

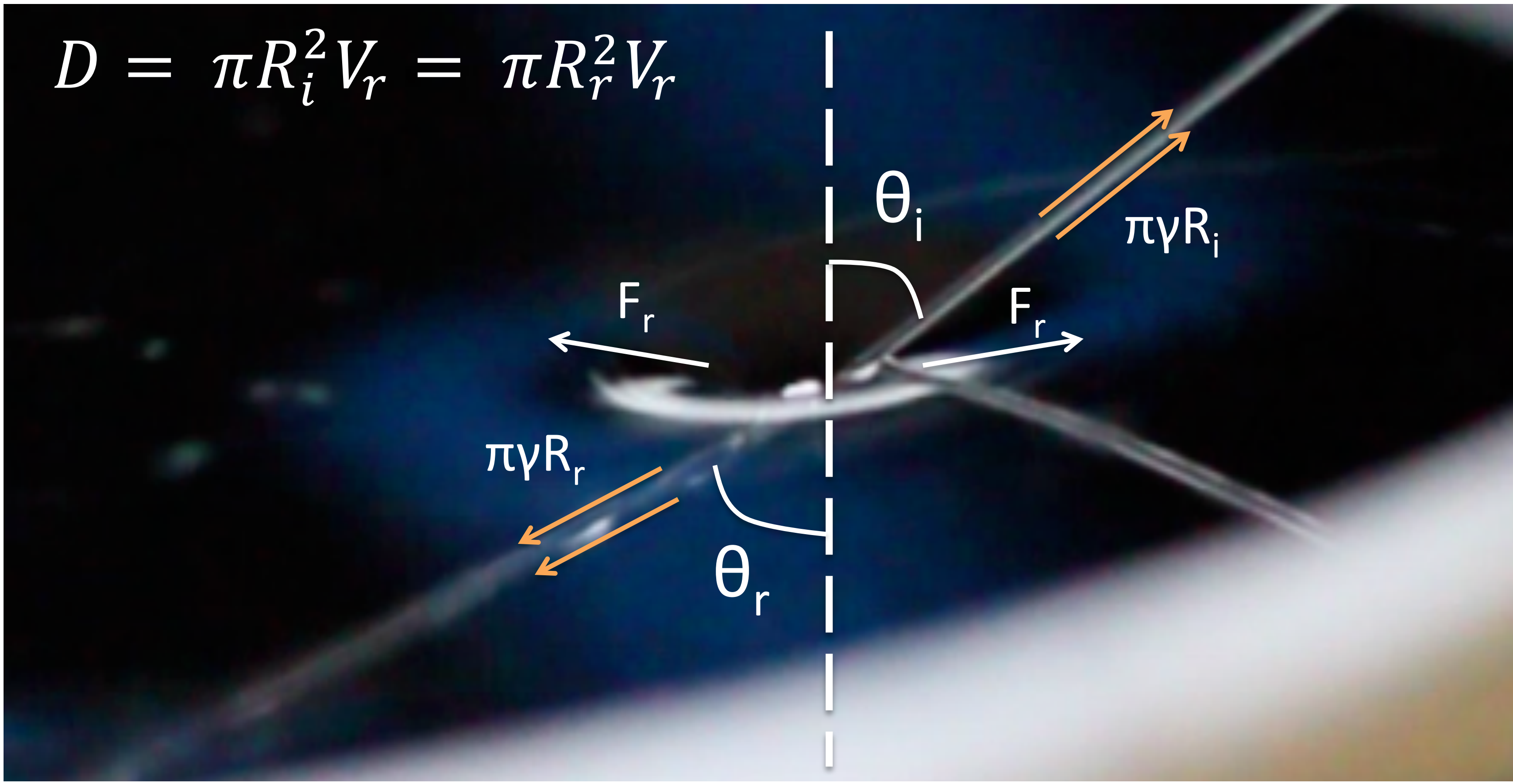
Error: 5.1%

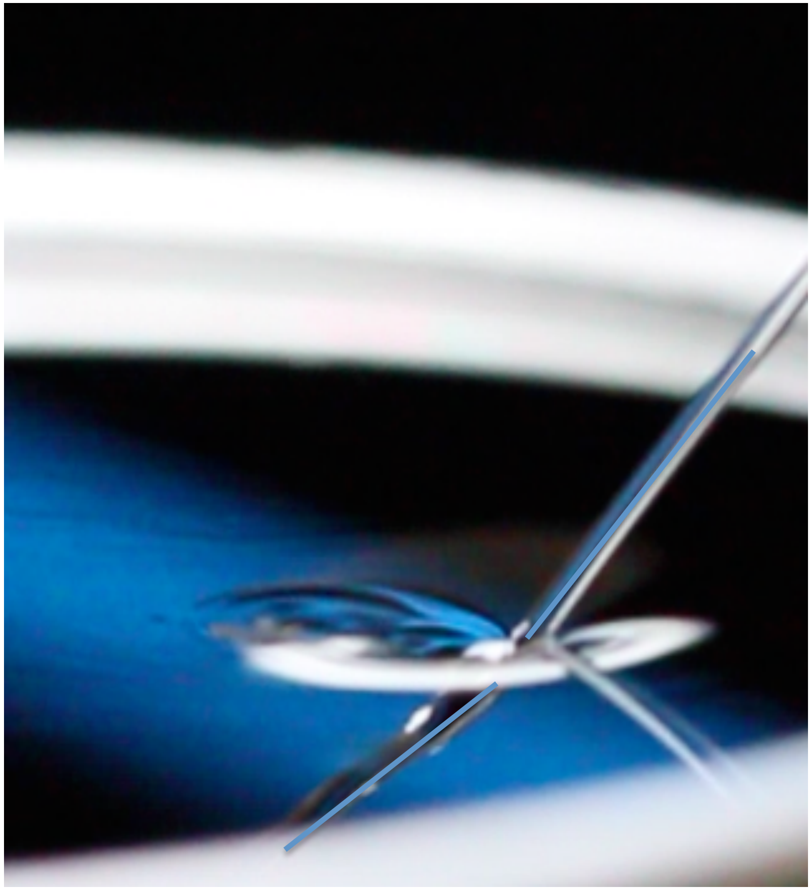
- R = 0.30mm
- γ = 26.2 ± 0.2 mN/m
- ρ = 10^3 kg/m^3
- W_e = 21

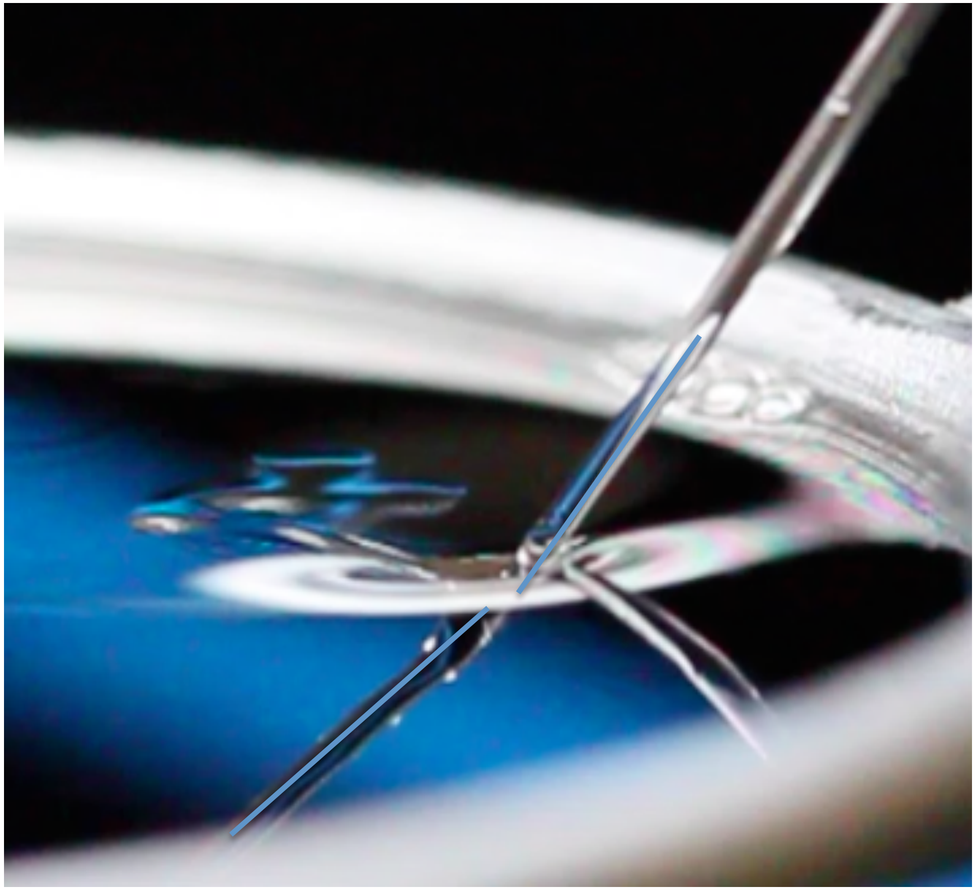
$n_{expected}$ = 1.30

$n_{obtained}$ = 1.236

Fluid diagram







Von Karman's vortex

- In fluid dynamics, a Kármán vortex street (or a von Kármán vortex sheet) is a repeating pattern of swirling vortices caused by the unsteady separation of flow of a fluid around blunt bodies.
- A vortex street will only form at a certain range of flow velocities, specified by a range of Reynolds numbers (*Re*), typically above a limiting *Re* value of about 90. The Reynolds number is a measure of the ratio of inertial to viscous forces in the flow of a fluid and may be defined as:

$$\mathrm{Re} = \frac{Vd}{\nu}$$

- And for our experiments:

$$R_e = 1.1 * 0.45 * \frac{10^{-3}}{1.004 * 10^{-6}}$$

$$R_e = 493.02$$