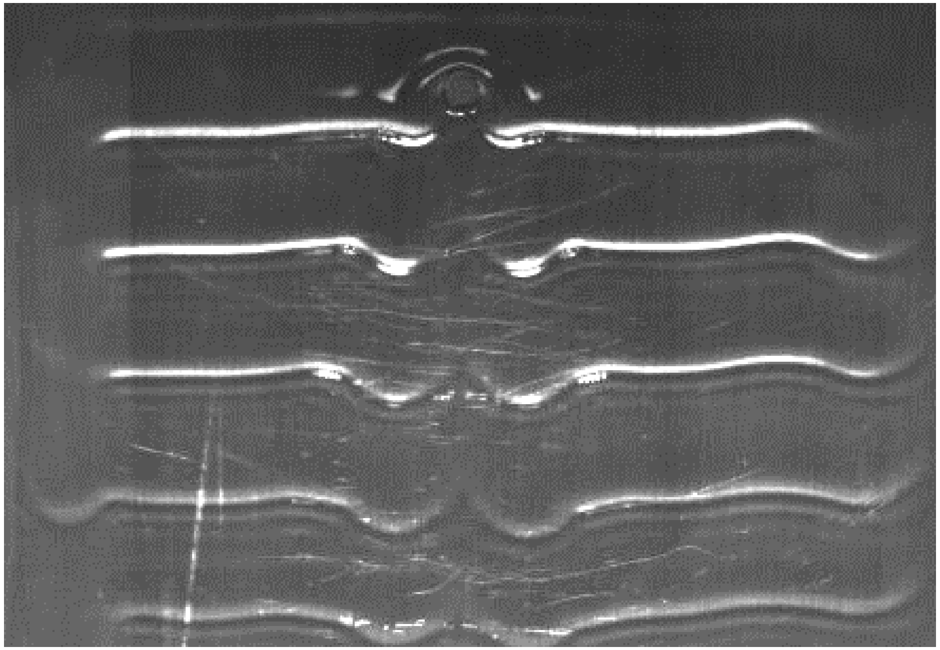
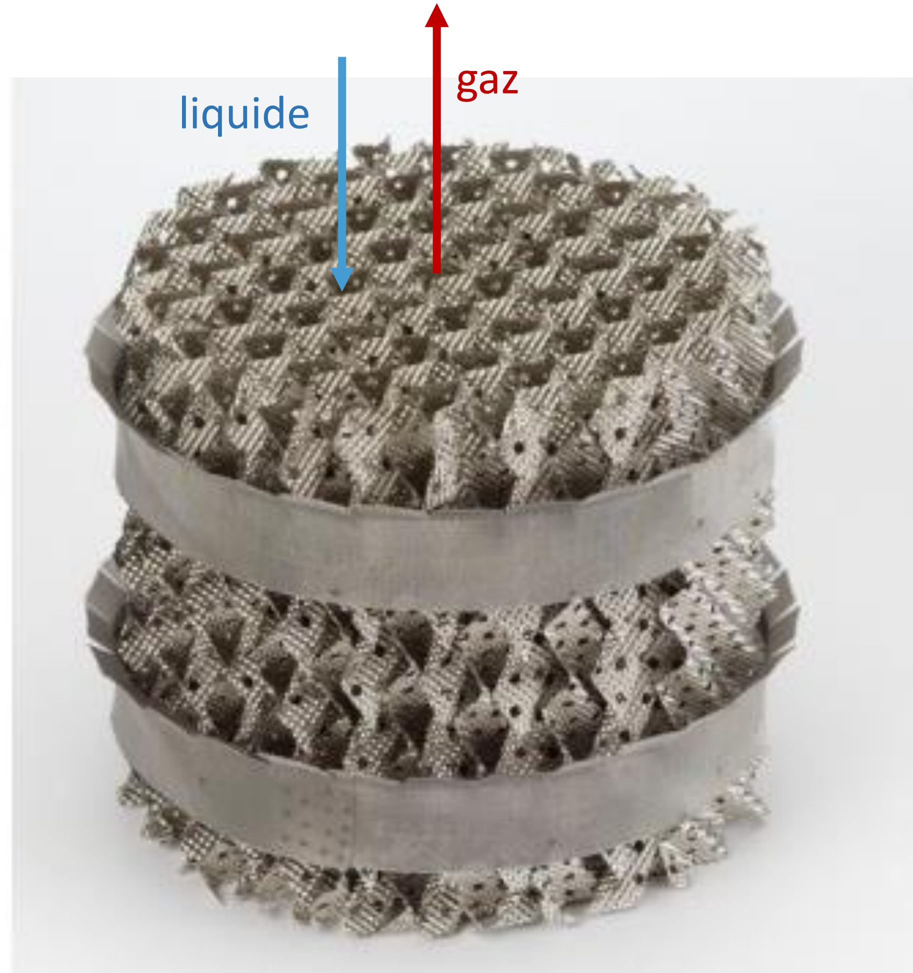
Film and rivulet flow through and around perforations

Lionel Vincent & Hervé Duval (LGPM), Mikaël Wattiau (AL)



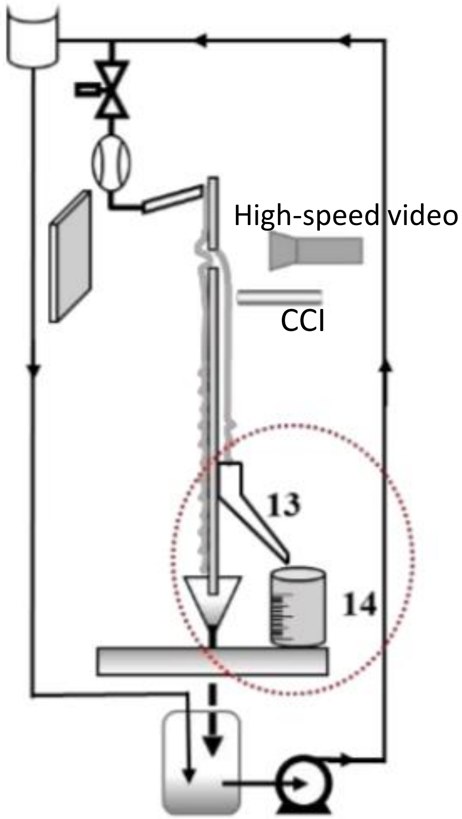
Context:
Air separation via cryogenic distillation

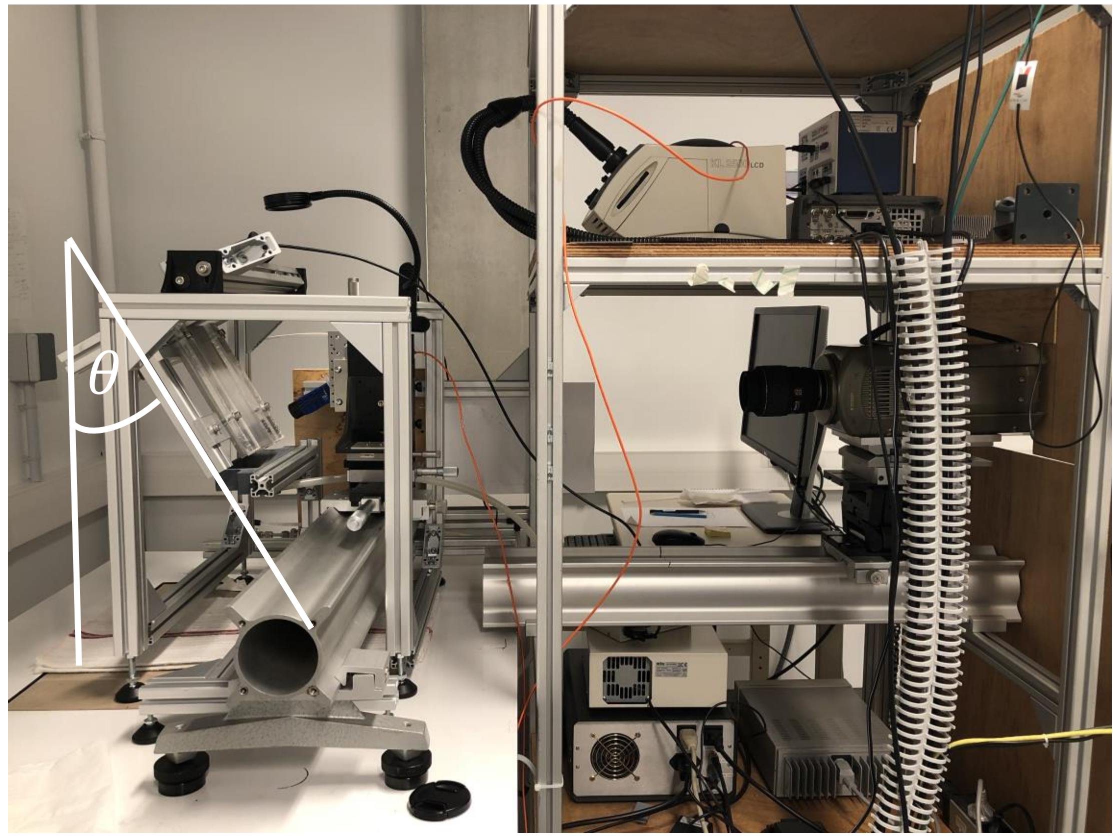


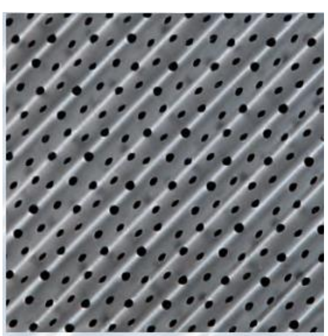
Goal : improve process efficiency by **enhancing liquide/gaz transfer**

Experimental setup

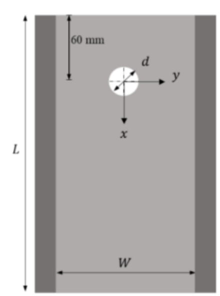
Overview







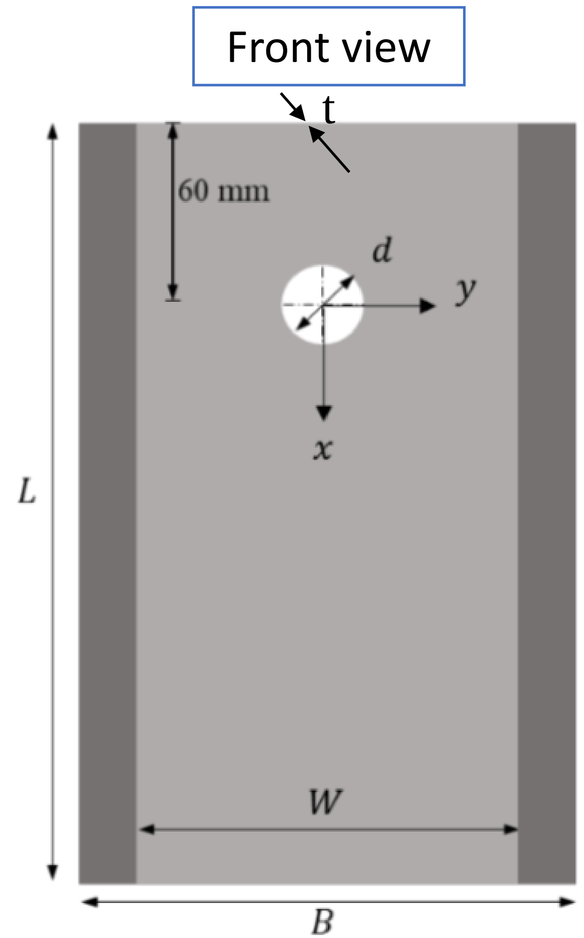
Experimental proxy:
single perforation
on a **flat plate**
with **variable θ**



Our focus:
interaction of
liquid phase with
perforation

Experimental setup

Experimental parameters

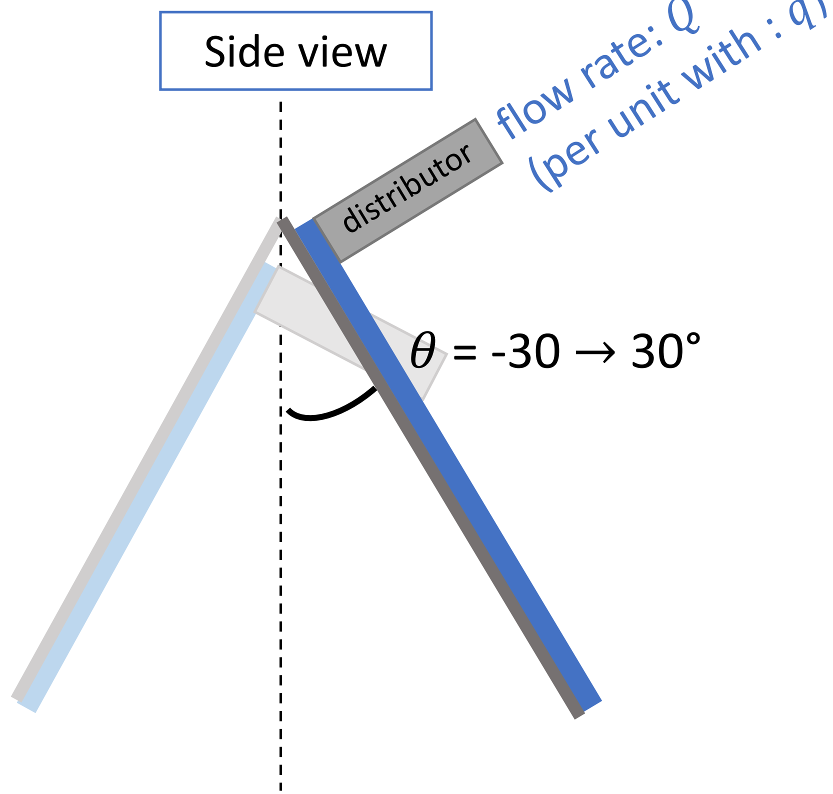


t = 1mm

d = 4 mm

L = 200 mm

W = 90 mm



Q ⇩

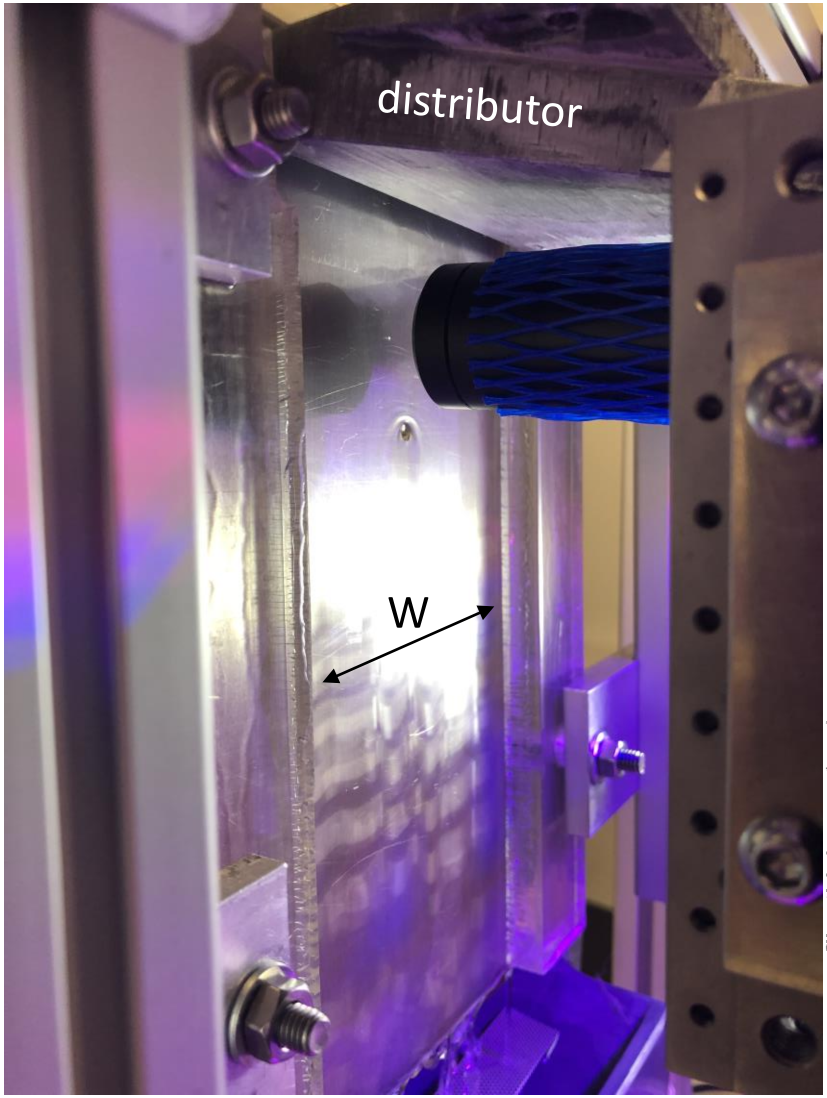
Propan-2-ol

Liquid	ρ (kg.m3)	μ (mPa.s)	σ (mN/m)	Θ (°)	Ka	Re
Propan-2-ol	786	2.05	21	11º-17º	348	20 - 42

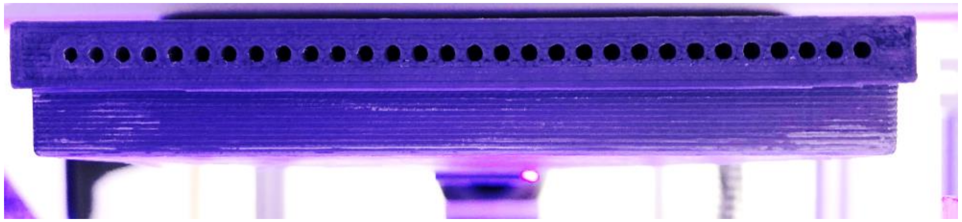
$Re \approx 106\, q[m^3/m.h] \approx 1.18\, Q[L/h]$

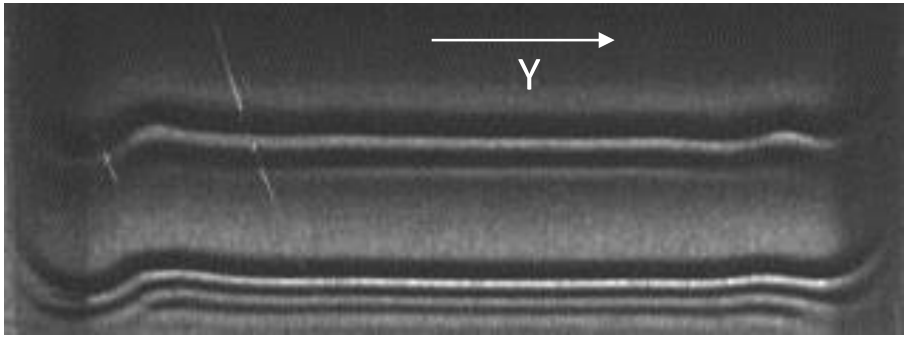
Experimental setup

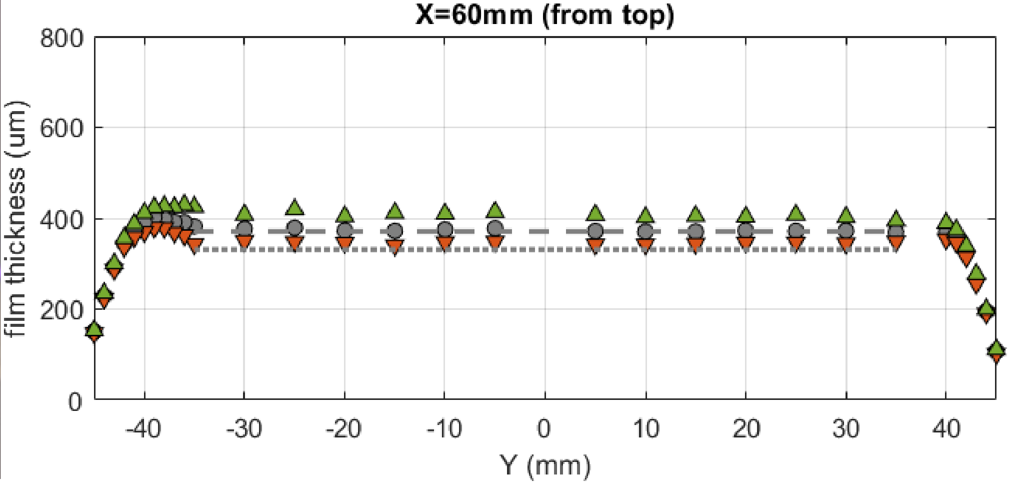
Liquid distribution



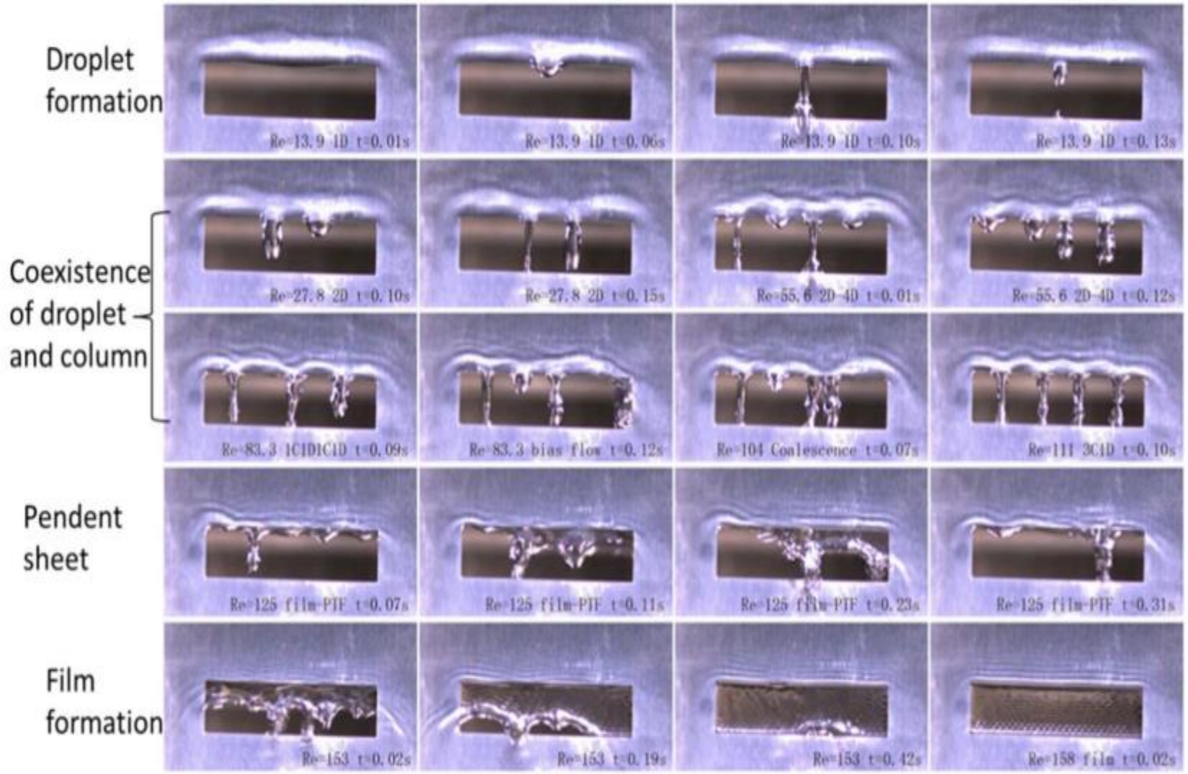
W



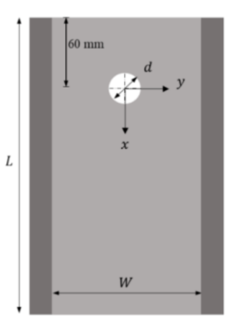


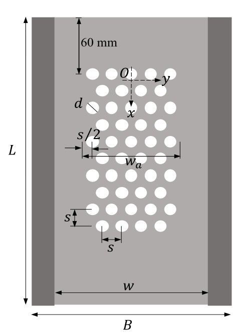


Literature: flow over perforation



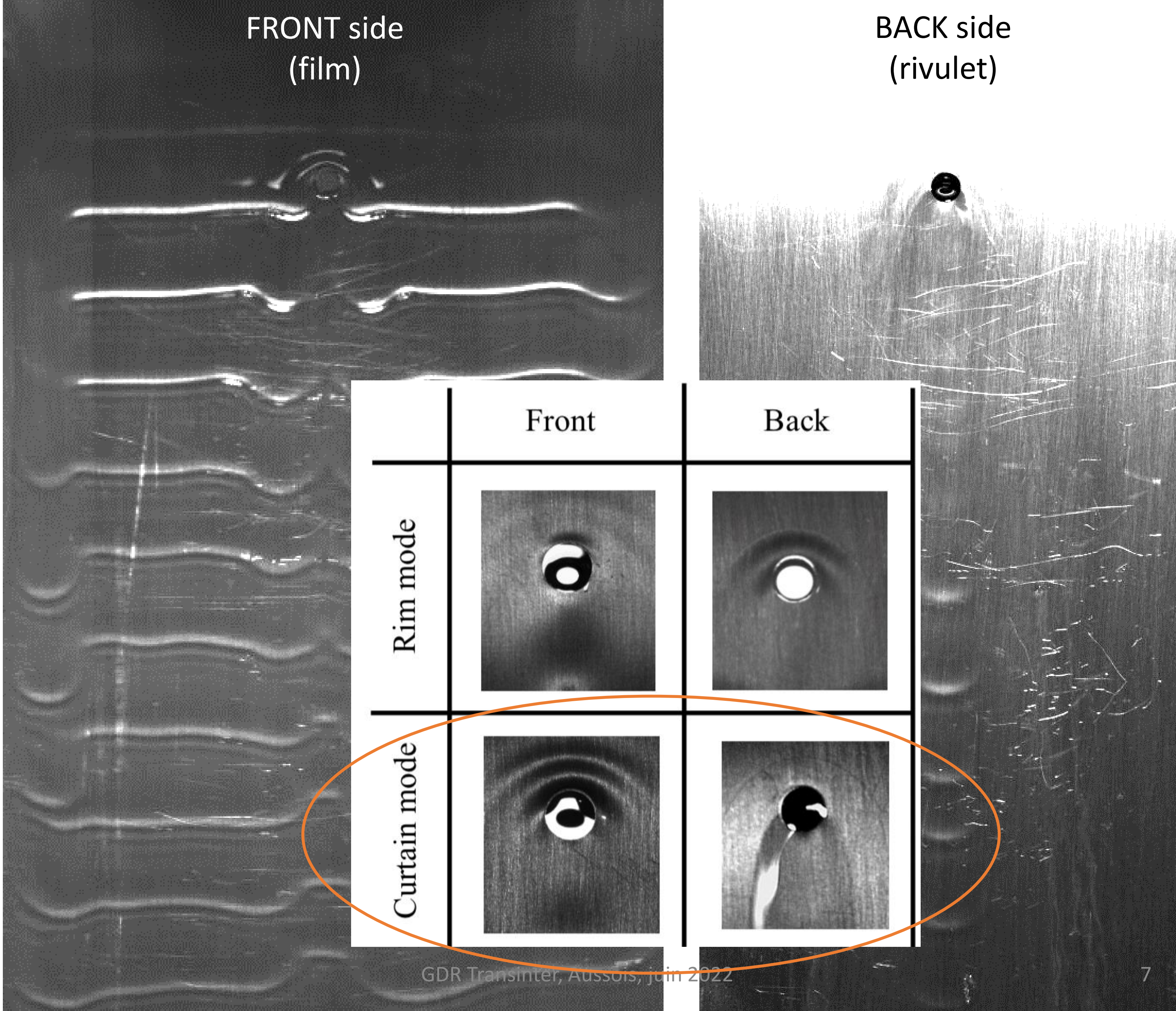
Xie H.; Hu J.; Wang C.; Dai G., Liquid flow transition and confined free film formation on a vertical plate with an open window, *Exp Therm Fluid Sci* (2018).



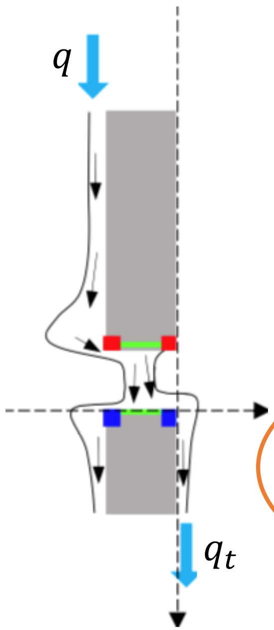


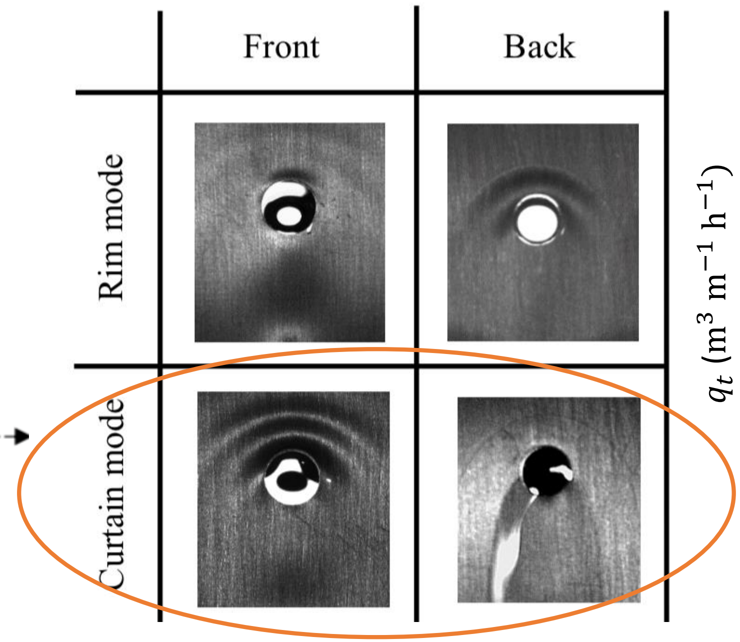
Iyer *et al.* , Experimental study of a liquid film flowing over a perforation. *AIChE Journal* (2021).

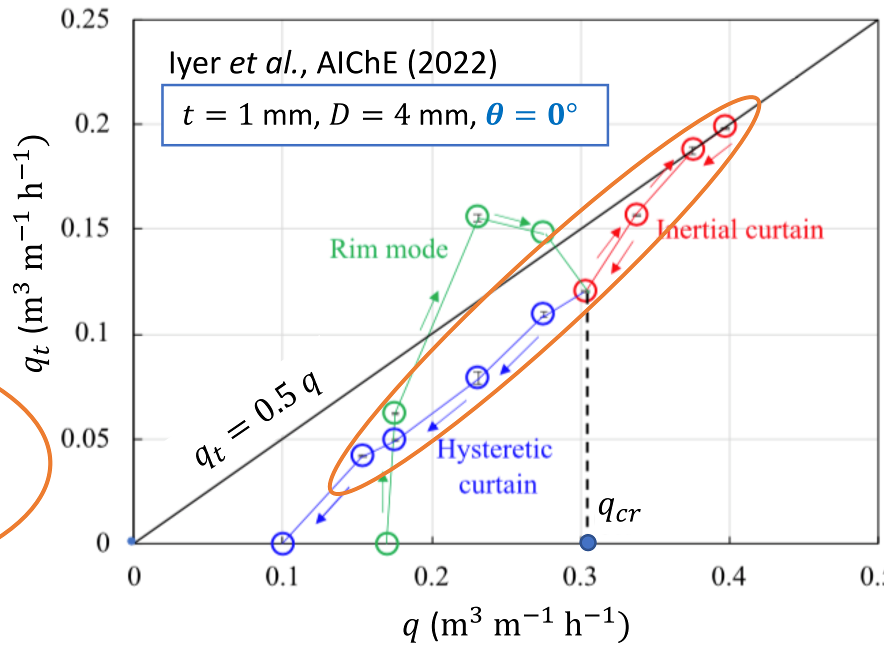
Iyer *et al.* , A comprehensive study of the liquid transfer from the front to the back of a vertical perforated sheet. *AIChE Journal* (2022).


FRONT side
(film)
BACK side
(rivulet)
Front
Back
Rim mode
Curtain mode

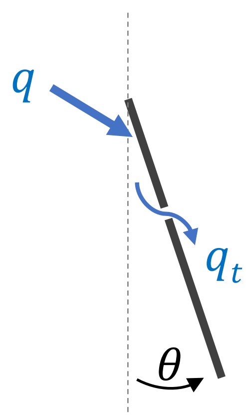
Flow over/through hole: rim or curtain?

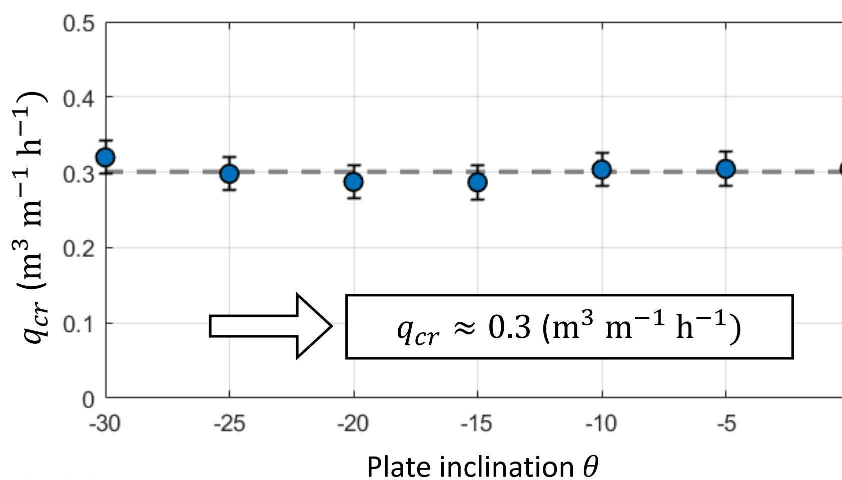




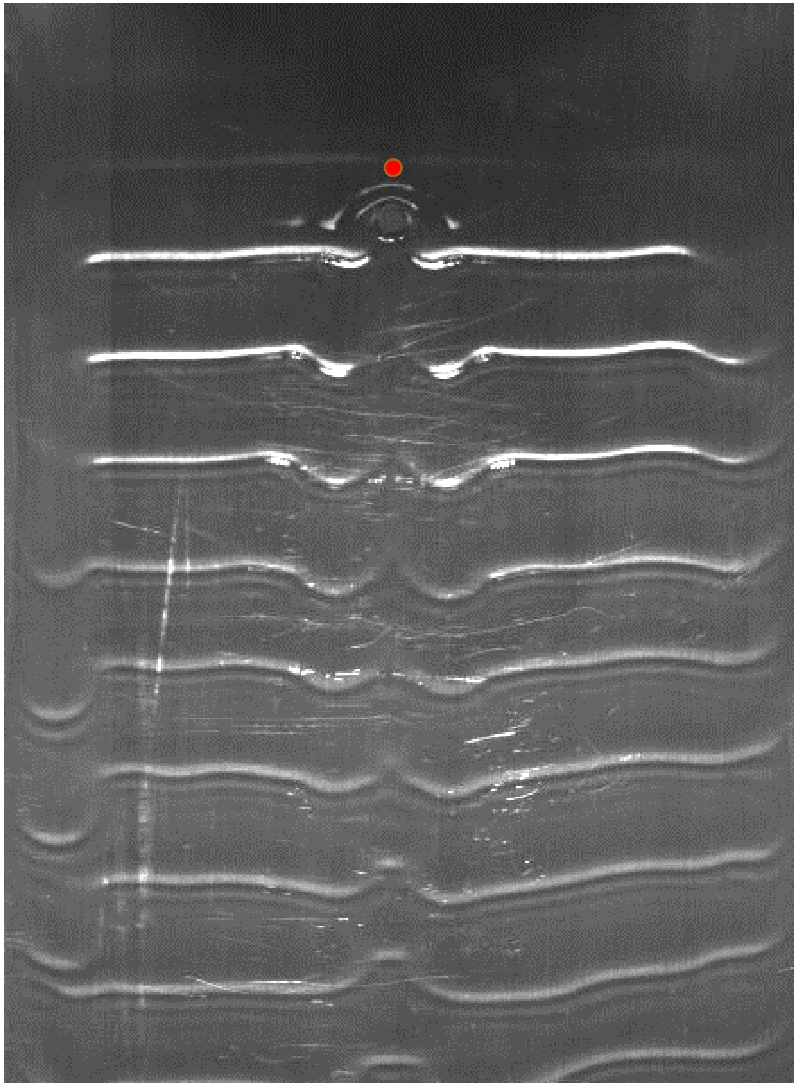


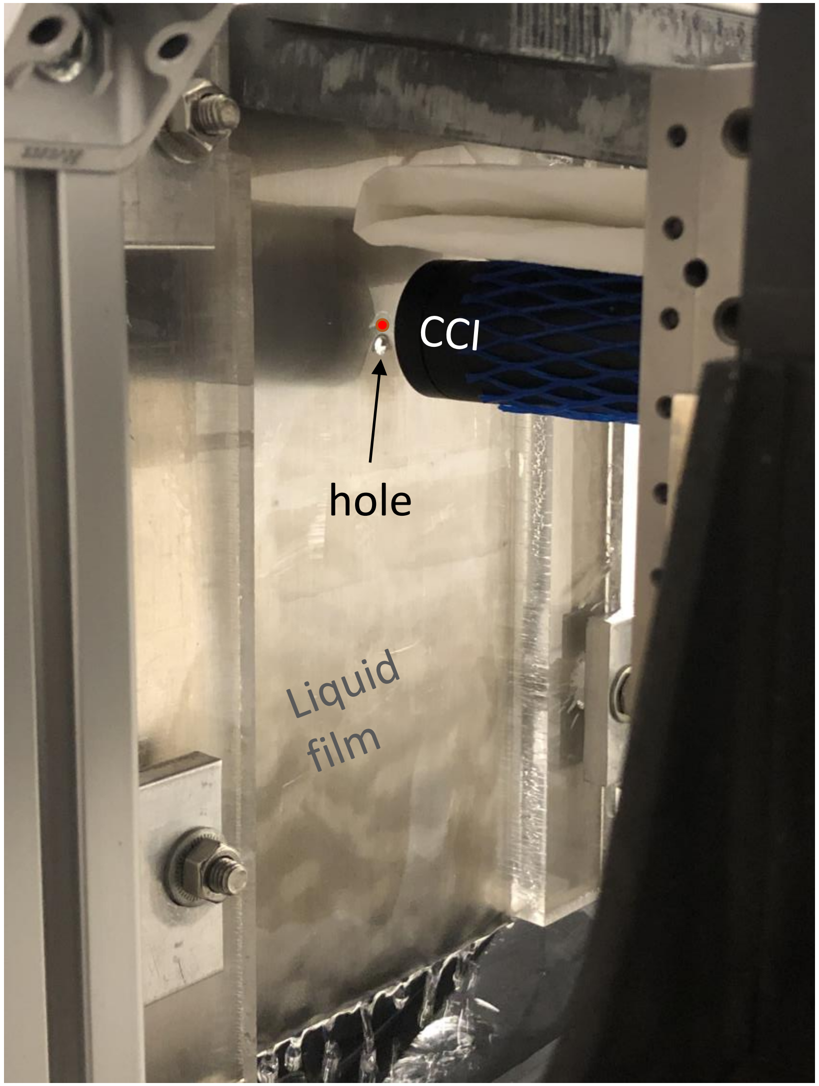
depends on plate inclination ?





Film thickness: spectral landscape

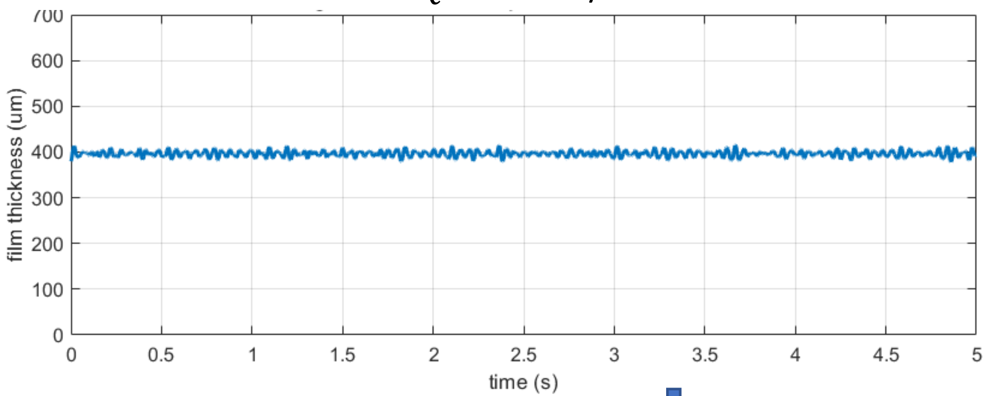




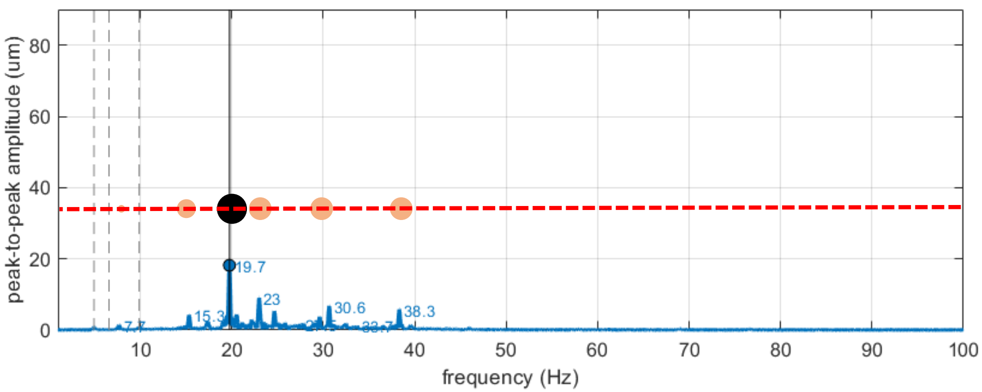
Film thickness: spectral landscape

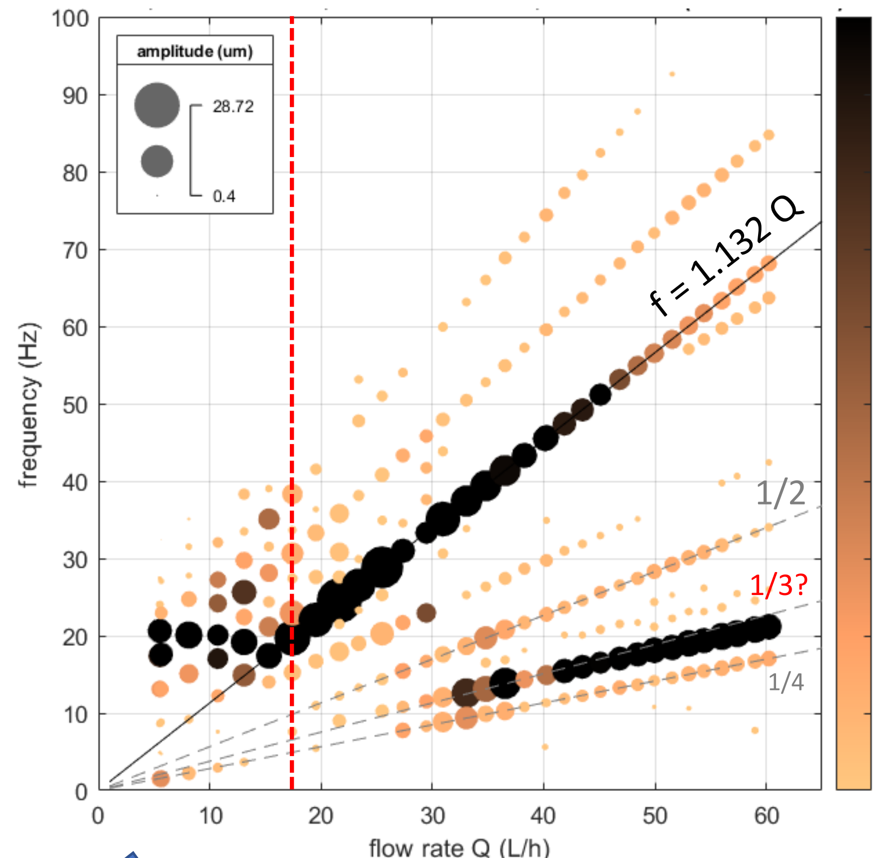
Front side, 2 mm above hole

$Q = 17.4$ L/h



fft





Peak identification
(all Q)

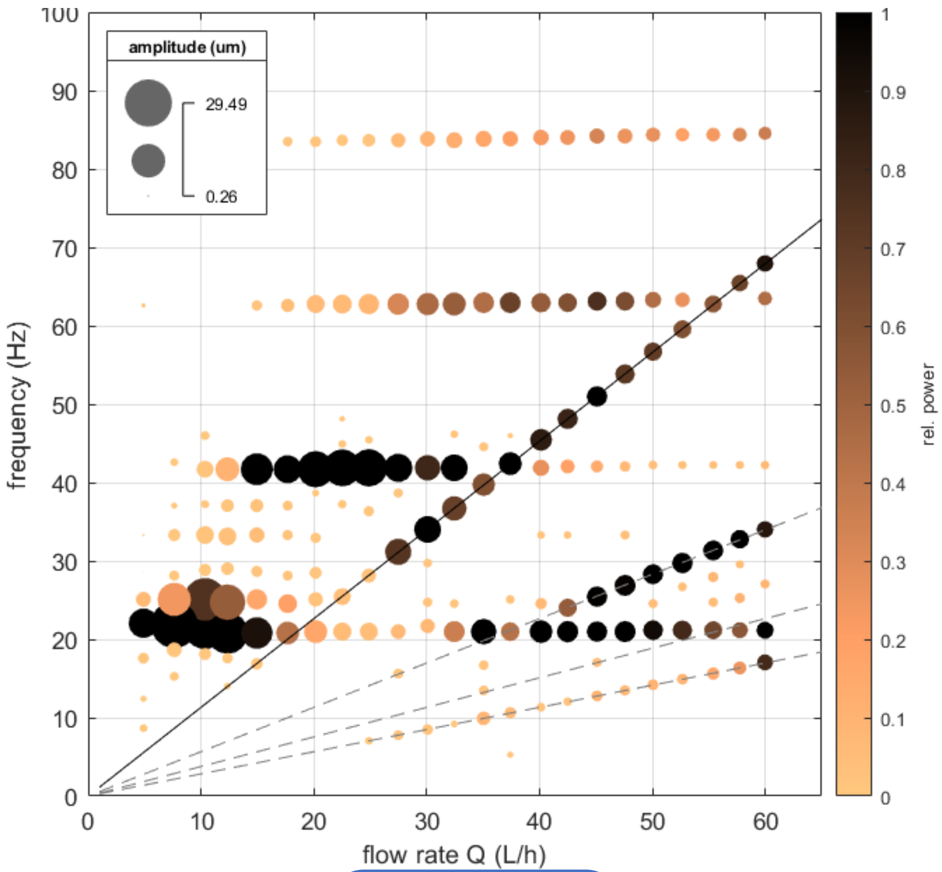
Direct flow
(no forcing)

CentraleSupélec

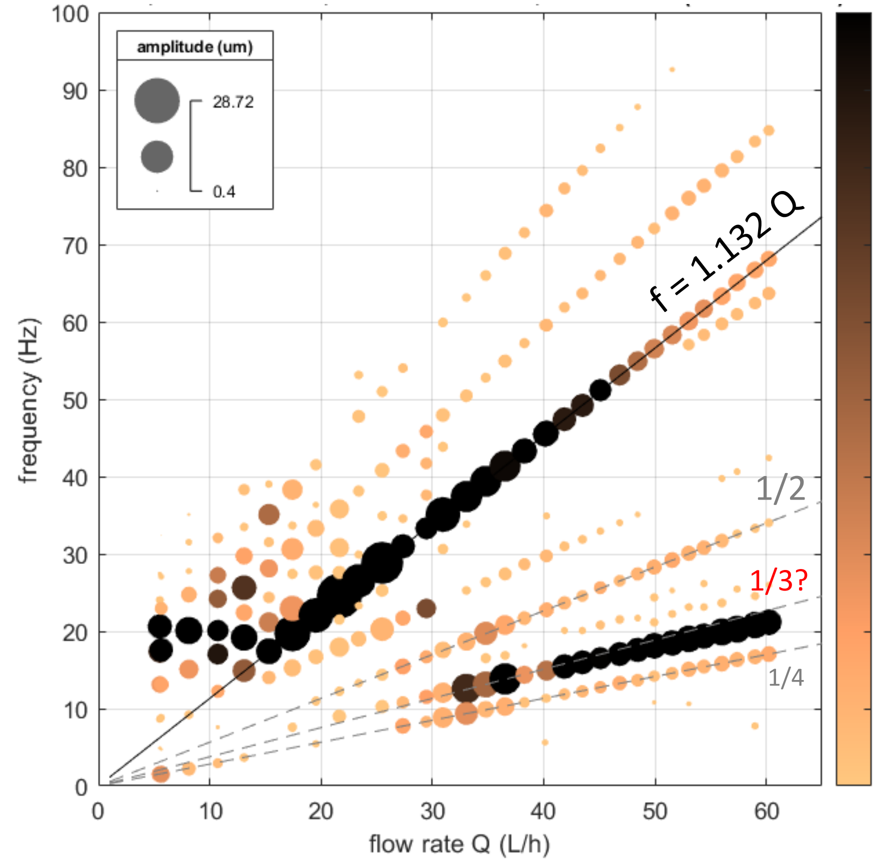
Film thickness: spectral landscape

Air Liquide

Front side, 2 mm above hole

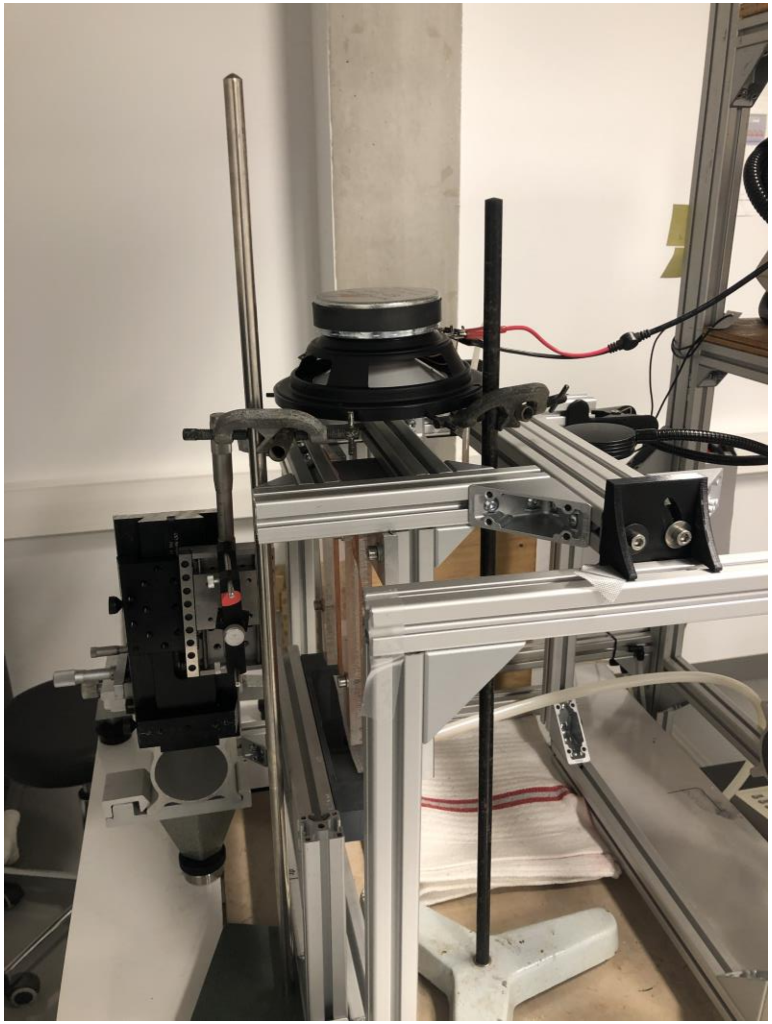


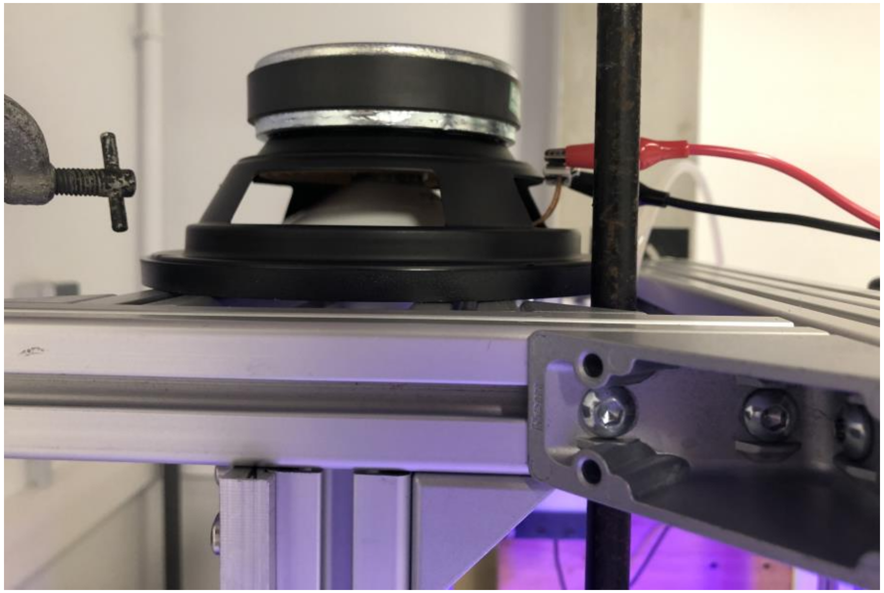
Pressure controller (no forcing)



Direct flow (no forcing)

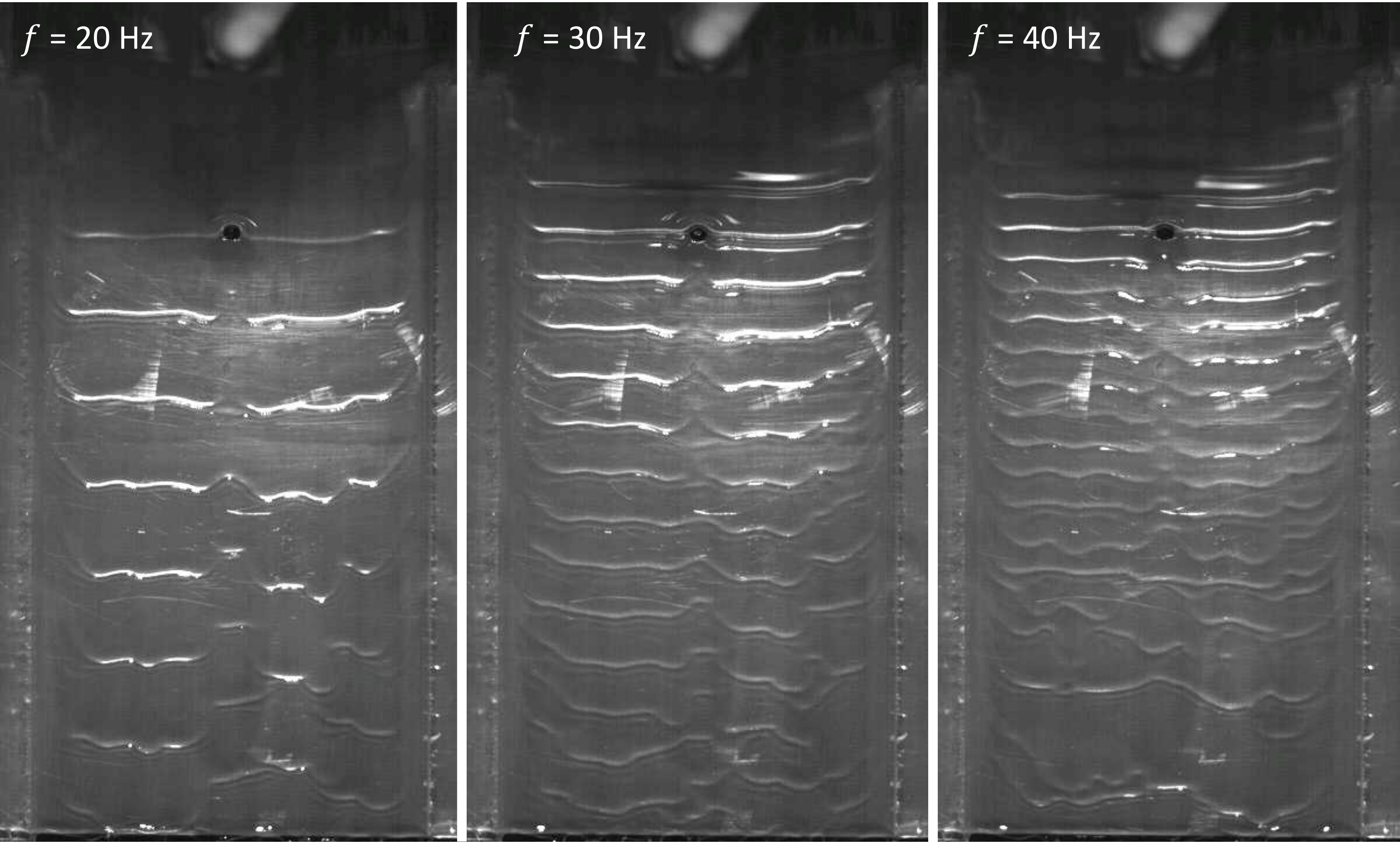
Periodic forcing





Periodic forcing

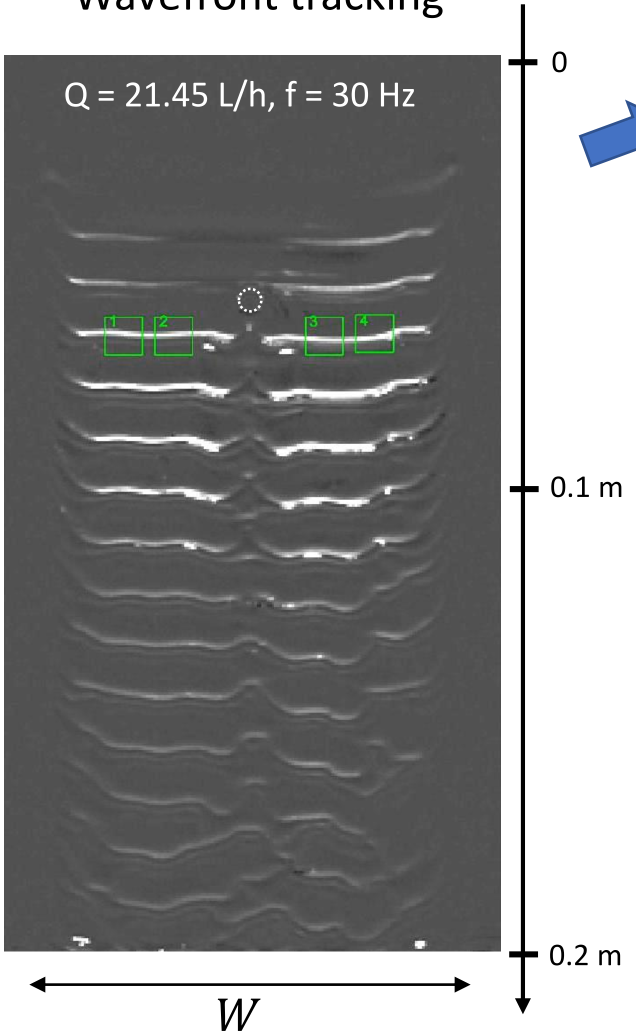
Q = 21.0 L/h



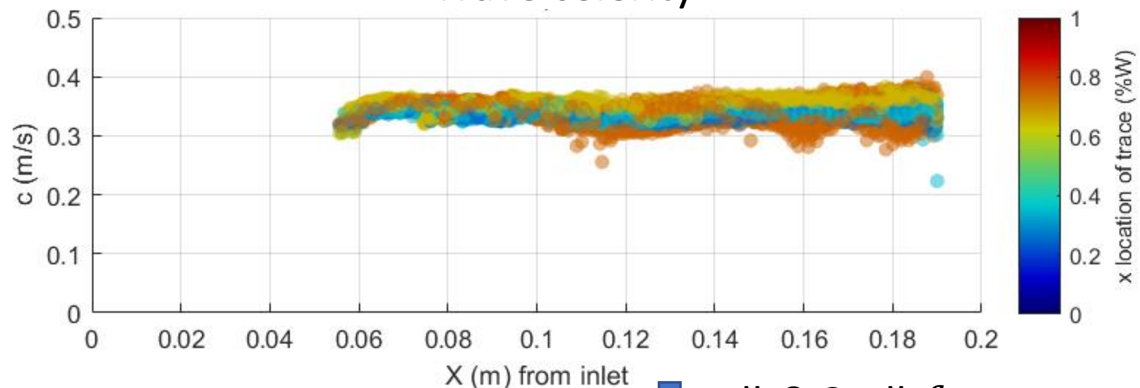
General wave behavior (away from hole)

CentraleSupélec · Air Liquide

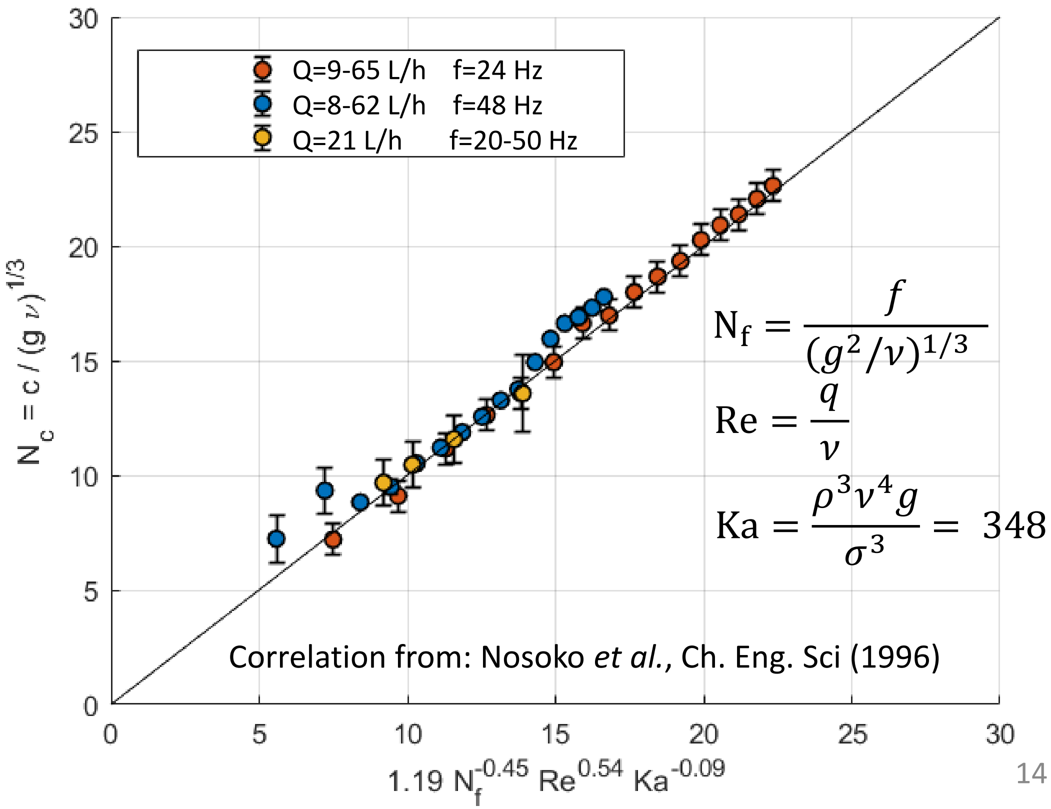
Wavefront tracking



Wave celerity



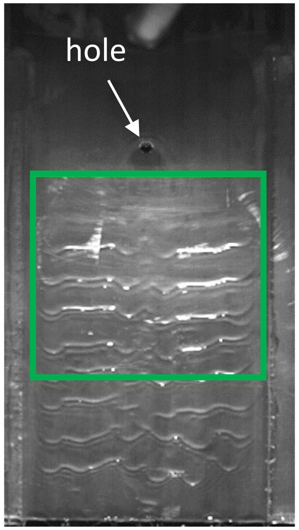
All Q & all f

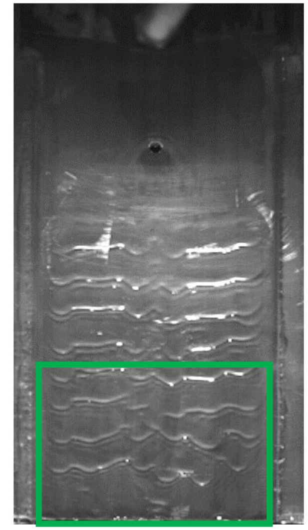


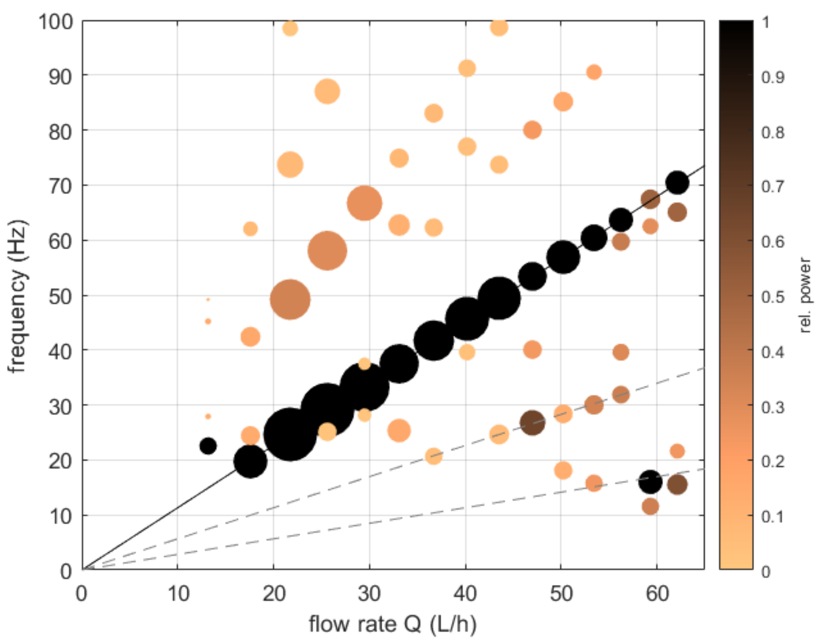
General wave behavior

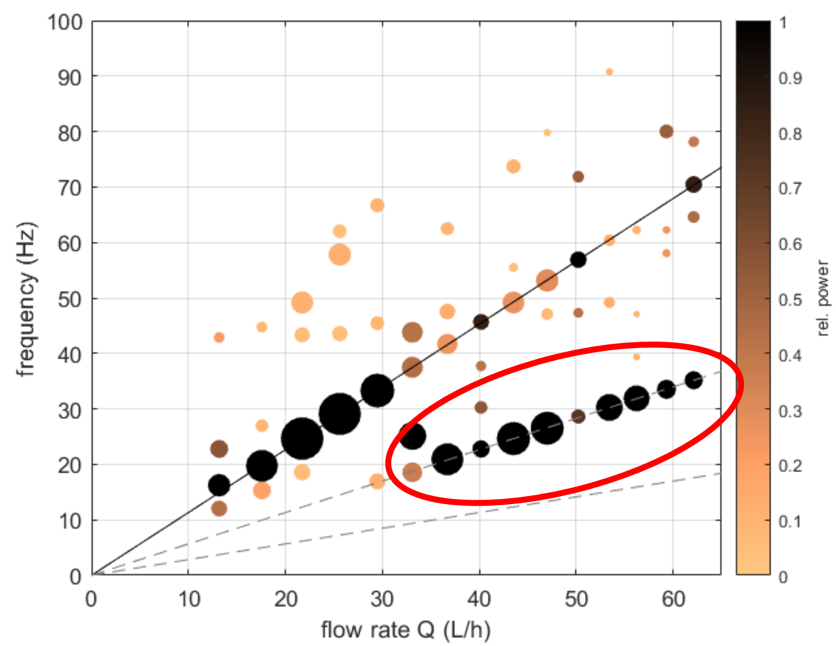
(setup #1)

Direct flow
(no forcing)



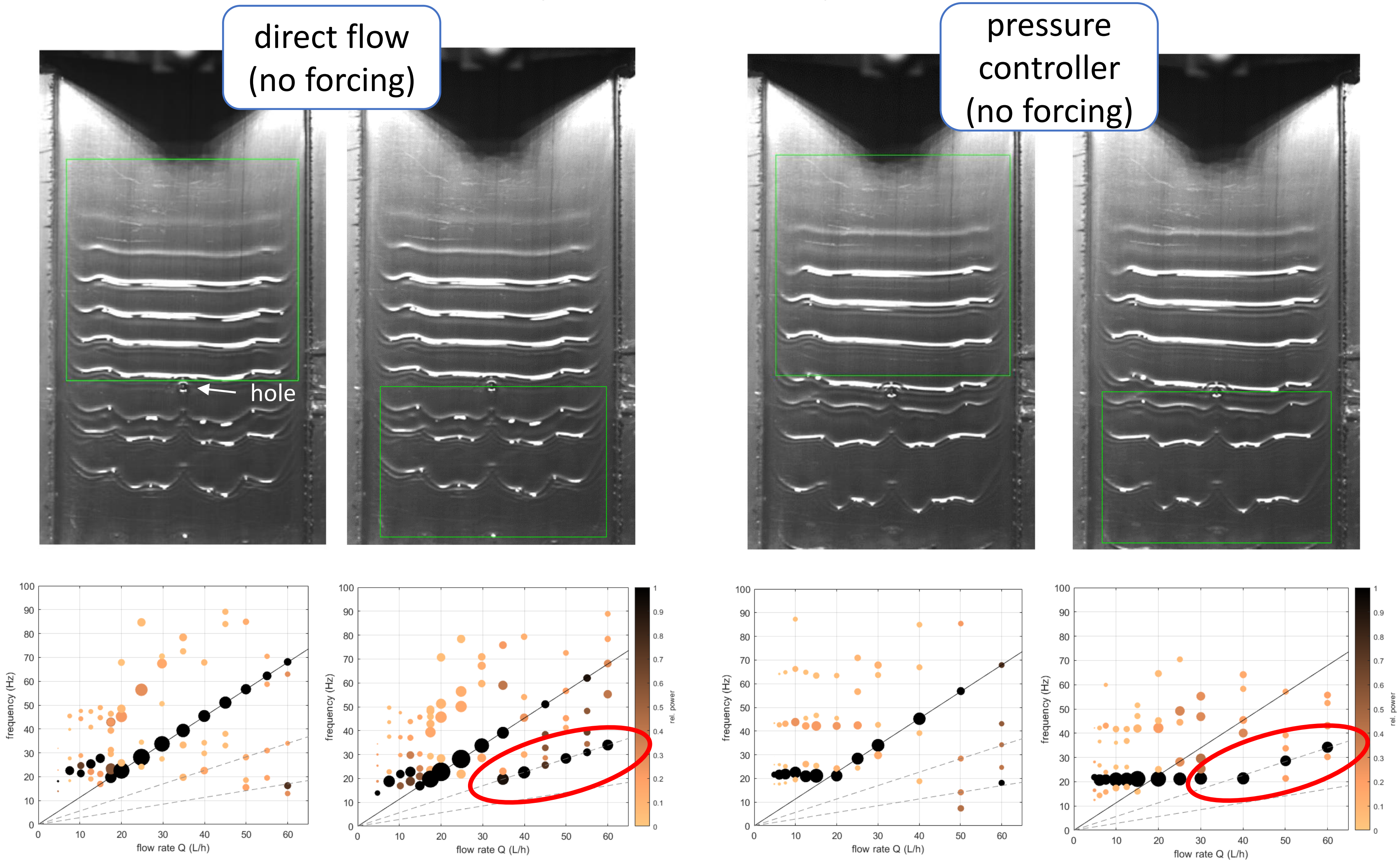






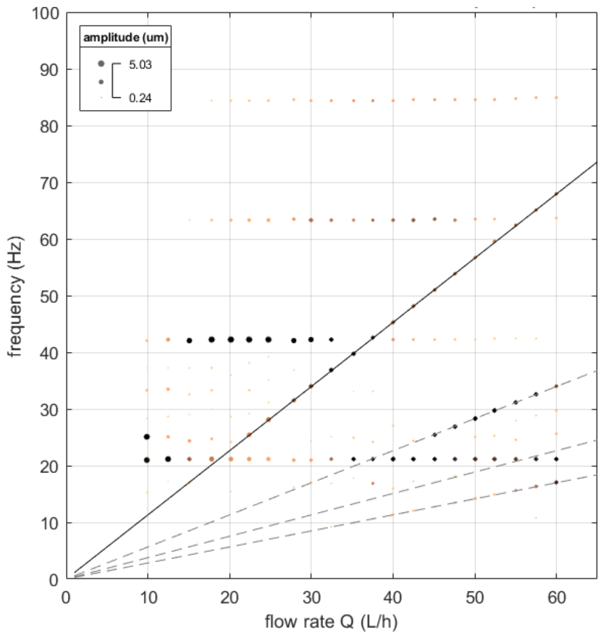
General wave behavior

(setup #2: hole in **lower** part)

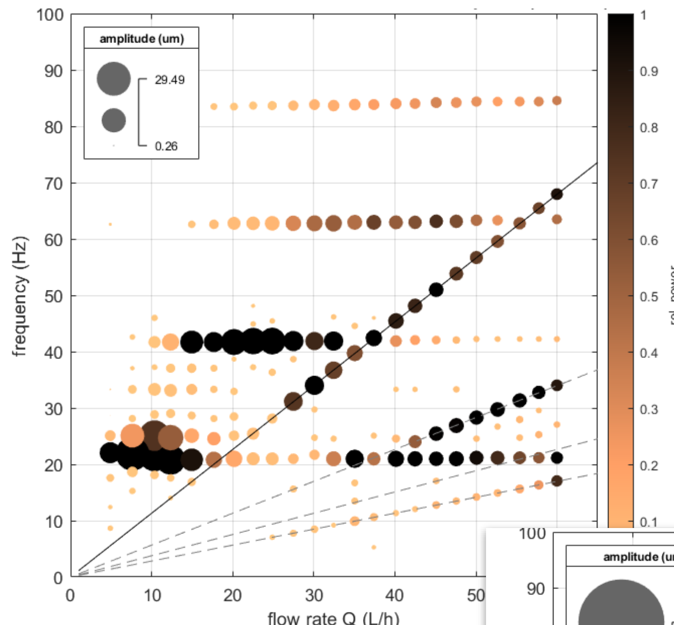


Wave growth *over* hole

15 mm above hole

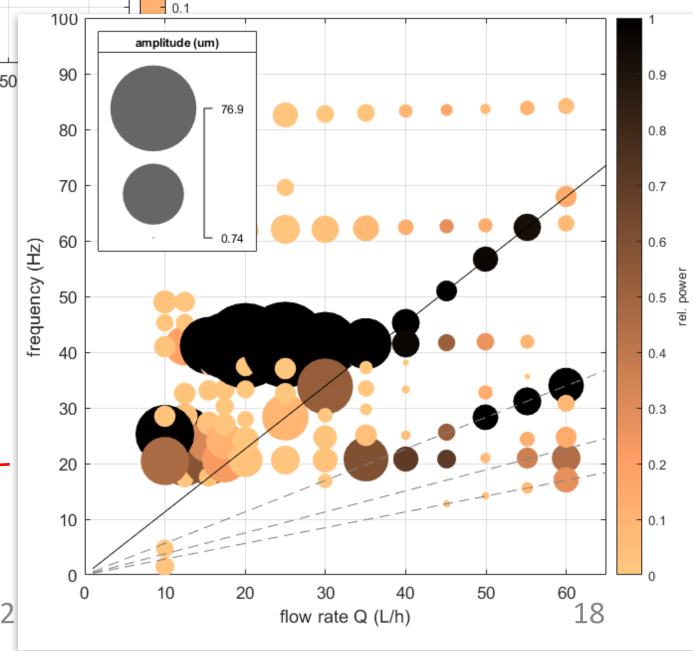


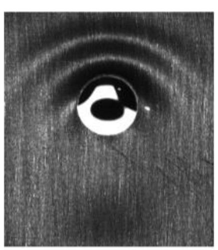
2 mm above hole

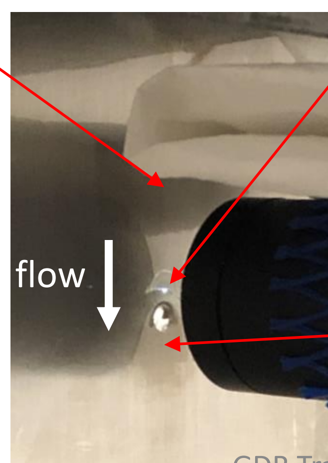


Pressure controller (no forcing)

2 mm *below* hole



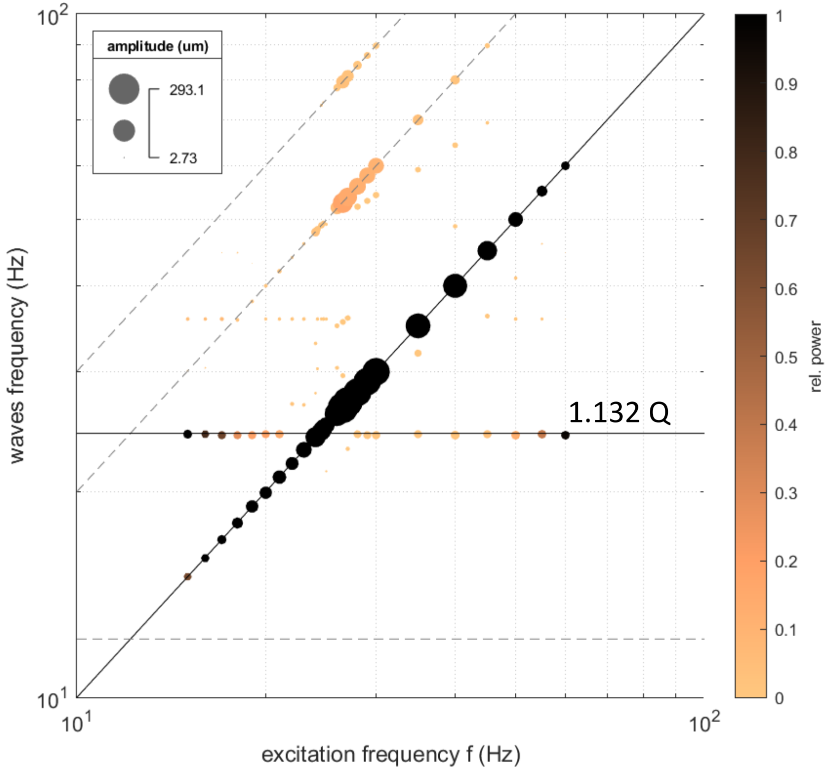




Wave growth *through* hole

BACK, 4 mm above hole, Q = 22 L/h

Small forcing amplitude

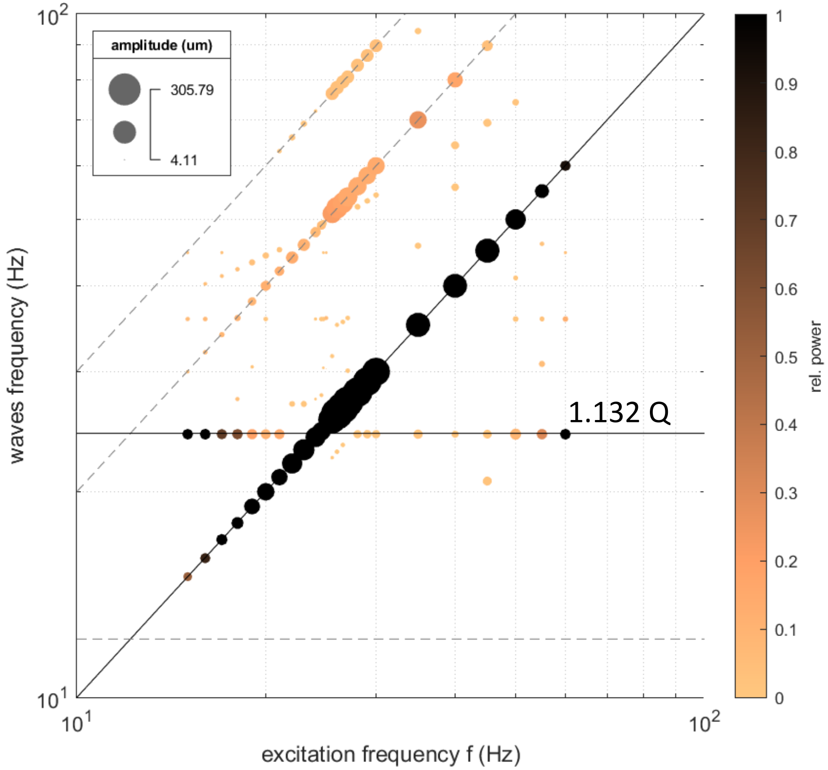


Direct flow, **with forcing**

Wave growth *through* hole

FRONT, 2 mm *below* hole, Q = 22 L/h

Small forcing amplitude



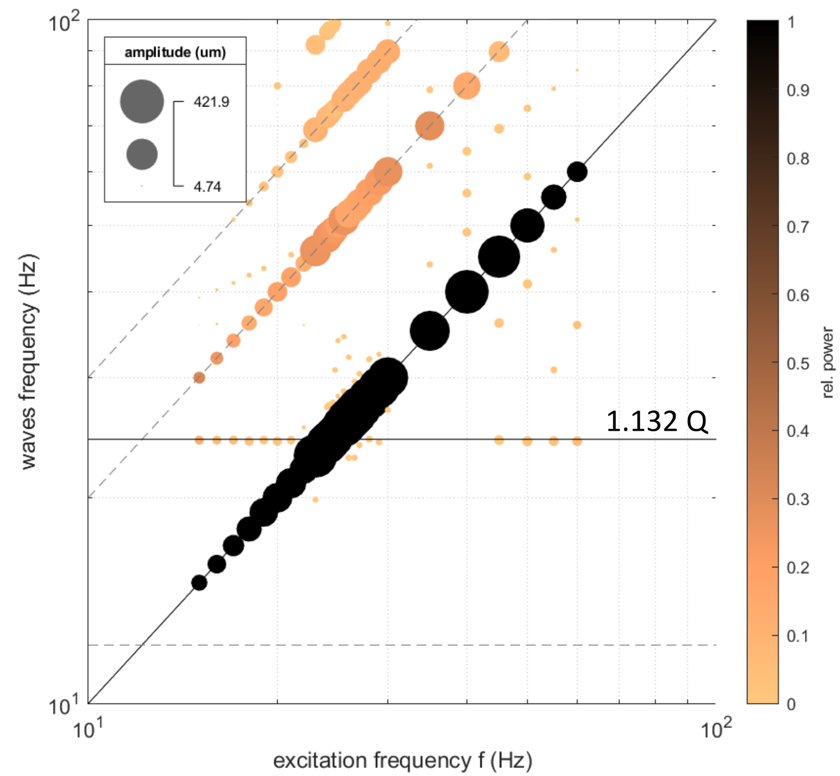
Direct flow, **with forcing**

Wave growth *through* hole

BACK, 4 mm above hole, Q = 22 L/h

Small forcing amplitude

Large forcing amplitude



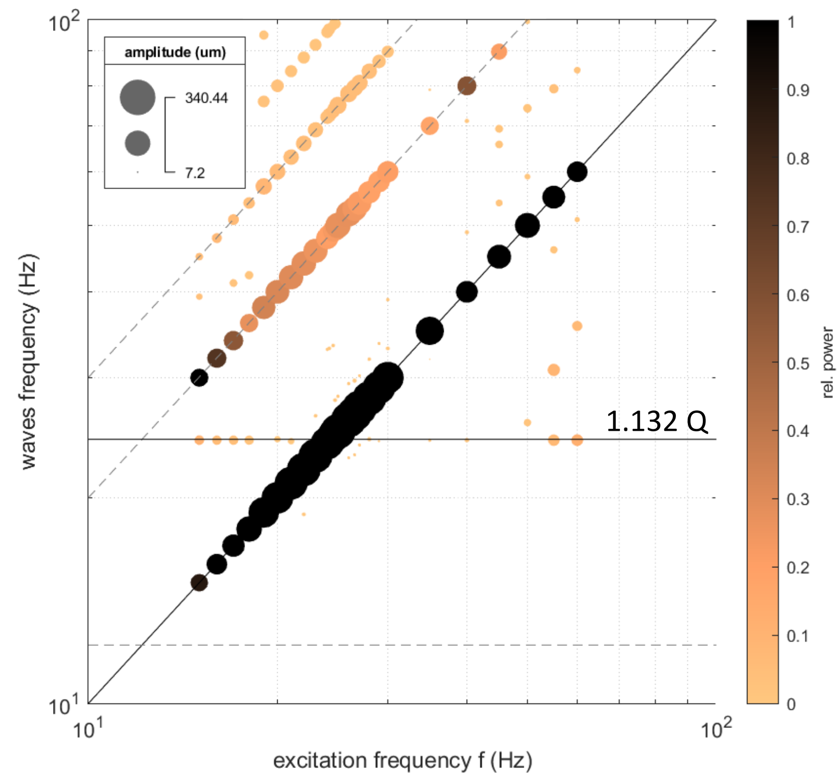
Direct flow, **with forcing**

Wave growth *through* hole

FRONT, 2 mm *below* hole, Q = 22 L/h

Small forcing amplitude

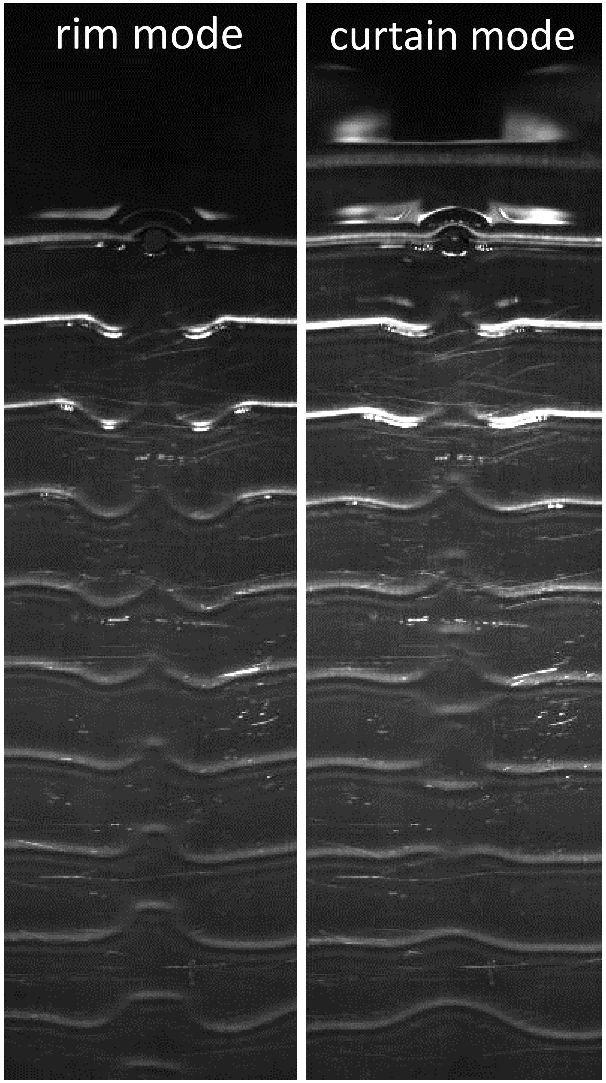
Large forcing amplitude



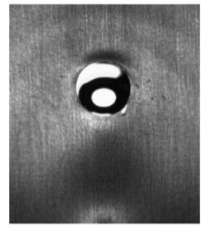
Direct flow, **with forcing**

Wave <> hole interaction

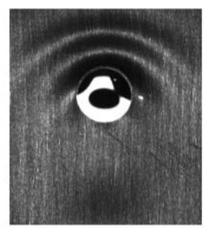
Q = **13.4** L/h, $f \approx 23$ Hz



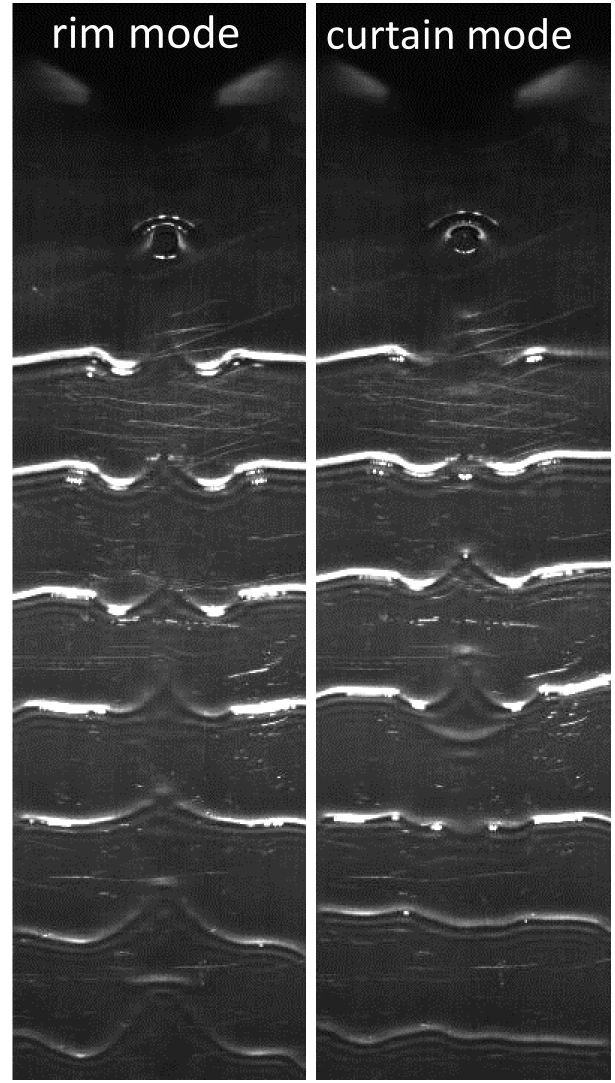
rim



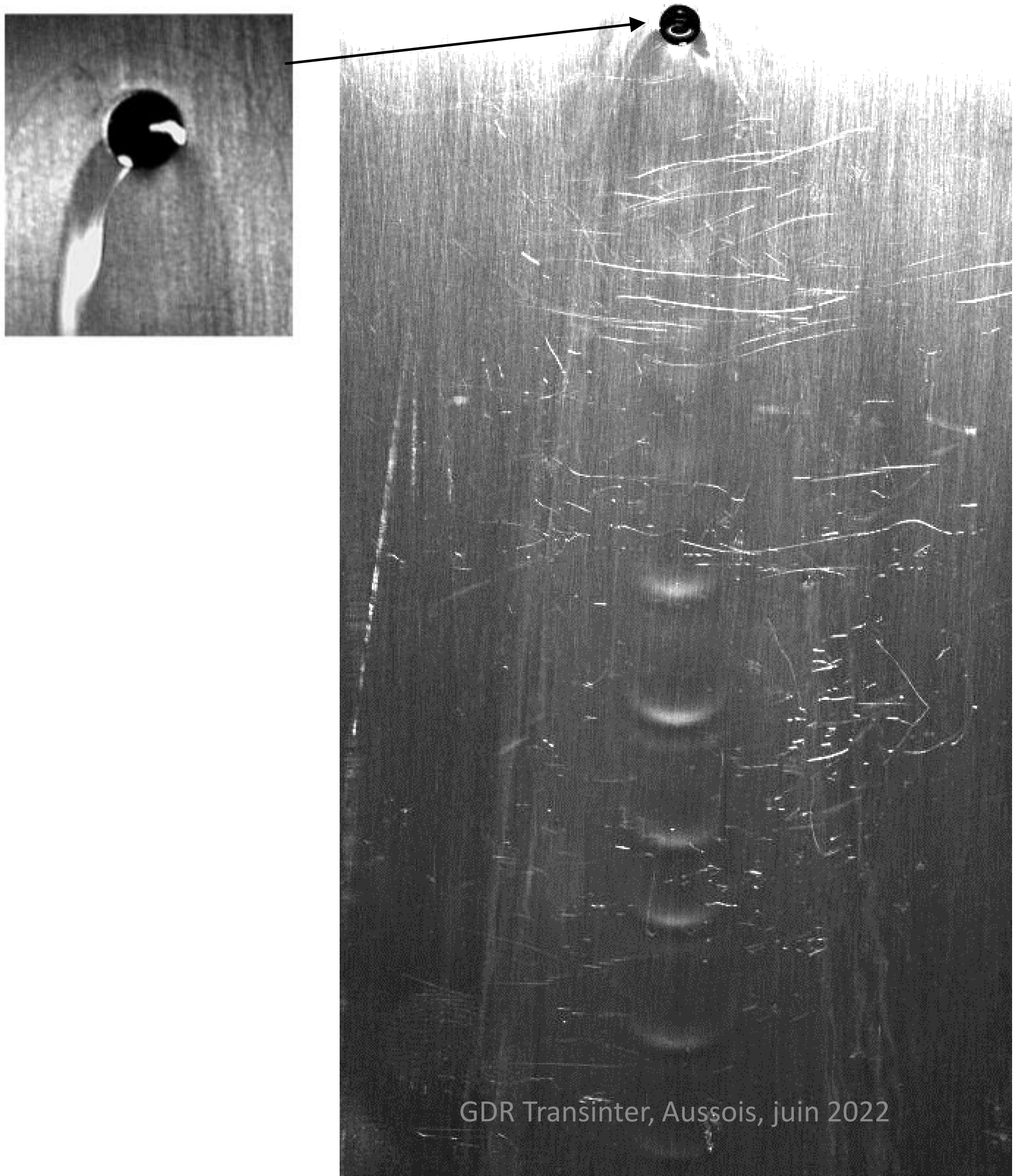
curtain



Q = **21.8** L/h, $f \approx 23$ Hz

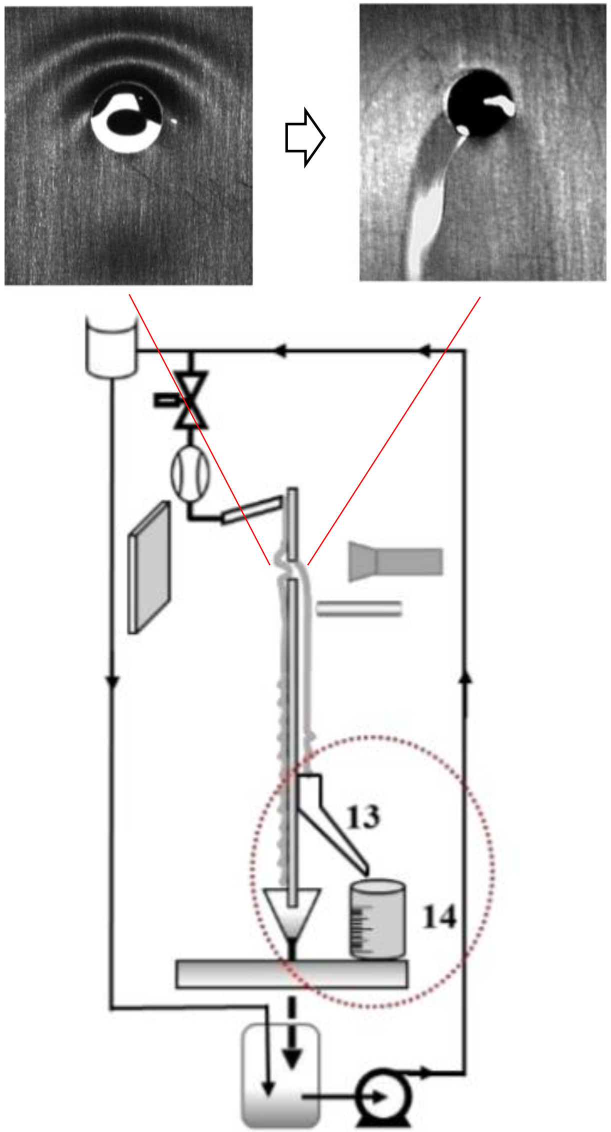


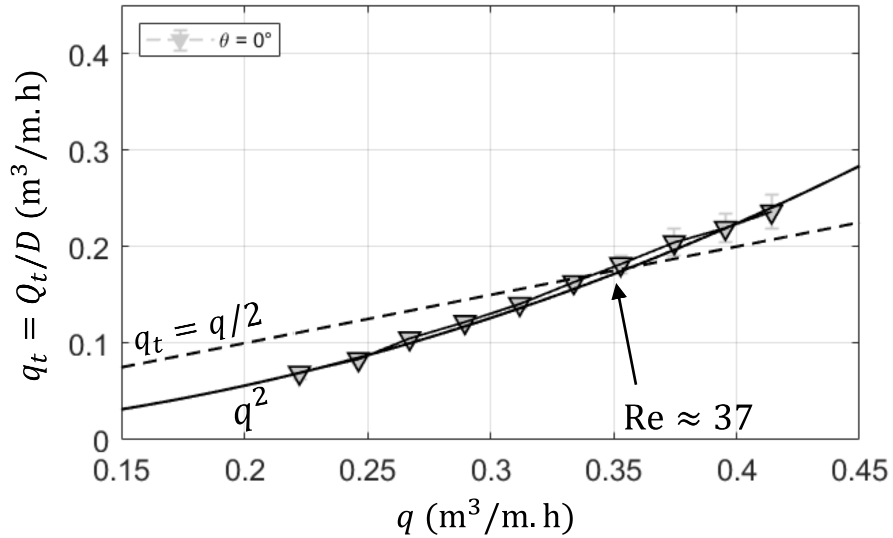
Rivulet flow



Flow rate transferred to rivulet

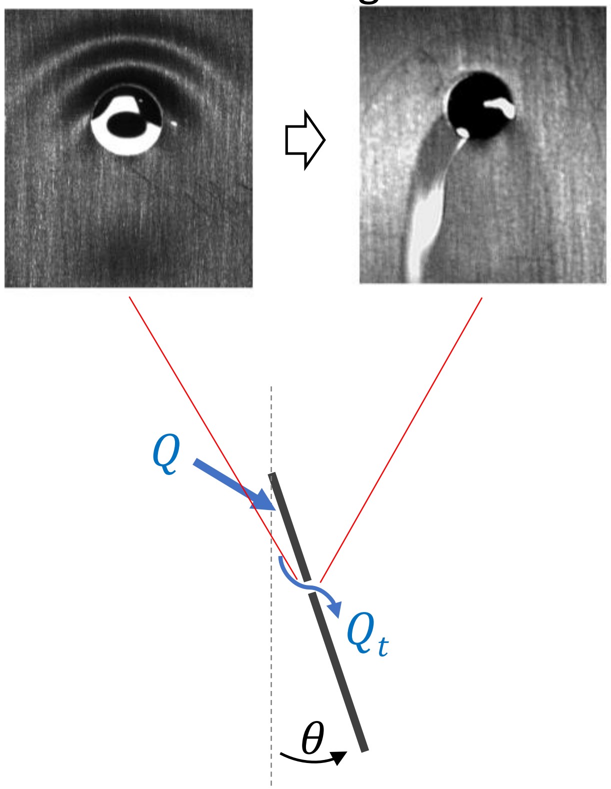
vertical plate ($\theta = 0$)

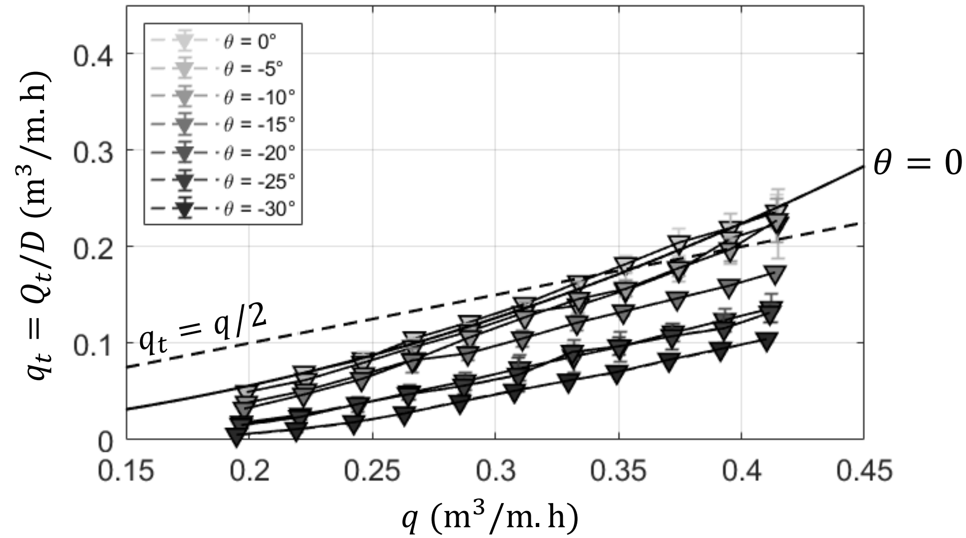




Flow rate transferred to rivulet

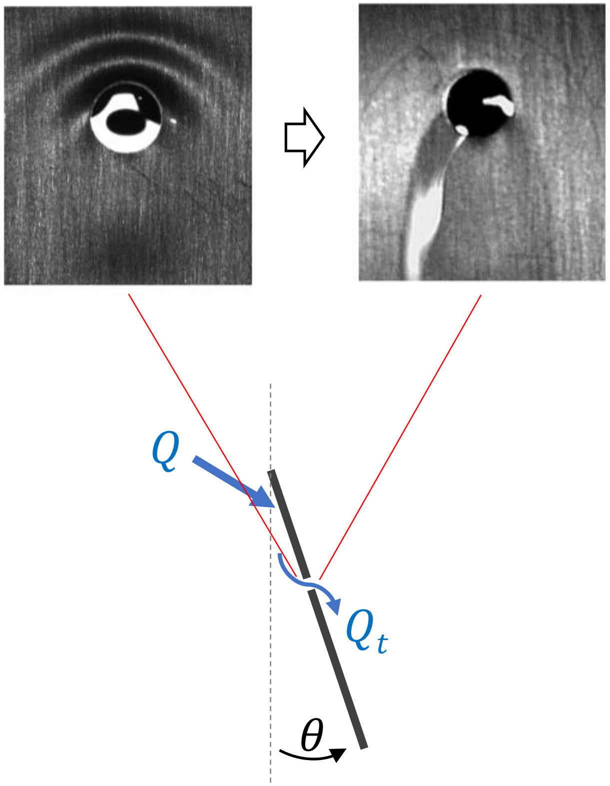
Negative inclinations ($\theta < 0$): gravity hinders transfer

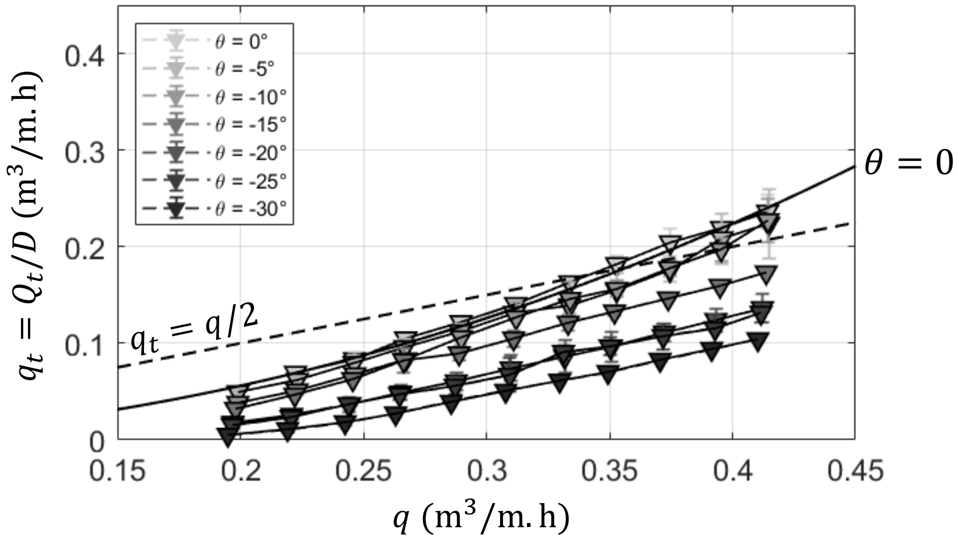




Flow rate transferred to rivulet

Negative inclinations ($\theta < 0$): gravity hinders transfer

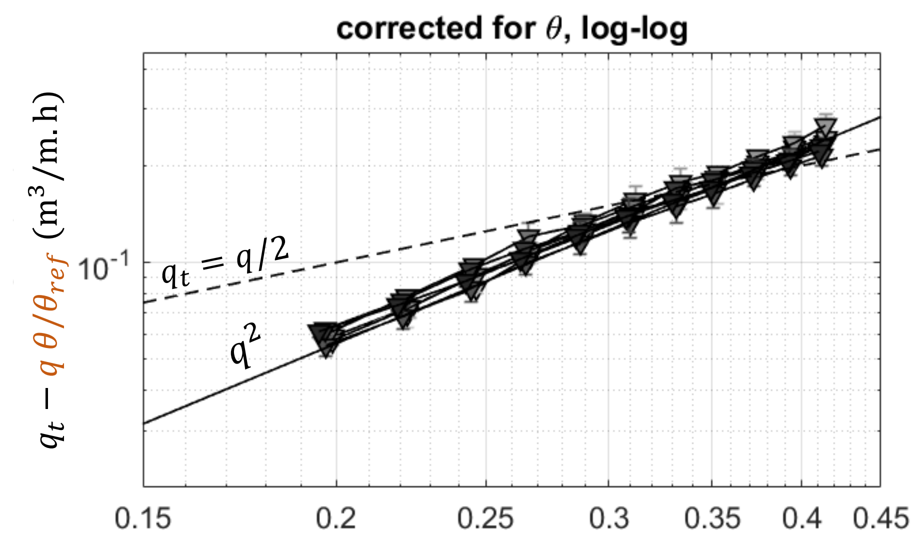




ad-hoc correction :

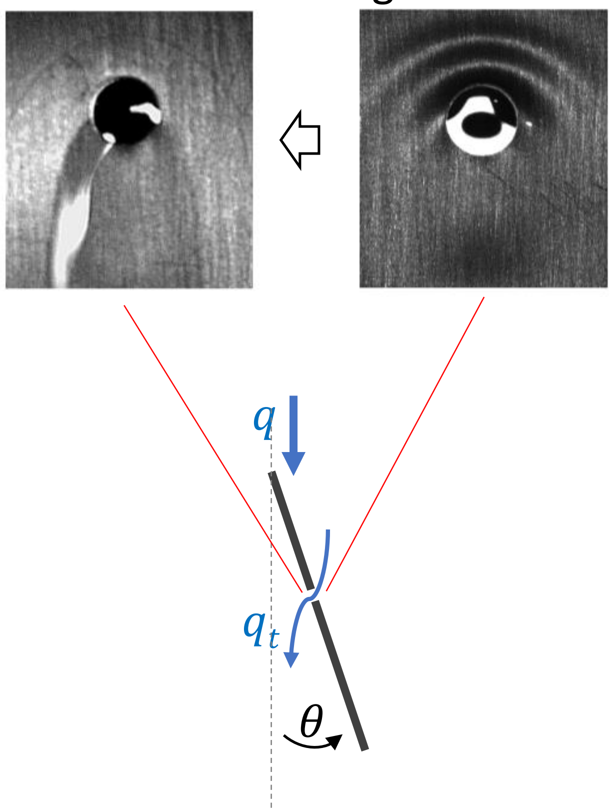
$q_t - q\,\theta/\theta_{ref}$

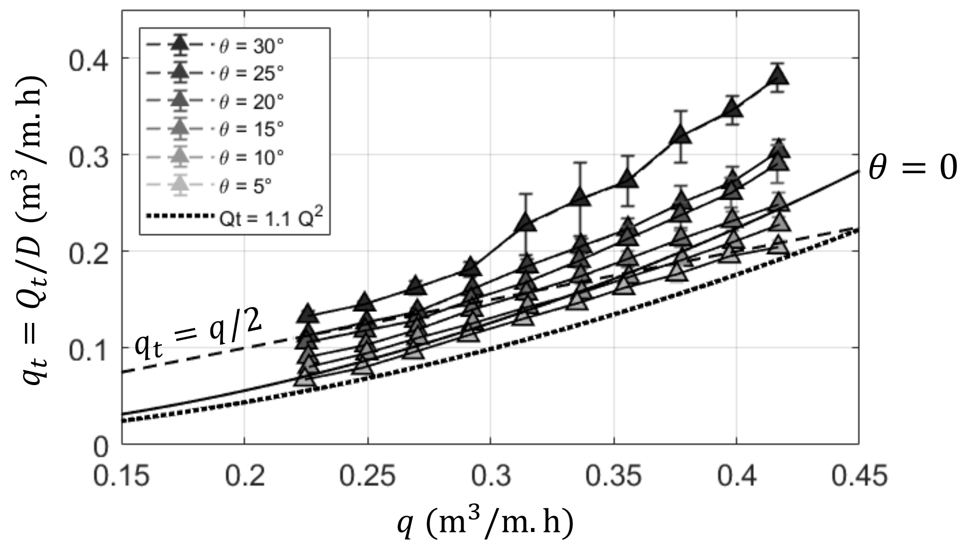
$\theta_{ref} = 105°$



Flow rate transferred to rivulet

Negative inclinations ($\theta > 0$): gravity favors transfer

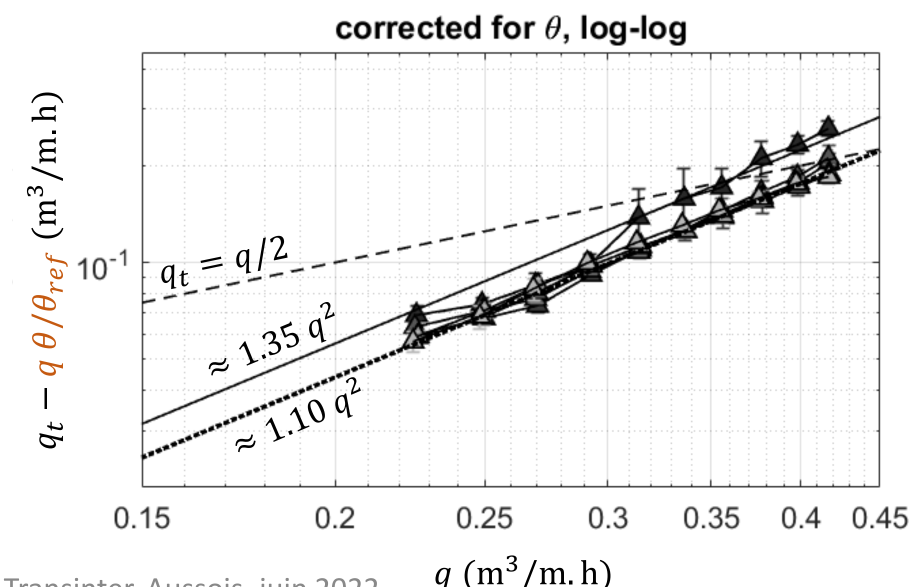




ad-hoc correction :

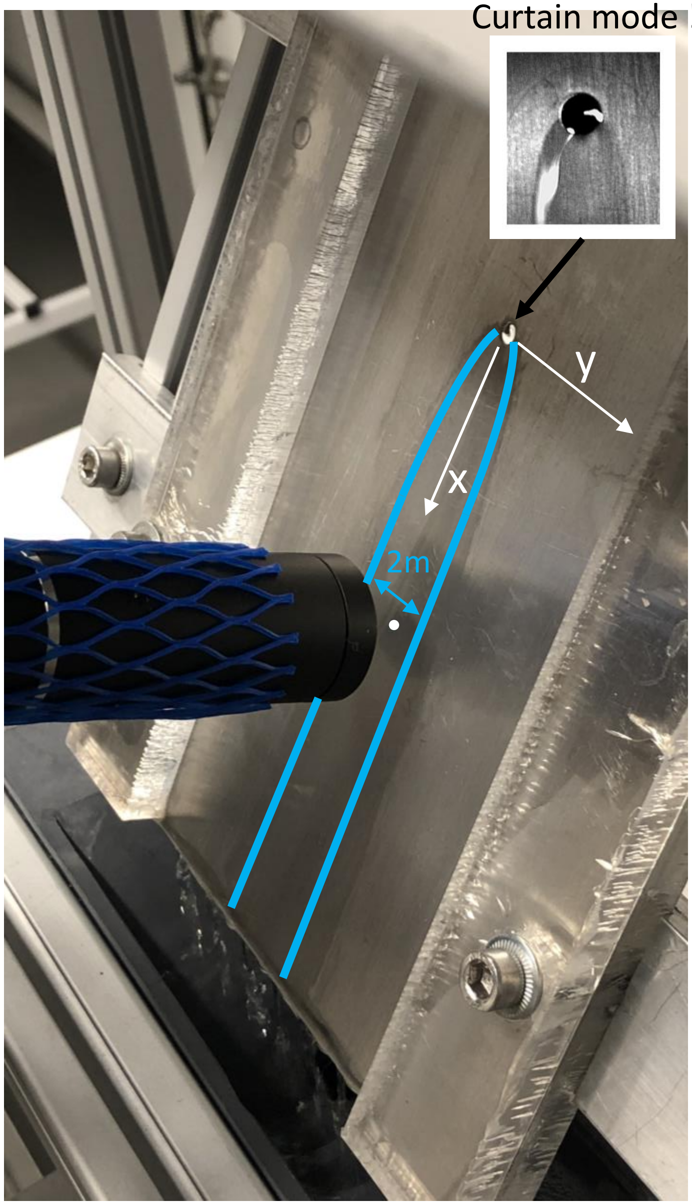
$q_t - q\ \theta/\theta_{ref}$

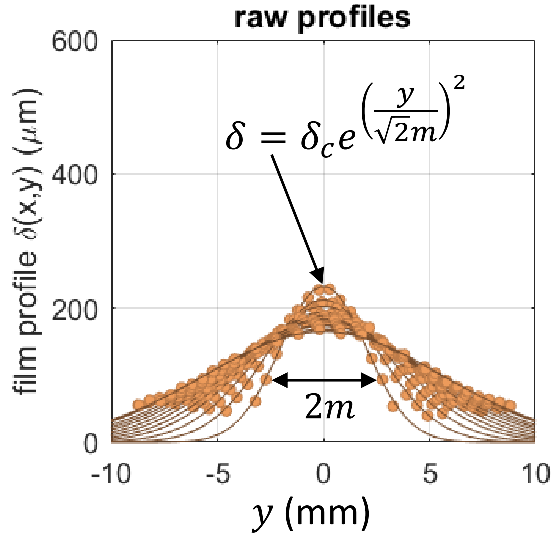
$\theta_{ref} = 105°$

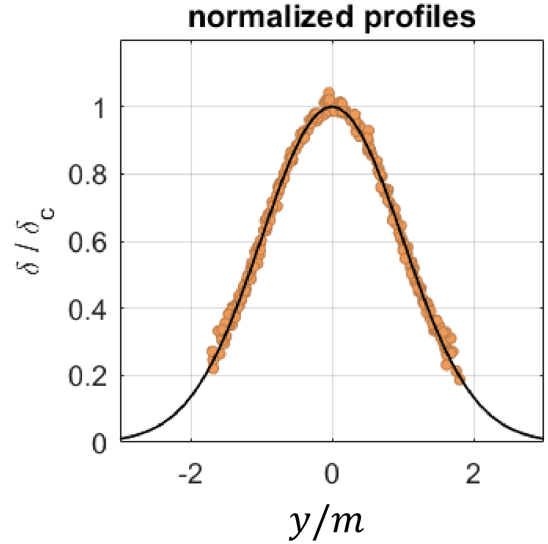


Rivulet spreading and flattening

$\theta < 0$: Rivulet spreading **on top** of plate



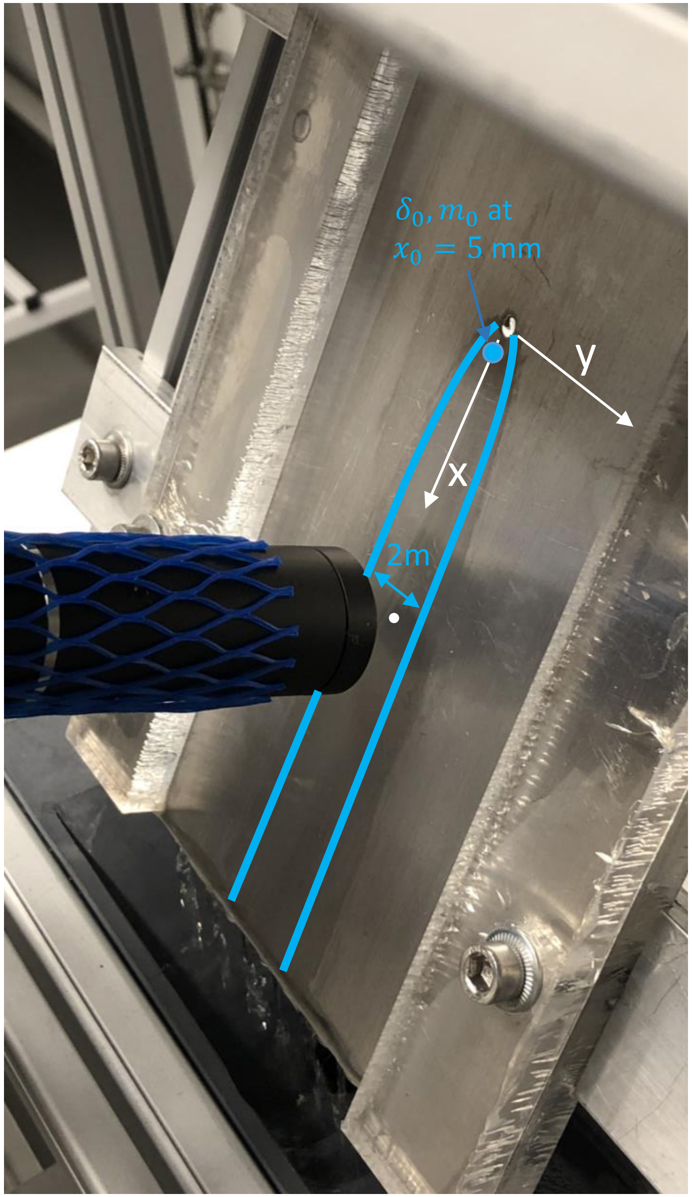


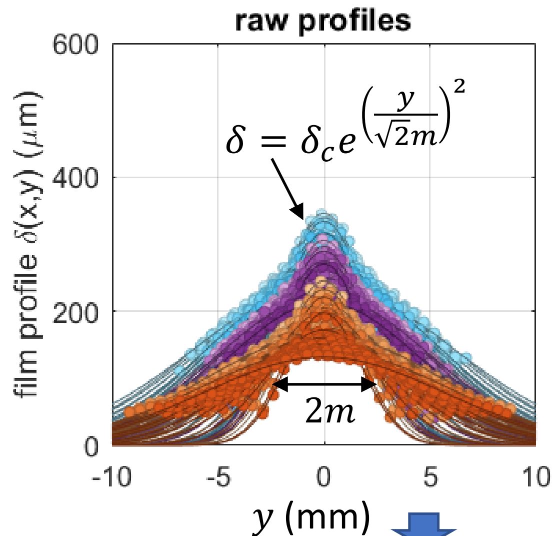


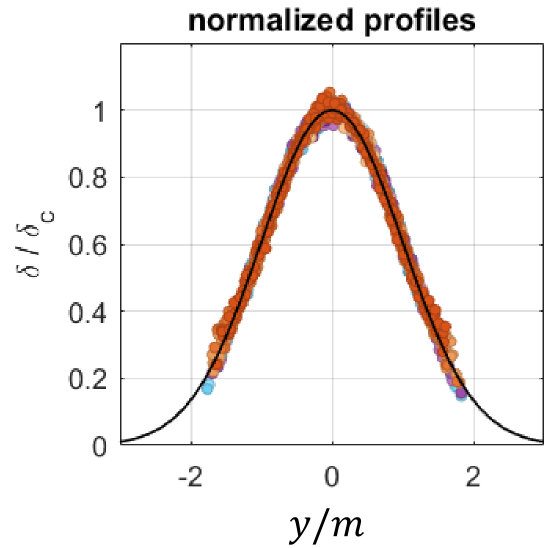
θ = -20°
Re = 26

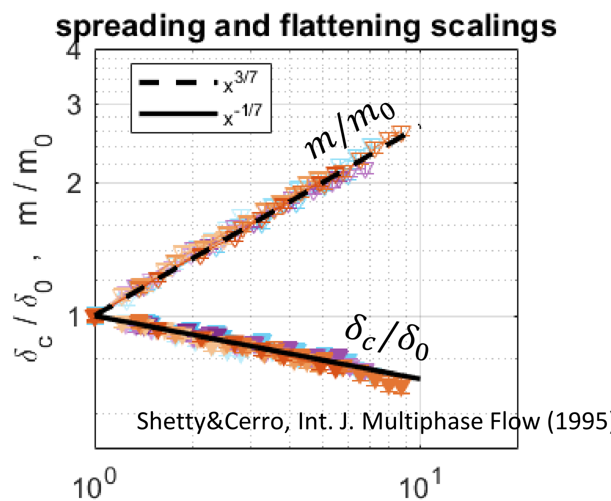
Rivulet spreading and flattening

$\theta < 0$: Rivulet spreading **on top** of plate







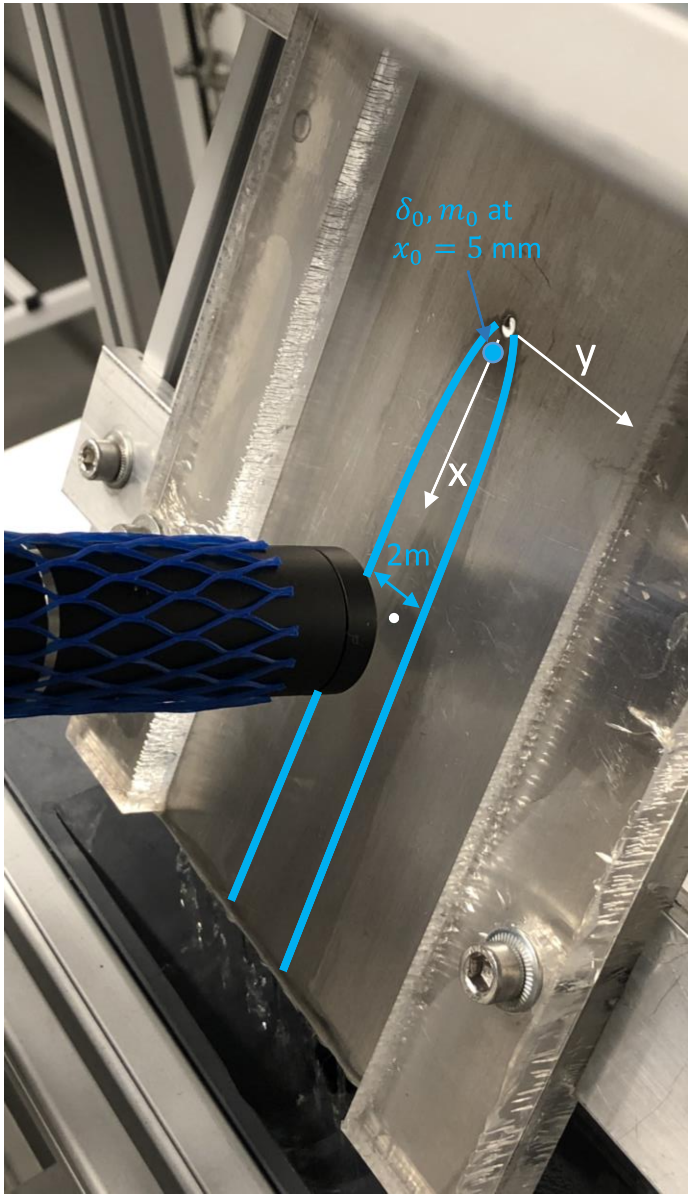


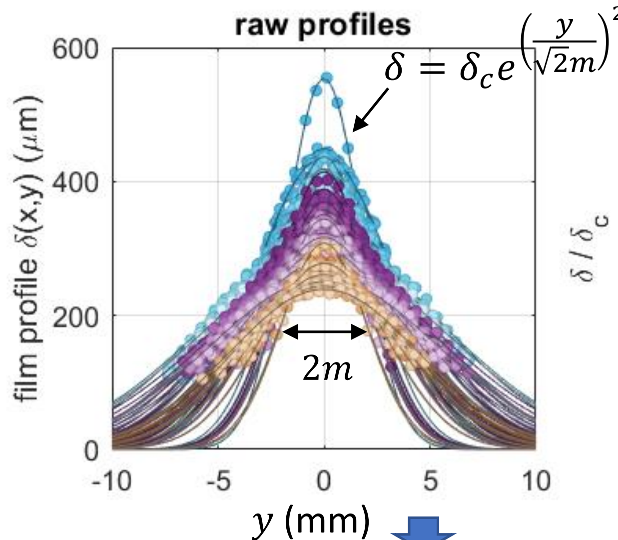
θ = -30° → -15°
Re = 26, 35, 44

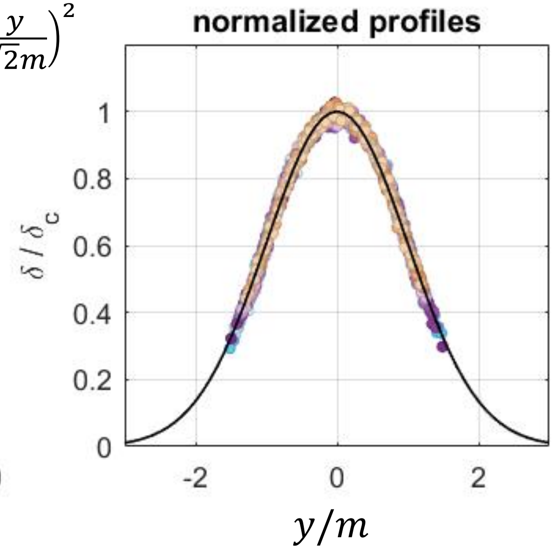
$$1 + \mathrm{G}\, x^* \qquad \mathrm{G} = \frac{(112/8)\tan(|\theta|)\delta_0}{2\, m_0}, \quad x^* = \frac{x - x_0}{2\, m_0}$$

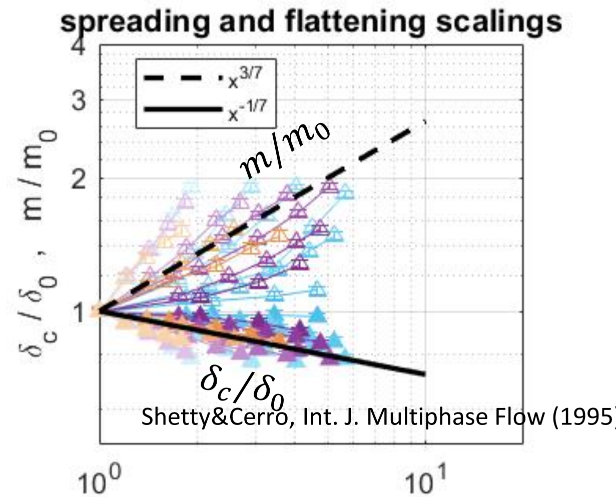
Rivulet spreading and flattening

$\theta > 0$: Rivulet spreading on **undersurface** of plate







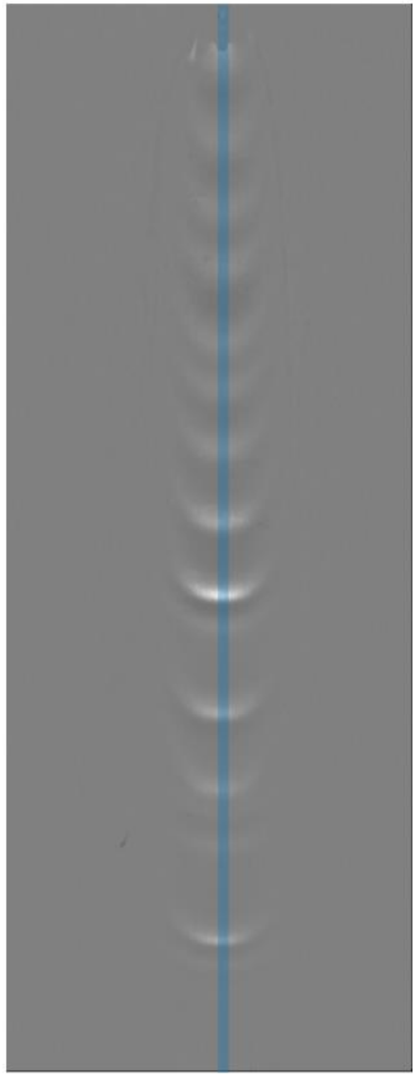


θ = 5° → 30°
Re = 26, 35, 44

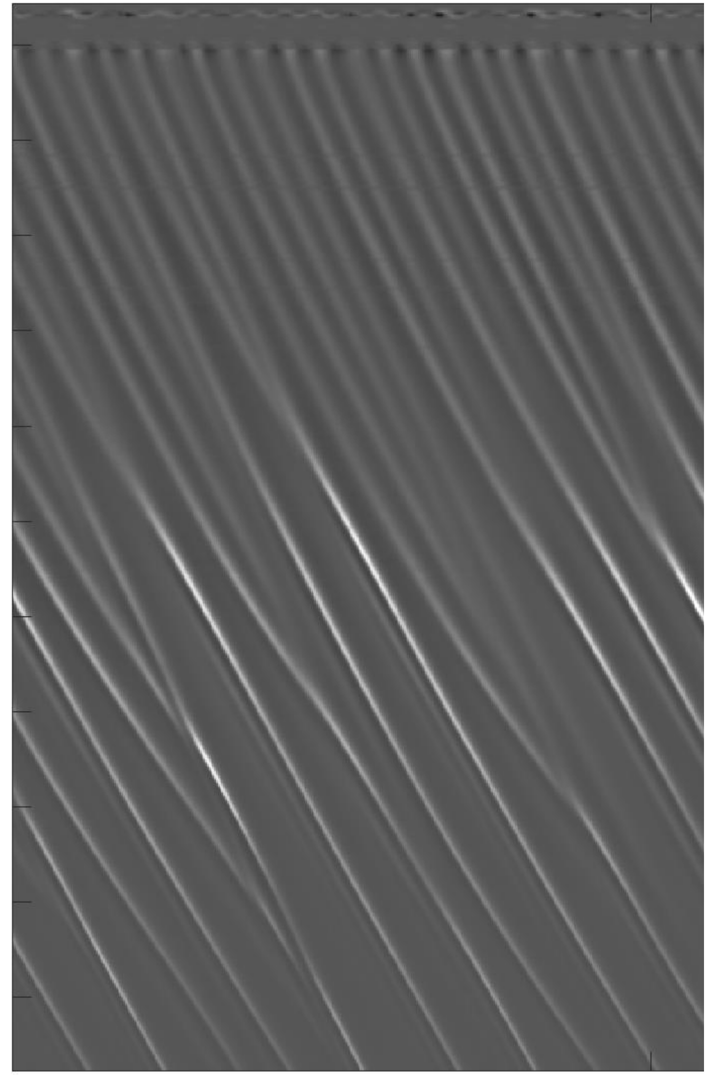
$$1 + \mathrm{G}\, x^* \qquad \mathrm{G} = \frac{(112/8)\tan(|\theta|)\delta_0}{2\, m_0}, \quad x^* = \frac{x - x_0}{2\, m_0}$$

Wave train characterisation
via high-speed videography

Raw movie



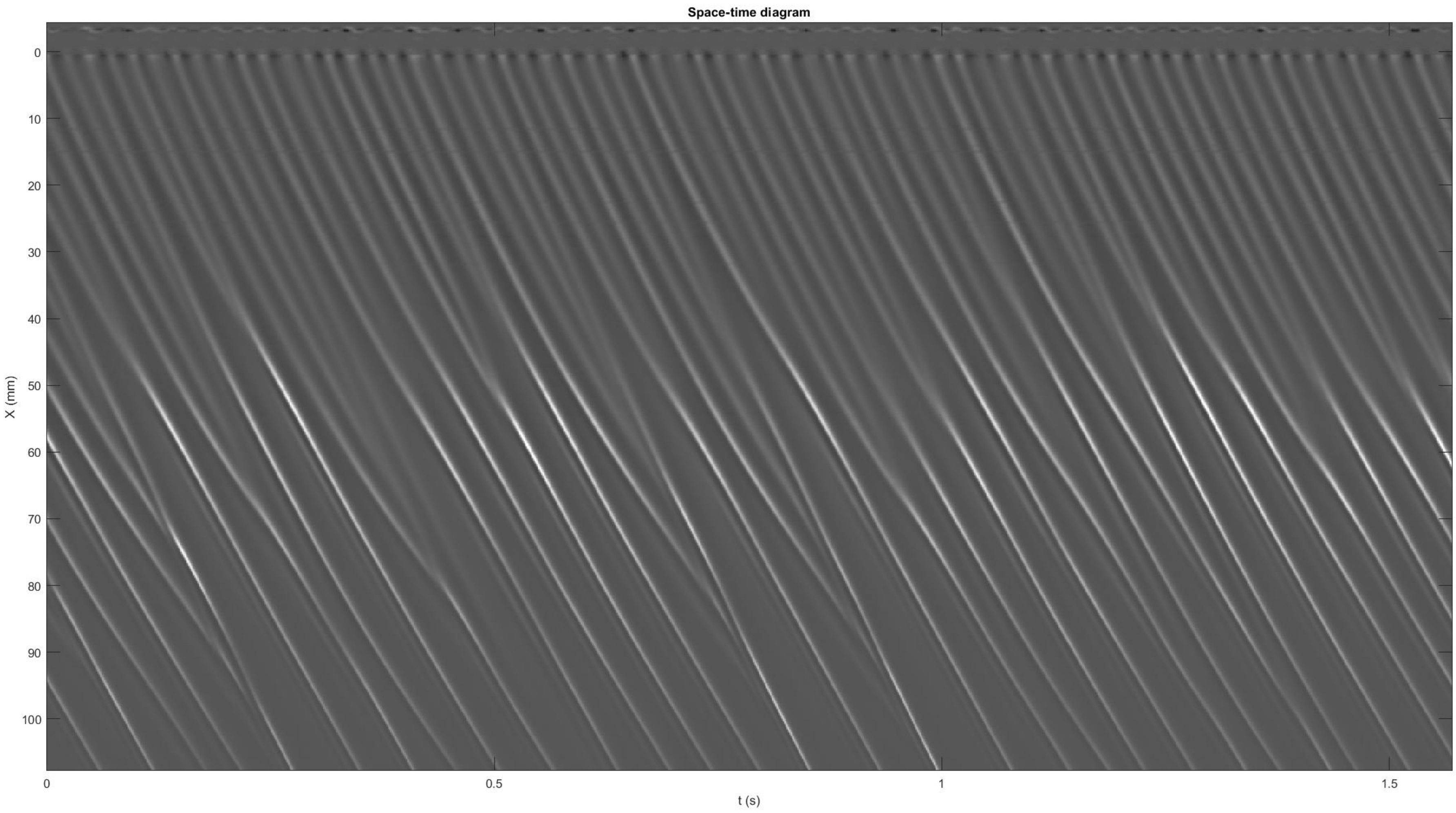
Background subtraction &
median line extraction



Space-time diagram

Wave train characterisation

Space-time diagram

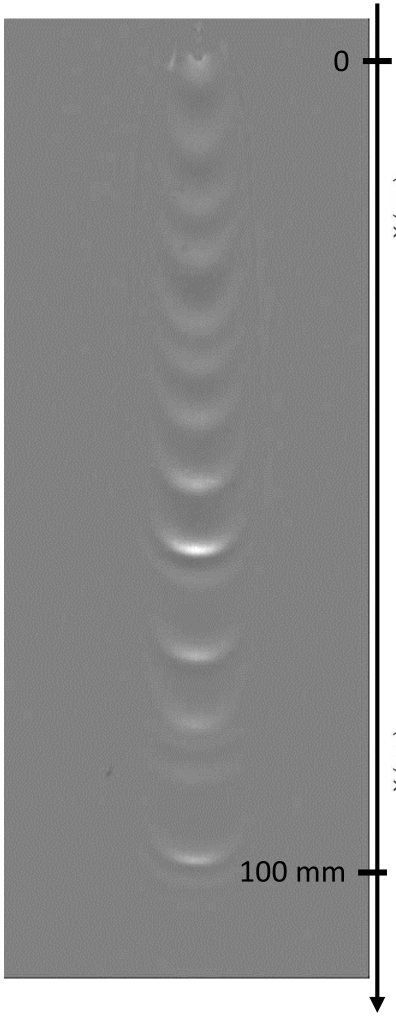


Wave train characterisation

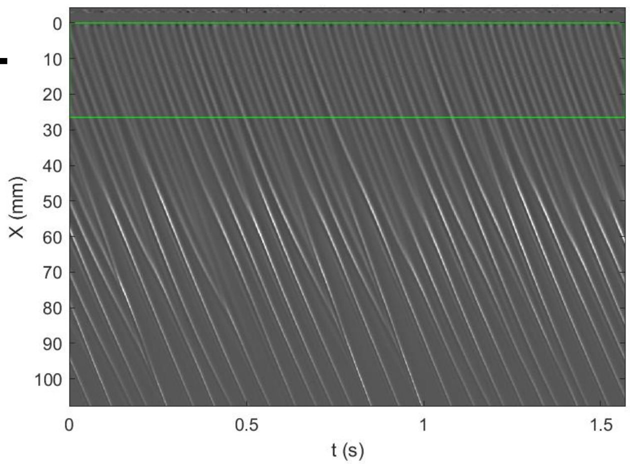
CentraleSupélec

Air Liquide

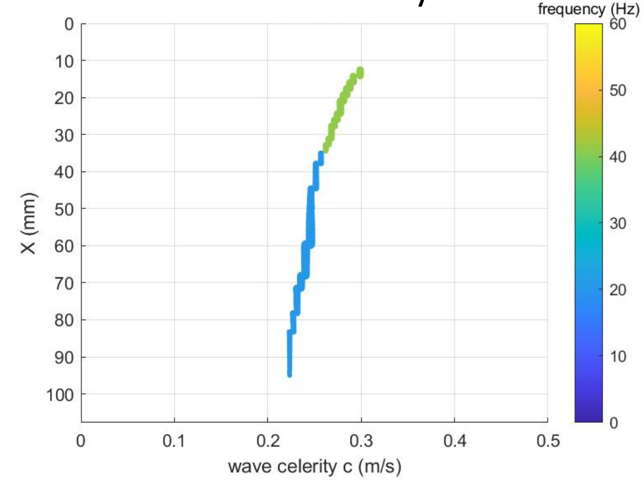
Typical **unstable** case (Q = 36.3 L/h)



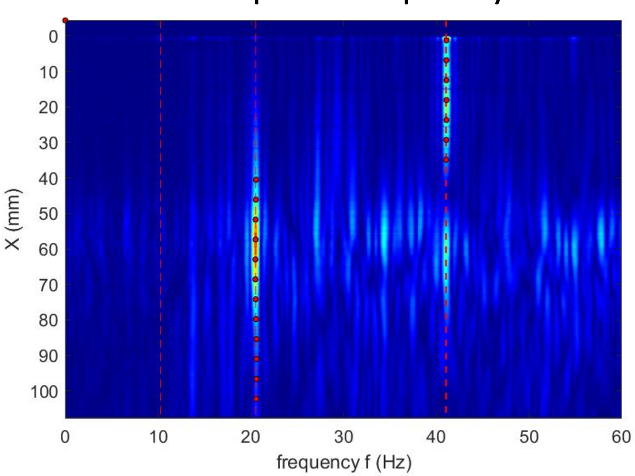
Space-time diagram



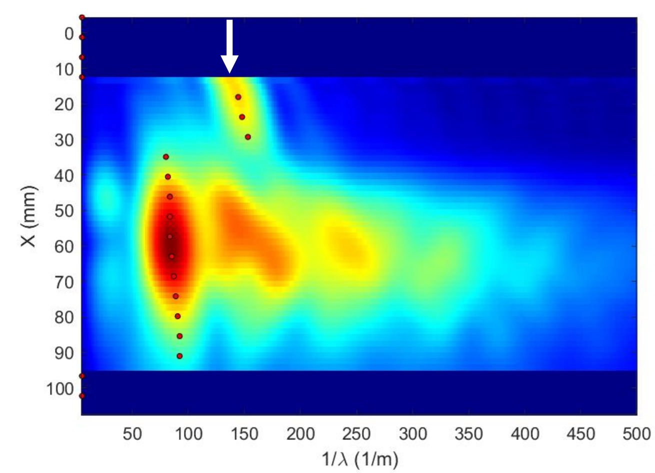
Wave celerity



Temporal frequency

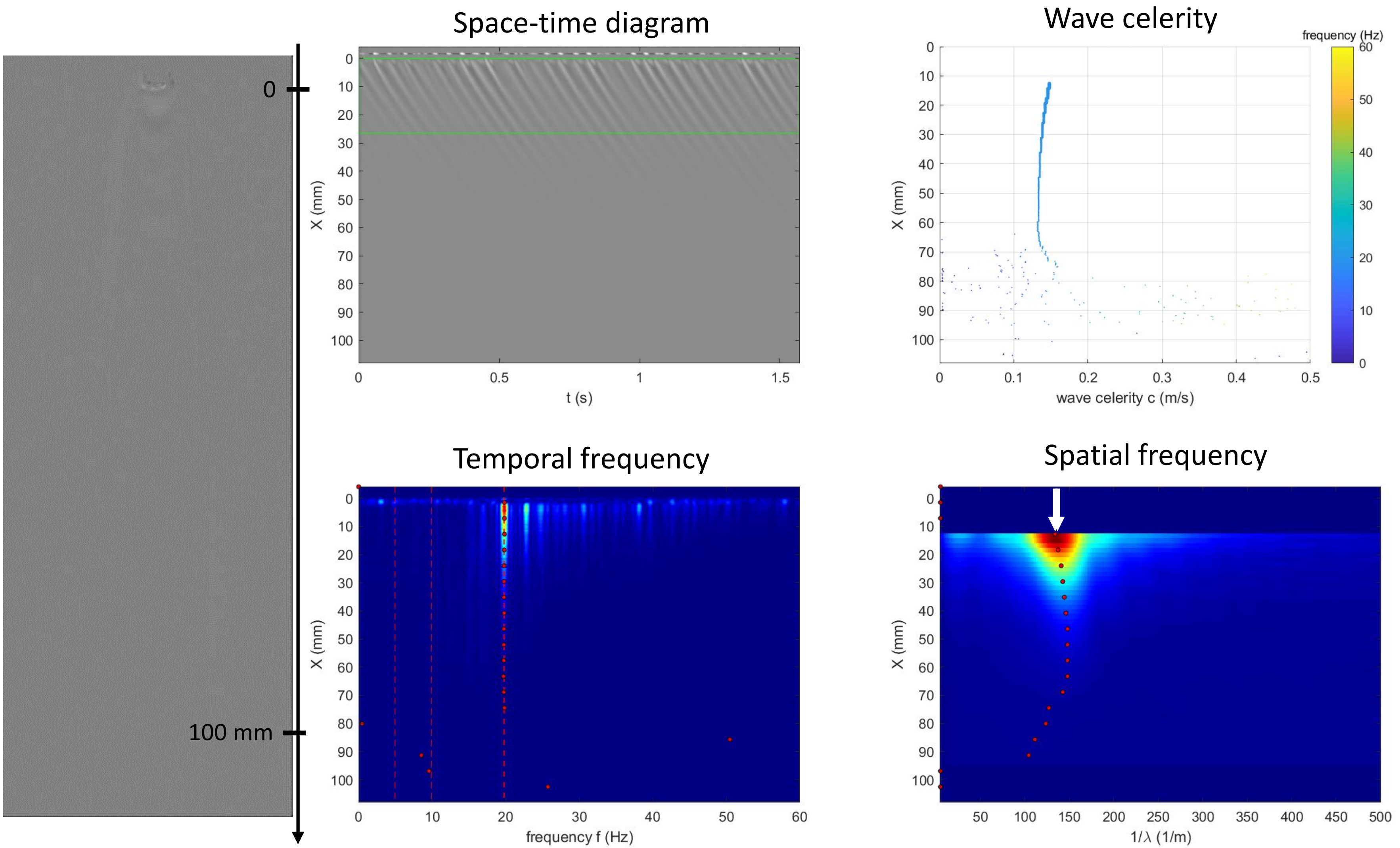


Spatial frequency



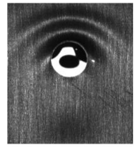
Wave train characterisation

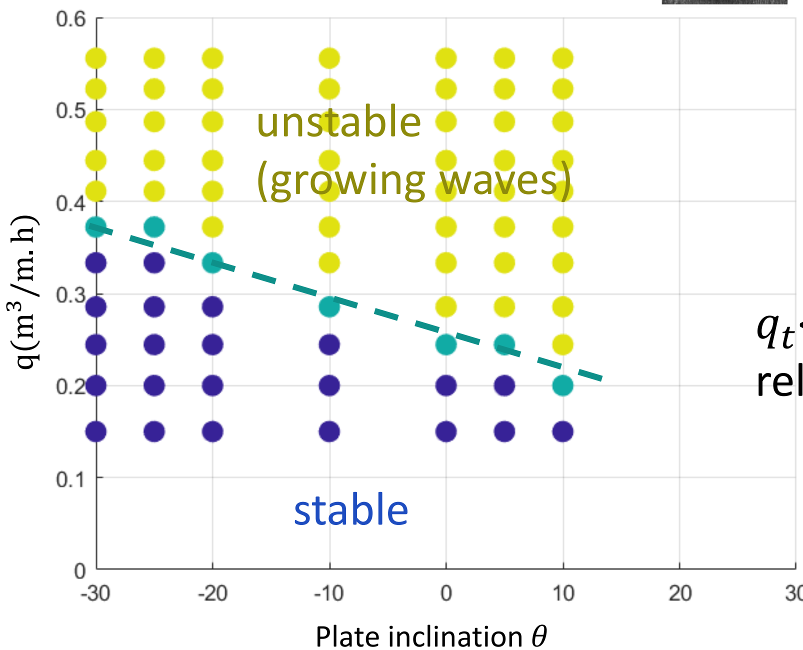
Typical **stable** case (Q = 17.5 L/h)



Rivulet neutral stability curve

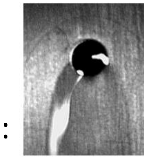
using flow rate on Front side:

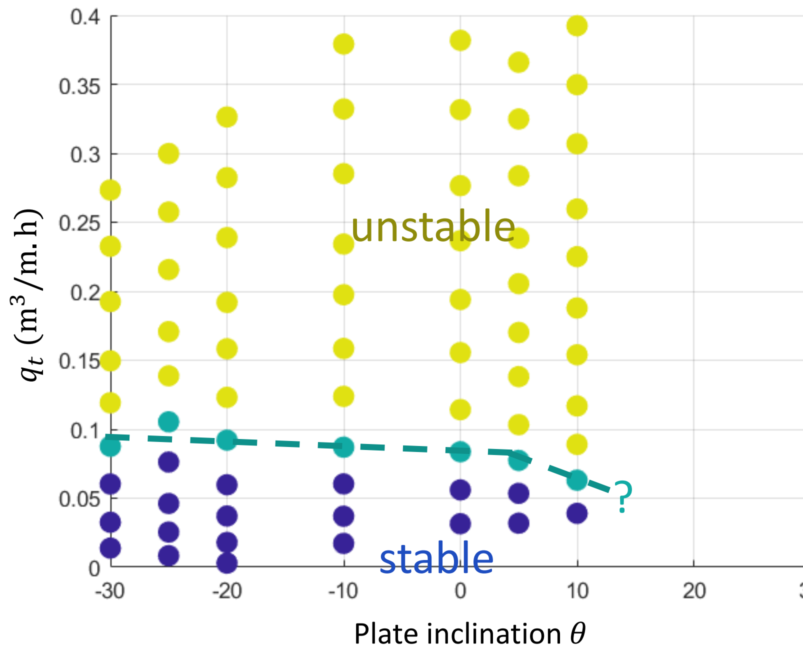




q_t <> q
relationship

using flow rate on back (rivulet) side:

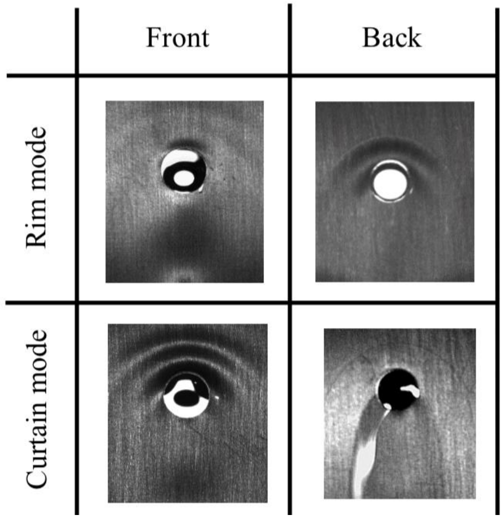




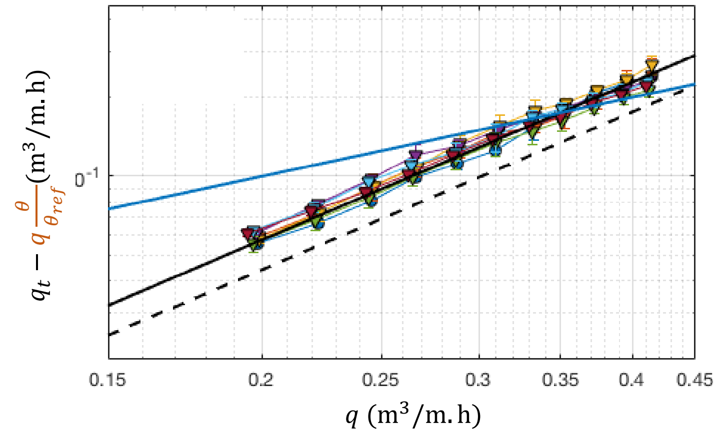
Take-home message(s)

CentraleSupélec
Air Liquide

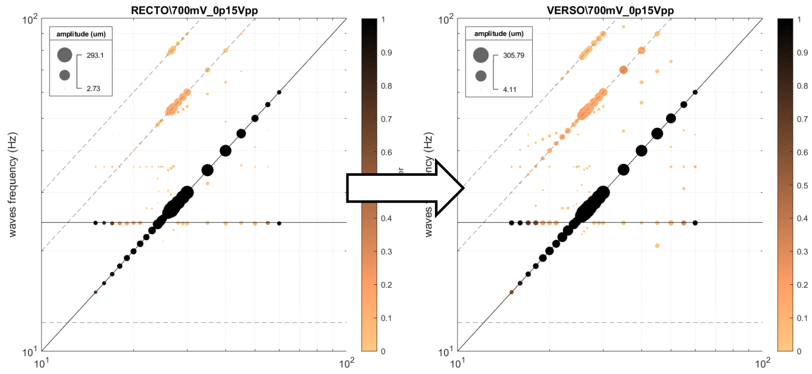
Rim <> curtain transition independant of θ



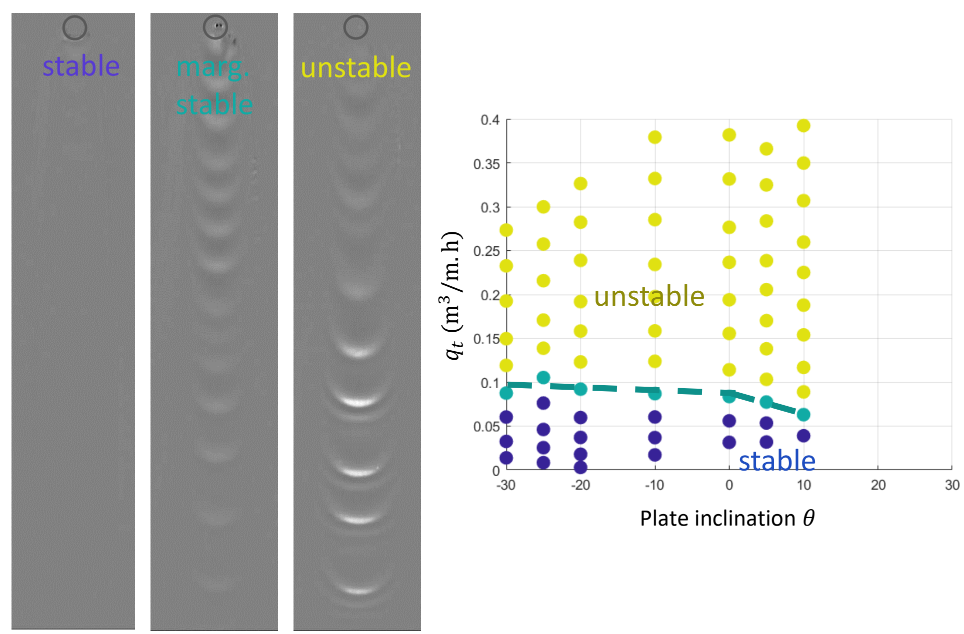
transferred flow rate $\propto q^2$ (regardless of θ)



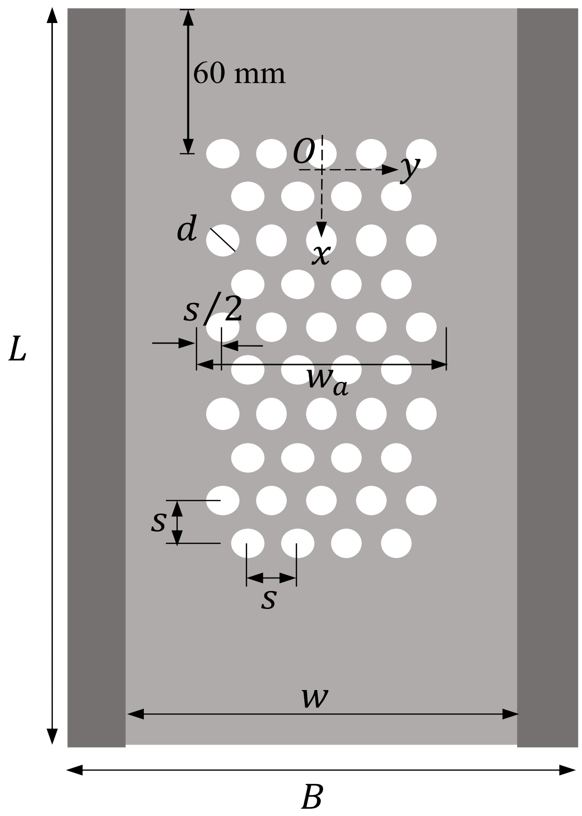
Holes are (mostly) transparent to waves

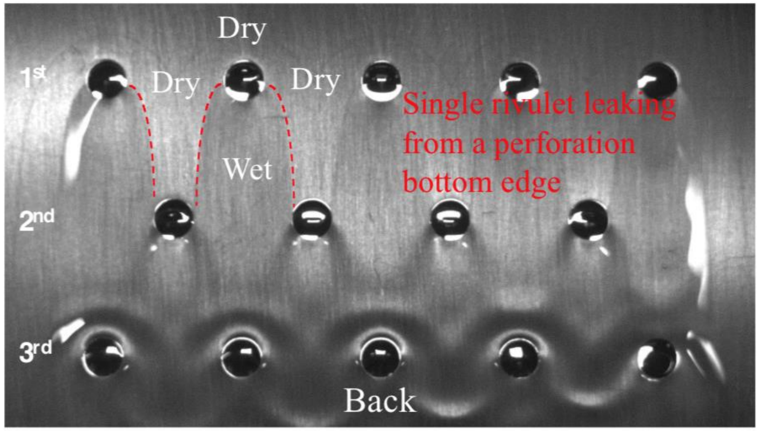


Rivulet stability



Ongoing work

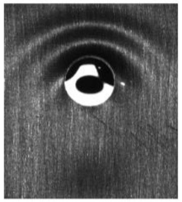


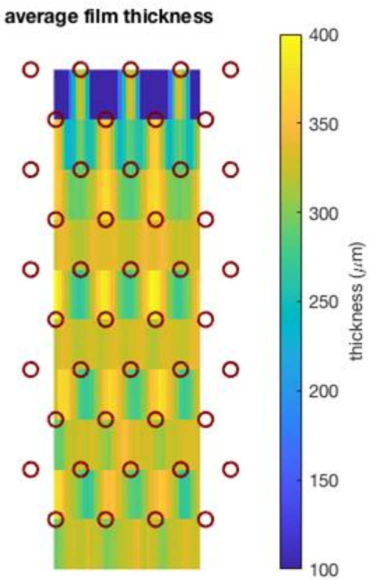


Iyer *et al.*, AIChE (2022)

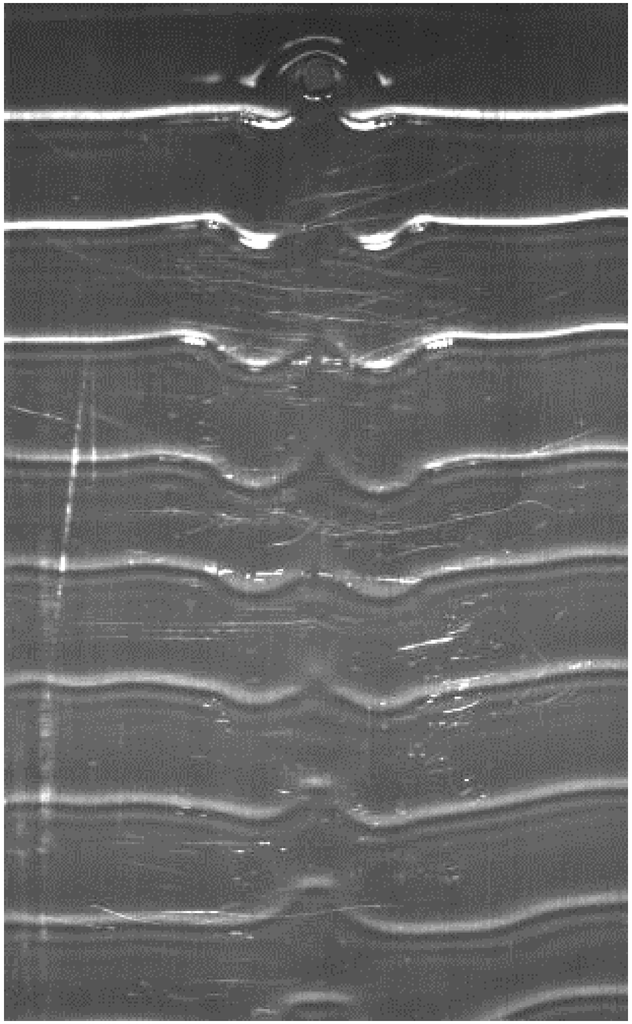
sources

obstacles



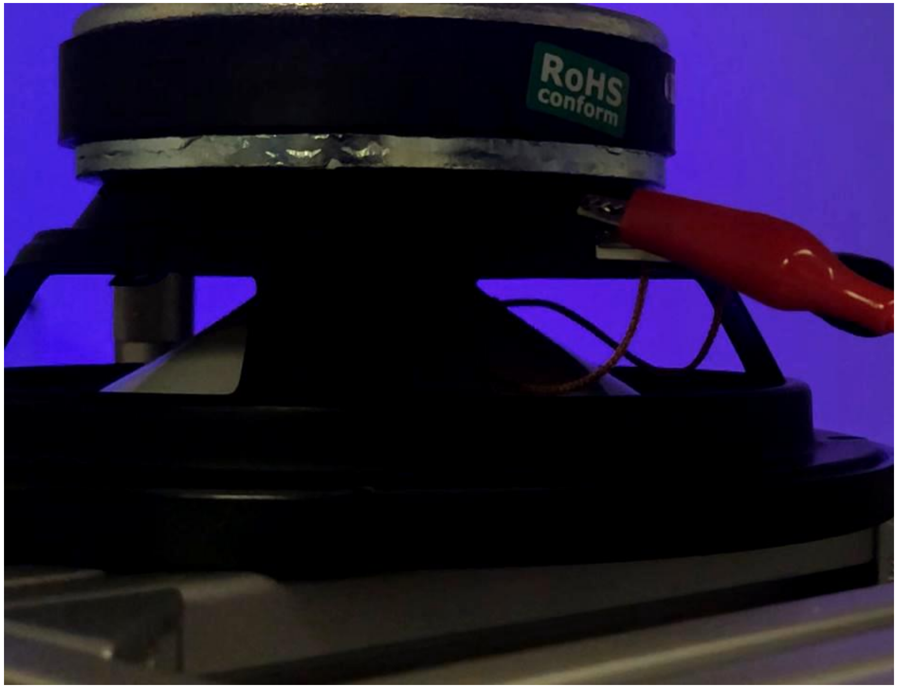


Thank you !

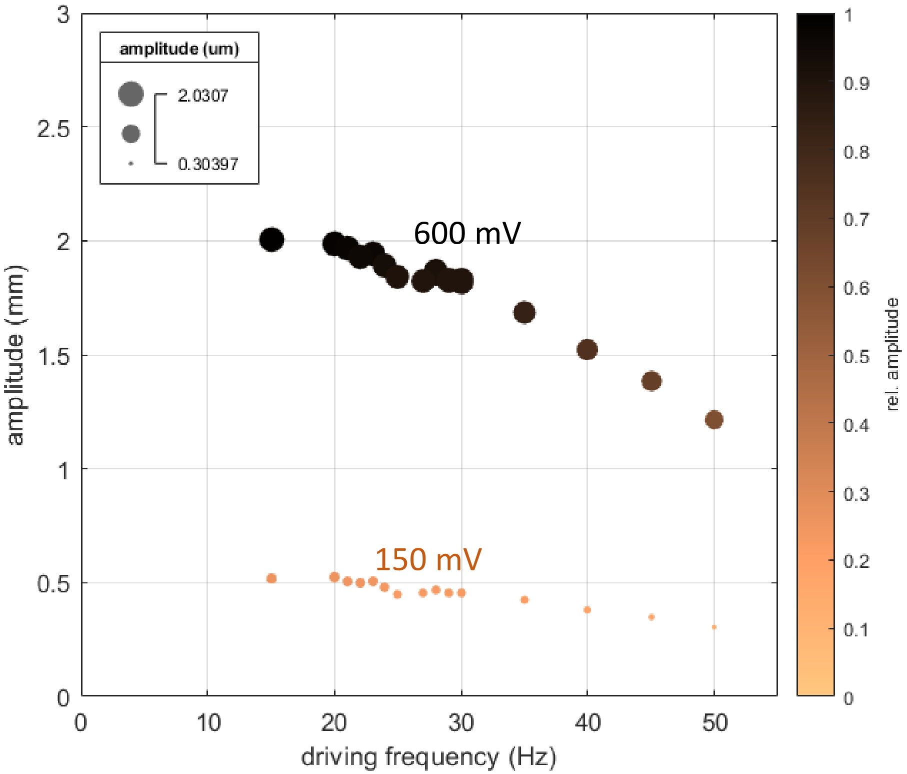


Backup slides

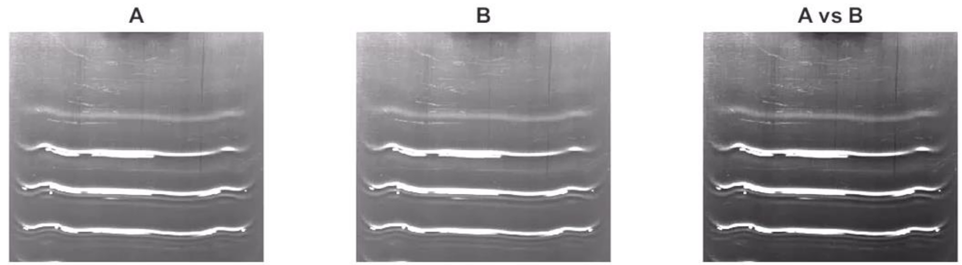
Speaker bandwidth test

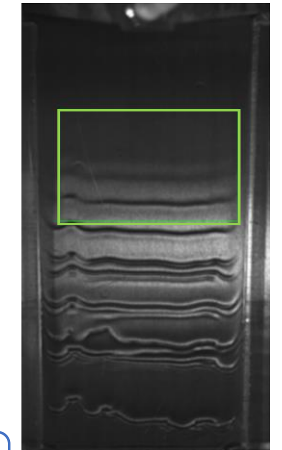


Membrane oscillation amplitude

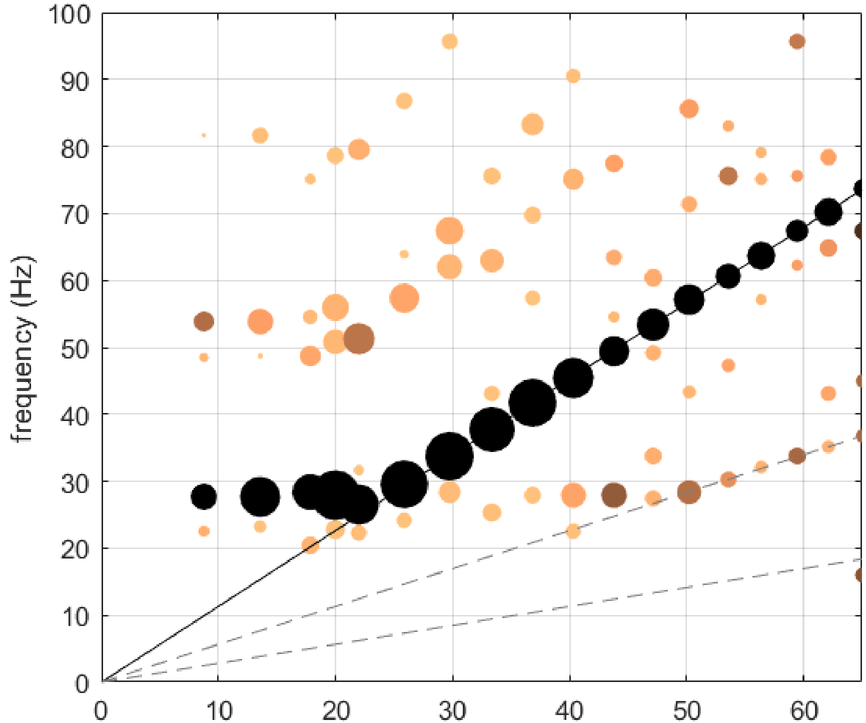


Does the flowmeter forces $f \propto Q$?

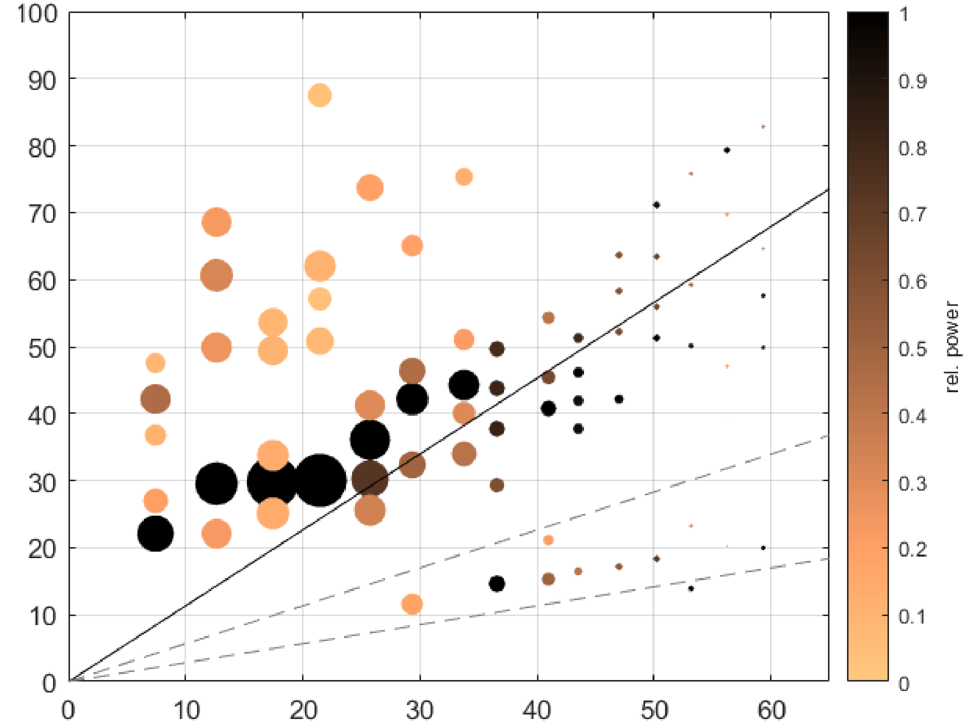




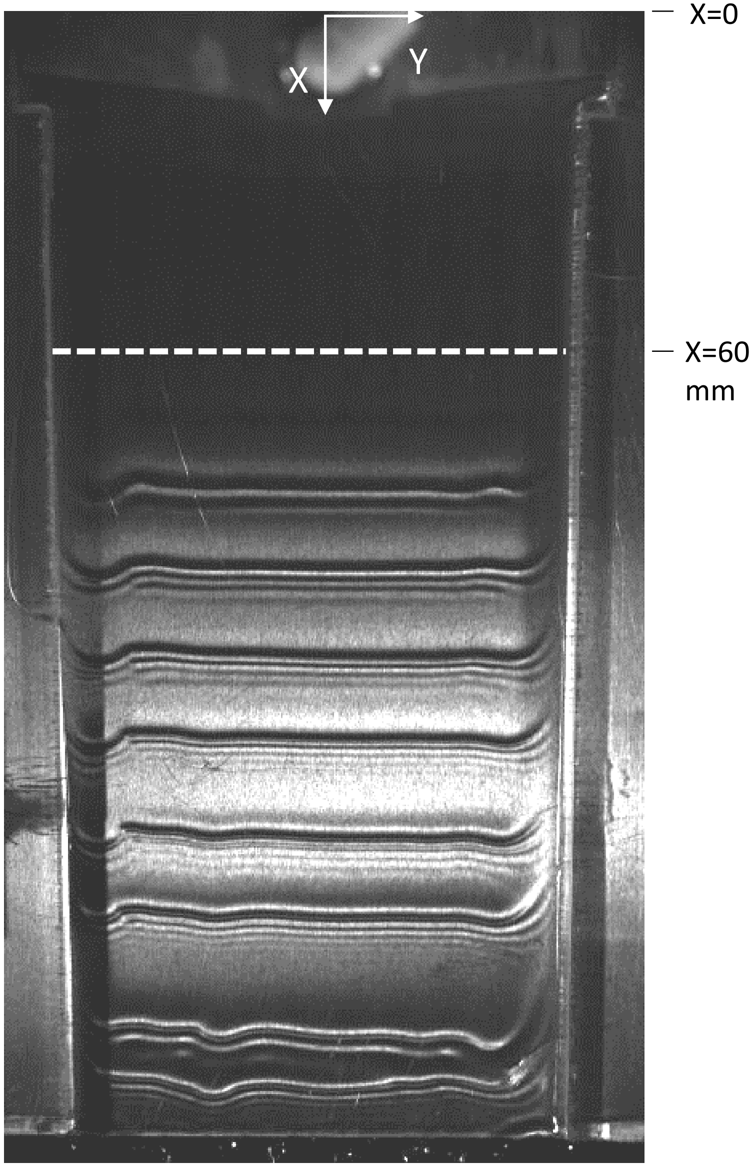
With flowmeter

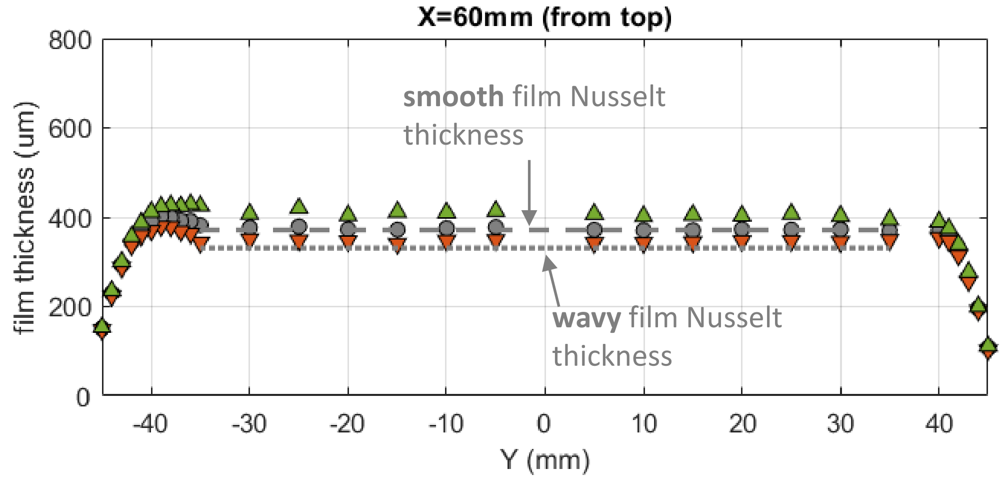


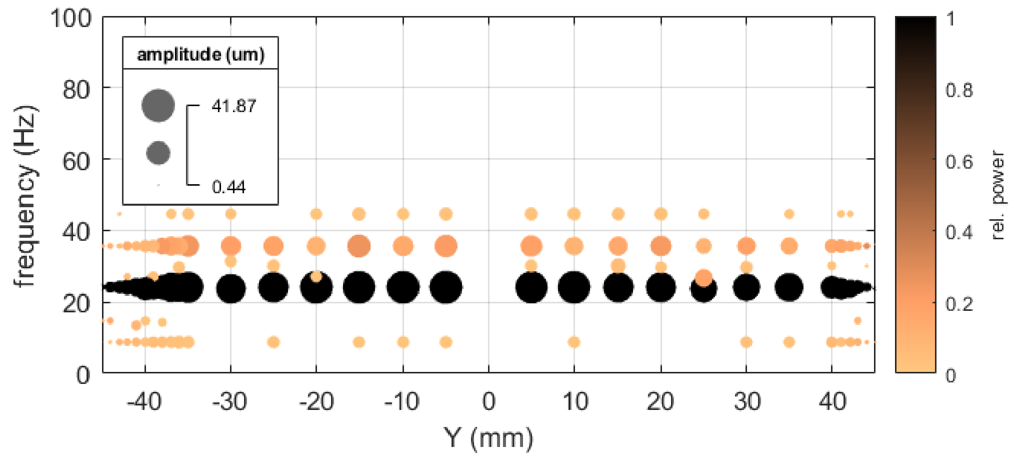
No flowmeter



Cross-flow film thickness profile (flat plate)

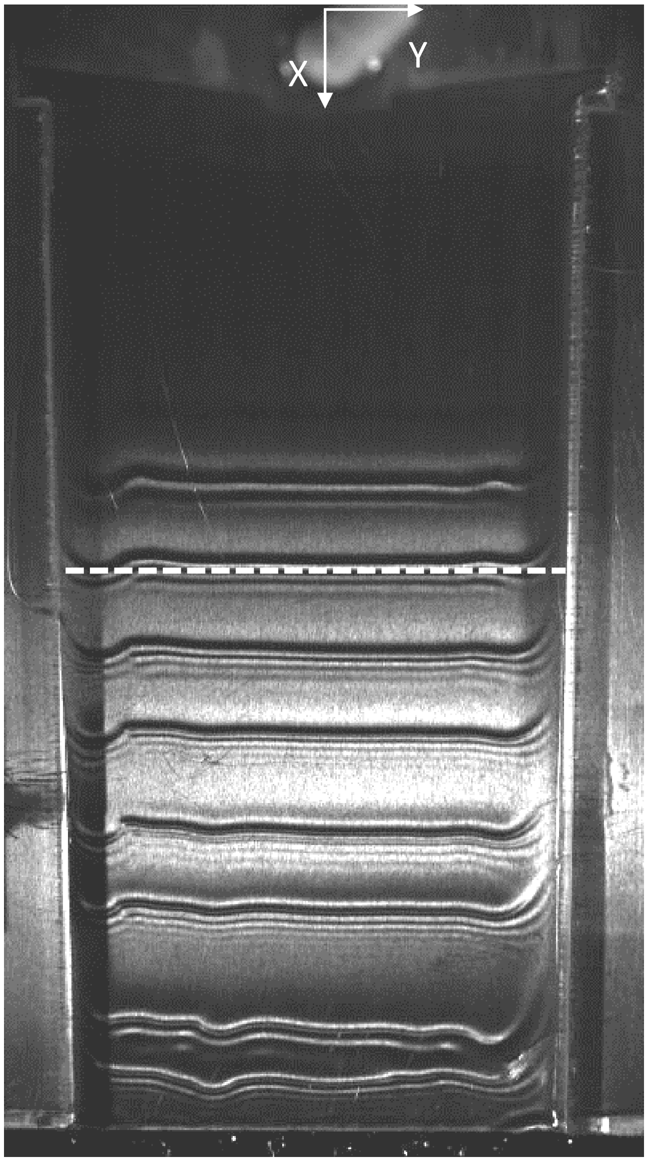


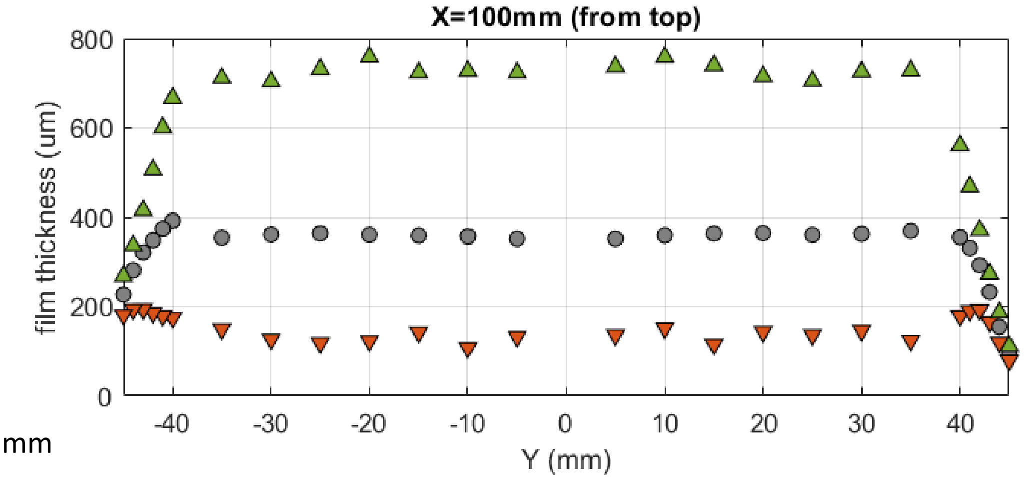


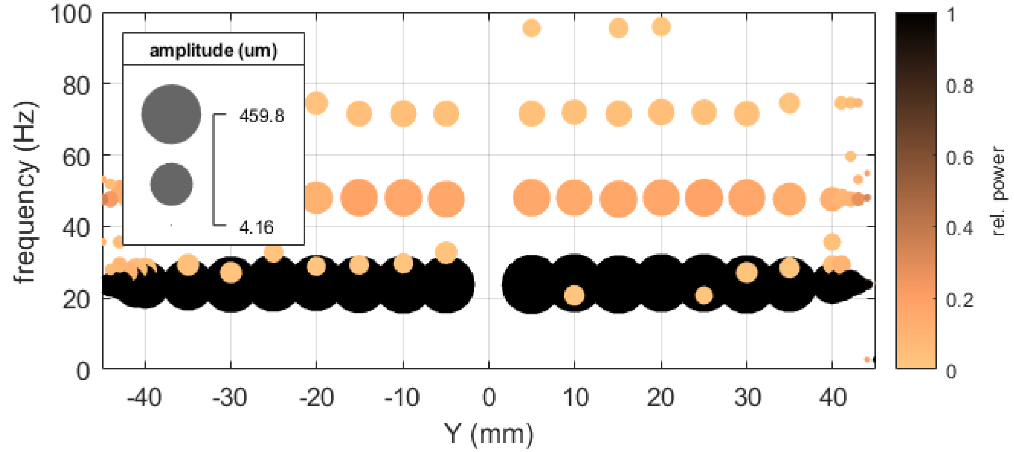


q = 21.1 L/h

Cross-flow film thickness profile (flat plate)

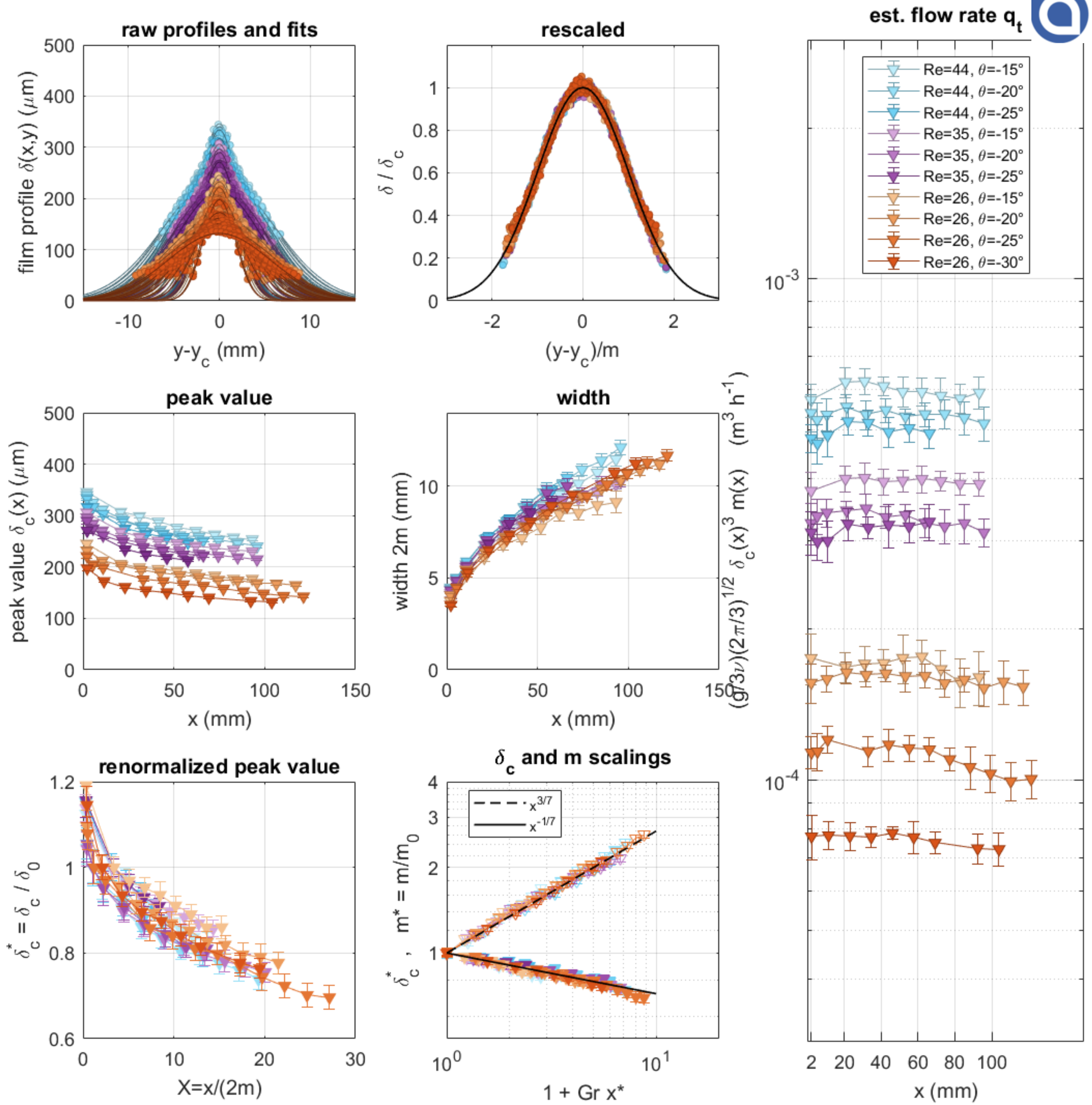




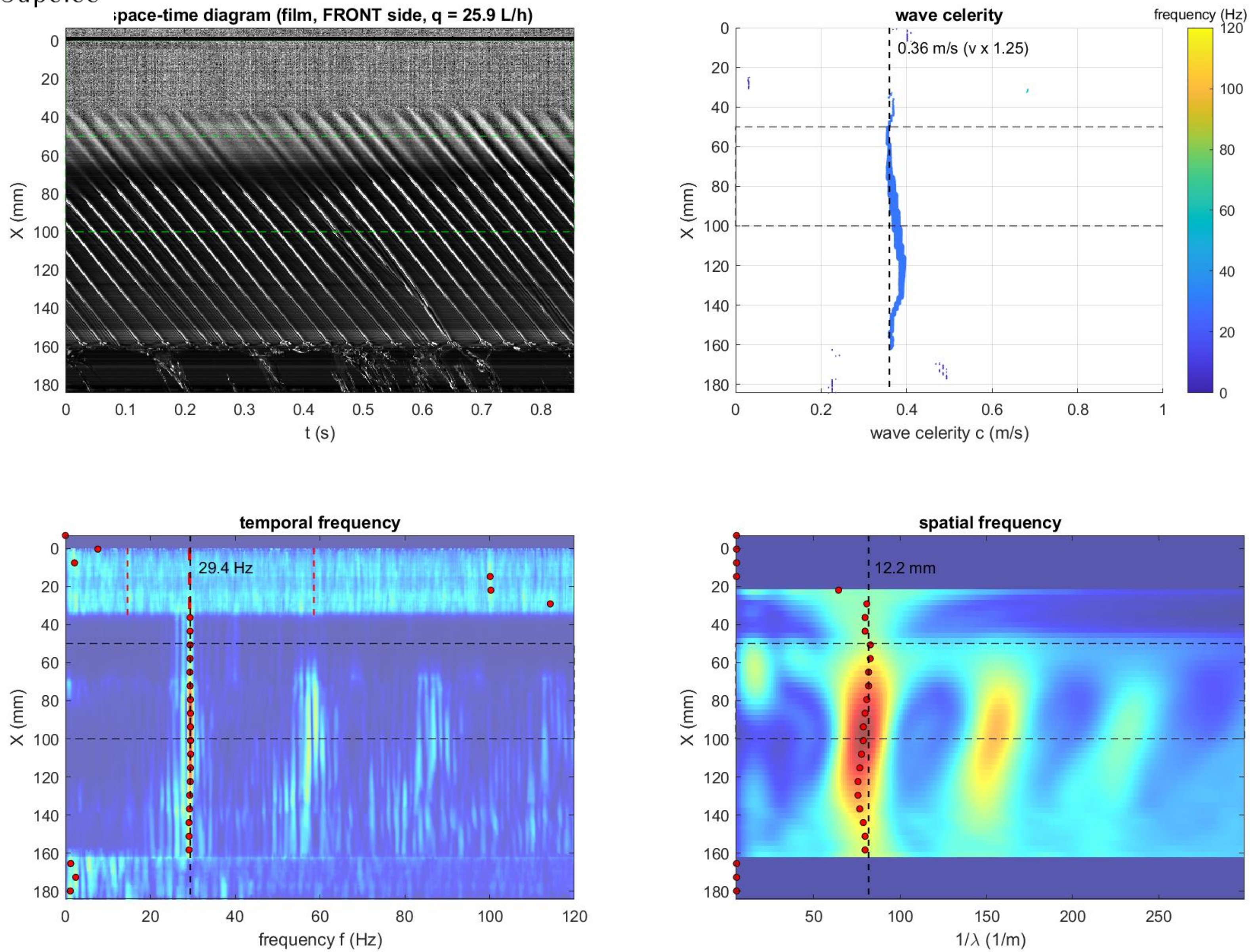


q = 21.1 L/h

Full CCI data

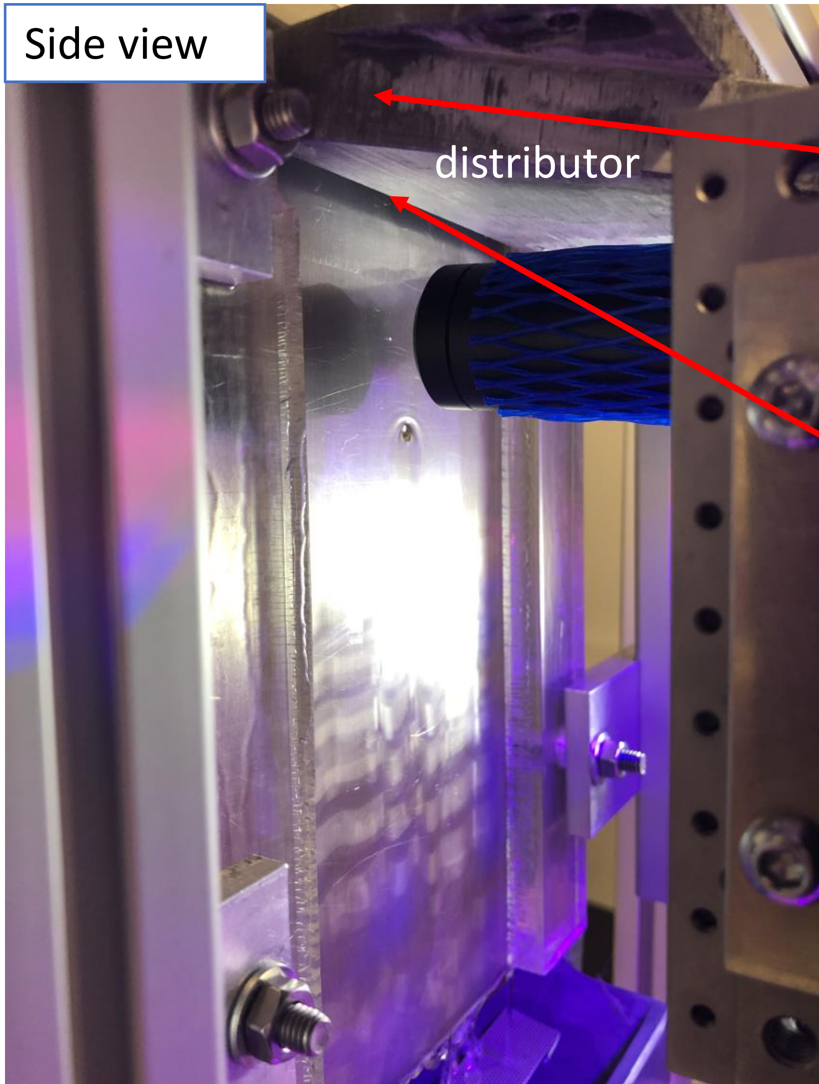


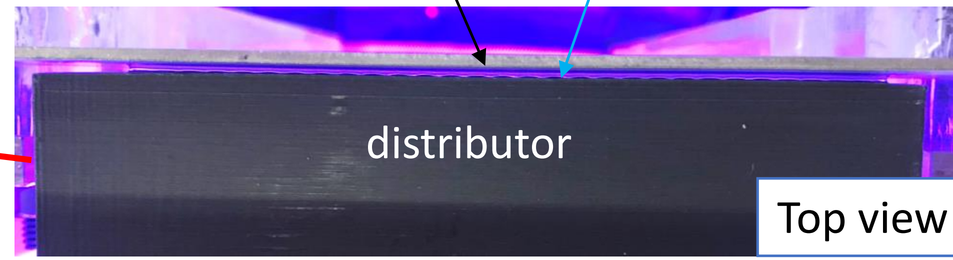
Wave train characterisation

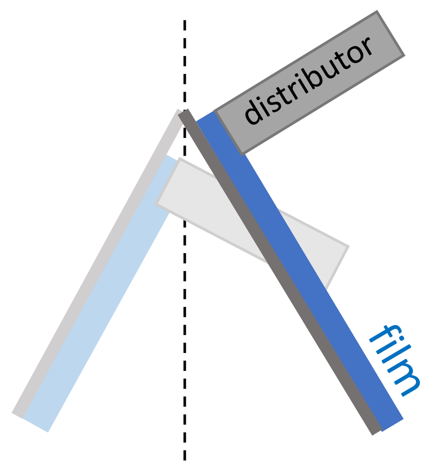


Experimental setup

Liquid distribution







Some industrial packings