The Role of Heat and Mass Transfer in Shaping a Sustainable Future

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Chair of Heat Transfer and Thermodynamics (HTT)

University Twente

Image source: science.nasa.gov

Today‘s journey

Optical measurement techniques and past challenges

Future challenges
(and my contribution)

Image source: Pexels, Pixabay

Where my journey began

Two-phase flow

Needles for imposed disturbance

Liquid film flow

Waves due to instabilities

Heated copper plate

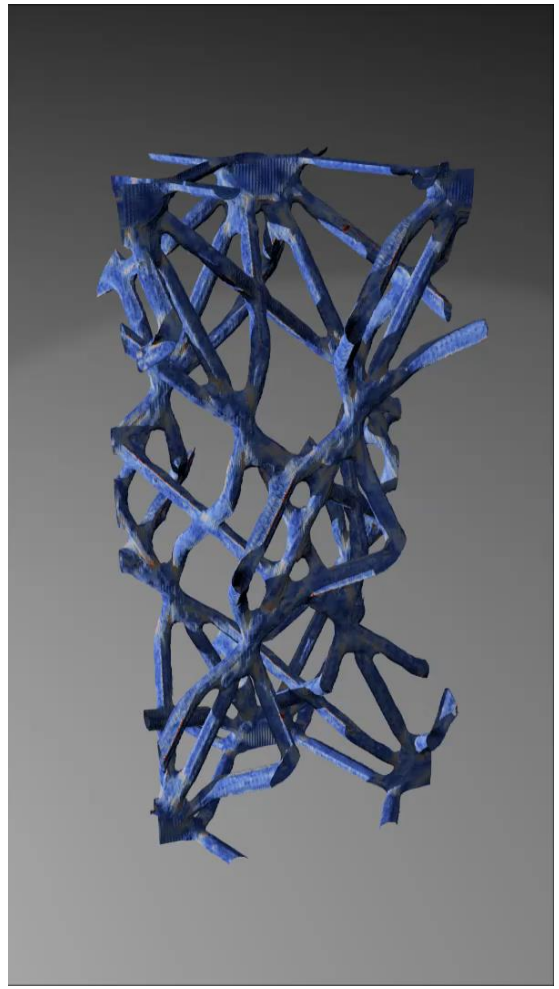
Capacitor plate for electric field

Rohlfs et al., *Exp. and Fluids*, 2012
Ehrenpreis et al. 2016

Where the journey began

Two-phase flow

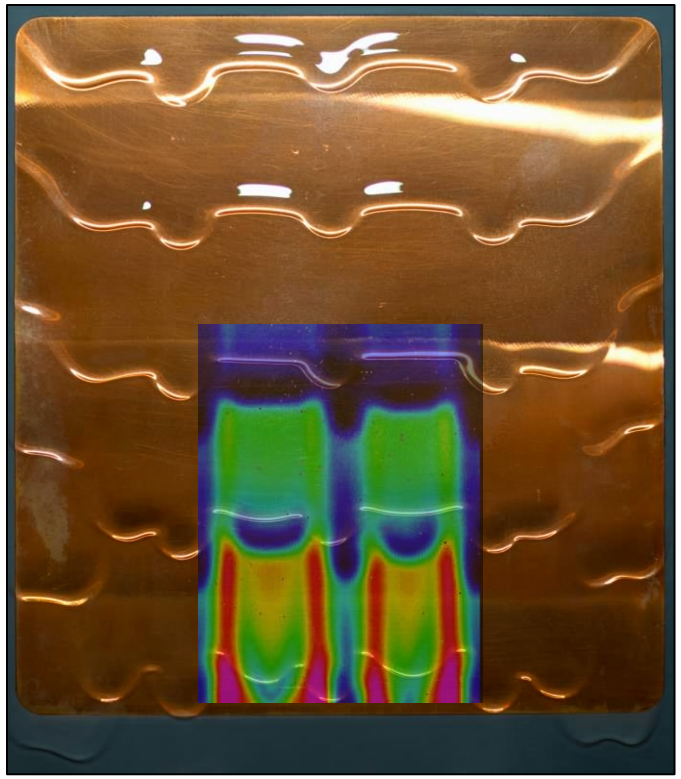
Rohlfs, South Africa, 2023



Research motivation:
Improve heat and mass transfer in two-phase flows by sophisticated models

Rohlfs et al., *Exp. and Fluids*, 2012
Ehrenpreis et al. 2016

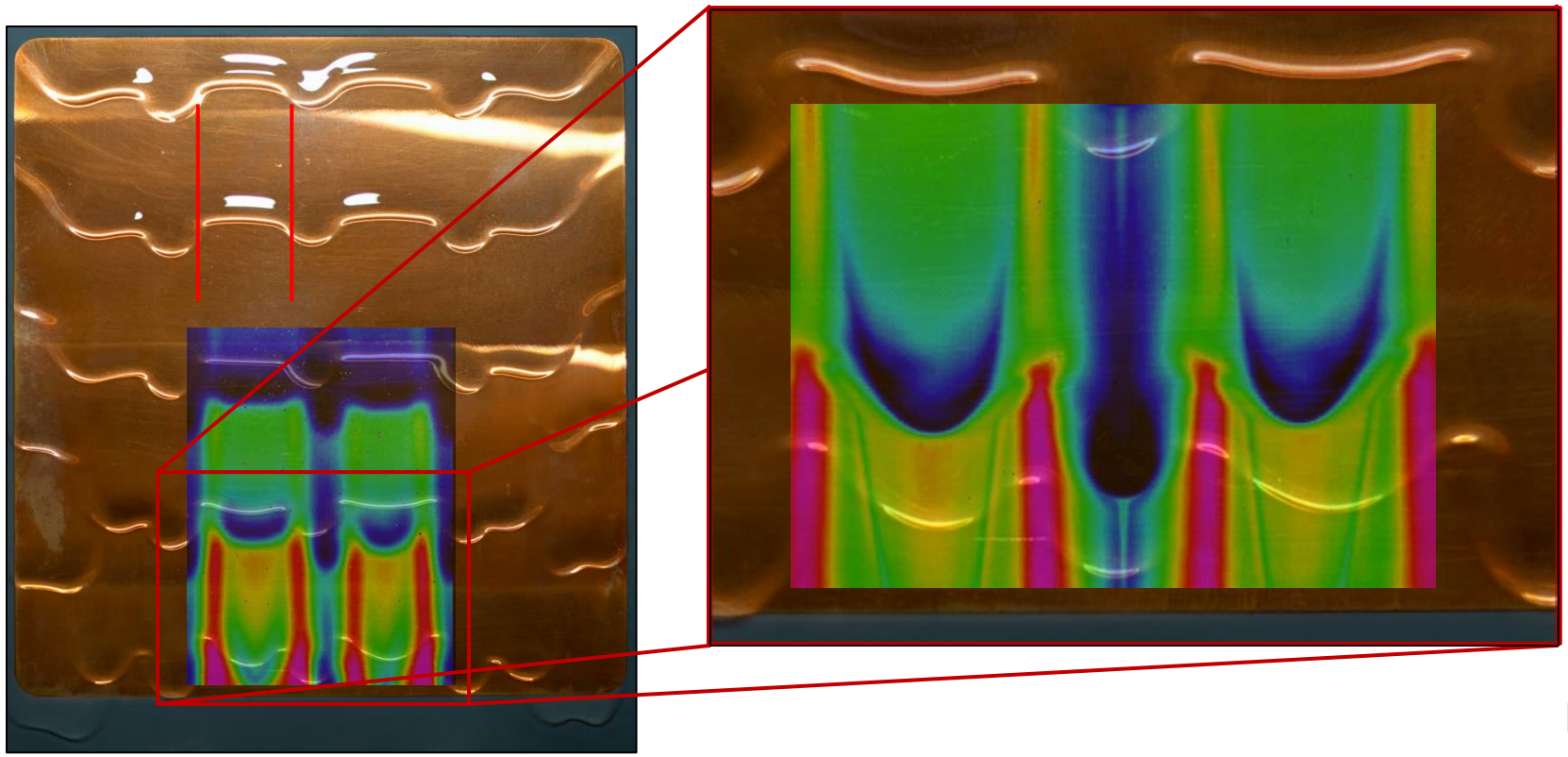
IR-Thermography



Reynolds Number:	4.5
Marangoni Number:	3.2
Frequency:	12Hz
Wavelength Λ_z:	30mm
Wall temperature:	65°C

Rohlfs et al., ITTW, 2013,
Haustein et al., Int. J. Heat and Mass Transfer, 2012

IR-Thermography



Reynolds Number:	4.5
Marangoni Number:	3.2
Frequency:	12Hz
Wavelength Λ_z:	30mm
Wall temperature:	65°C

Key results:
Hot streak development is connected with vertical wave fronts

Rohlfs et al., ITTW, 2013,
Haustein et al., Int. J. Heat and Mass Transfer, 2012

Confocal chromatic imaging

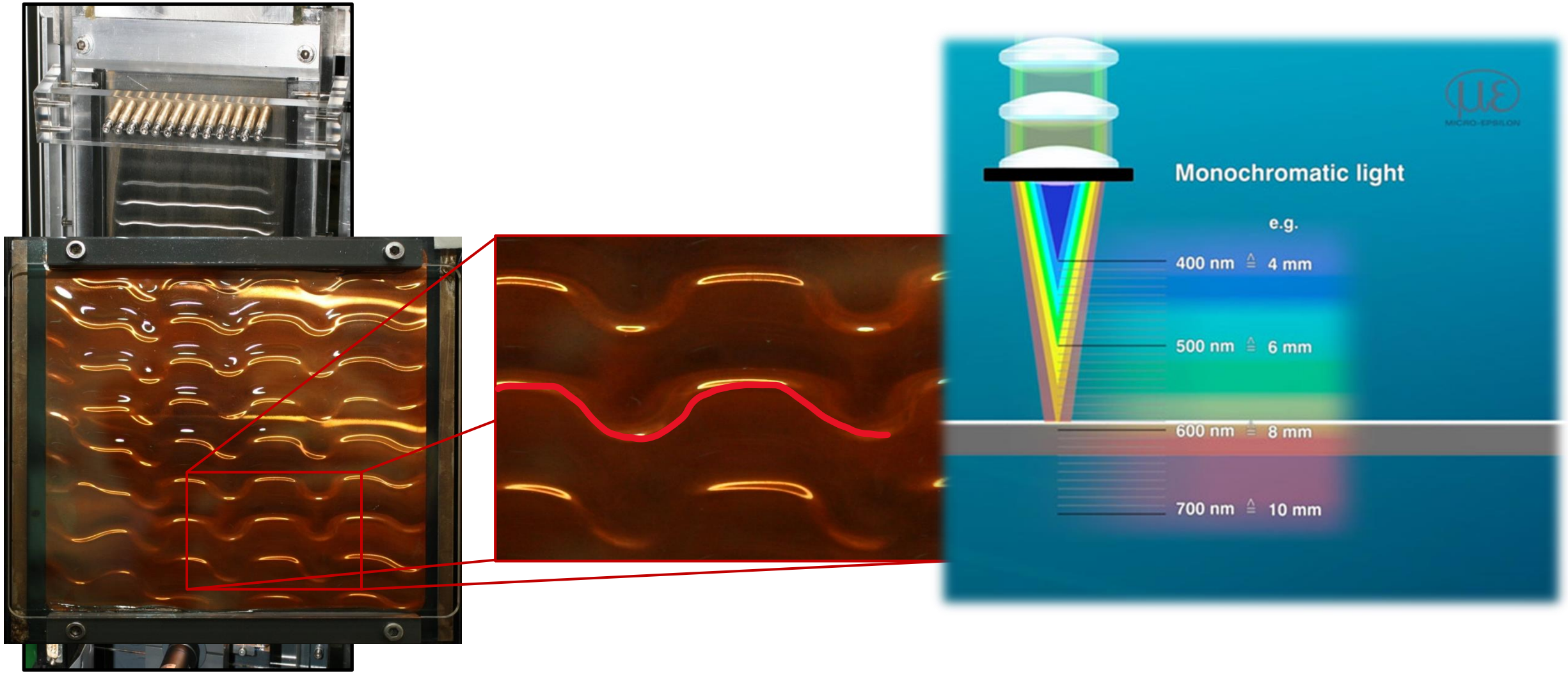
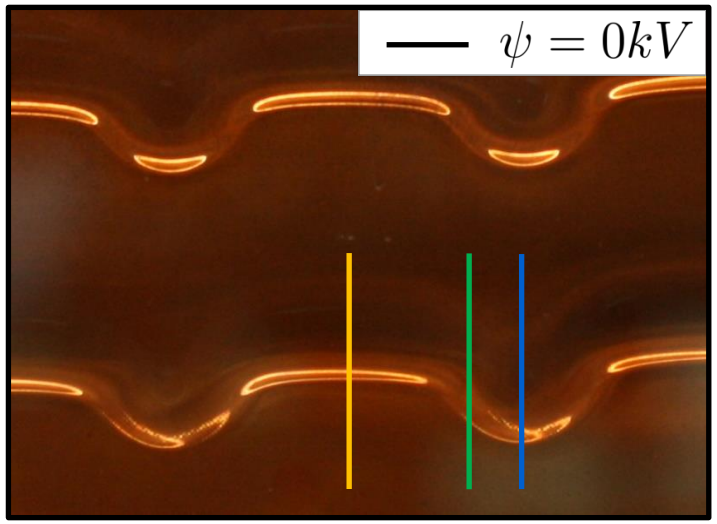
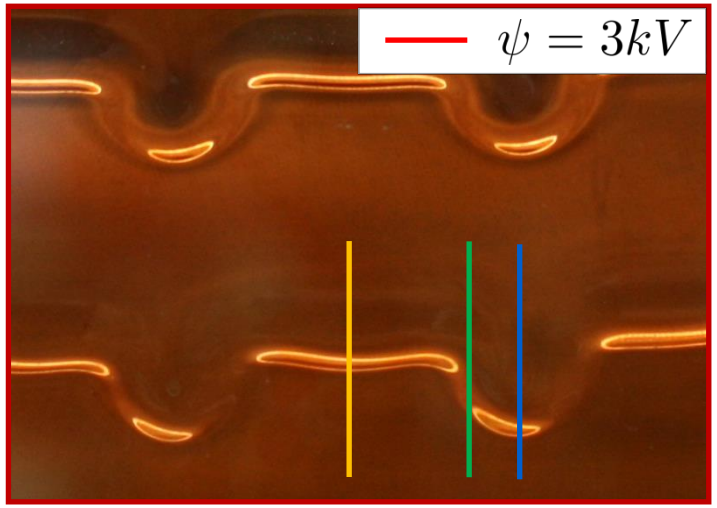
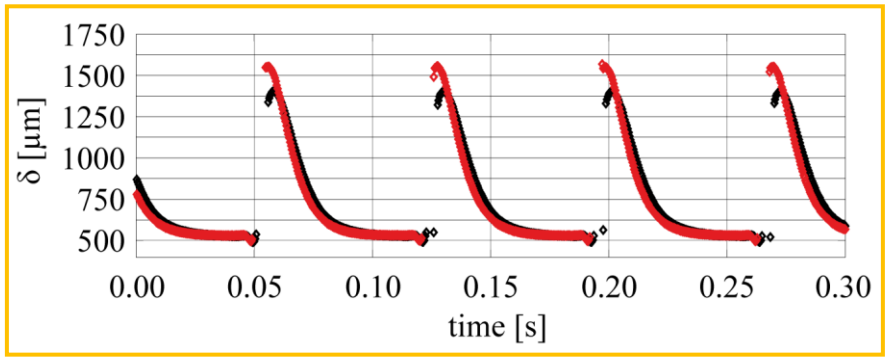


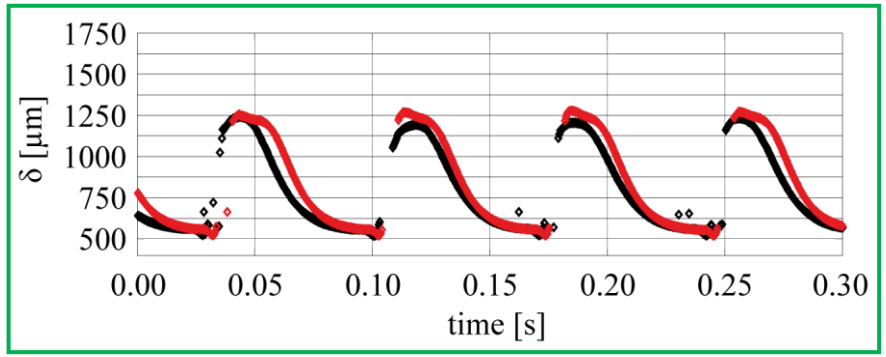
Image source: Micro-Epsilon

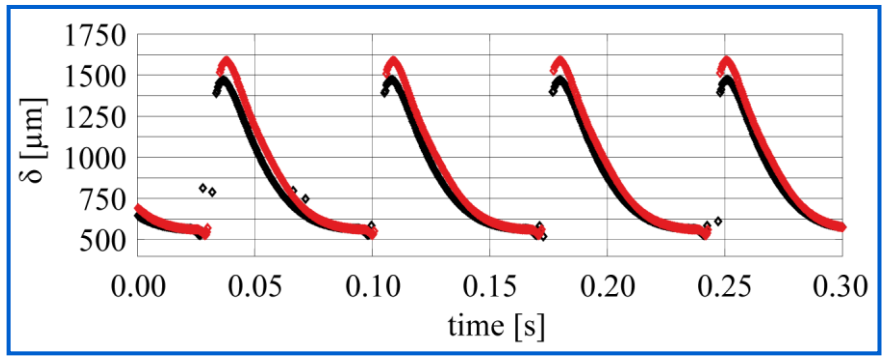
Wave profiles influenced by electrostatic forces



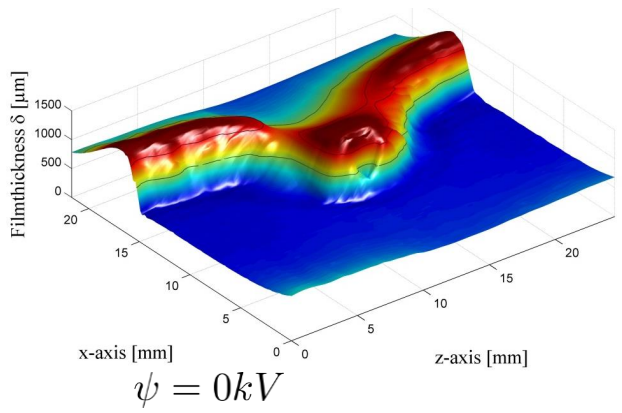








Reconstructed interface



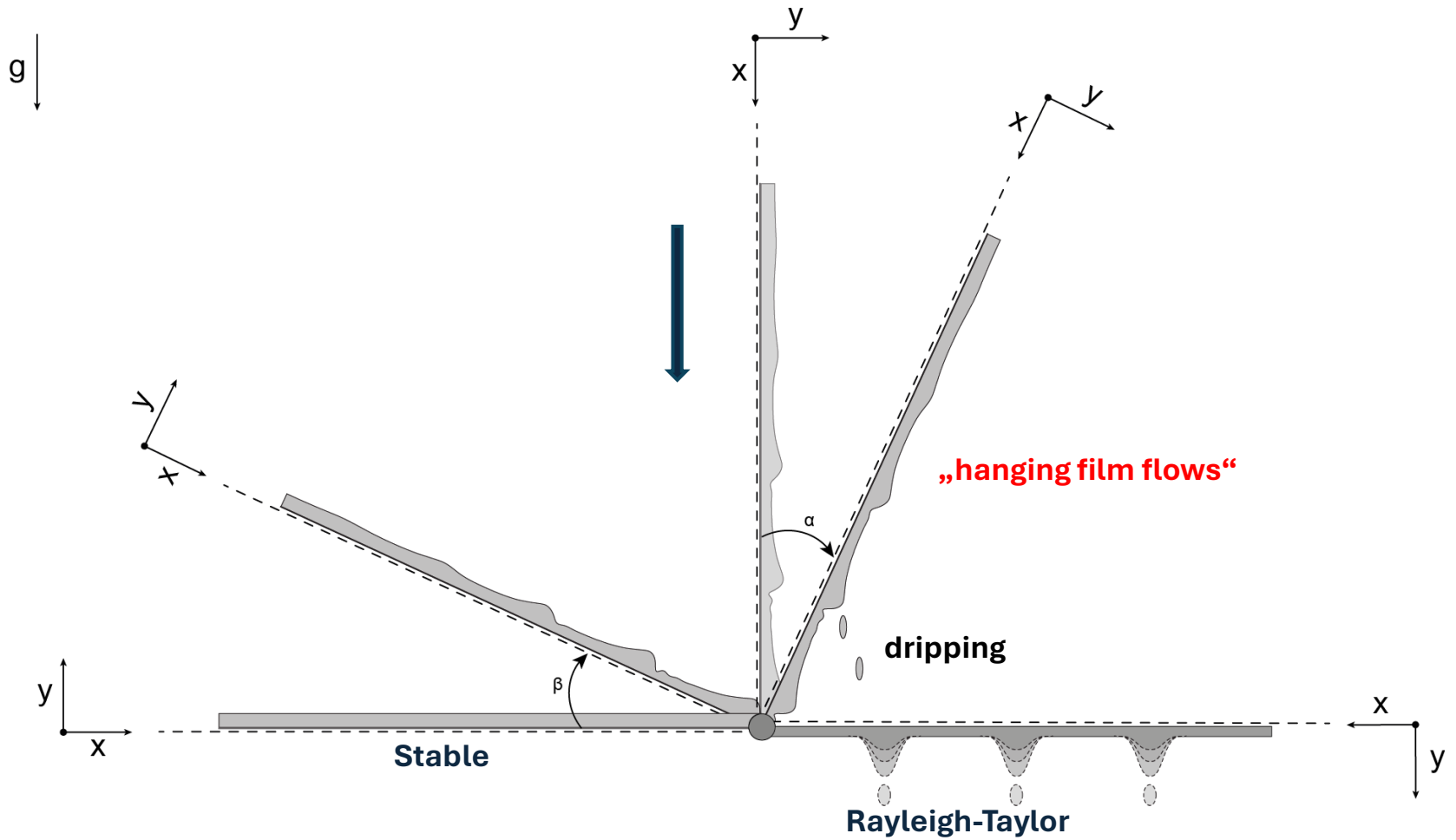
$\psi = 0kV$

Key results:

- Electrostatic surface force pulls on the liquid surface (in wall-normal direction)
- Data for model validation

Rohlfs et al., *Exp. in Fluids*, 2012

New research direction: Dripping

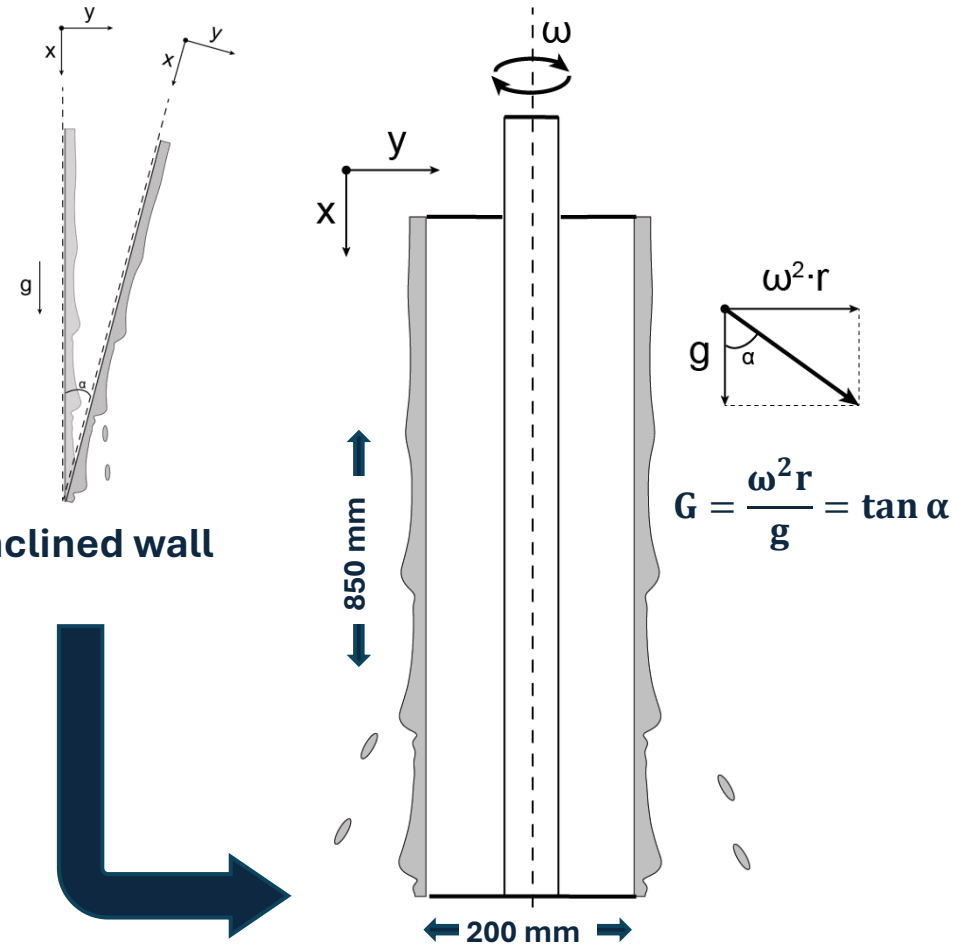


DFG Project 2018: Characterization and prediction of dripping on planar and circular surfaces

Scheid et al., *Physics of Fluids*, 2016
Rohlfs et al., *J. Fluid Mechanics*, 2020

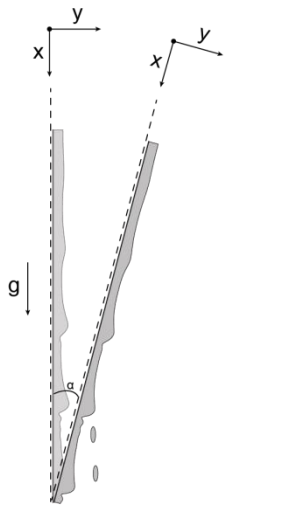
DFG Deutsche Forschungsgemeinschaft

High-speed visualization

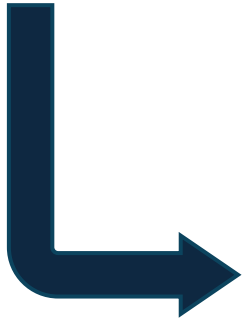


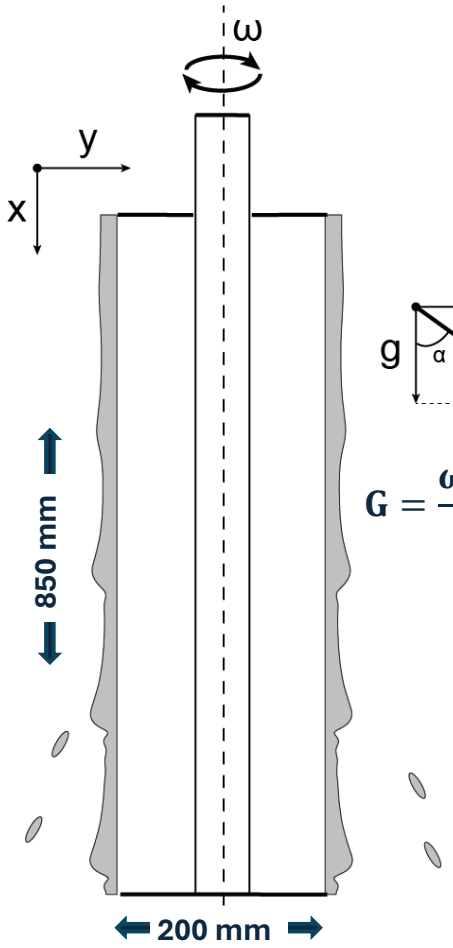
Rietz et al., *J. Fluid Mechanics*, 2017
Rietz et al., *Physical Review Fluids*, 2021

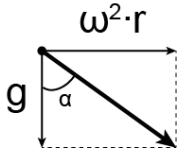
High-speed visualization



Inclined wall





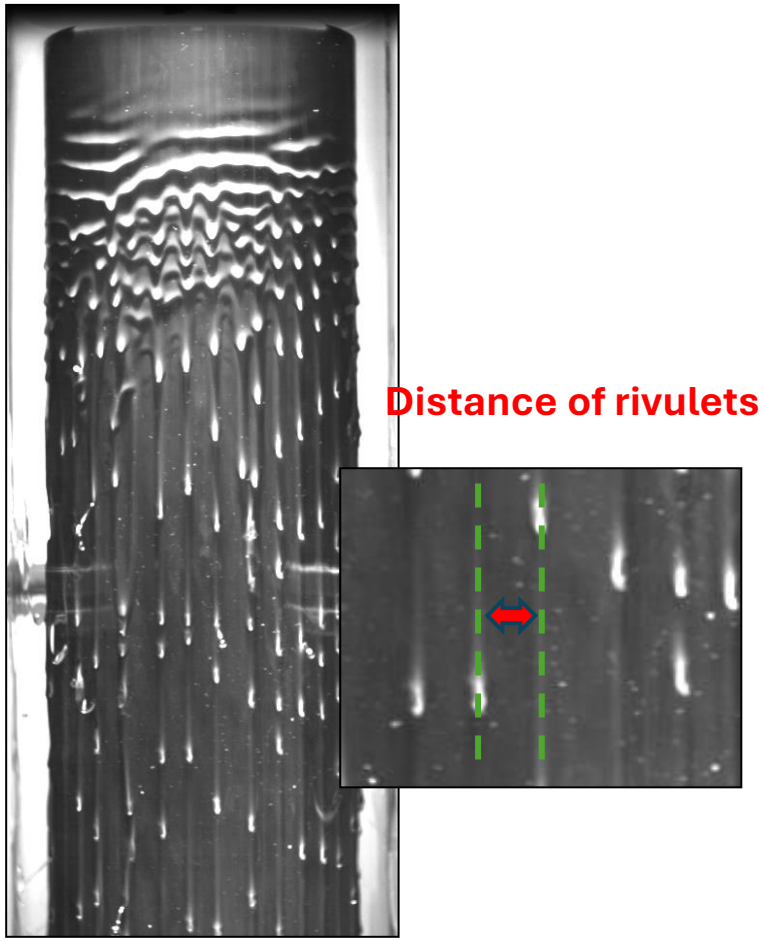


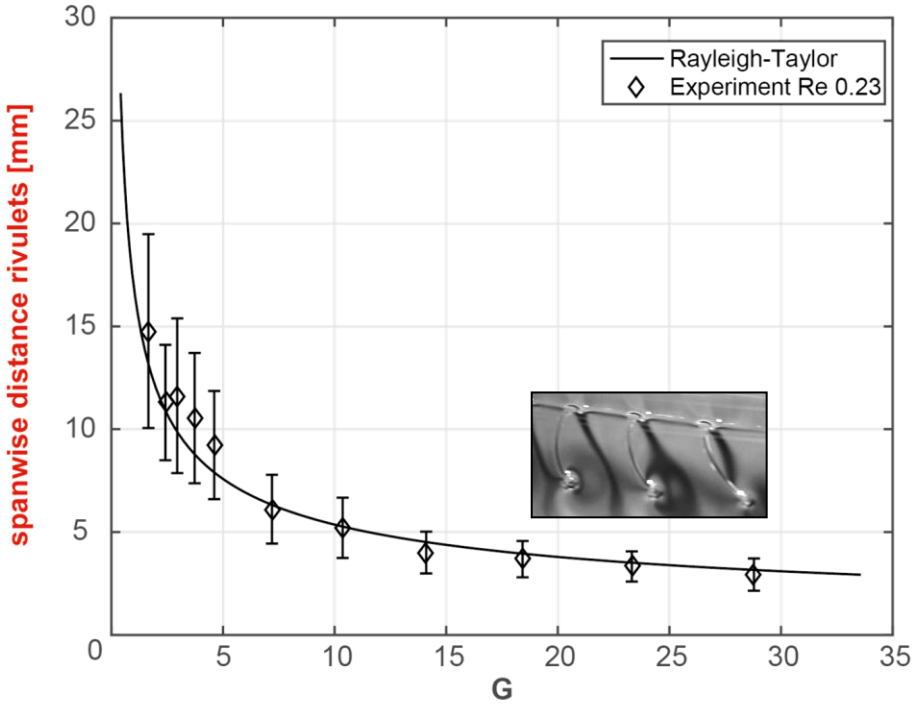
$$G = \frac{\omega^2 r}{g} = \tan\alpha$$

71 rpm α = 29° **95 rpm** α = 45°

Rietz et al., *J. Fluid Mechanics*, 2017
Rietz et al., *Physical Review Fluids*, 2021

Experimental results: Scaling laws



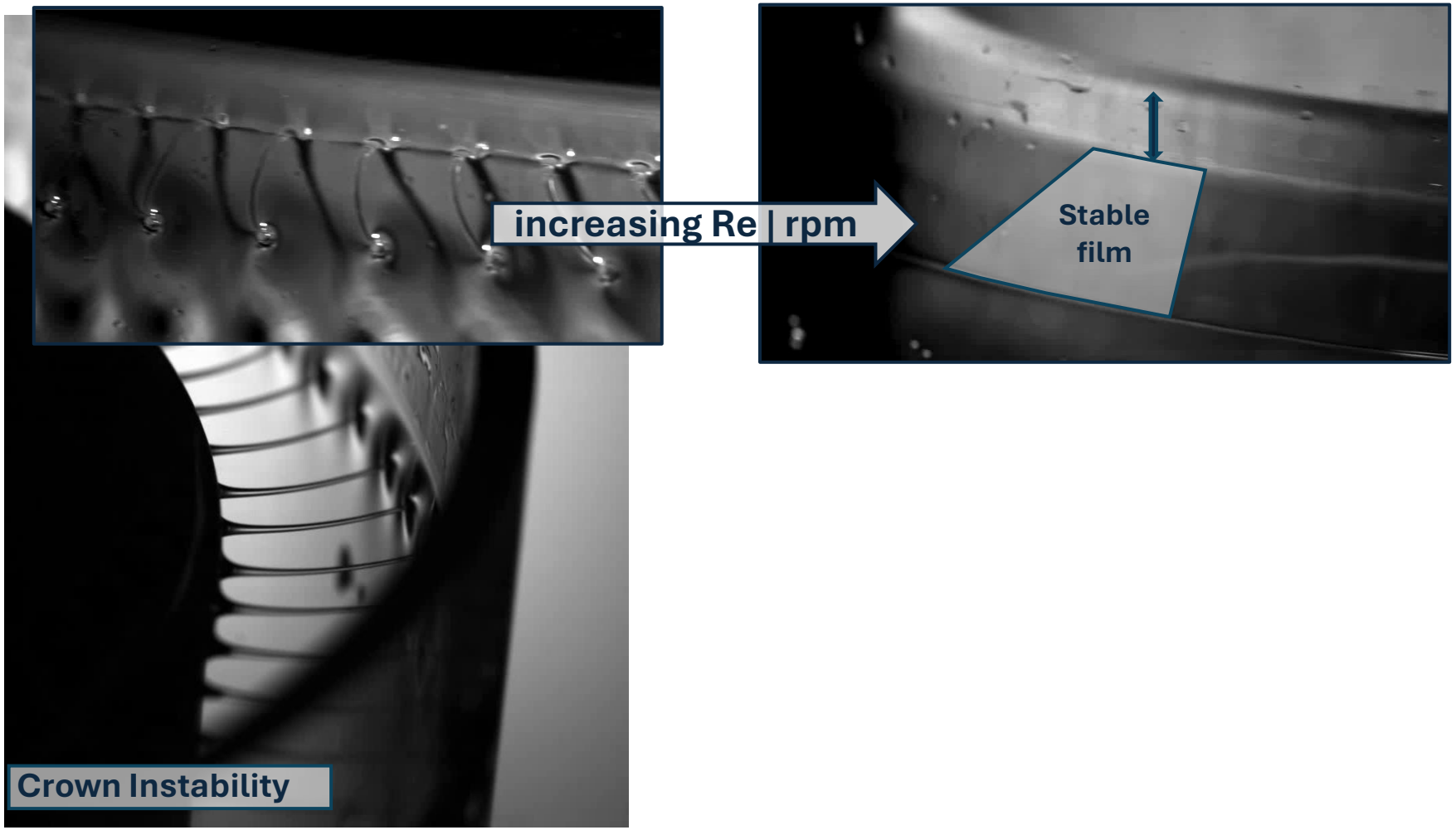


Key result:
Rivulets and their growth are dominated by Rayleigh-Taylor instability

Rietz et al., *J. Fluid Mechanics*, 2017
Rietz et al., *Physical Review Fluids*, 2021

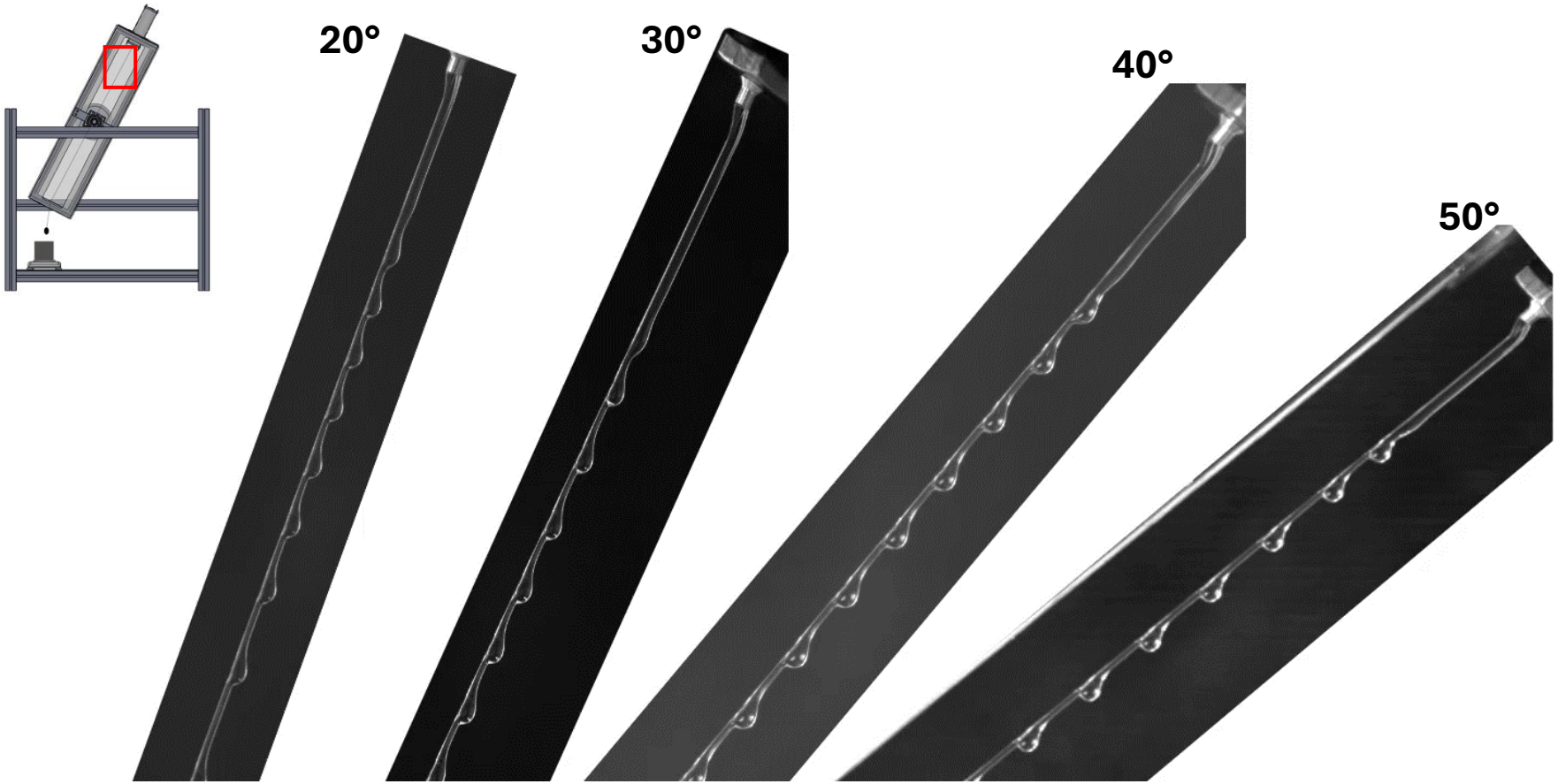
High-Speed visualization

Immediate dripping



Rietz et al., *J. Fluid Mechanics*, 2017
Rietz et al., *Physical Review Fluids*, 2021

Visualization of dripping on fibers



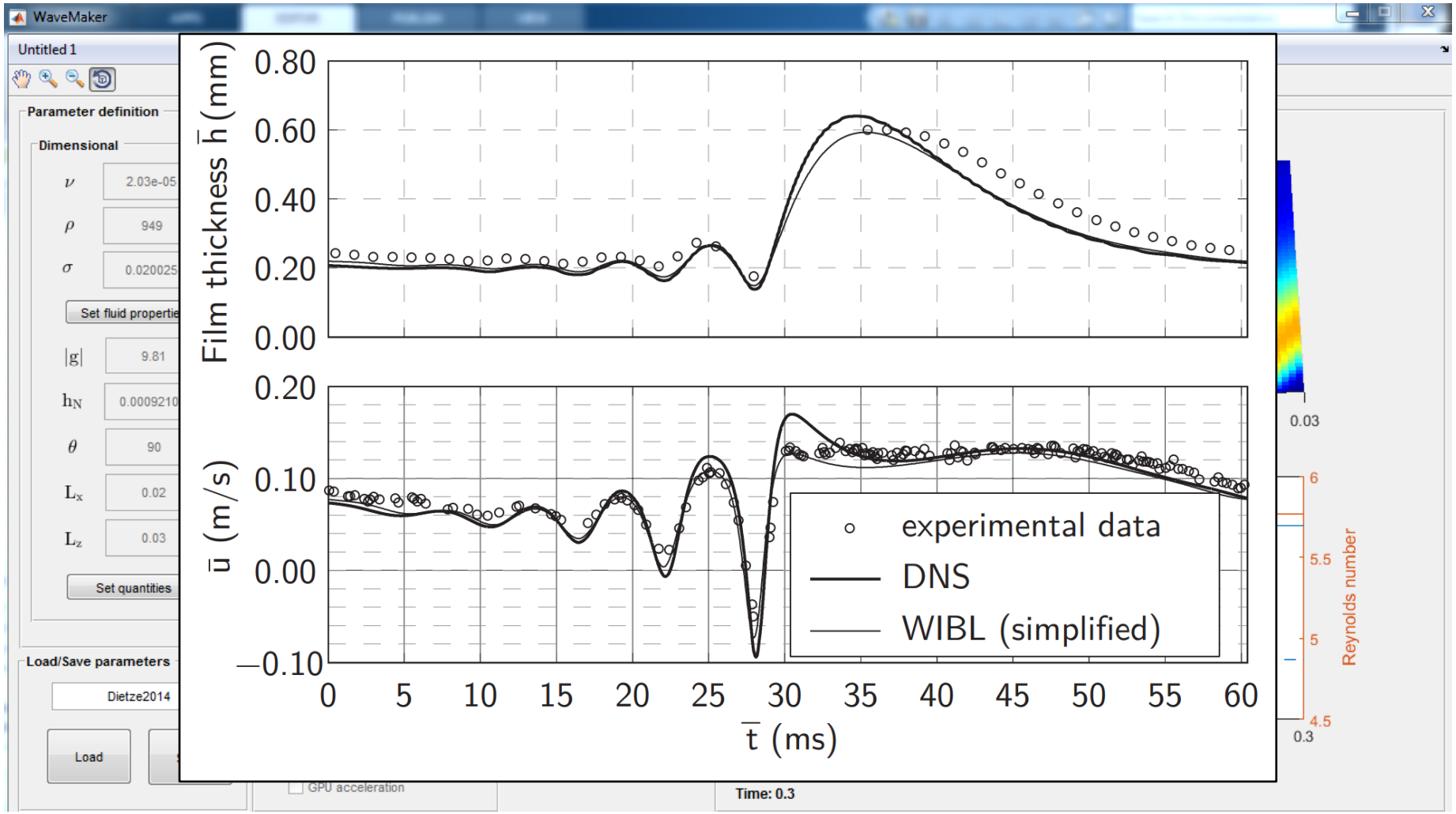
Key result:

- Characterization of dripping
- Link to convective and absolute instability
- Map of different dripping mechanisms

DFG Deutsche Forschungsgemeinschaft

Pour Karimi et al., *IMA, 2022*

Validation of numerical tools

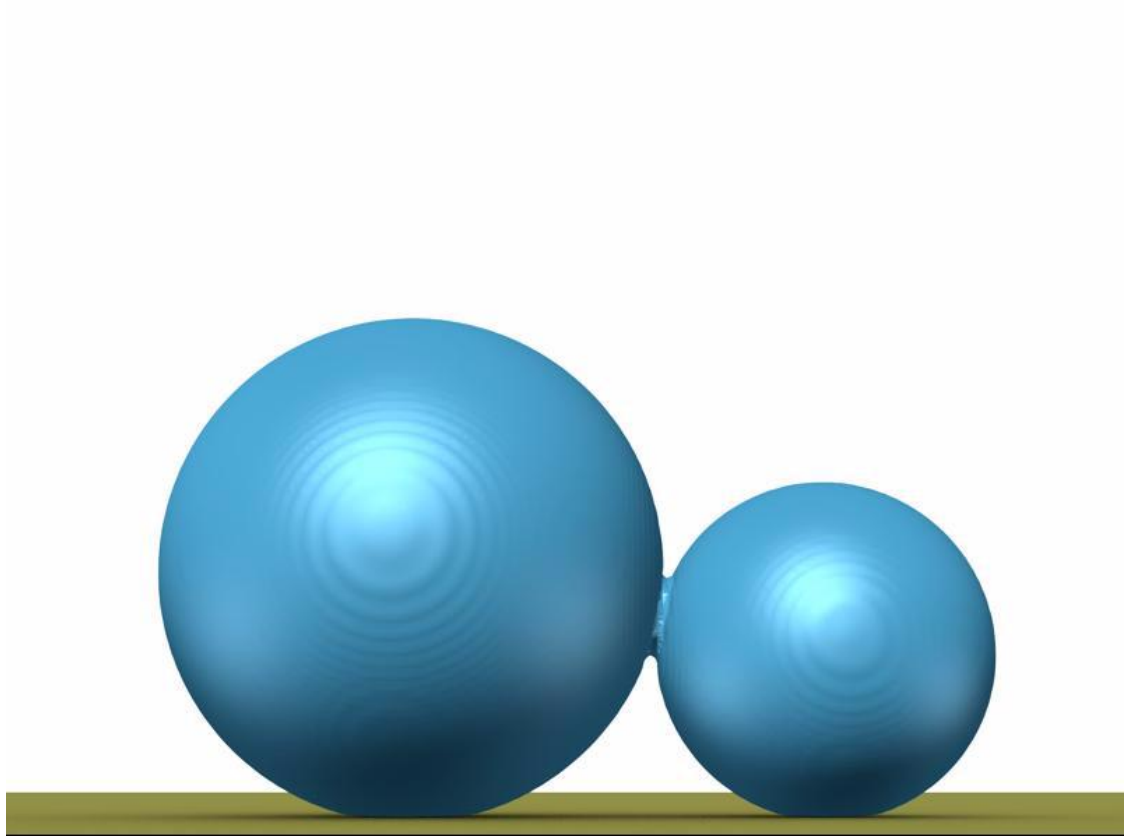


Key result:

- Matlab tool for simulating 3-D waves (Integral Boundary Layer Model), **openSource**
- Validated by quantitative comparison to experiments
- DNS results agree less with experiments

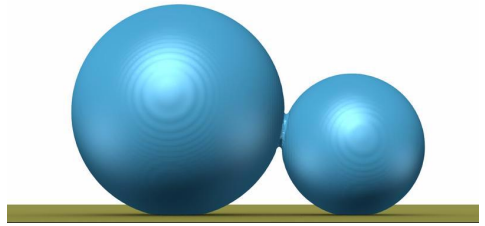
Rohlfs et al., *SoftwareX*, 2018
Exp. data: Dietze et al. *J. Fluid Mechanics*, 2009 (not contrib.)

Validation of numerical tools



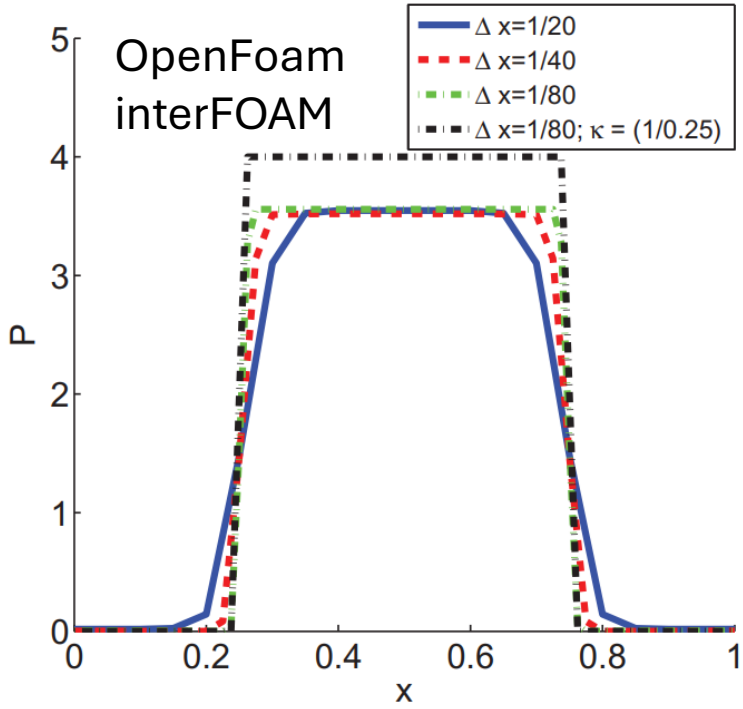
Wasserfall et al., *Physical Review Fluids*, 2017

Validation of numerical tools



$$\Delta P = \frac{2\sigma}{R}$$

Pressure jump across interface

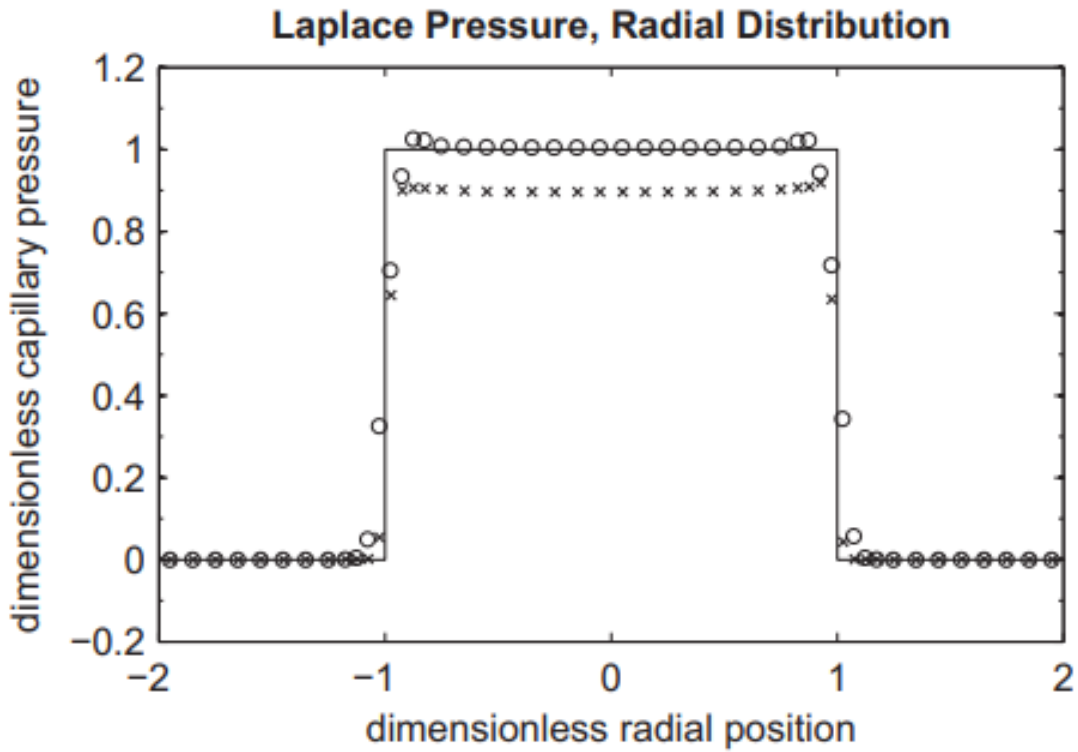


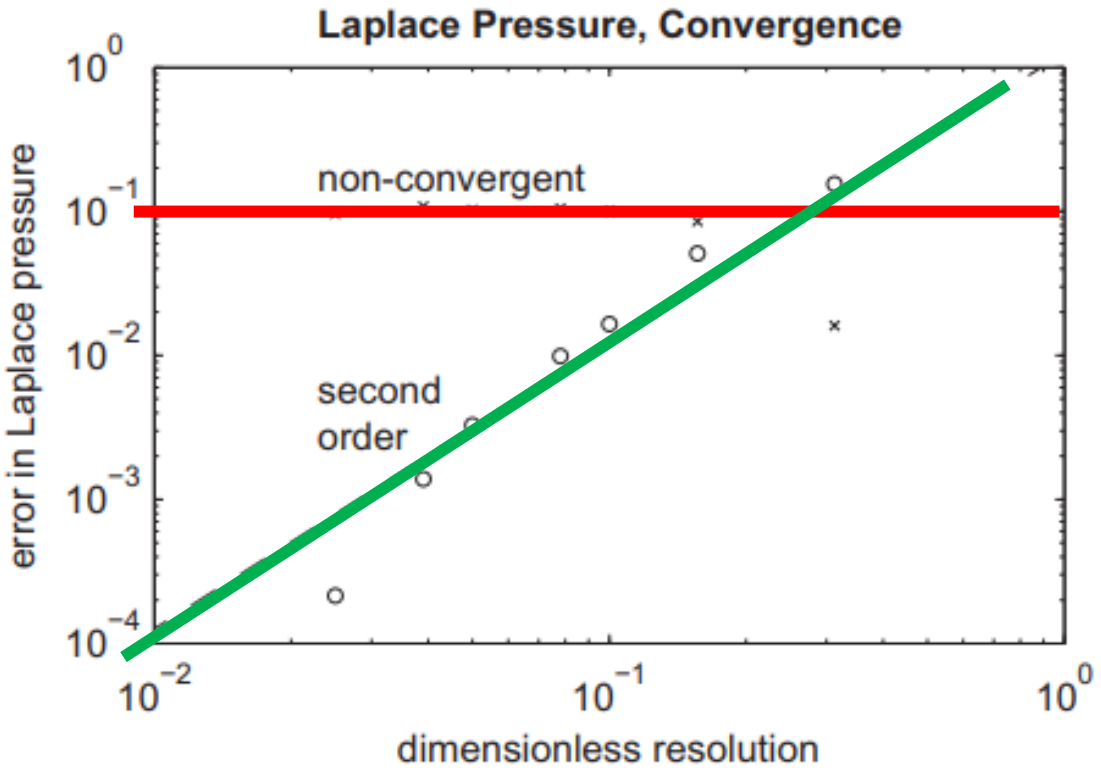
Systematic underprediction of the pressure jump

→ No convergence

Wasserfall et al., *Physical Review Fluids*, 2017

Improvement of numerical tools





Key results:

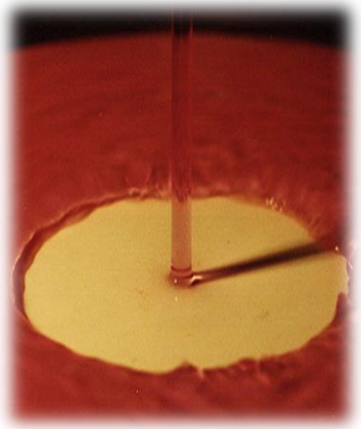
- Improved advection scheme
- Correct prediction of the pressure jump with second order convergence

x – original interFoam

o – smooth interface compression

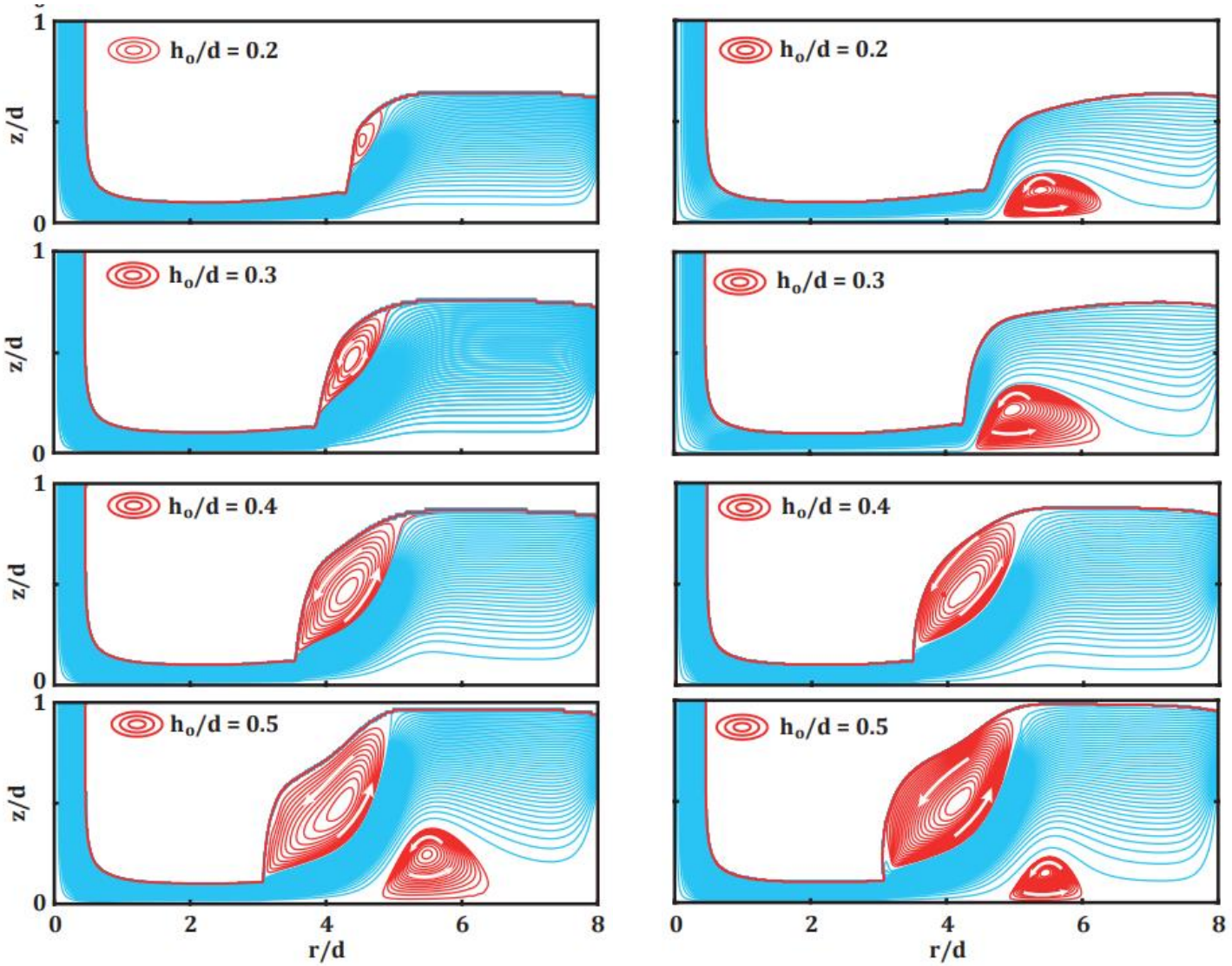
Rohlfs et al., *Multiphase Science and Technology*, 2020

Improvement of numerical tools



Incorrect pressure (interFoam)

Corrected pressure (SMICFoam)



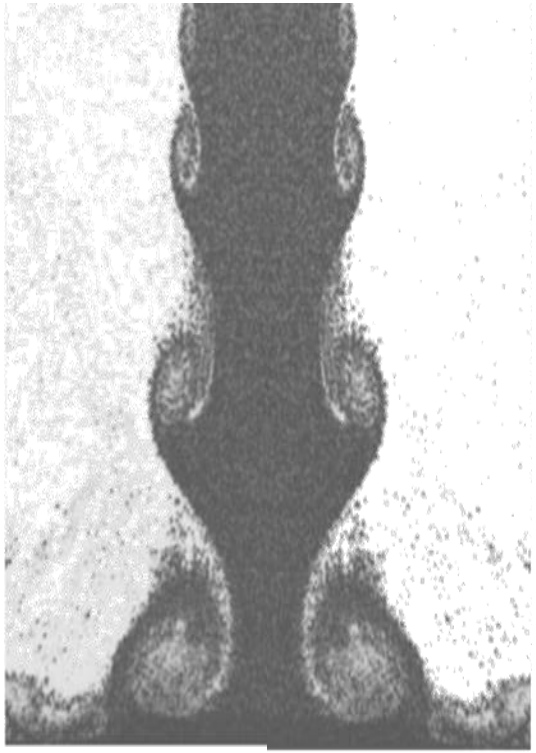
Key results:

- Correct prediction of the hydraulic jump in circular jet impingement
- Good agreement with experimental observations

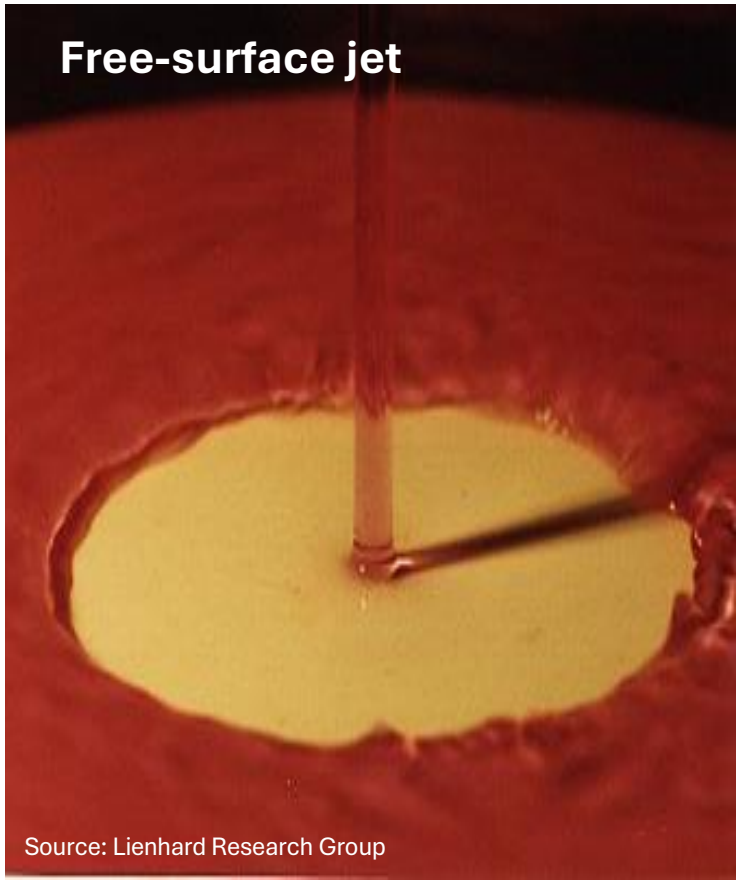
Askarizadeh et al., *Physical Review Fluids*, 2019
Askarizadeh et al., *Atomization and Sprays*, 2020

Physics of jet impingement

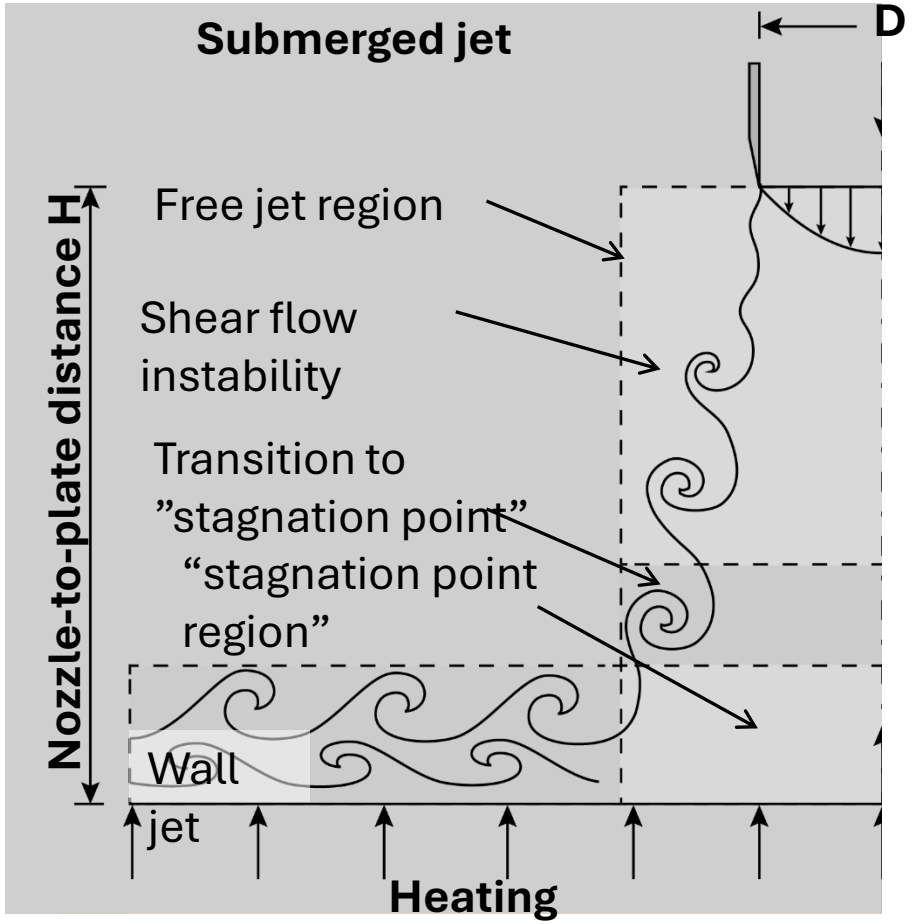
Submerged jet



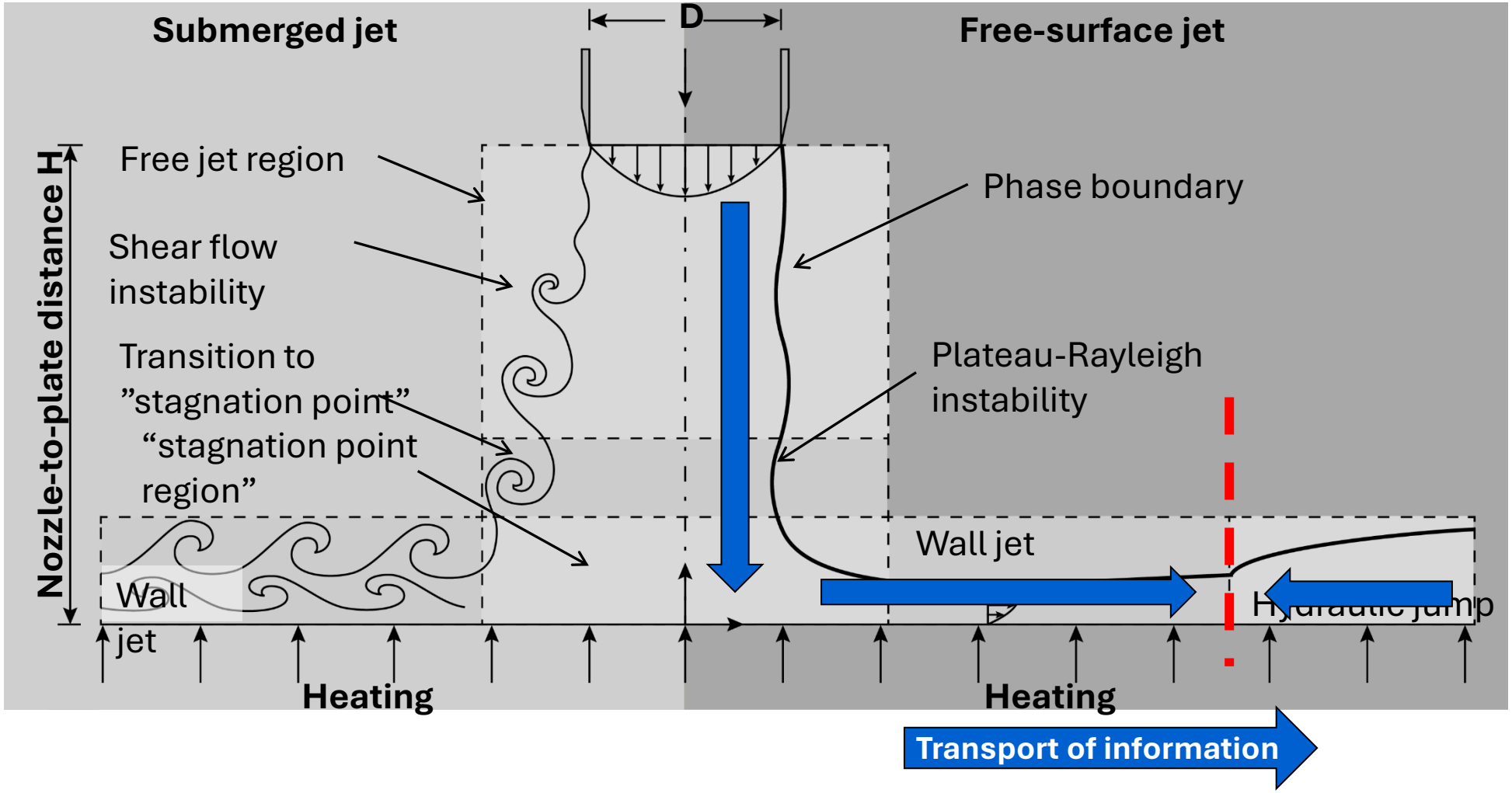
Source: Angioletti et al. 2003



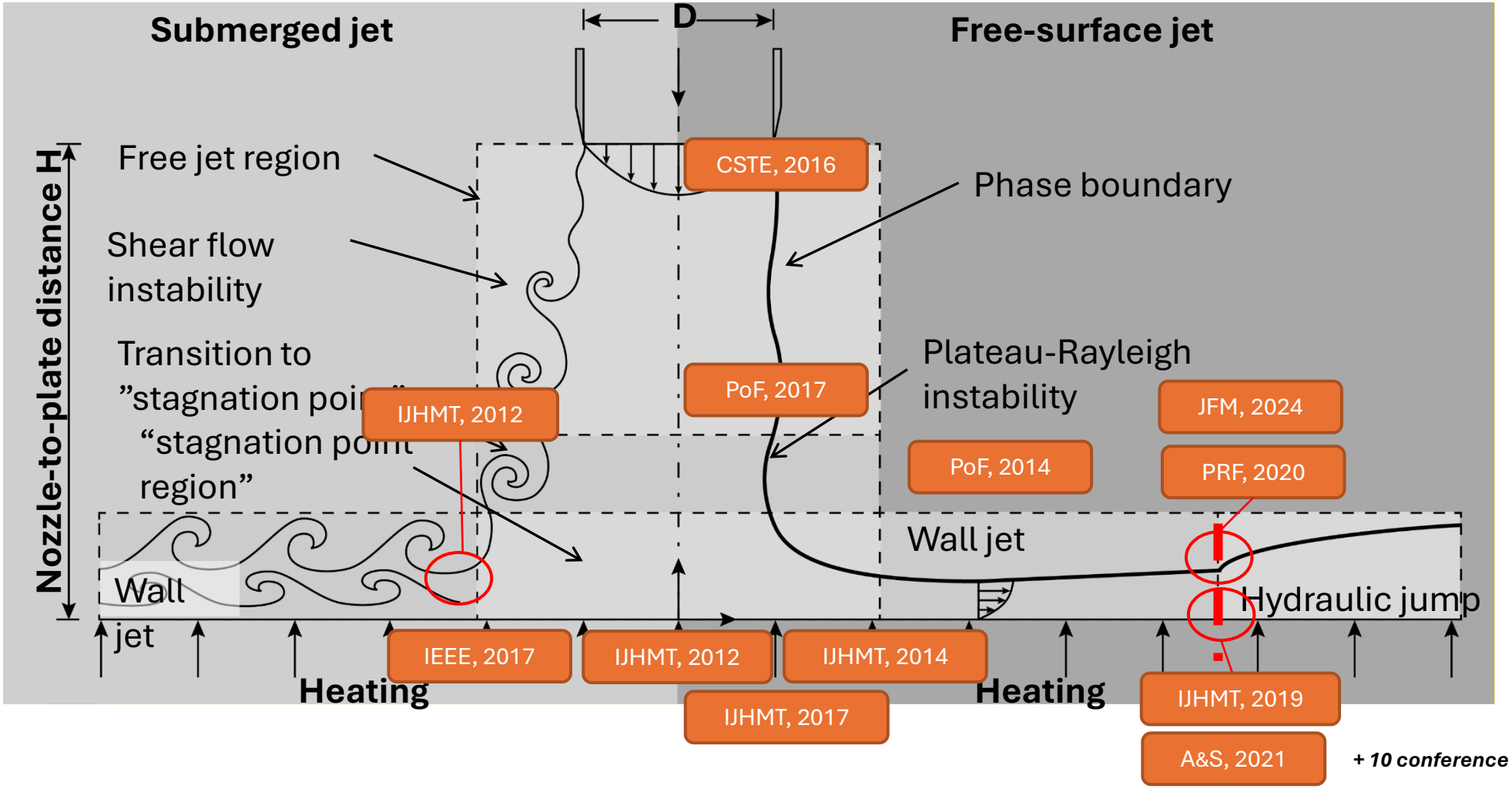
Physics of jet impingement



Physics of jet impingement

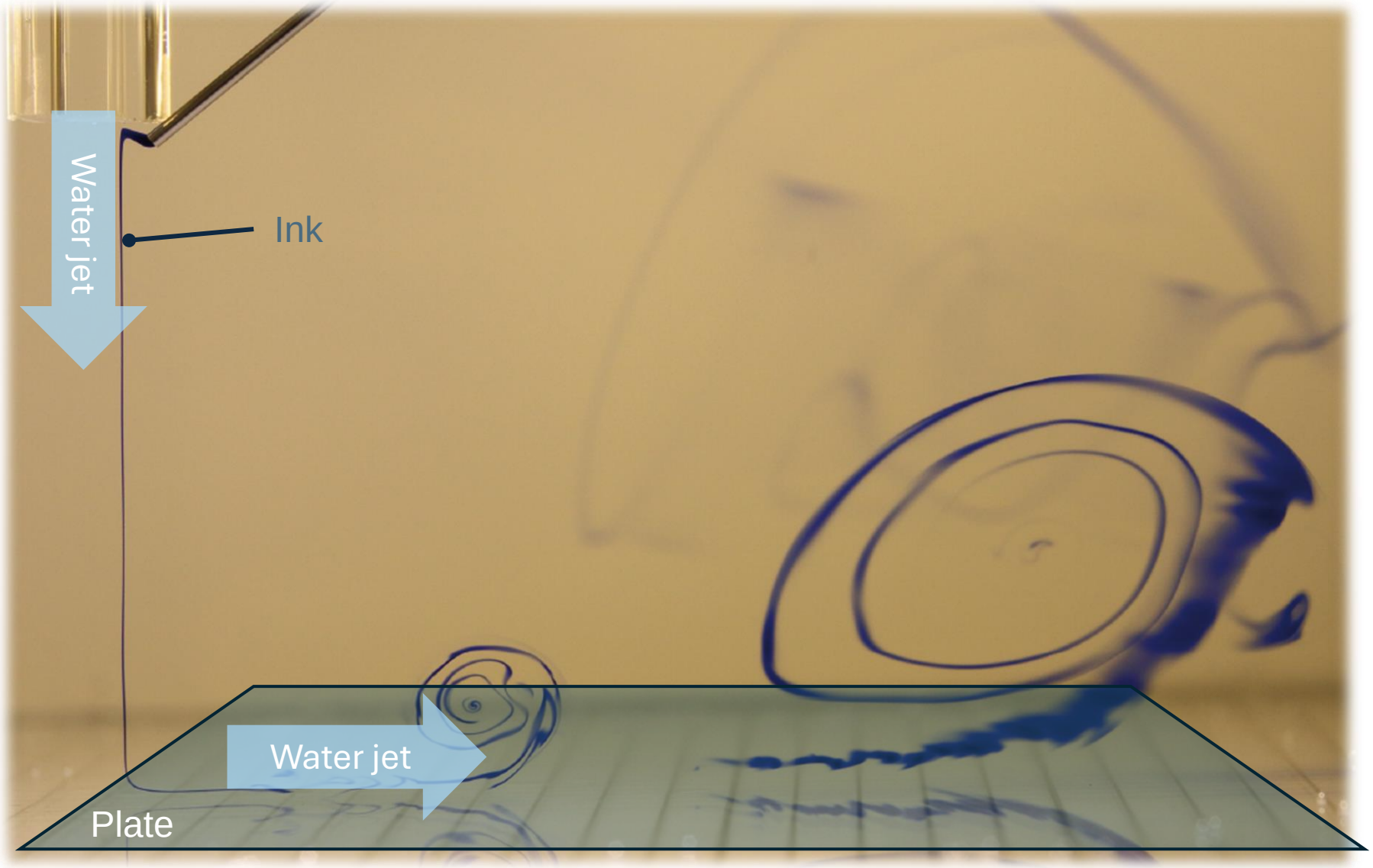


Physics of jet impingement

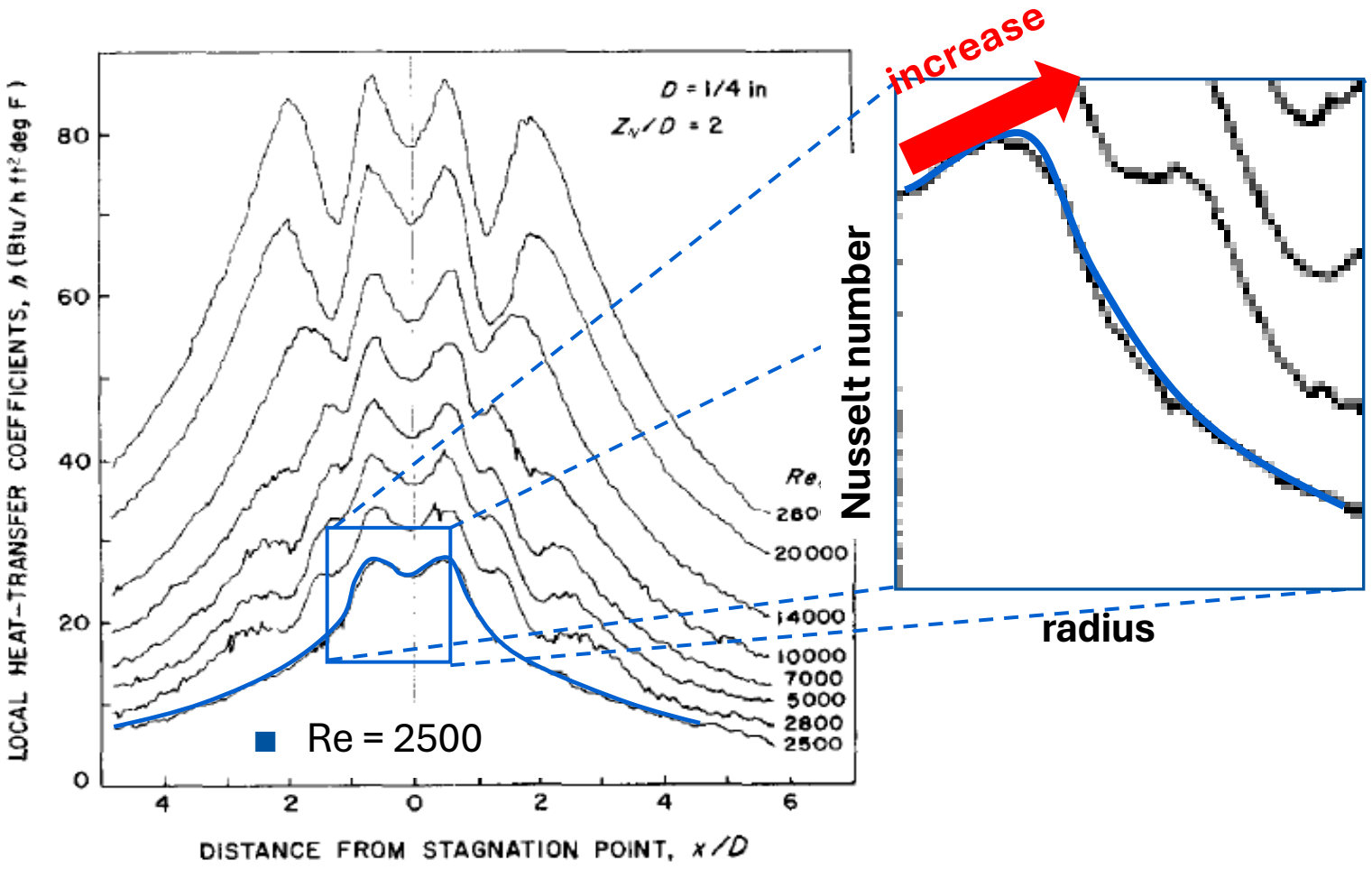


+ 10 conference proceedings

Pathline visualization



Key results in jet impingement



Increasing Nusselt number in flow direction

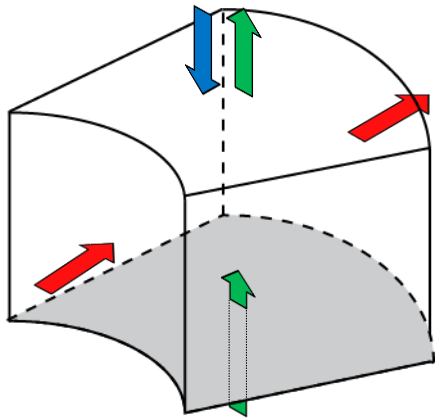
Reduced wall temperature despite heating

Gardon R. and Akfirat J.: The role of turbulence in determining the heat-transfer characteristics of impinging jets, Int. J. Heat Mass Transfer 8 (10) (1965) 1261–1272.

Van der Meer, T. H.: Heat transfer from impinging flame jets. Dissertation (1987), TU Delft, The Netherlands

Key results in jet impingement

Energy balance near the wall for the stationary solution:



Change of the advective heat transport in radial direction
\+ Change of conduction in axial direction
= Change of the advective heat transport in axial direction

Assumption: Conduction in radial direction is negligible

With the continuity equation it follows:

$$\frac{\partial T(r,x)}{\partial r} = \frac{k}{\rho c_p}\frac{1}{v(r,x)}\frac{\partial^2 T(r,x)}{\partial x^2} - \frac{u(r,x)}{v(r,x)}\frac{\partial T(r,x)}{\partial x}$$

Condition for an increasing Nusselt number

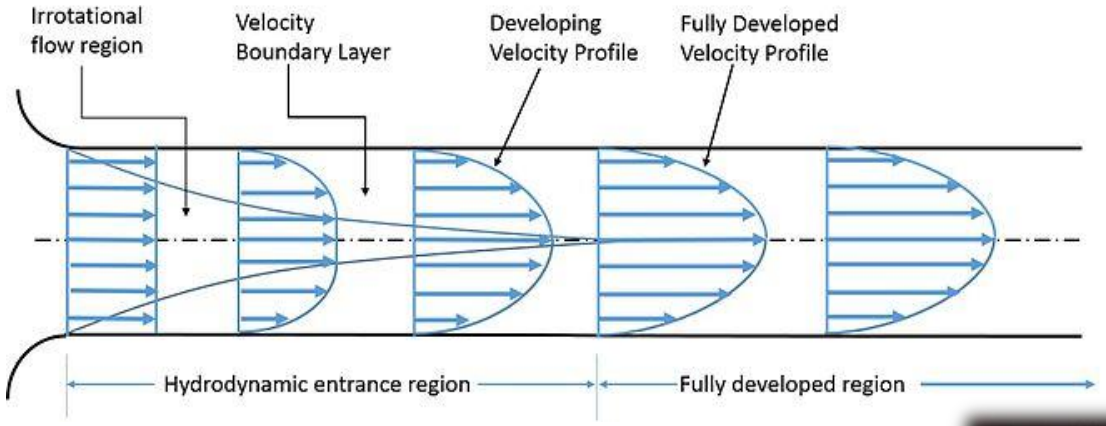
$$\frac{\partial \mathrm{Nu}}{\partial \mathrm{r}} > 0 \quad \Leftrightarrow \quad \frac{\partial T(r,x)}{\partial r} < 0$$

Critical wall-normal velocity:

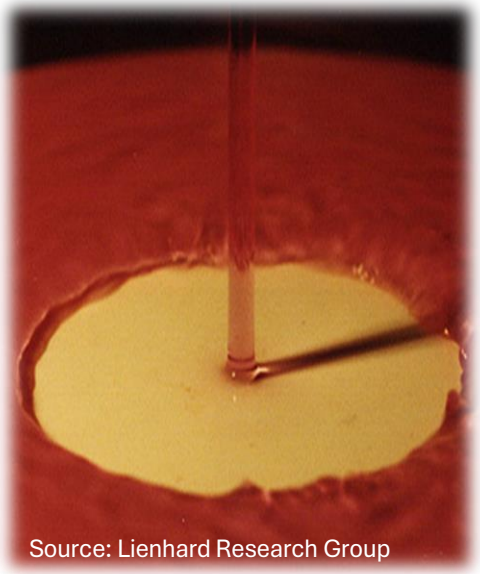
$$u(r,x) > \frac{k}{\varrho c_p}\frac{\partial^2 T(r,x)}{\partial x^2}\frac{1}{\frac{\partial T(r,x)}{\partial x}}$$

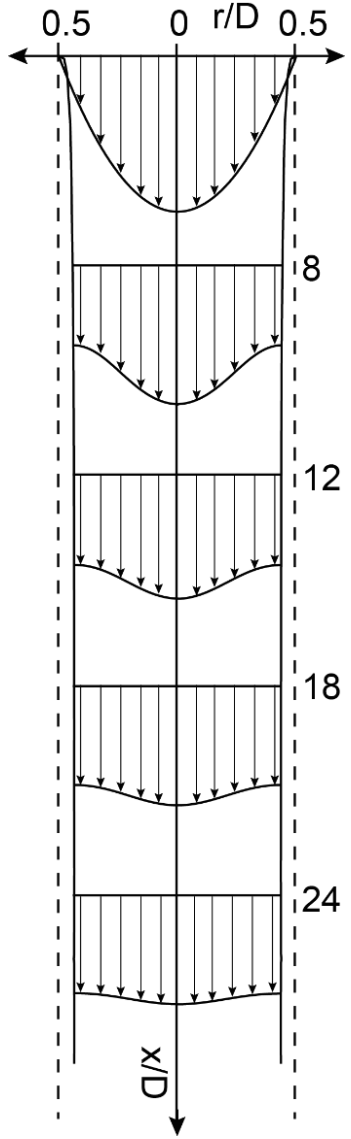
Rohlfs et al., Int. J. Heat and Mass Transfer, 2012

Key results in jet impingement



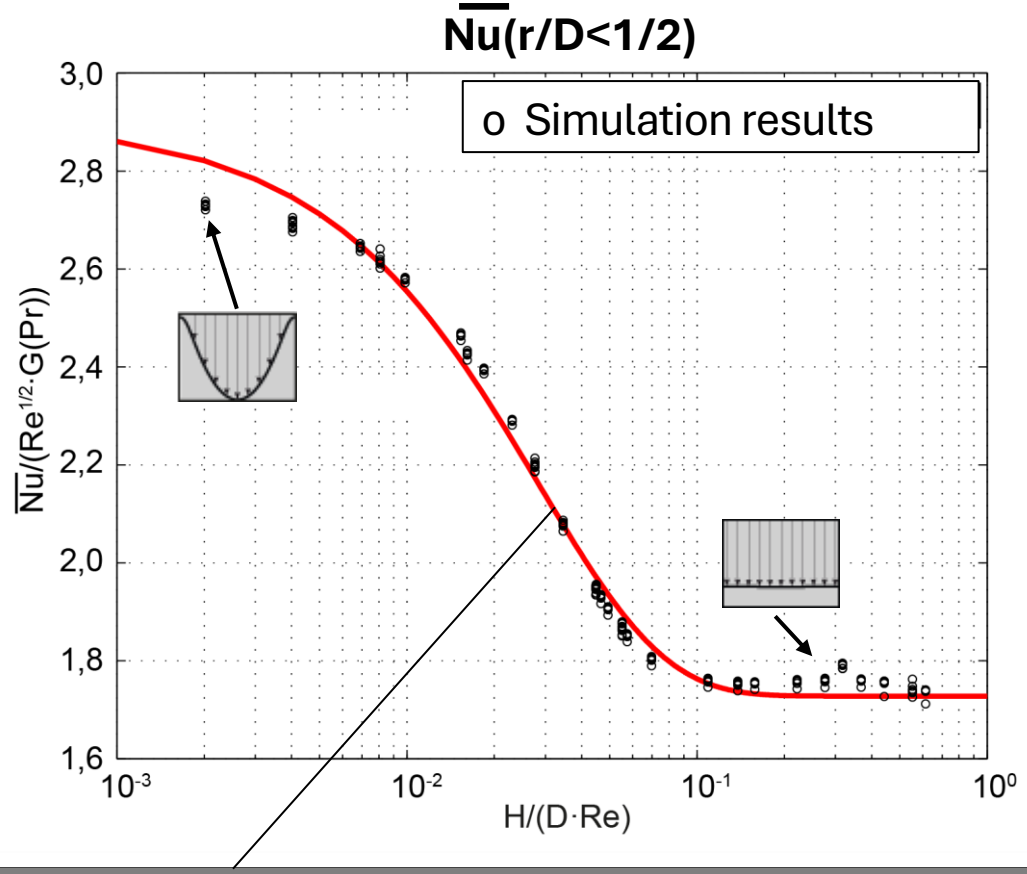
Known length scale: $\frac{H}{D \cdot Re}$





Cimbala, John M. (2006-01-01). *Fluid mechanics: fundamentals and applications*. McGraw-Hill Higher Education.

Key results in jet impingement



Parameter range:

Hydrodynamics:

73 < Re < 2000

4 < H/D < 110

Heat transfer:

constant heat flux

0.07 < Pr < 1300

Unified correlation function

$$\frac{\overline{Nu}}{Re^{\frac{1}{2}}G(Pr)} = a\left(\frac{4}{3}+\frac{2}{3}exp^{-b\frac{H}{D\,Re}}\right)-c$$

Fit parameters: $a = 1.71$, $b = 35.5$, $c = 0.54$

Rohlfs et al., Int. J. Heat and Mass Transfer, 2014

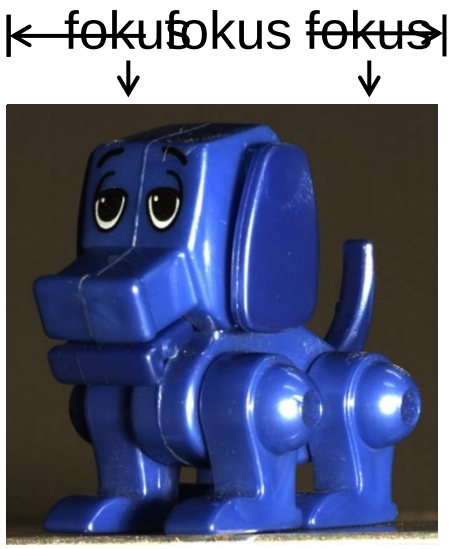
Single camera 3-D Particle Image Velocimetry

Light-Field Imaging Technique

Principle:

Change in perspective

Refocussing



Research question:

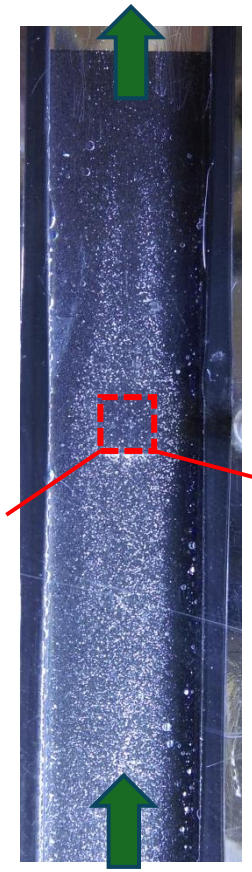
Can a single light field camera adequately measure a 3-D velocity field?

ZIM
Zentrales Innovationsprogramm Mittelstand

Rietz et al., Int. Symp. on Particle Image Velocimetry, 2015

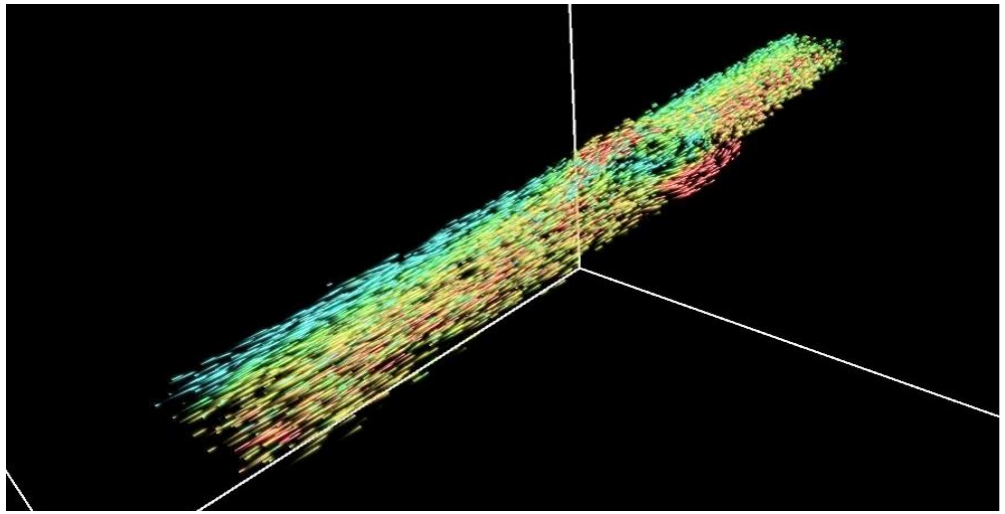
Single camera 3-D Particle Image Velocimetry

➔ **Channel flow with obstacle**

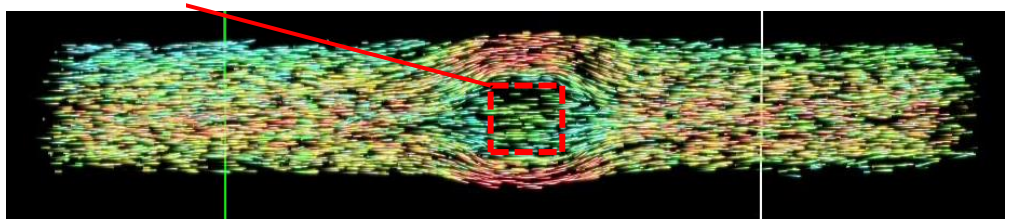


Square obstacle

3D view



Front view



Key results:

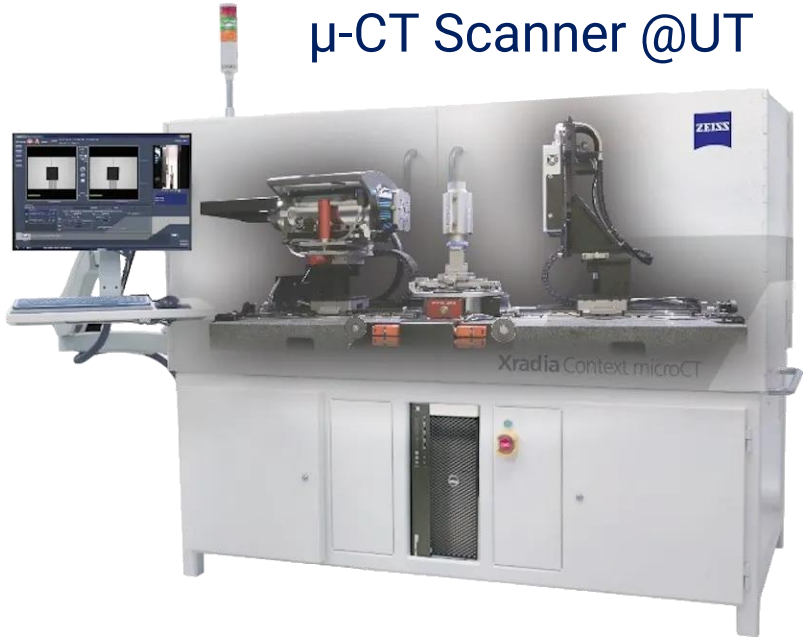
- Resolution:
  - Lateral up to 3-10 µm
  - Axial 430 µm
- Uncertainty in velocity
  - Lateral: 0.04 mm/s
  - Axial: 2.2 mm/s

ZIM Zentrales Innovationsprogramm Mittelstand

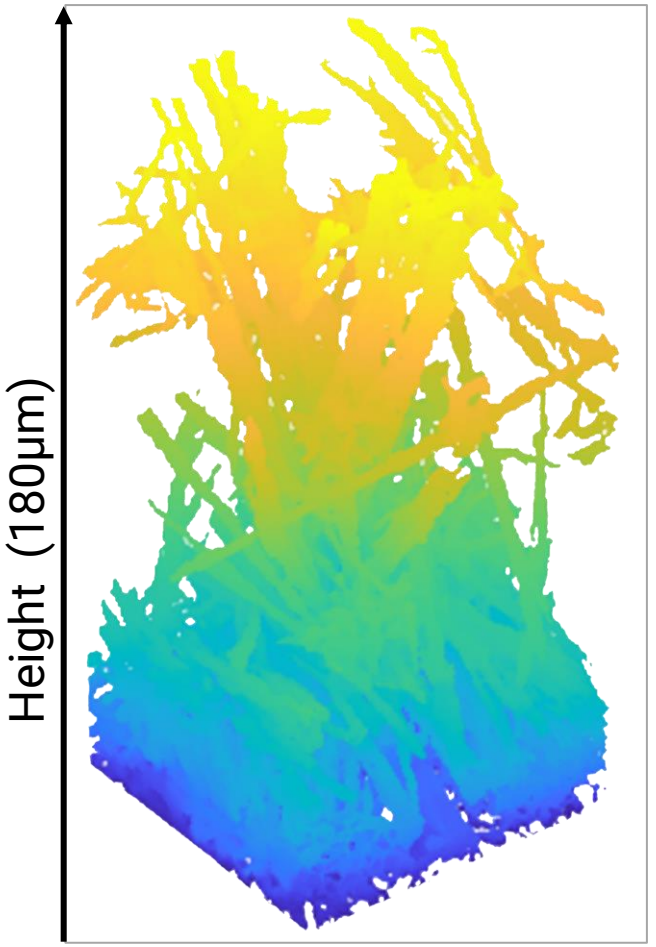
Rietz et al., Int. Symp. on Particle Image Velocimetry, 2015

Computed tomographic scanner

μ-CT Scanner @UT



Proof of principle: Urea crystal

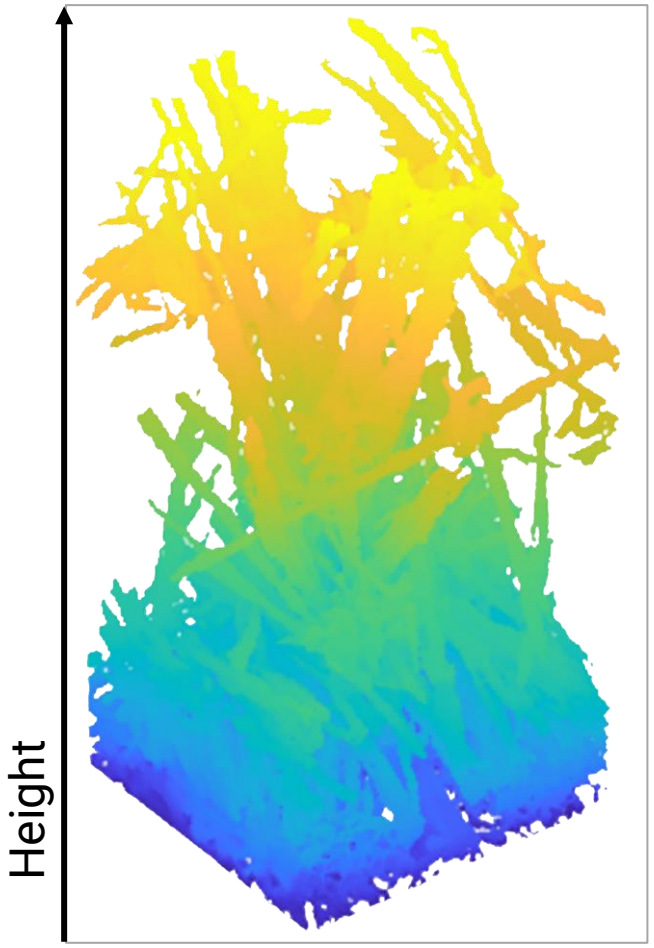


Scanned sample

Research questions:

- Transport properties in porous materials
  - Thermal energy storage materials
  - Frost (dendrites)
  - Foams
- Growth of dendrite structures
  - Frost
  - Crystals

Computed tomographic scanner

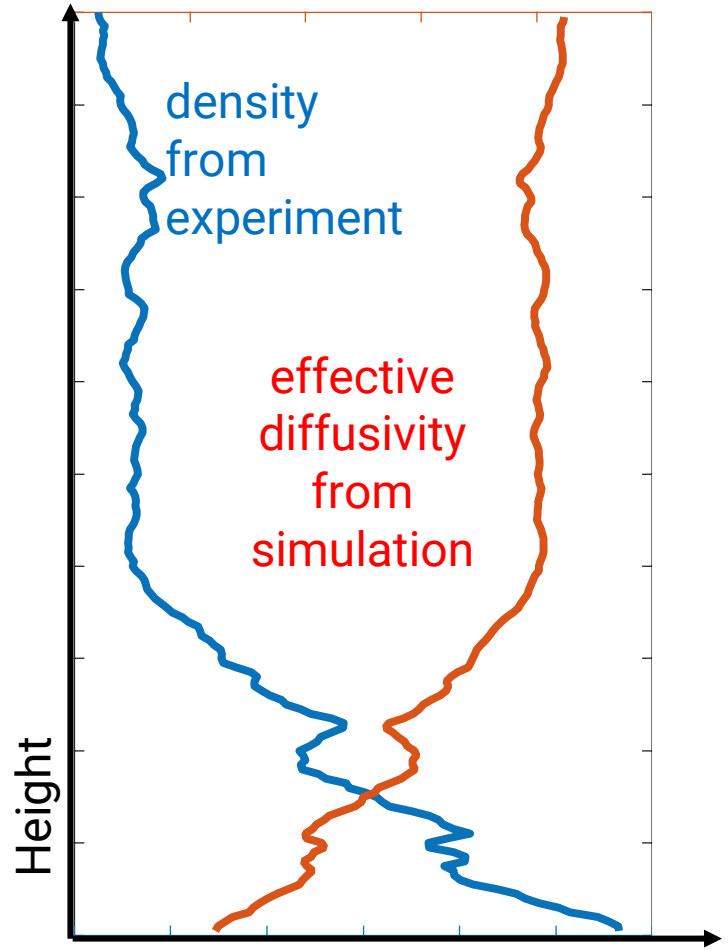


Scanned sample

Solve transport equations with heterogeneous properties

$$0 = \lambda(x,y,z)\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right)$$

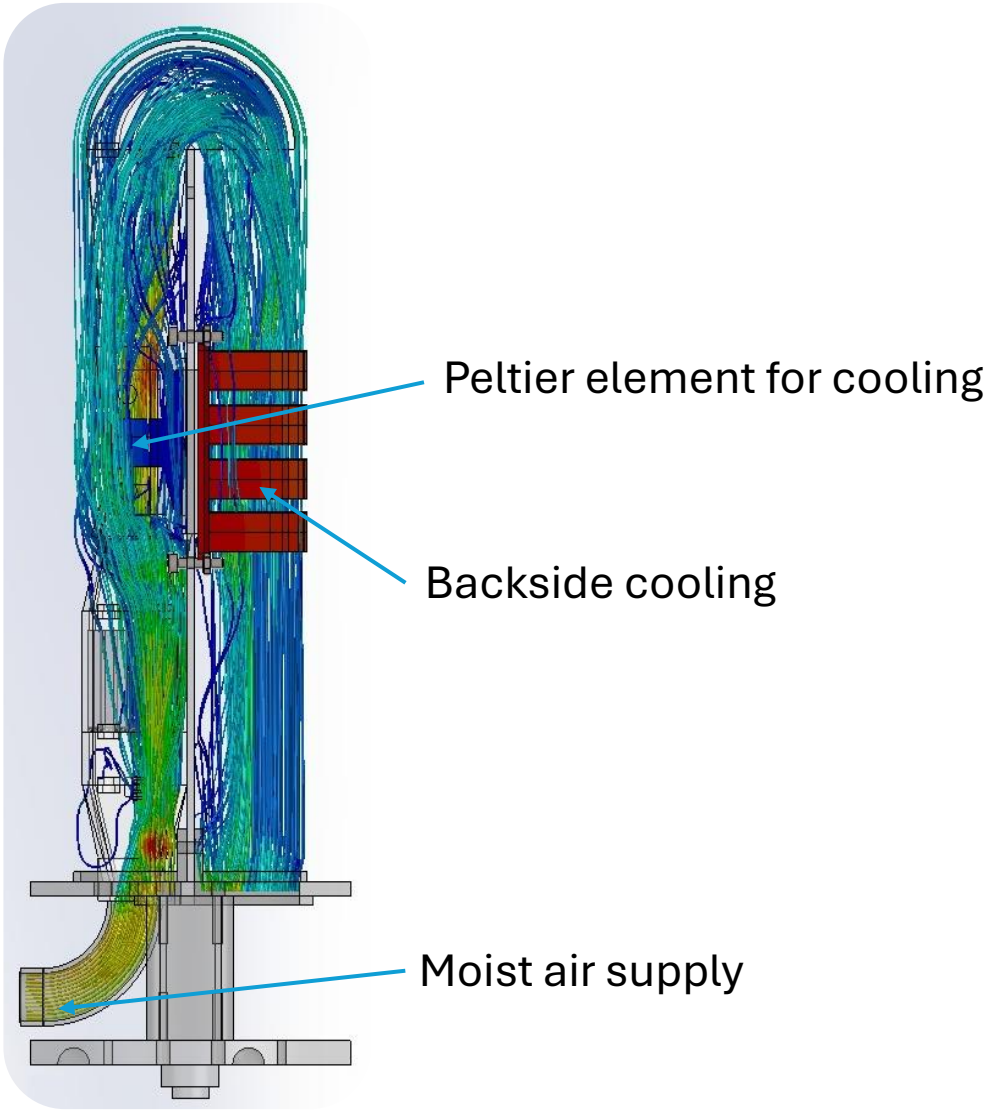
$$\lambda_{\text{eff.}}(\mathrm{x}) = \frac{\dot{q}''(x)}{\bar{T}(x) - \bar{T}(x+dx)}$$



Numerical sample analysis

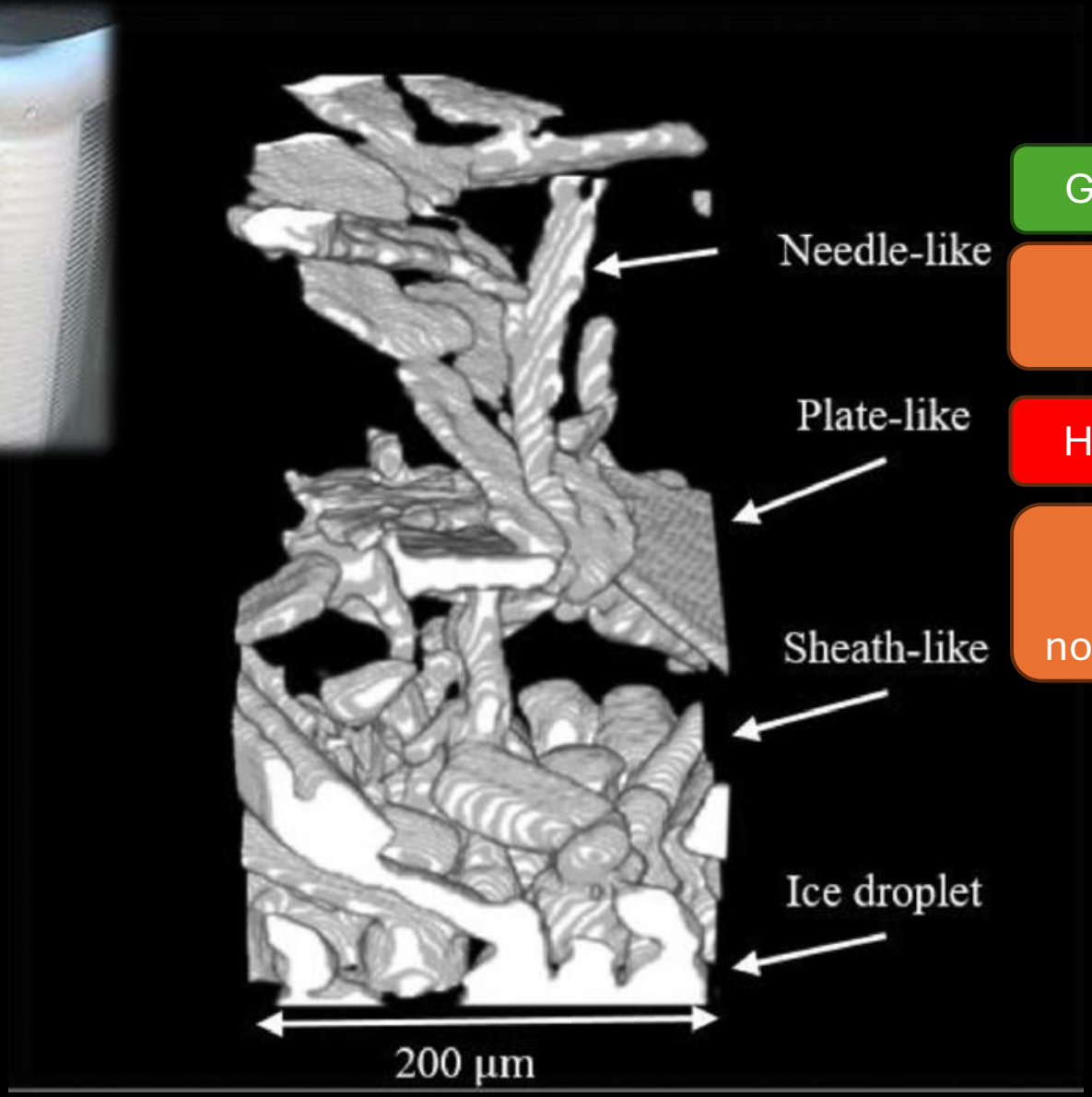
Labuschagne et al., Intern. Heat Transfer Conference, 2023

In-situ frost growth experiments



Labuschagne et al., IHTC Conference 2023

Characteristics of frost



Good mass diffusion

Reduced thermal diffusion

Hider mass diffusion

Good thermal diffusion, but not normal to heat transfer

Local transport properties are needed to model the growth process accurately

Today‘s journey

Optical measurement techniques and past challenges

Future challenges
(and my contribution)

Image source: Pexels, Pixabay

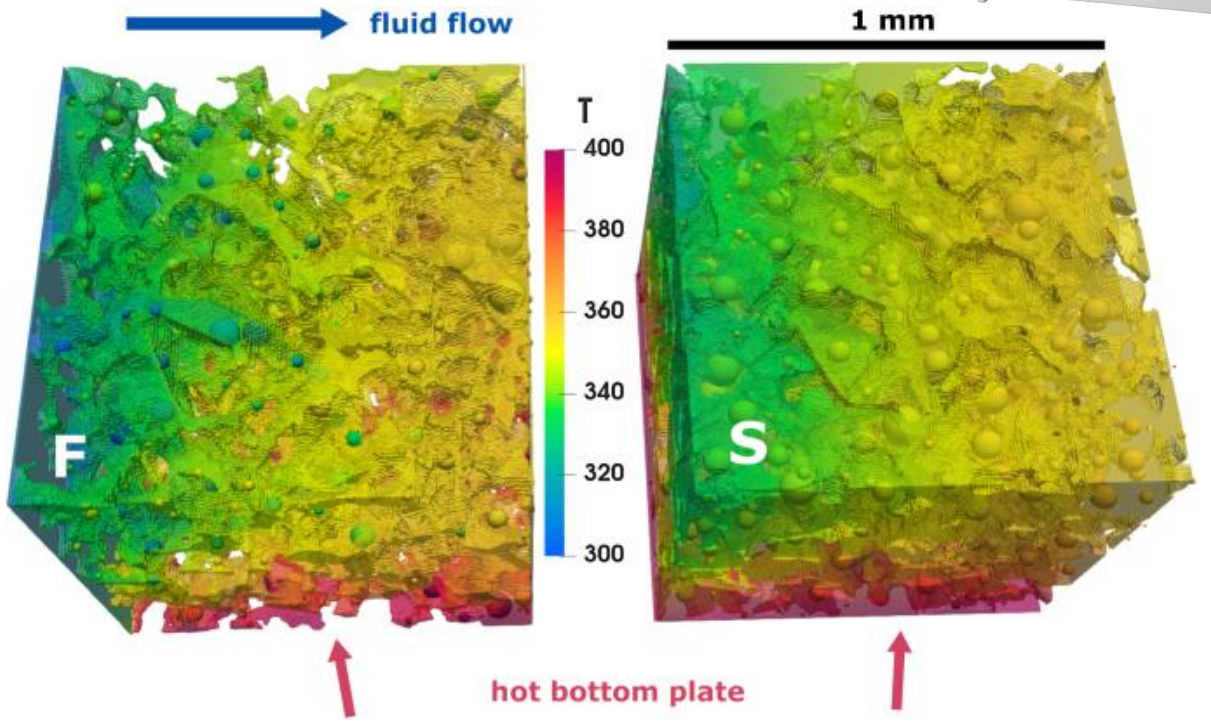
Source:
United Nations

Future challenges (and my contribution)

Thermal energy storage

- Thermo-chemical storages
- Phase change materials

→ Heat & mass transfer in porous media



T. Koch et al. 2021 (other work)

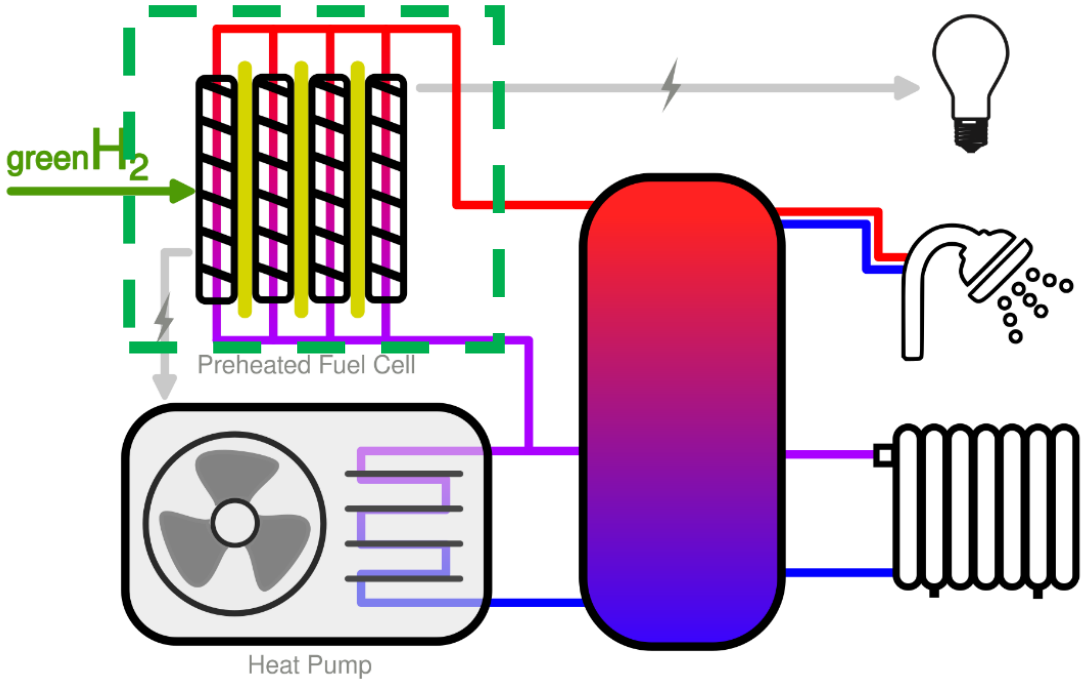
Project with UT partners:
Jaimy Gebbaken, Abhishek Singh

Future challenges (and my contribution)

Thermal energy storage

Hydrogen production and conversion

HX-ELECTRODE: SYSTEM INTEGRATION OF FUEL CELL AND HEAT PUMP



06/2024 - 05/2027

Project in cooperation with:
Prof. John Linkhorst (TU Darmstadt), Canan Acar (UT)

Bundesministerium für Wirtschaft und Klimaschutz

Future challenges (and my contribution)

Thermal energy storage

Hydrogen production and conversion

CO_2 capture and storage

- Production and characterization of CO_2-absorbing particles

Project in cooperation with UT partners:
Y Long, CW Visser, M Mehrali, Prof. ten Elshof, Prof. W Brilman, O Nguon, J Jiang

Long et al., ICCHMT Conference, 2023

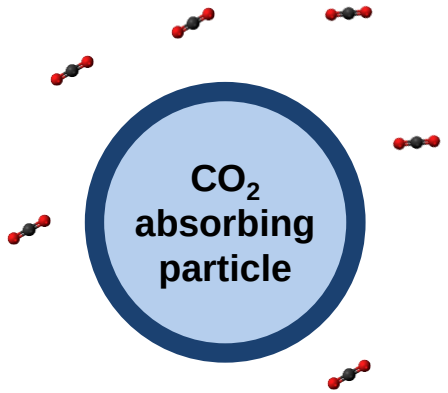
Future challenges (and my contribution)

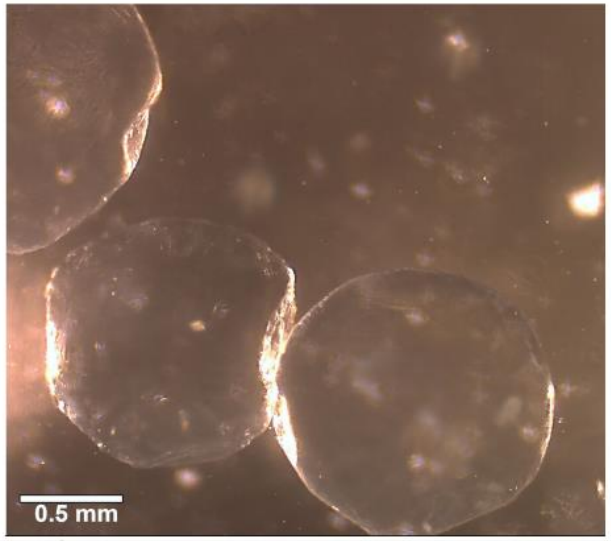
Thermal energy storage

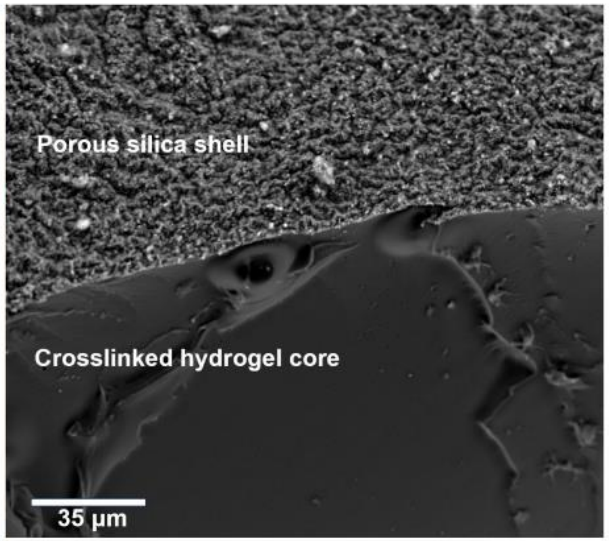
Hydrogen production and conversion

CO_2 capture and storage

- Production and characterization of CO_2-absorbing particles





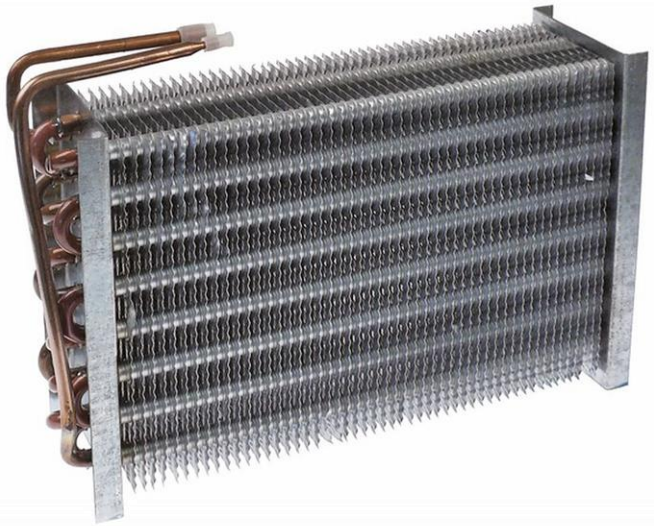


Project in cooperation with UT partners:
Y Long, CW Visser, M Mehrali, Prof. ten Elshof, Prof. W Brilman, O Nguon, J Jiang

Long et al., ICCHMT Conference, 2023

Future challenges (and my contribution)

Frost formation
on heat pumps



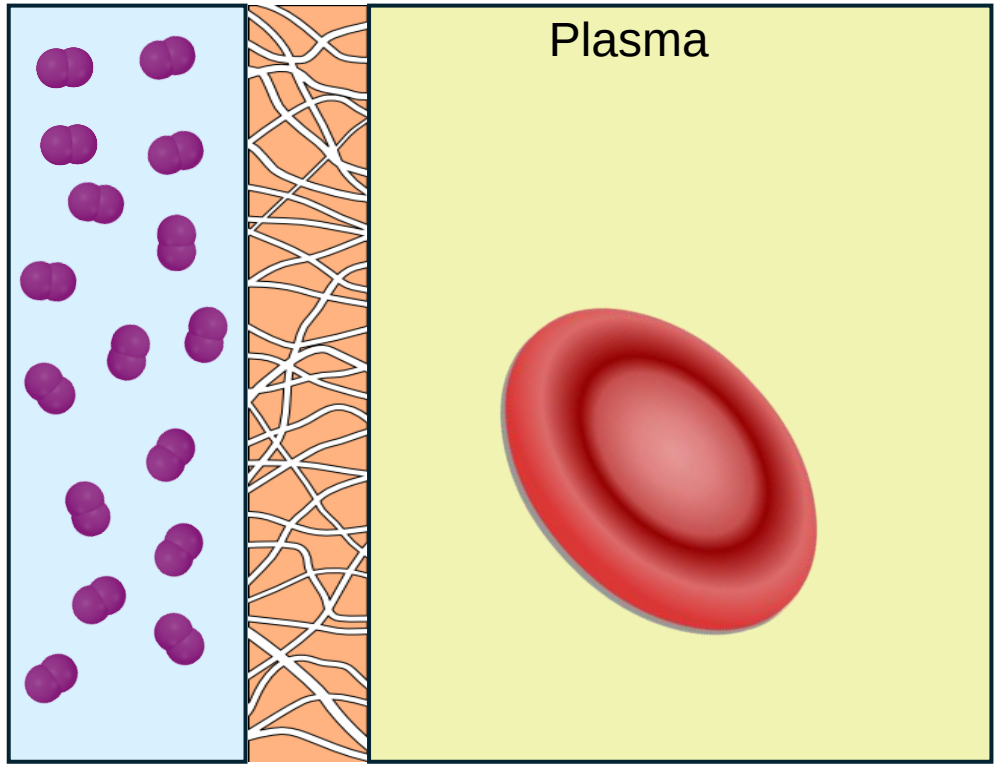
Research with:
A. Labuschagne, T. Zhu

Labuschagne et al., IHTC conference 2023

Future challenges (and my contribution)

- O_2 and CO_2 transfer in artificial lungs

Artificial lung

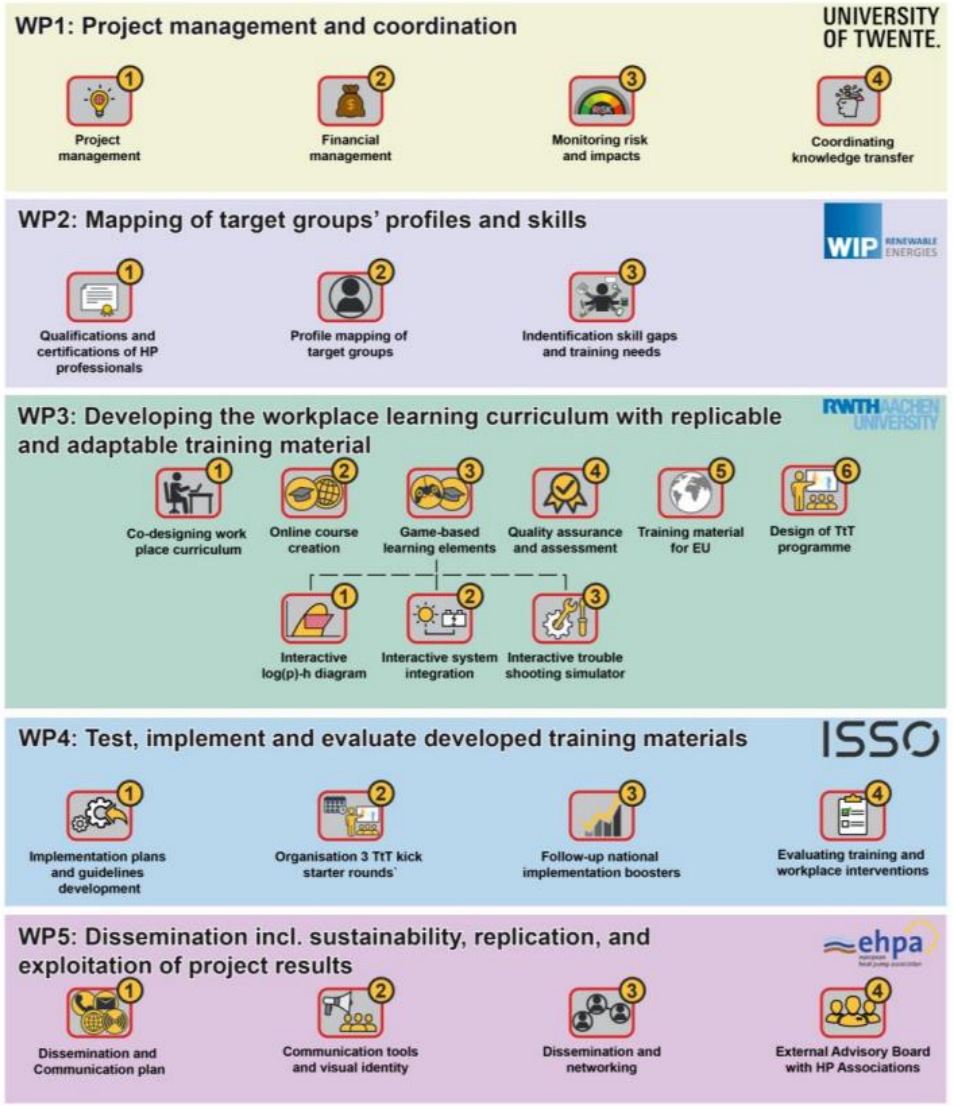


Research in cooperation with:
Prof. Jutta Arens (UTwente),
Jaimy Gebbeken

Gebbeken, Master Thesis, 2023

HeatCraftHP:
Training heat pump installers

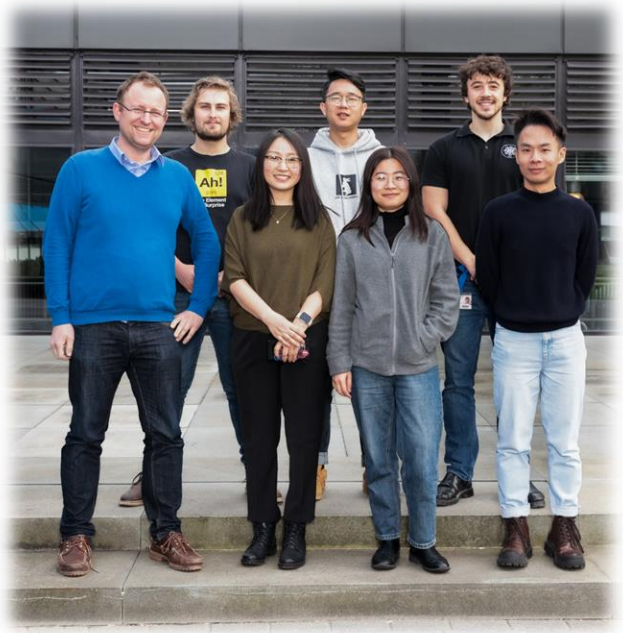
HEATQUIZ



Co-funded by the European Union

Project HeatCraftHP: 10/2024 – 09/2027

To be continued …



HTT Group, March 2024

Source:
United Nations

Vision and mission

Future challenges (and my contribution)

- Mass transport in the human kidney

Artificial lung

Kidney

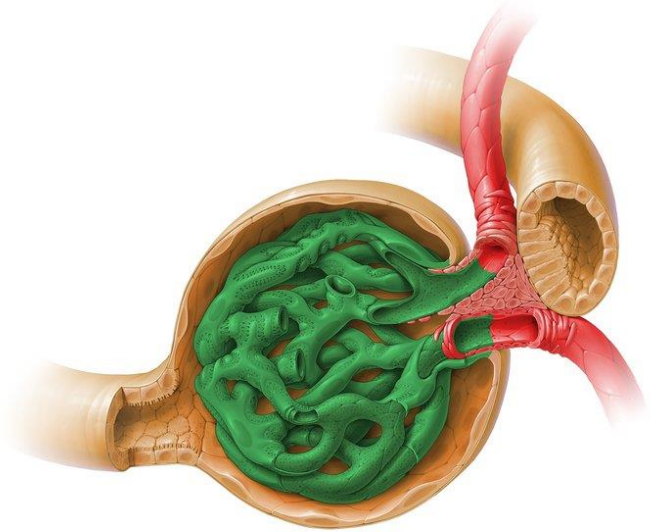
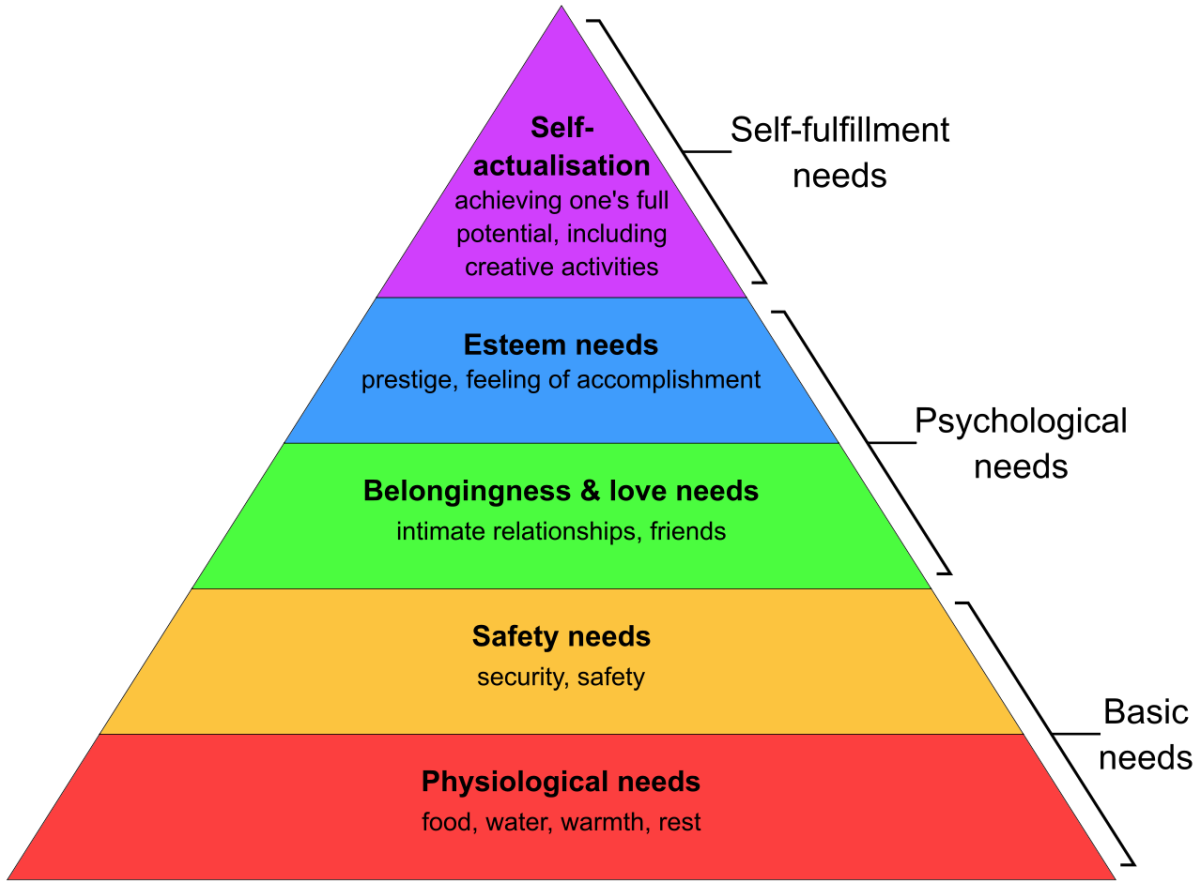


Image source: Kenhub.com

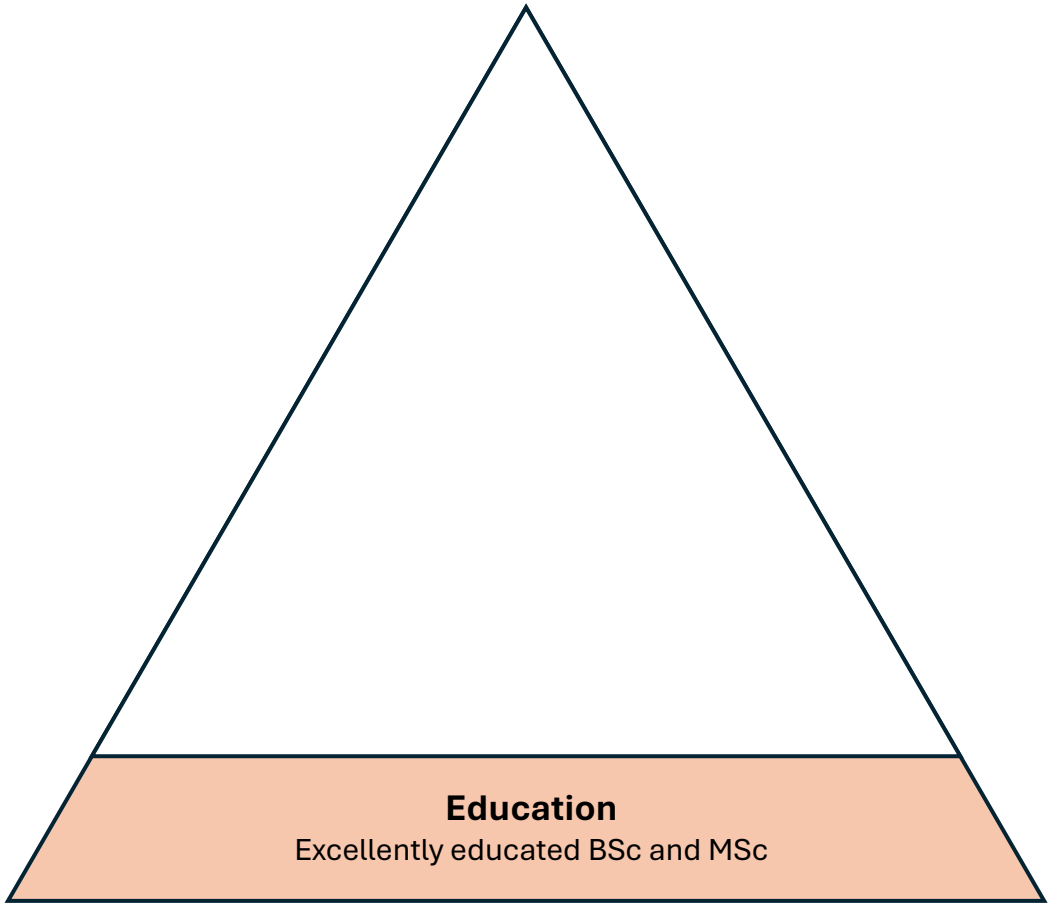
Research in cooperation with:
Prof. Christoph Kuppe (UKA)

Vision and mission



Maslow's hierarchy of needs

Vision and mission



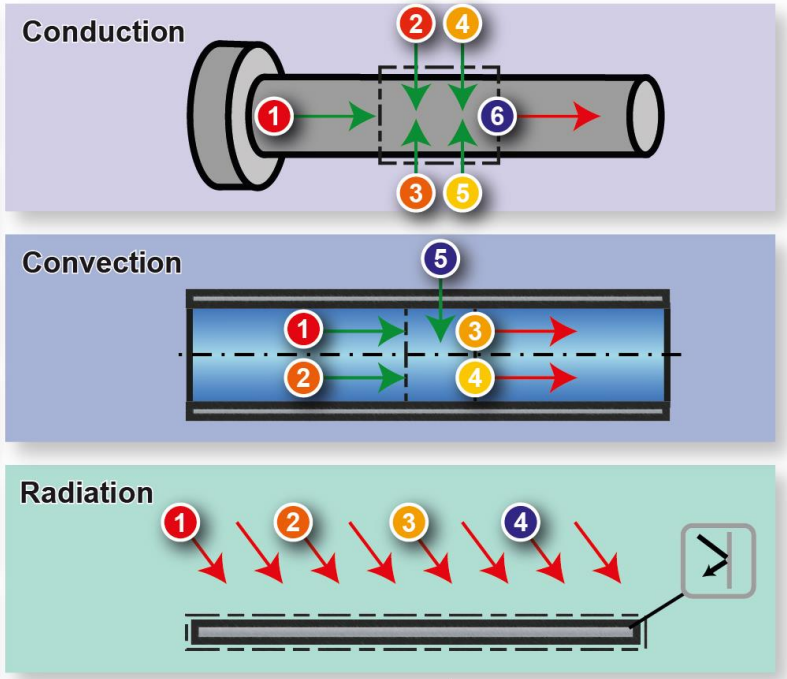
Hierarchy of scientific success

Heat transfer: Balances
Systematic problem approach

HEATQUIZ

Stepwise approach:

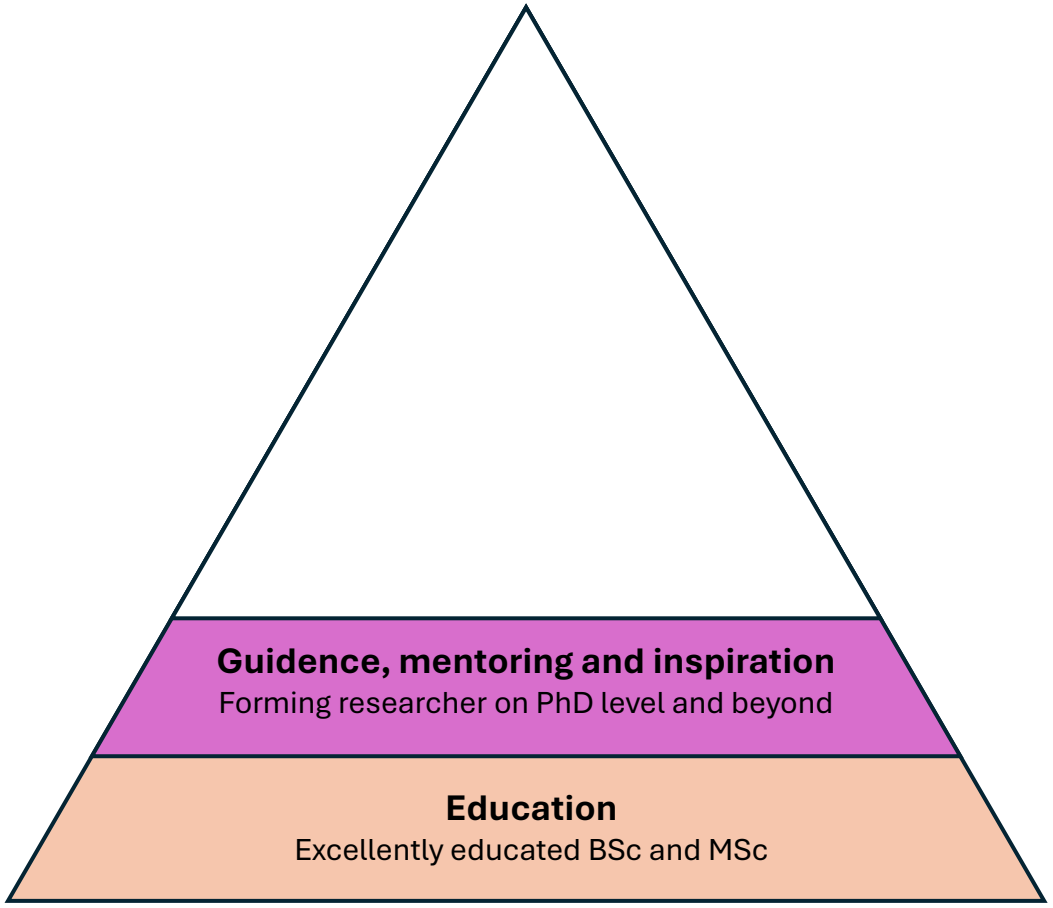
1. Define the domain
2. Define the balance
3. Define the fluxes
4. Substitute and rewrite
5. Define initial and boundary conditions
6. Solve the problem



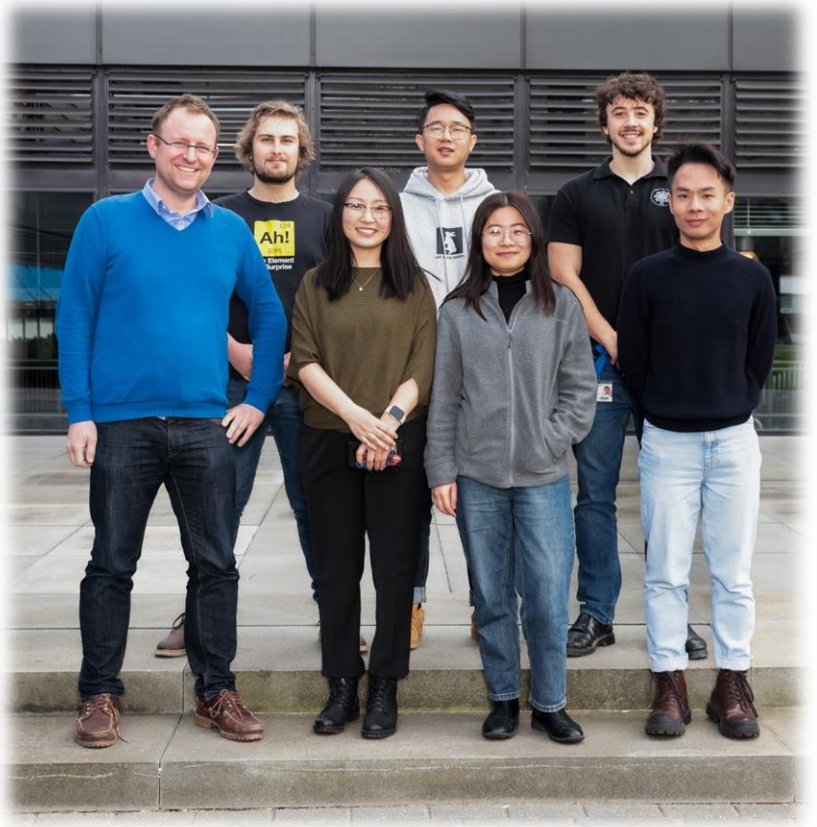
Prof. Dr. Dr. Wilko Rohlfs
University of Twente | w.rohlfs@utwente.nl

UNIVERSITY OF TWENTE. | RWTH AACHEN UNIVERSITY

Vision and mission

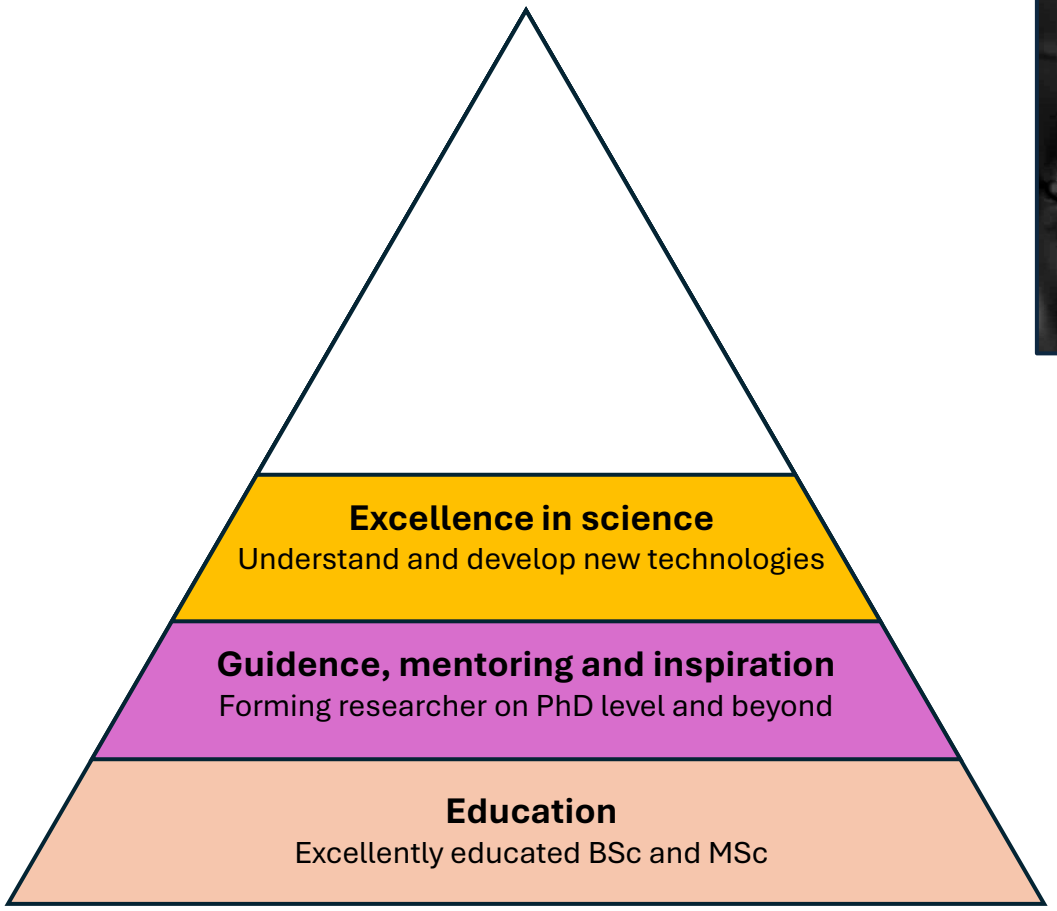


Hierarchy of scientific success

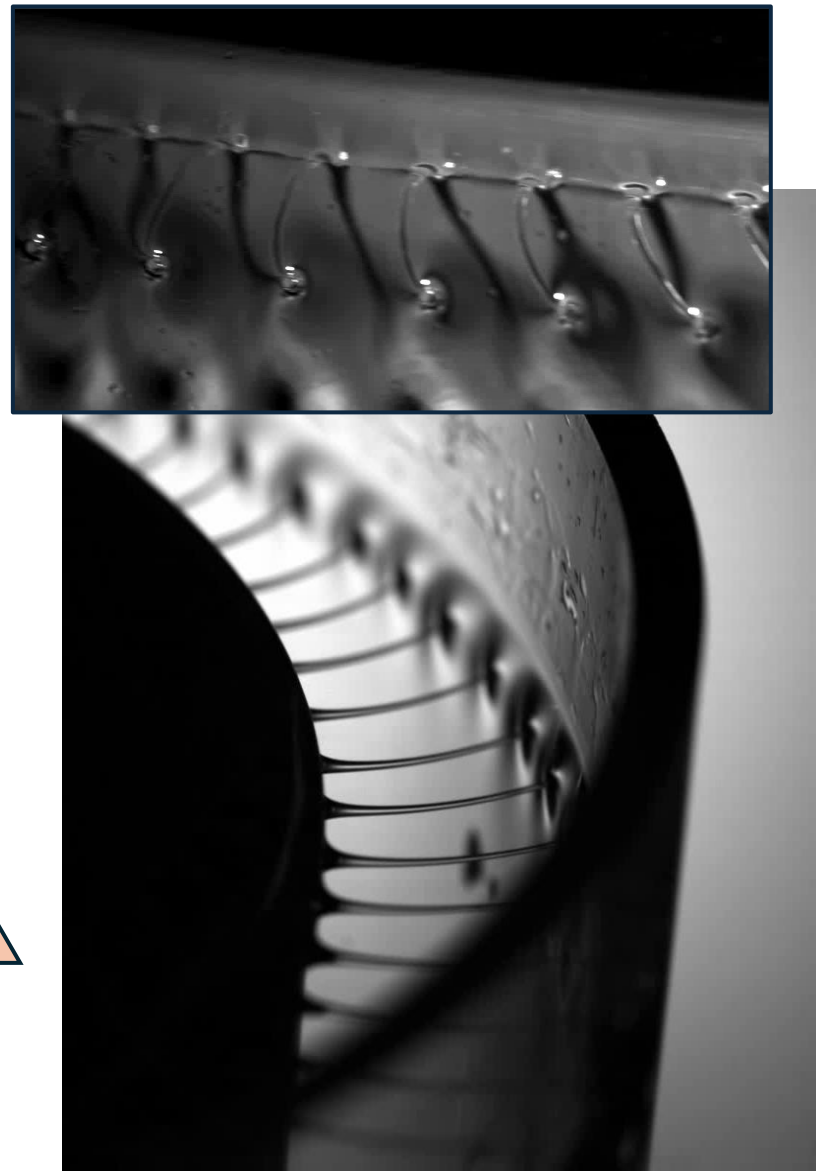


HTT Group, March 2024

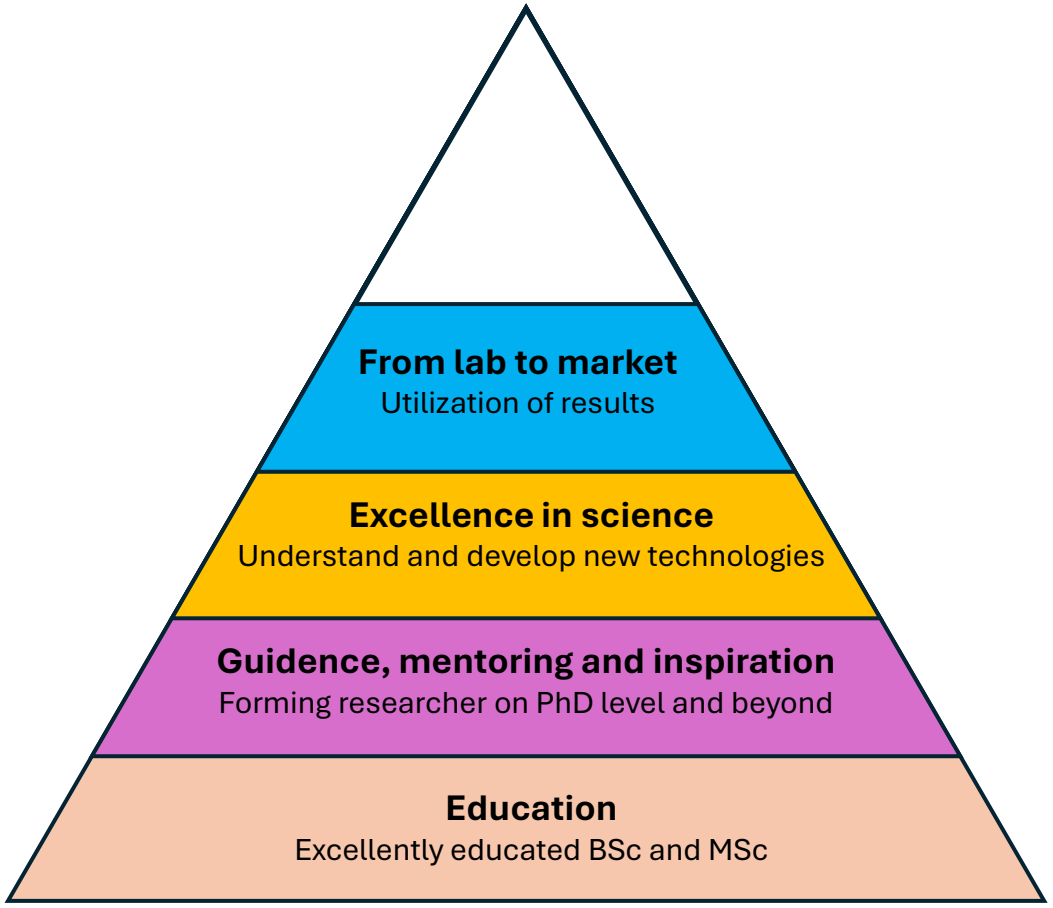
Vision and mission



Hierarchy of scientific success



Vision and mission



Hierarchy of scientific success

BDR THERMEA GROUP

Wickeder Westfalenstahl
Wickeder Group

THALES

HONDA

Orange Water Works

BAXI INNOTECH
fuel cell heating

ASML

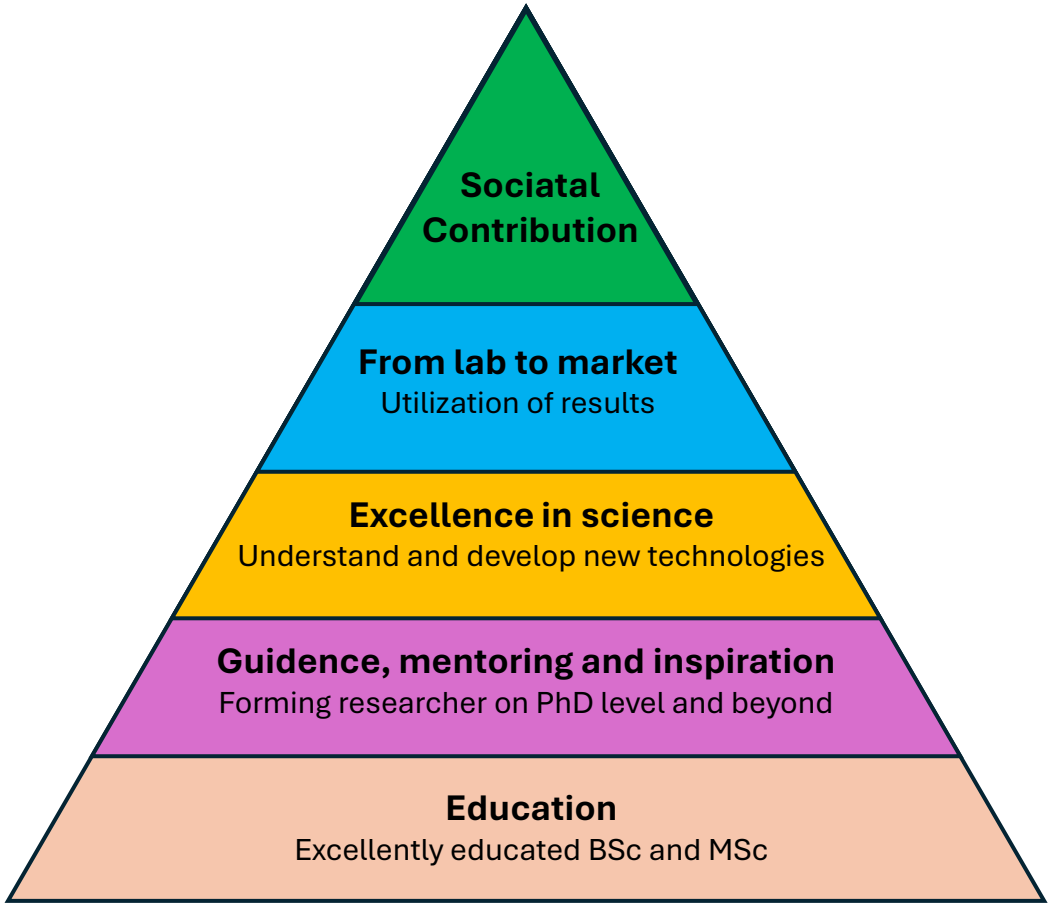
TotalEnergies

ehpa
european heat pump association

Hamacher Maschinenbau GmbH
Leistungsstarke Spezialmaschinen und -anlagen

ulamo

Vision and mission

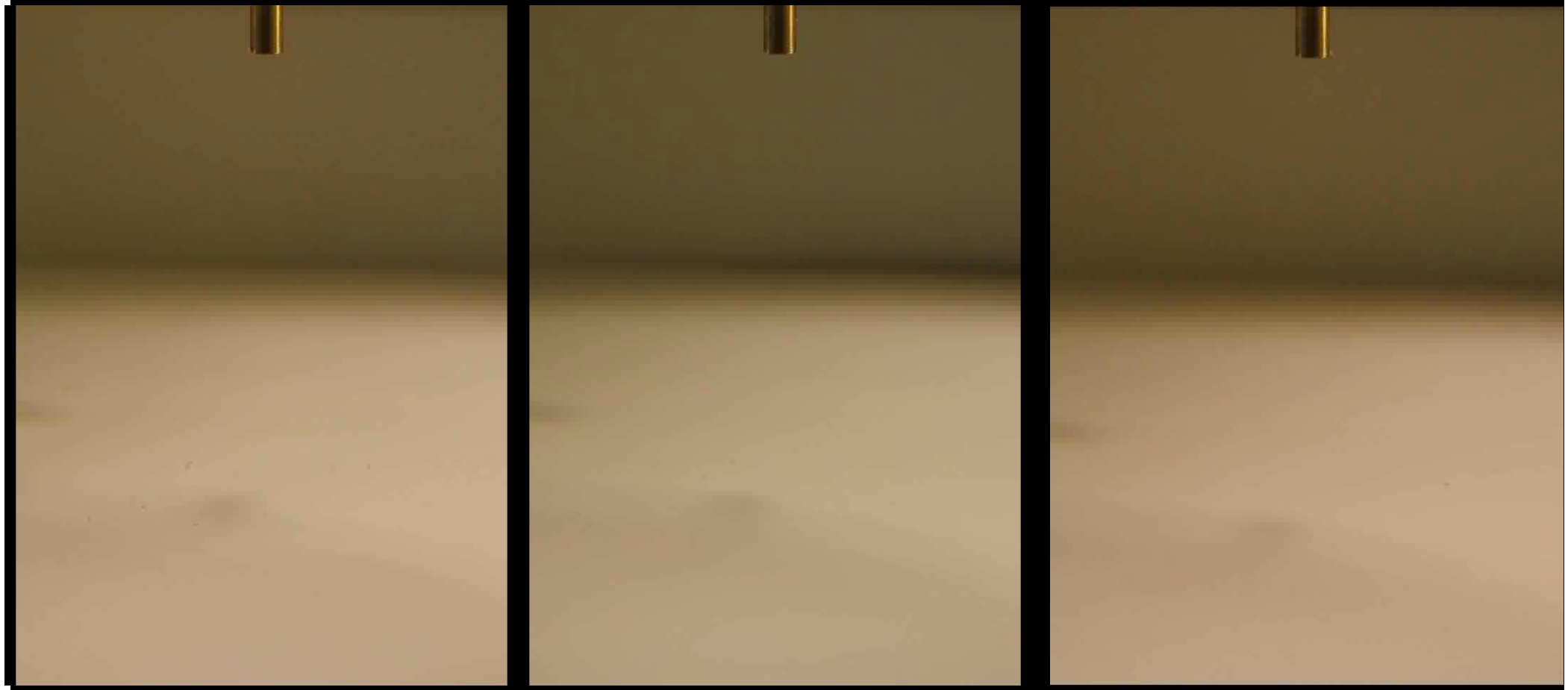


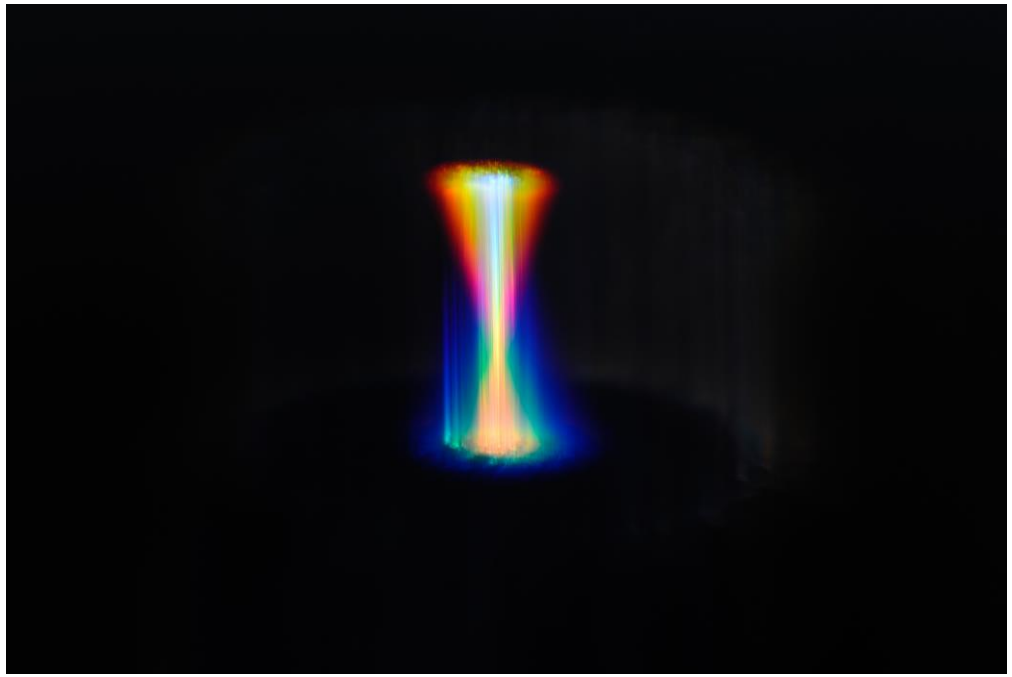
Hierarchy of scientific success

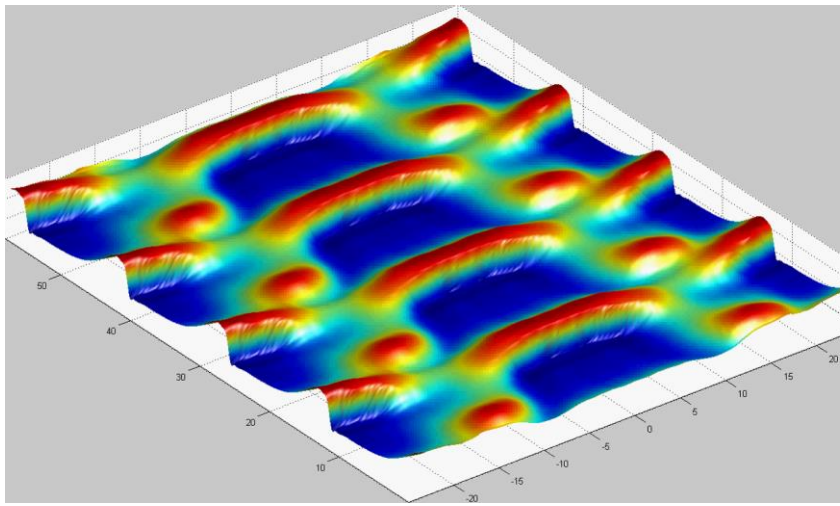
Re = 2500

Re = 1600

Re = 800



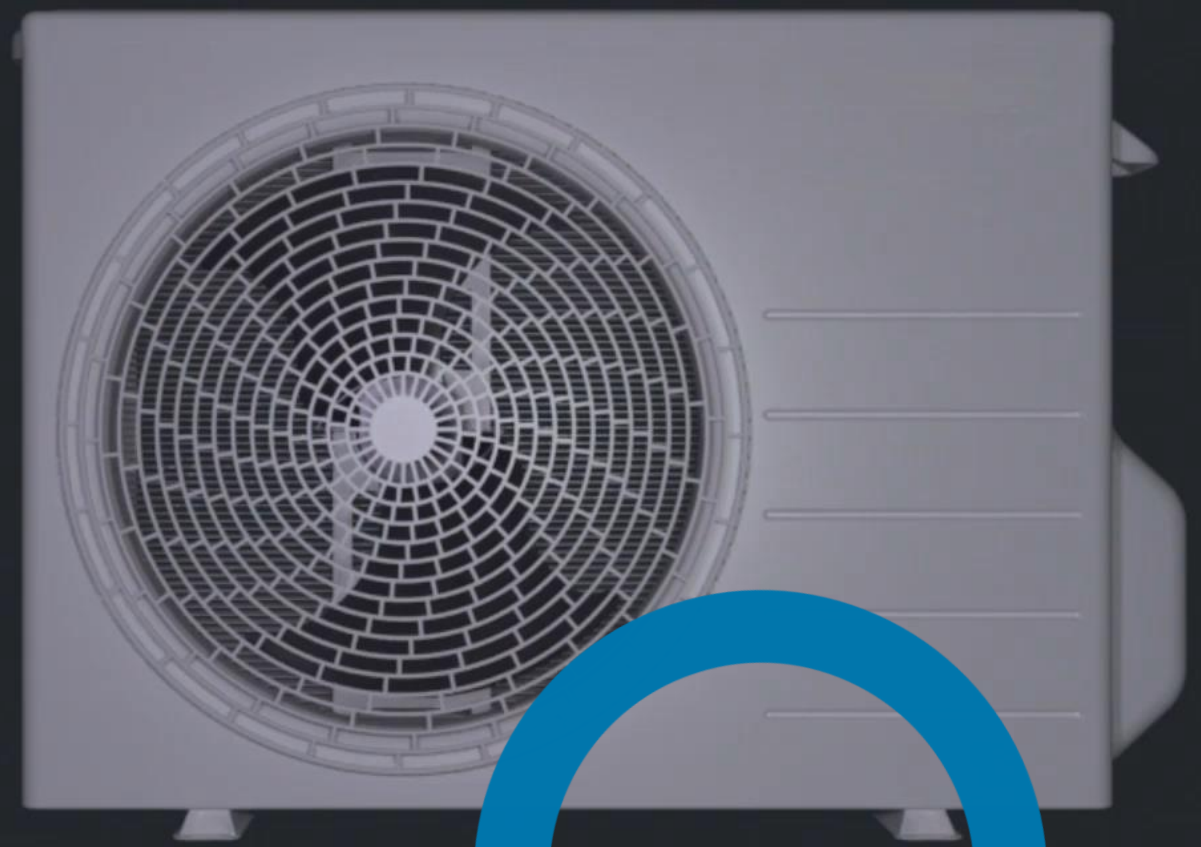



50
40
30
20
10
-20
-15
-10
-5
0
5
10
15
20

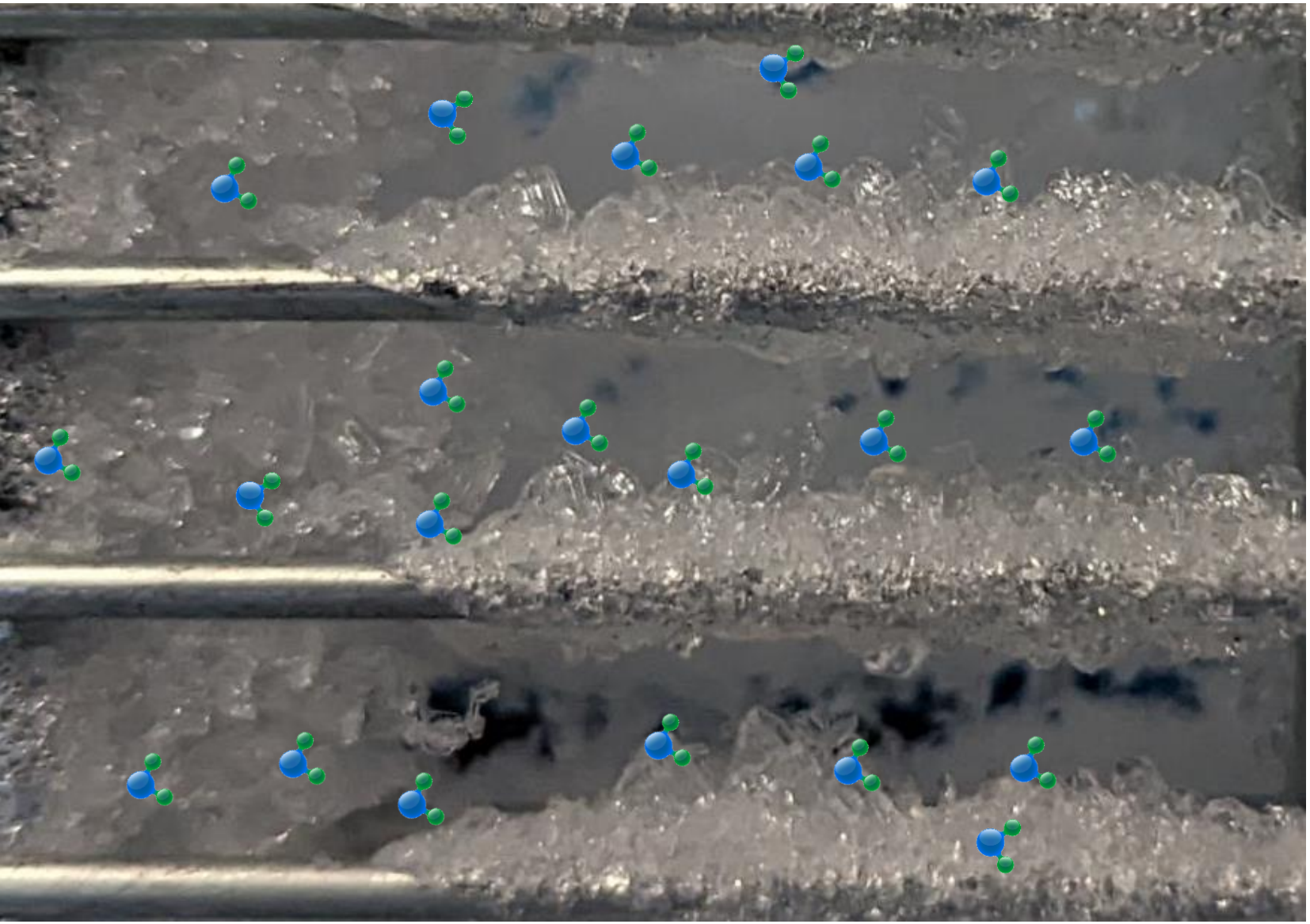
From large scale

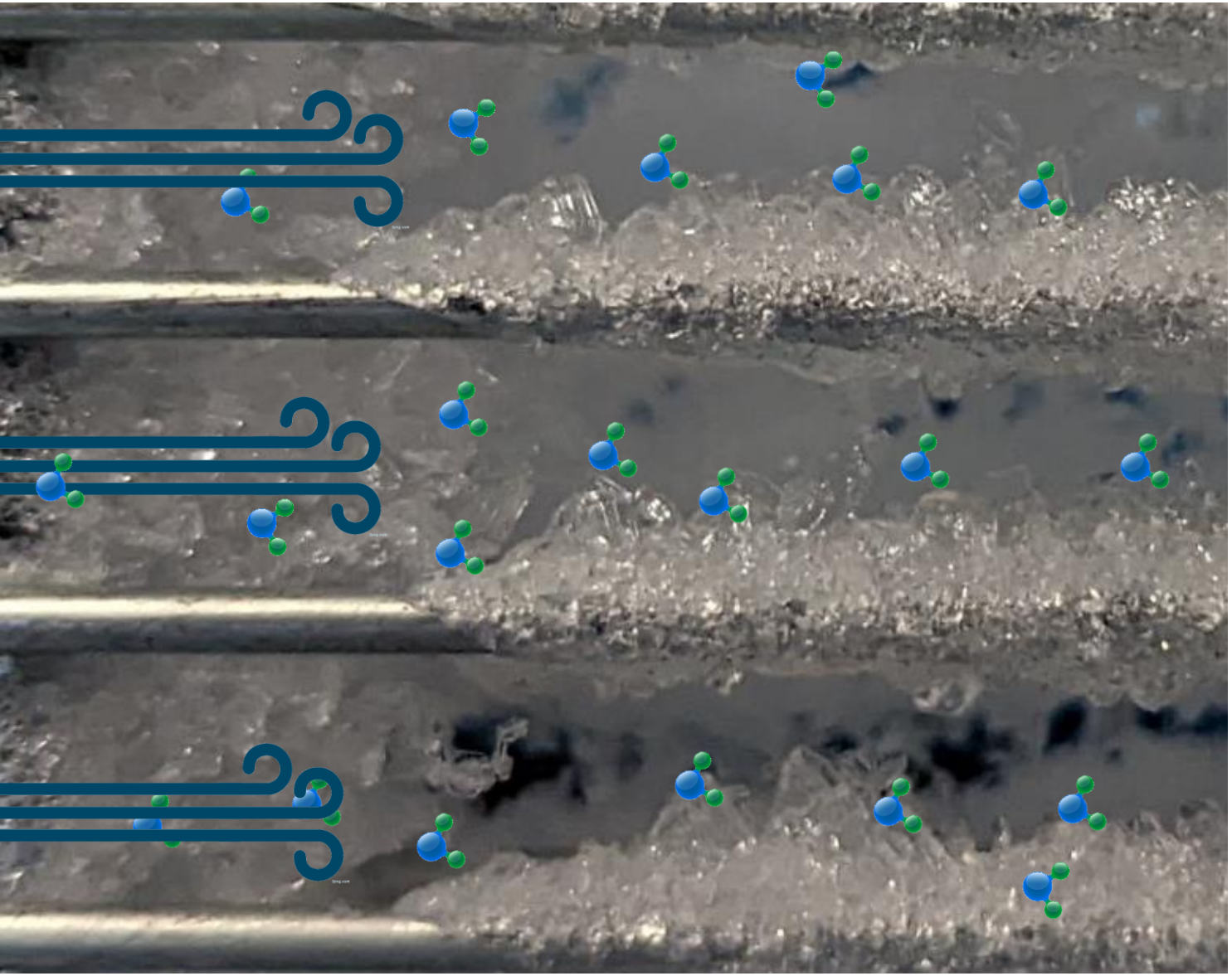
to small scale

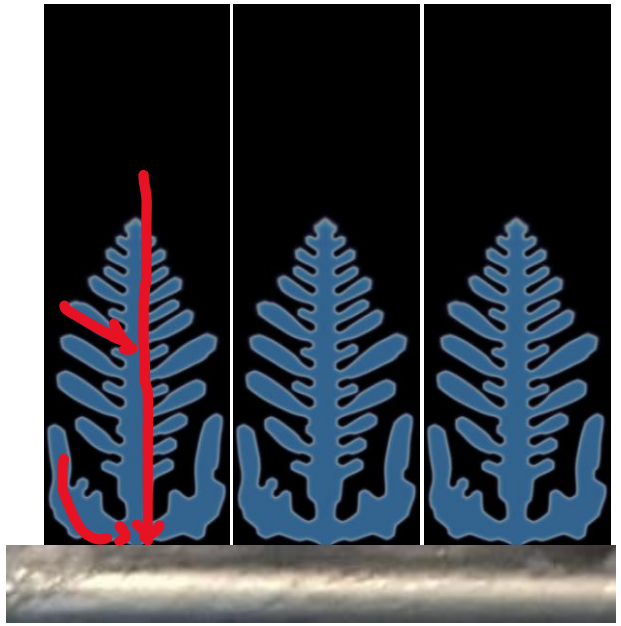
Physics of frost formation



Austin Labuschagne, Tingting Zhu, Jaimy Gebbeken, …



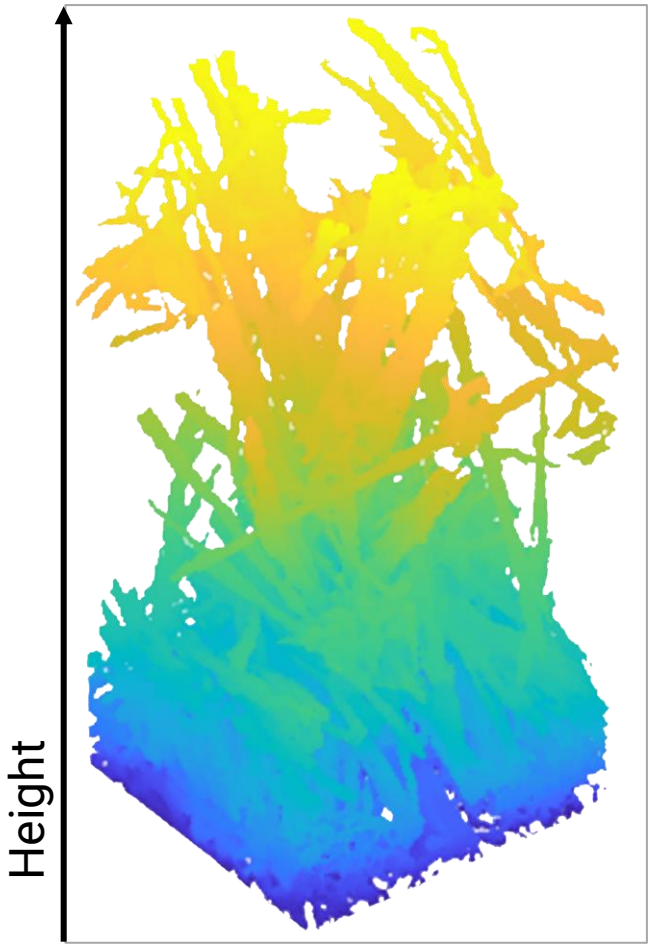




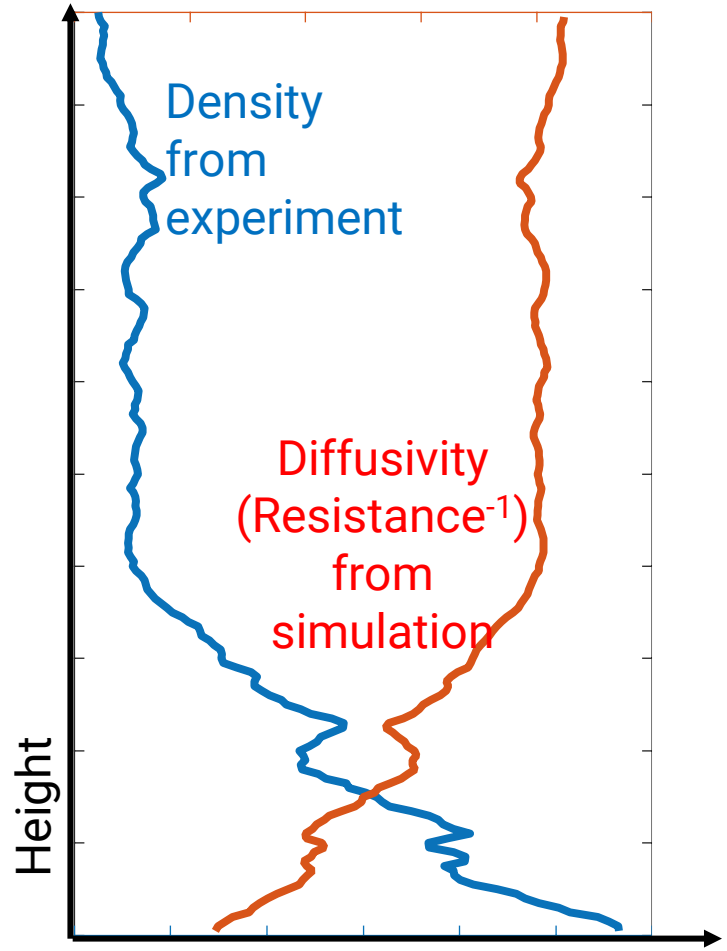
Experimental characterization

μ-CT Scanner @UT

Proof of principle: Urea crystal



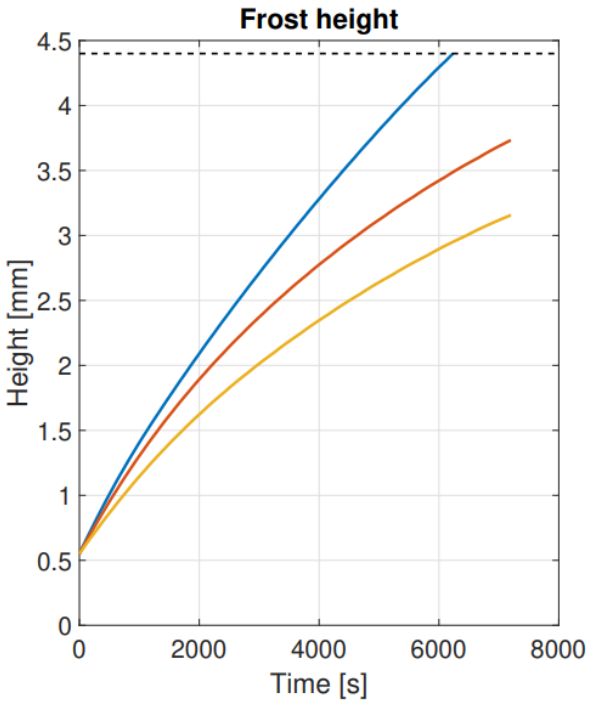
Scanned sample



Numerical sample analysis

Numerical modeling

Frost growth model

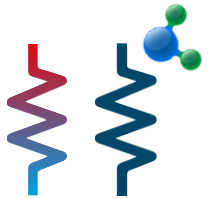


Relative humidity

- 80%
- 72%
- 60%

- Fast computation
- Based on conservation laws
- Influence on heat exchange

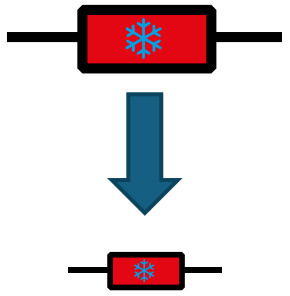
- Resistances required for closure



How can this research improve heat pump performance?

How can frost structures be altered?

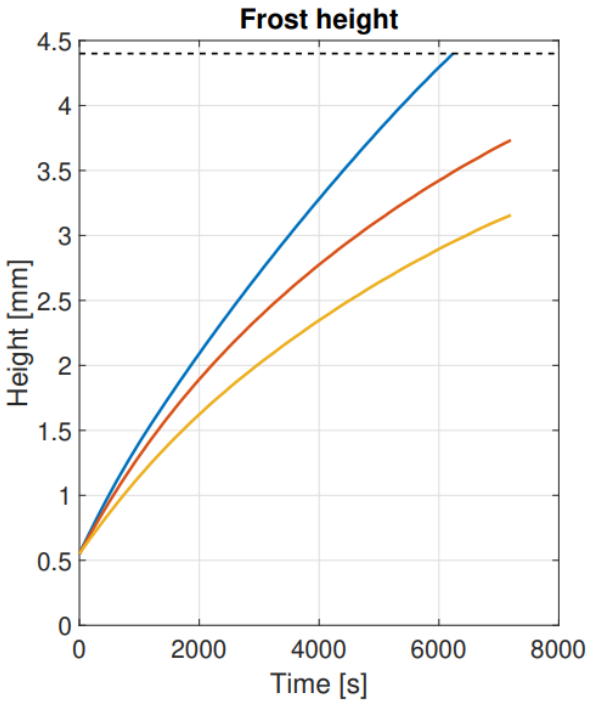
Reduce resistance



Avoid channel blockage

Numerical modeling

Frost growth model



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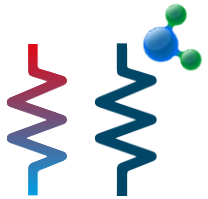
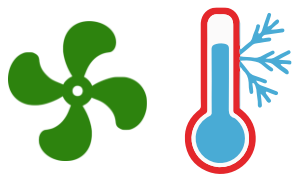
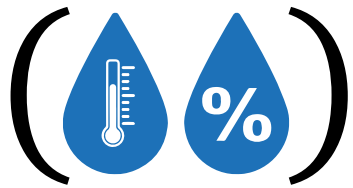


How can this research improve heat pump performance?

How can frost structures be altered?

Parameter control:





Scientific impact

In situ visualization of frost formation in a channel flow

High resolution data of thermal/transport properties

Improve models to predict frost formation

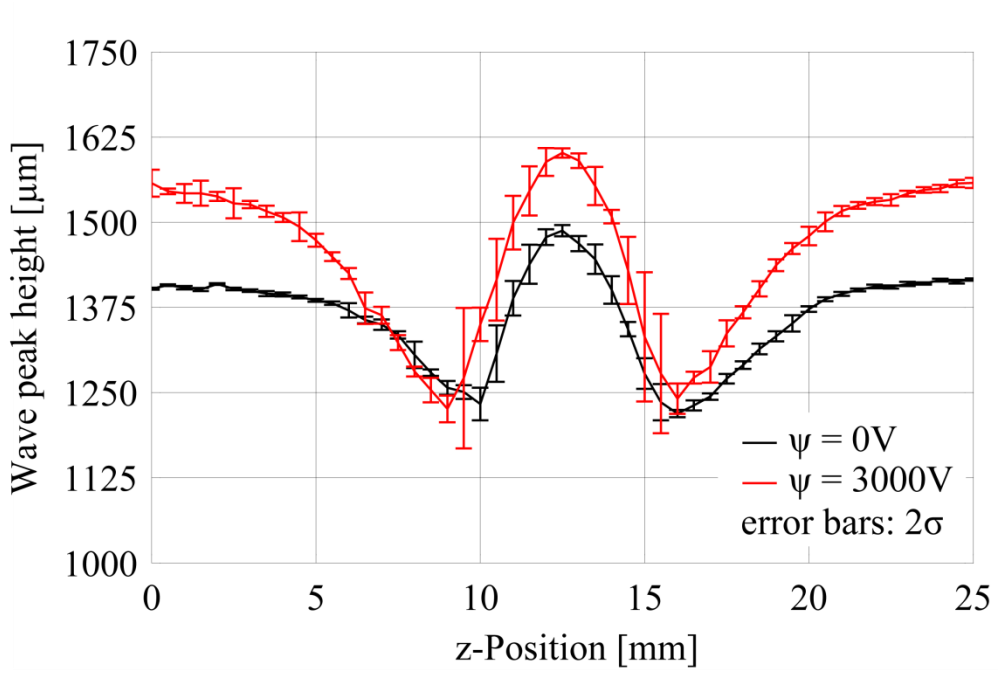
Social impact

Increase heat pump performance by adapting fan speed, surface temperature, and geometry

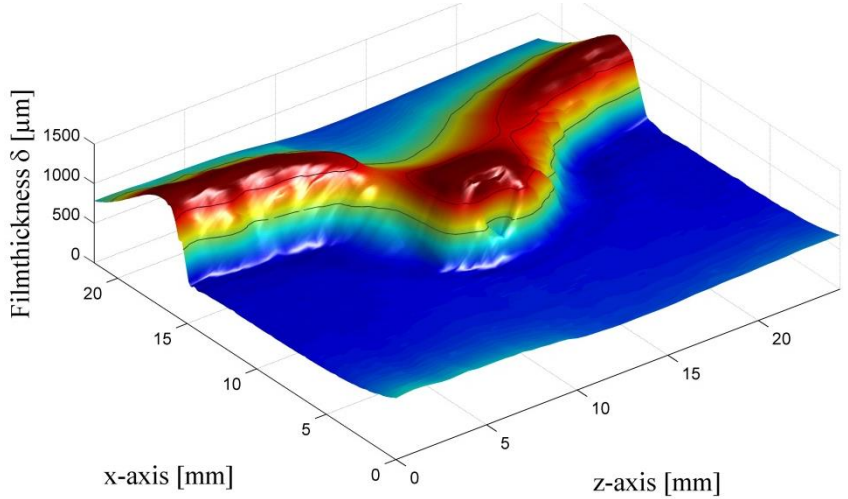
Reduce environmental footprint and cost

Backup

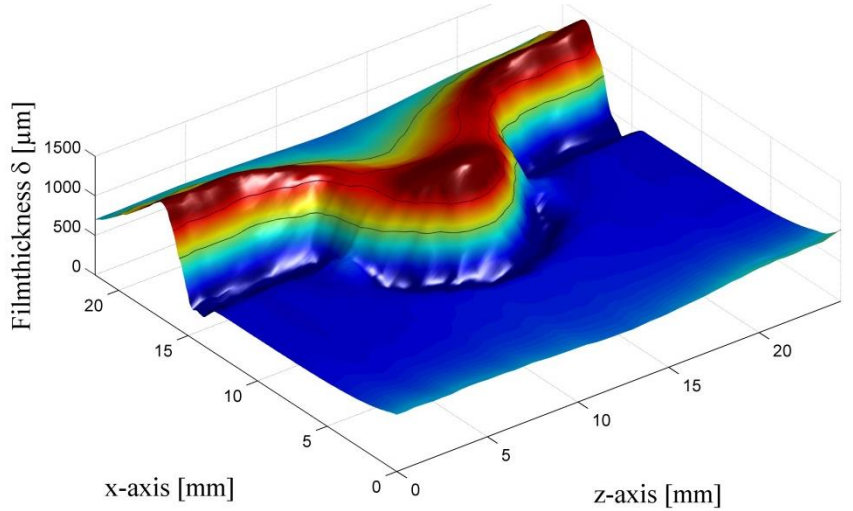
Results: Electrostatic surface forces



Reconstructed interface



Field off: $\psi = 0kV$



Field on: $\psi = 3kV$

Key result:
Electrostatic surface force pulls on the liquid surface (in wall-normal direction)

Rohlfs, Dissertation, 2015
Rohlfs et al., J. Fluid Mechanics, 2017