ESPRESSO Experimental Facility

Exploitation workshop

28 November 2023 - 30 November 2023

Objectives of ESPRESSO Facility

1. Contribute to our understanding of the physics surrounding the interaction between the solid-liquid interface, the surrounding flow, the heat fluxes from the flow into the ice-layer, and the role of turbulence.
2. Generate high-fidelity experimental data suitible for numerical benchmarking purposes:
   - Well defined boundary conditions.
   - Non-intrusive, whole-field experimental techniques: particle image velocimetry (PIV) and laser induced fluorescence (LIF).

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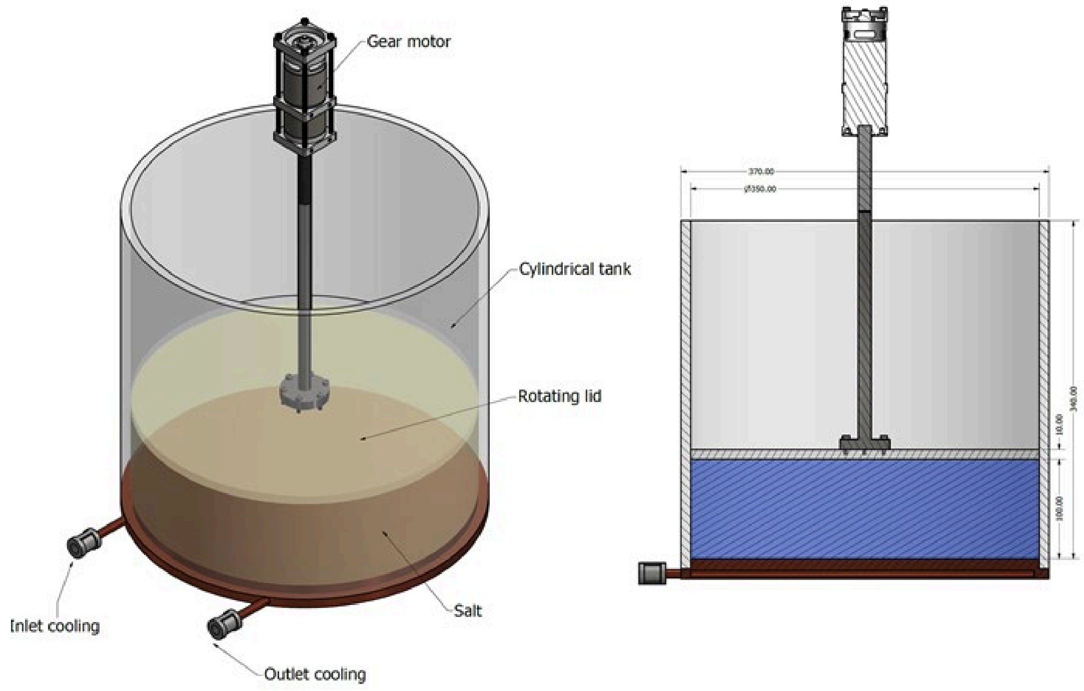
From original to current concept

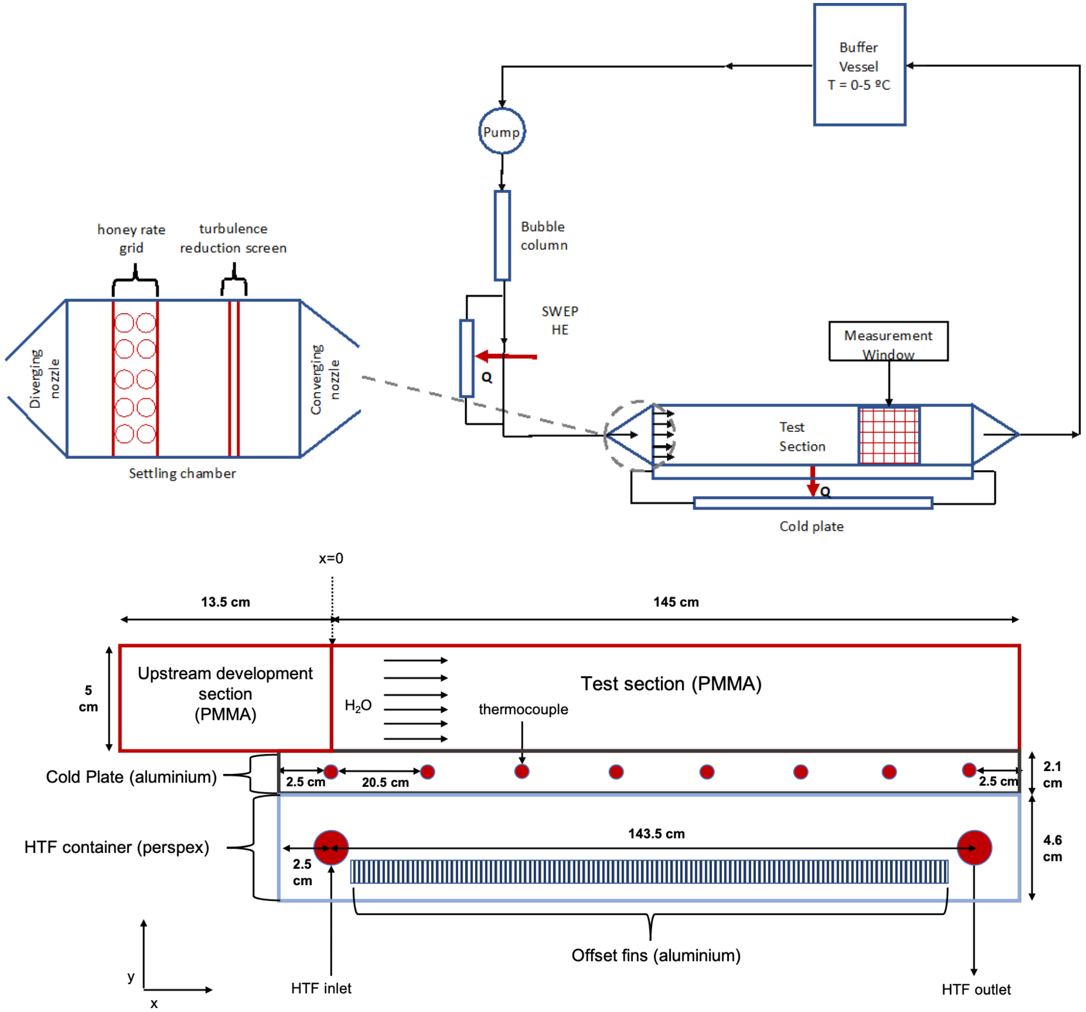
- Original ESPRESSO concept: cylinder with a rotating top lid and a cold plate at the bottom using an ionic liquid (EAN) as phase change material.
- Reasons for departing from original concept:
  1. Velocities decreased exponentially from the top to the bottom, so there would be little interaction between flowfield and ice-layer.
  2. Thermophysical properties of EAN are not well-described (for instance, the thermal conductivity is unknown).
- Chosen concept: water tunnel with a square channel section in which ice is grown:
  1. Relevant case for MSFR (freezing in heat exchanger).
  2. Quantitative experimental data is lacking for both the laminar and turbulent cases.
  3. Thermophysical properties of water are well known, and close to the melting point water has a Prandtl of O(10).



Sketch of the original ESPRESSO concept, featuring a cylinder with a rotating top lid and a cold plate at the bottom.

Design of experimental facility (ESPRESSO)

- Rectangular duct $(h \times b \times l = 5 \times 5 \times 145\ cm)$ made of PMMA to guarantee optical acess.
- Water flow controlled by pump with an electronic frequency drive, maximum flow rate is 1.4 L/s.
- Cold plate (offset fin design) capable of reaching -20 ° C.
- Precooling of inlet through brazed plate liquid heat exchanger to a minimum temperature of 0 ° C.
- Combination of converging nozzle and settling chamber with honeycomb grid and turbulence reduction screens for imposing uniform inlet condition.
- Sensors are included for recording the cold-plate, inlet and outlet temperatures, as well as the flow-rate.



Design schematics of the ESPRESSO facility: entire loop (top) and zoom in of the test section and the heat sink (bottom).

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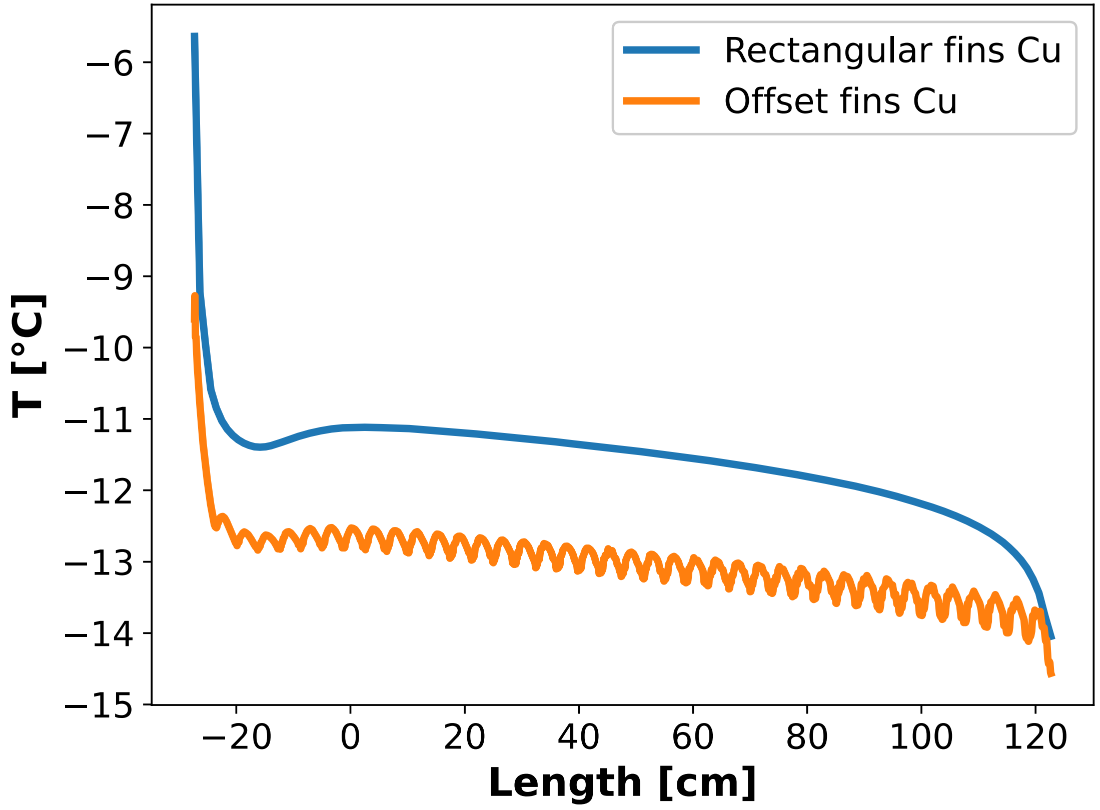
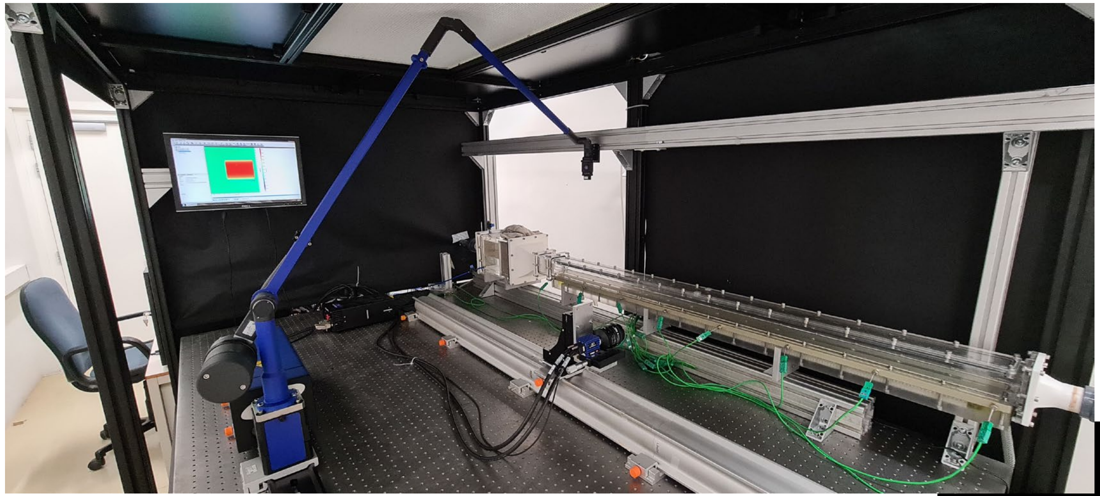
Design of cold plate

- Proper design of the cold plate is needed to ensure a well-described boundary condition.
- Objective is to maximize the heat transfer rate between the cold plate and the channel flow.
- As predicted by literature and confirmed through a COMSOL simulation, an offset fin configuration offers better heat transfer characteristics compared to the rectangular fin designs.
- Real-time cold plate response measured by 8 equally spaced thermo-couples, used to formulate the cold plate boundary condition in numerical simulations.

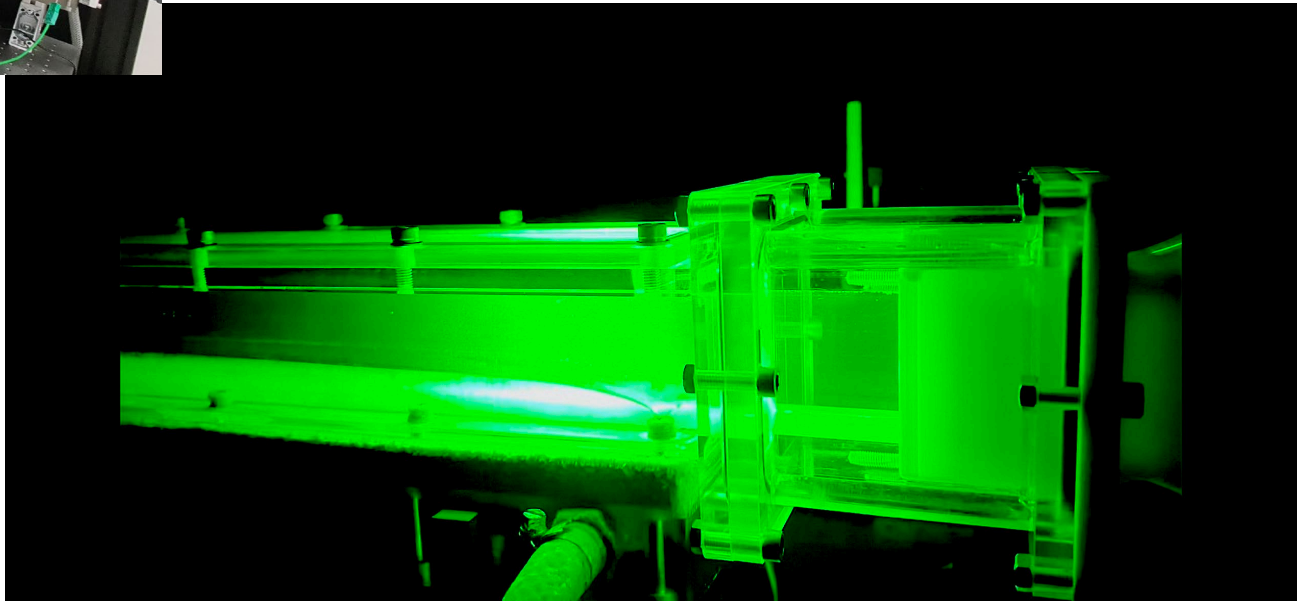


Predicted temperature profile along the length of the cold plate, from COMSOL simulations.

Finalized experimental facility (ESPRESSO)



- Planar Particle Image Velocimetry & Laser Induced Fluorescence.
- 5W shuttered continuous laser (diode pumped, 532 nm).
- High speed CMOS camera (LaVision MX4M).
- Borosilicate glass particle seeding (1.1 gcm^{-3}, 9-13 μm, Stk = 1.5E-6 for Re = 500).
- Rhodamine B (tenperature sensitive) & rhodamine 110 (reference) dyes for temperature measurements.



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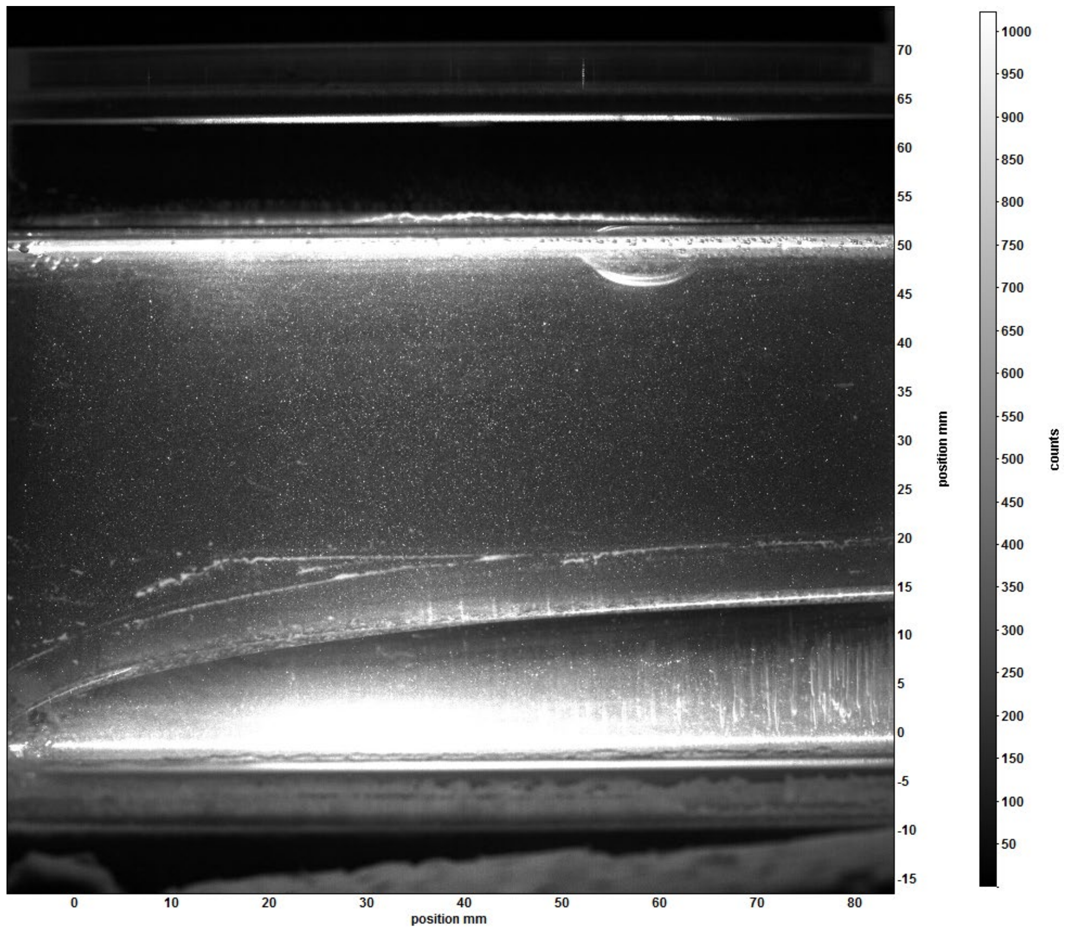
Visualization of Ice-Layer

- Growth of ice-layer from cold-plate succesful.
- Ice-layer well visualized with laser-sheet illumination and CMOS camera.
- Experimental challenges:
    1) Reflections from aluminum cold plate, perspex walls, and ice-layer.
    2) Blind spots laser and camera (due to screws, o'ring grooves etc).
    3) Uneven illumination from laser sheet.
    4) Condens formation on perspex walls due to cold temperatures.
    5) Determination of exact onset of ice-formation.



Ice-layer after 90 min for Re $\approx$ 474, $T_{in} \approx$ 5 °C, $T_{set} \approx$ -10 °C.

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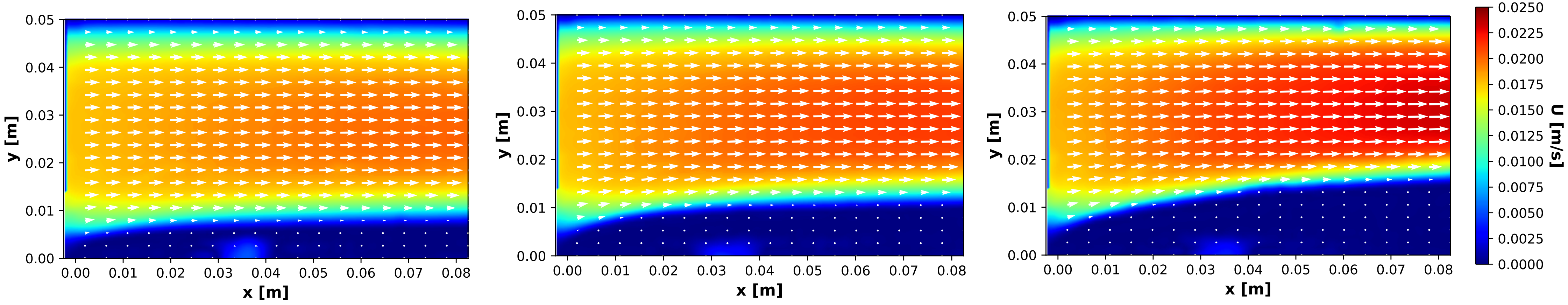
PIV velocity measurements

- Image pre-processing: non-linear sliding average substraction (filter size = 5 pixel) followed by a min-max filter and an intensity normalization filter.
- Vector calculation: Multi-pass: 3 x (64 x 64) with 75% overlap, 1 x (32 x 32) with 50% overlap
- Postproccessing: removal of outliers through median filter and specification of out of bounds velocity values, followed by a statistical averaging and a 3×3 Gaussian smoothing filter.
- Acceleration of bulk flow as ice-layer grows.
- Theory predicts: heat transfer from fluid to solid-liquid interface increases, heat transfer from cold plate to ice-layer decreases as the ice-layer thickens. Steady state solution for certain parameter combinations.



Flowfield after respectively 10, 30 and 90 min for Re ≈ 474, T_{in} ≈ 5 °C, T_{set} = -10 °C.

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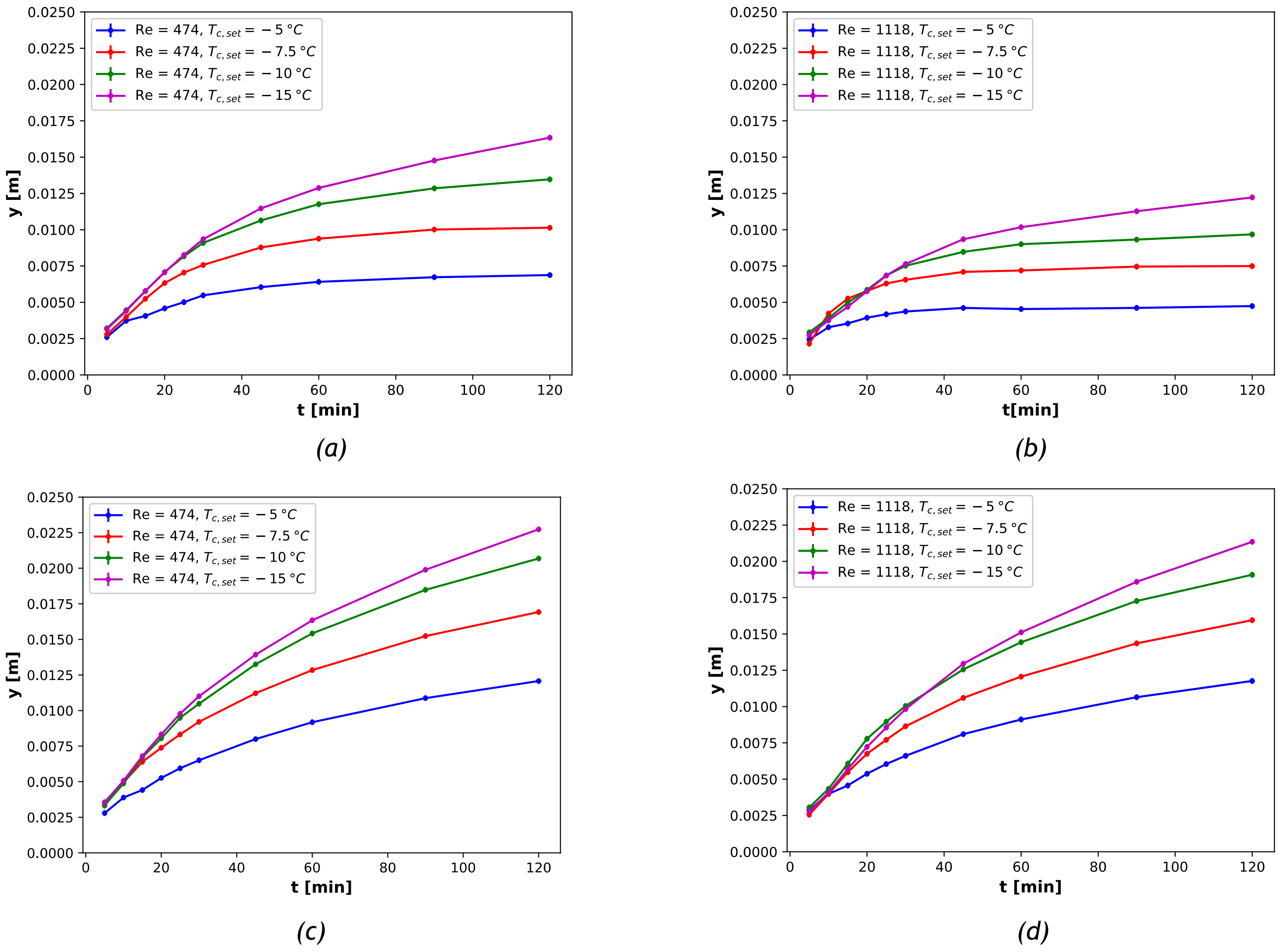
Ice layer measurements

- Ice-layers evaluated through a manual tracing using the *WebPlotDigitizer* software.
- Parametric study performed for two different flow rates and four different cold plate temperatures.
- For lower cooling parameters, the ice reaches a steady state thickness near the inlet.
- An increase in the flow-rate has a larger effect on the ice-growth rate near the inlet of the channel than in the center.



Ice layer thickness measurements at x = 5 cm for Re = 474 (a) and Re = 1118 (b), and x = 75 cm for Re = 474 (a) and Re = 1118 (b).

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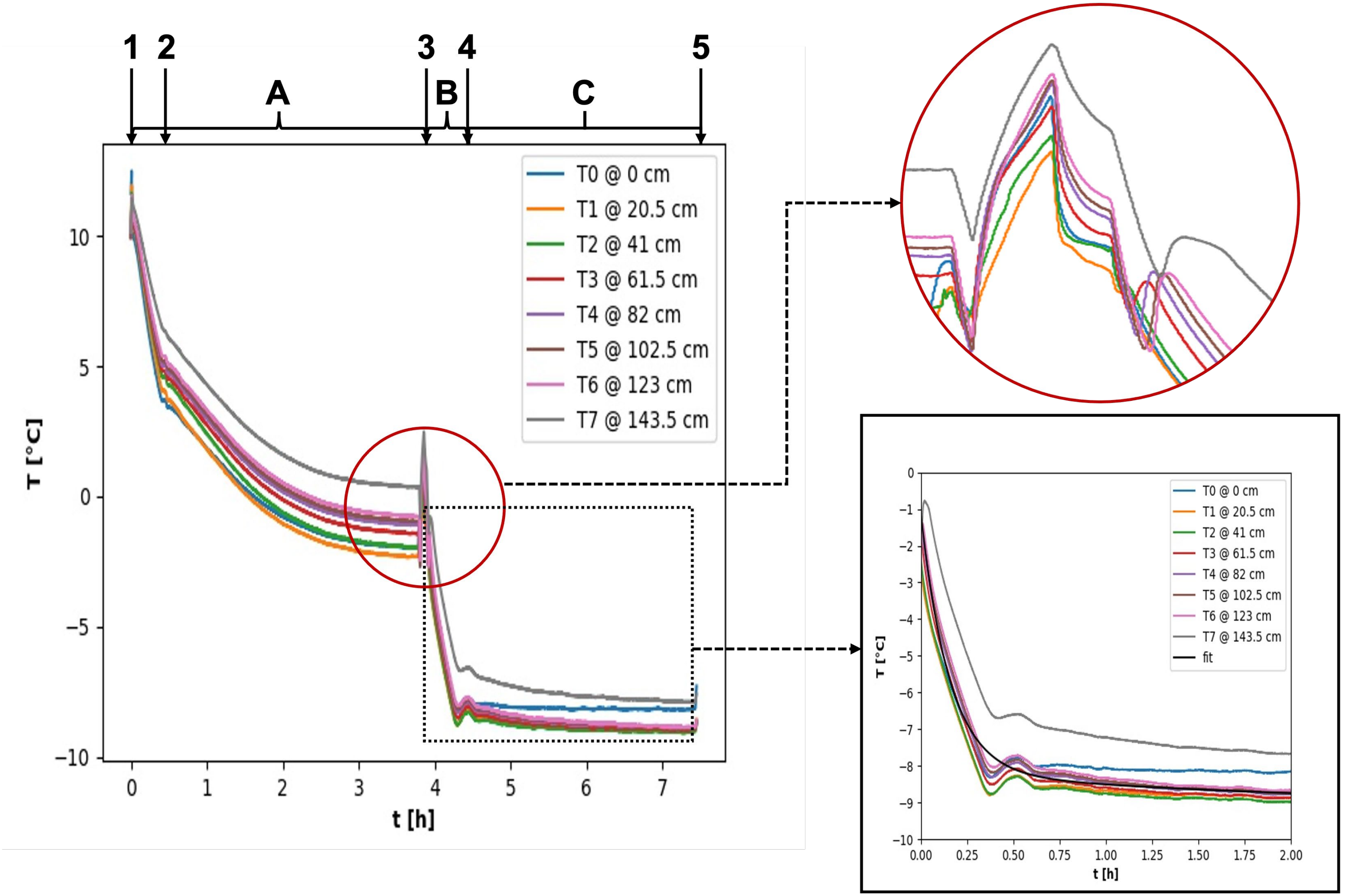
Determination of Experimental Boundary Condition

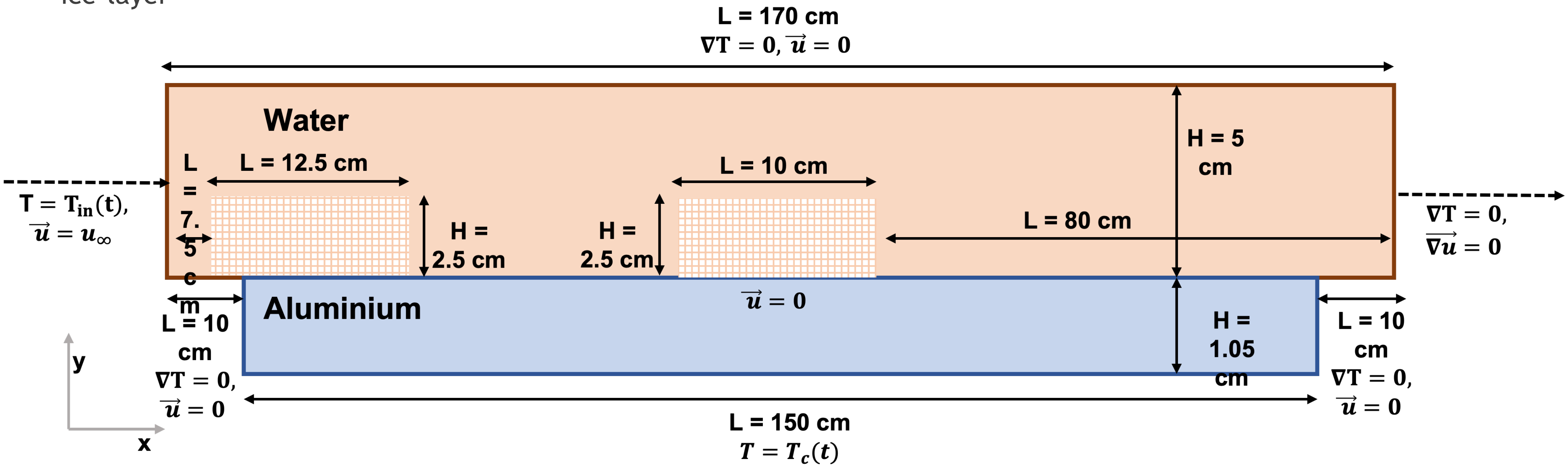
- Cold plate temperatures recorded by 8 equally spaced thermo couples
- Onset of ice-formation marked by a sudden sharp increase of the cold-plate temperature, used to determine the zero-time instant in our experiments.
- Sequence of the thermocouples' response showed that ice nucleation first occurs at the inlet of the channel, from which the ice subsequently spreads over the entire cold plate surface.
- Fit used to describe temperature evaluation of the cold-plate in time, used as input for numerical simulations.



Temperature response of the cold plate, and resulting fit function.

Comparison of Experimental Results with Numerical Simulations

- 2D numerical domain.
- Linearized enthalpy approach with DG-FEM.
- Constant thermophysical properties for each phase (except for the thermal expansion coefficient) and use of Boussinesq approximation.
- Extension of inlet and outlet to avoid issues with inlet and outlet boundary conditions due to growth of the ice-layer



Computational domain.

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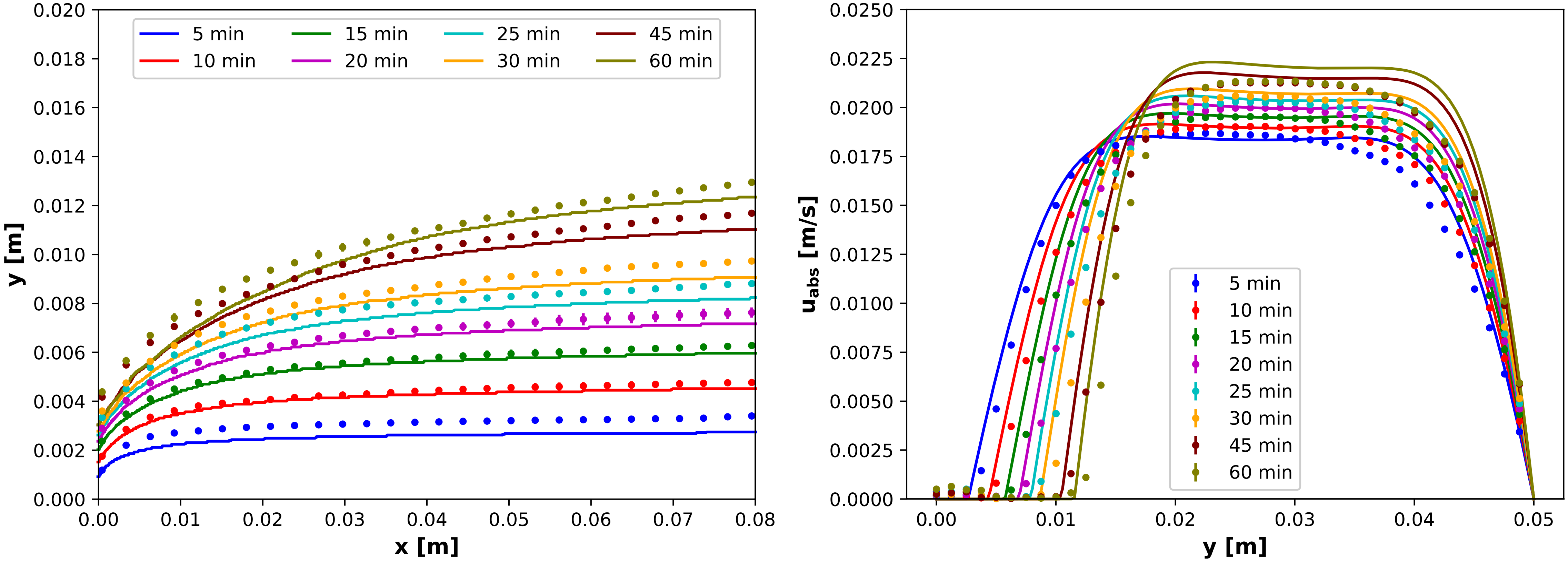
Comparison of Experimental Results with Numerical Simulations (inlet)



Comparison of experimental transient ice-growth and velocity profiles with the 2D simulation results, for the inlet of the channel.

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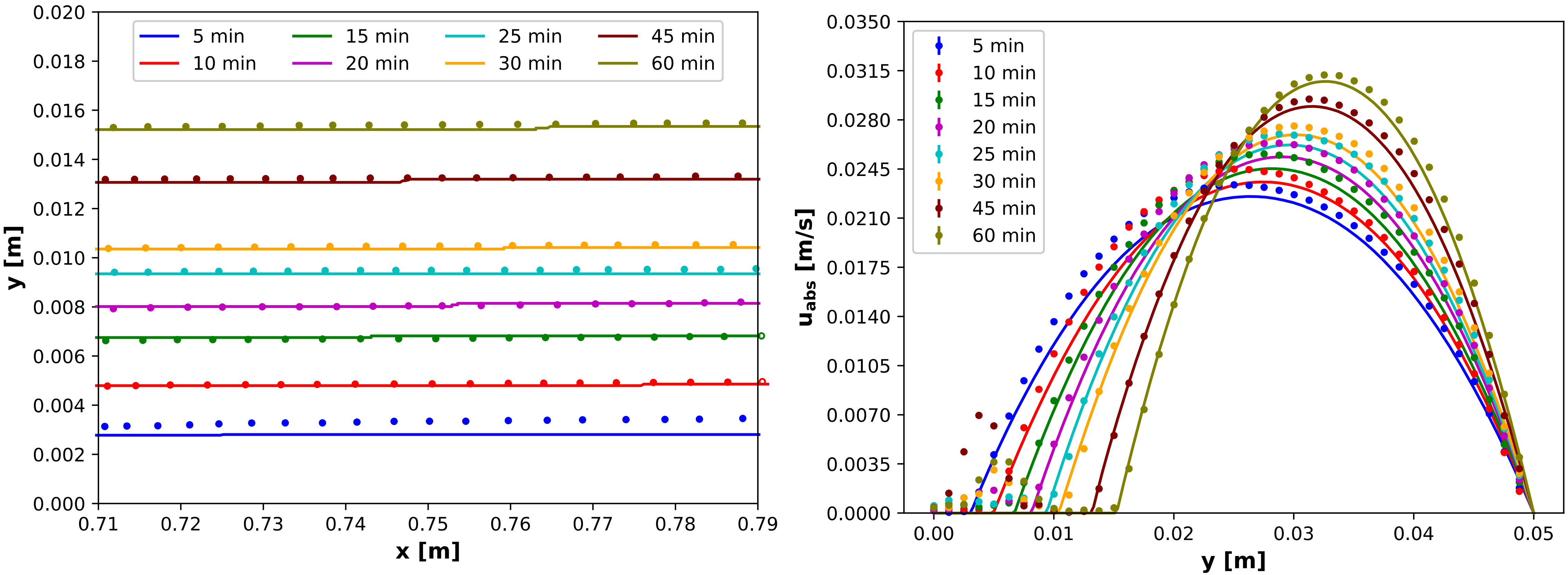
Comparison of Experimental Results with Numerical Simulations (center)



Comparison of experimental transient ice-growth and velocity profiles with the 2D simulation results, for the center of the channel.

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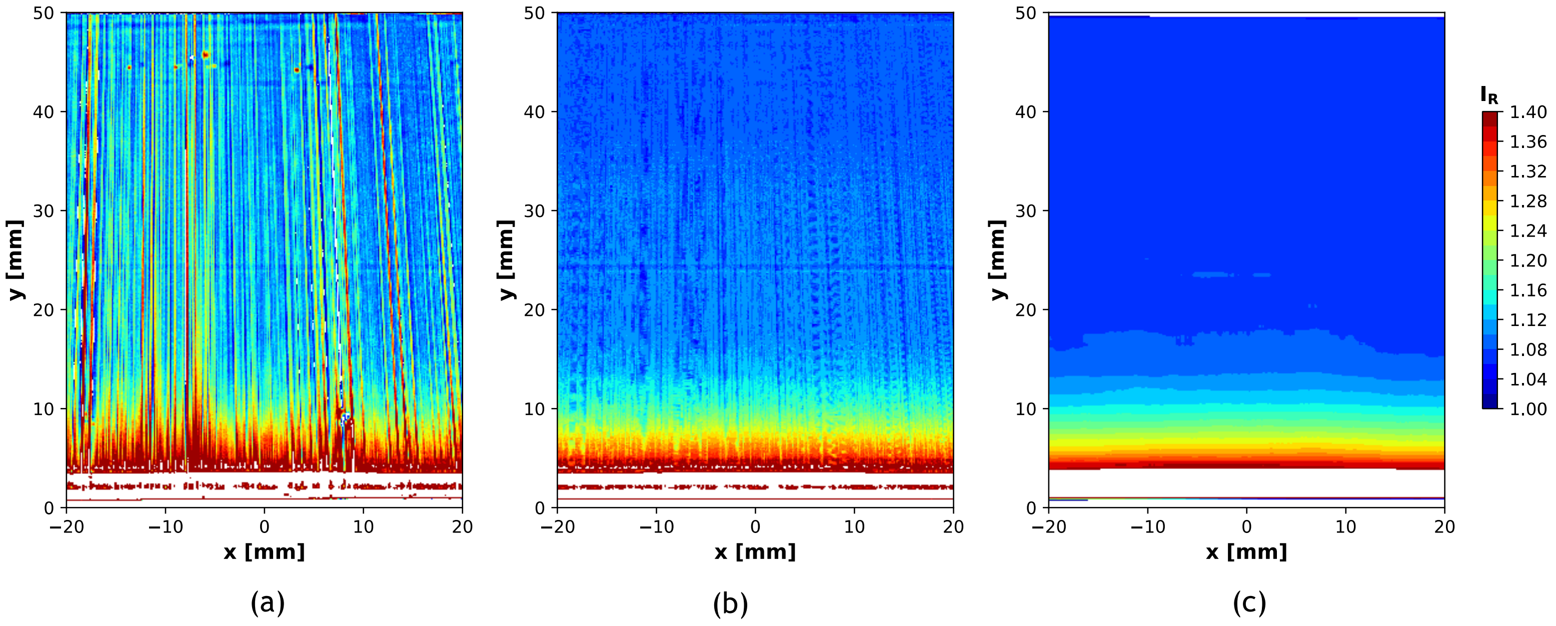
LIF temperature measurements: postprocessing

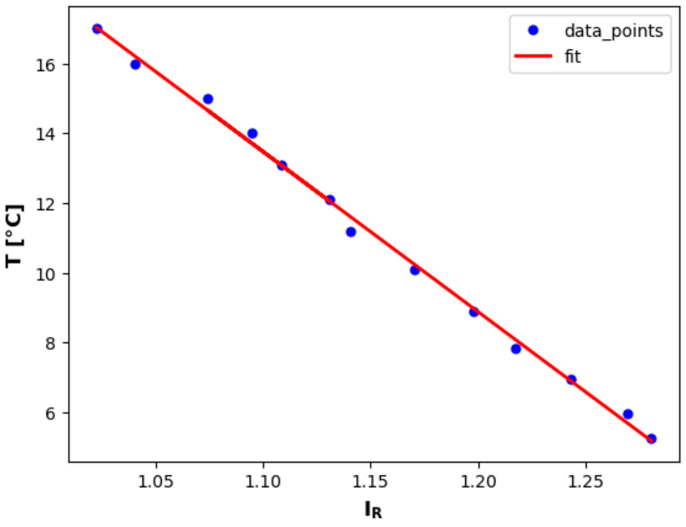
- Main challenge: spatial variation in image intensity due to other factors then temperature difference (such as scattering by air bubbles, the ice-water interface or other reflective surfaces) which can cause striations and other artefacts.
- Solutions:
  - Use of black aluminium tape to block reflections from cold plate and perspex back wall as much as possible.
  - Magnetic wiper to clear air bubbles as much as possible.
  - Postprocessing of data: outlier removal & smoothing.



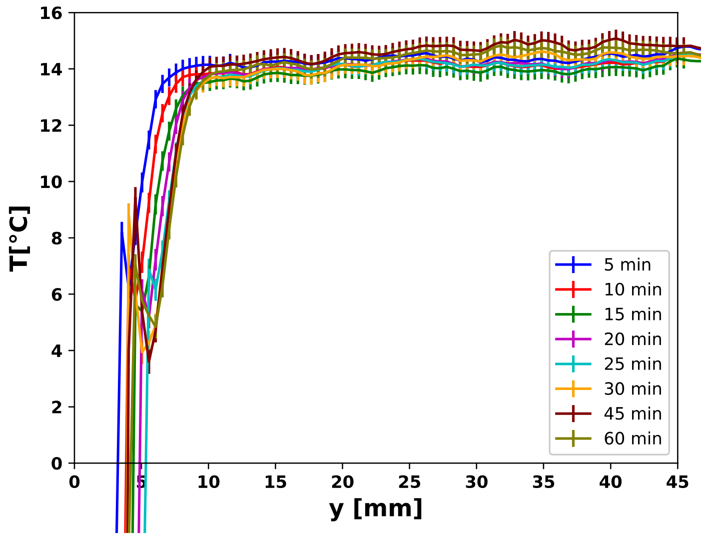
Intensity ratio ma[after the different postprocessing steps (pre-processing (a), striation removal (b), smoothing c), taken at the center of the channel for t = 5 min. Experimental settings were Re ≈ 474, $T_{in,set}$ ≈ 15 °C, $T_{c,set}$ = -10 °C.

LIF temperature measurements: temperature calculation.

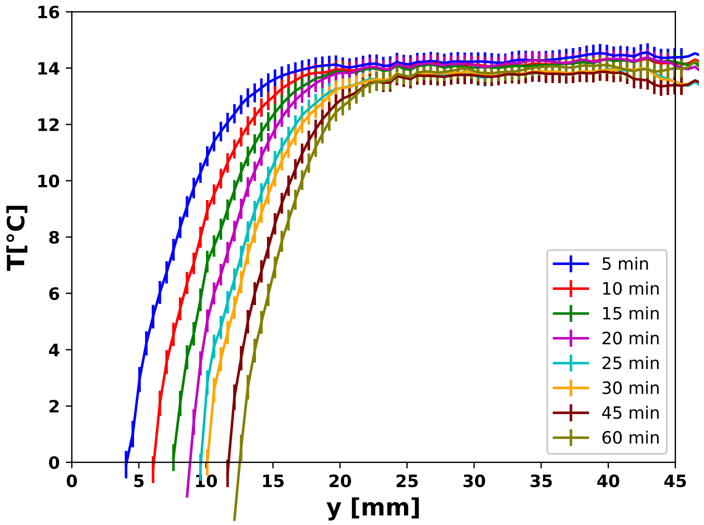
- Temperature calibration through ratiometric measurements performed for a series of uniform temperatures in the channel. Linear relationship assumed.
- Quantitative uncertainty analysis gives an uncertainty of $\sigma = 0.3 - 0.6\ °C$
- Good results obtained for a sufficiently large temperature difference of 15 °C between the bulk and the melting point. However, some artefacts were present near the ice-layer (especially at the inlet) due to scattering of the laser light.



Temperature calibration.



Temperature profiles at x = 5 cm, for Re ≈ 474, $T_{in,set}$ ≈ 15 °C, $T_{c,set}$ = -10 °C.



Temperature profiles at x = 75 cm, for Re ≈ 474, $T_{in,set}$ ≈ 15 °C, $T_{c,set}$ = -10 °C.

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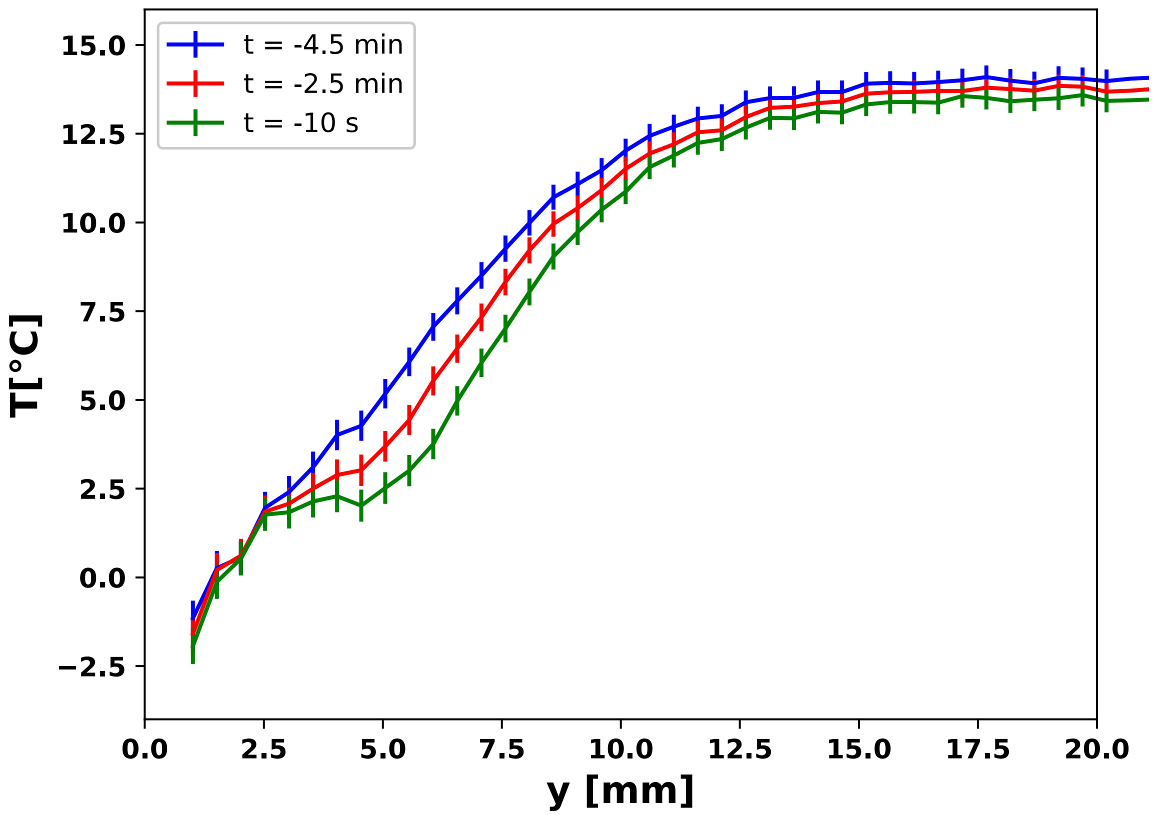
Evidence of subcooling

- Sudden increase of cold plate temperature attributed to subcooling effects prior to nucleation.
- Approximately 2 °C of subcooling was measured prior to the freezing of water flowing over a cold flat plate by *Savino et al* in 1967 using thermocouples.
- Our current LIF measurements support these findings.
- Anomalous behaviour of temperature profile (especially at t = - 10 s) observed, possibly due to enhanced natural convection as a result of the subcooling.



Temperature profiles taken for various times prior to the onset of ice formation. x = 75 cm, Re ≈ 474, $T_{in,set}$ ≈ 15 °C, $T_{c,set}$ = -10 °C.

Conclusions

- A comprehensive and well-described experimental data set was generated for transient freezing in laminar internal flow.
- The onset of ice-formation was found to coincide with a sudden increase of the cold plate temperature, attributed to subcooling effects. This was later confirmed by LIF temperature measurements.
- An overall good agreement was observed between the experimental results and the numerical simulations, with observed discrepancies attributed to the use of a 2D computational domain, the use of constant and isotropic thermophysical properties for each phase, the use of the *Boussinesq* approximation, and possible systematic errors during the experiments.
- LIF is a promising technique for performing non-intrusive temperature measurements in solid-liquid phase change experiments. However, further improvements are needed to increase the accuracy (especially for small temperature ranges) and reduce the noise and artefacts due to the scattering of the laser light.

Dissemination Experiments

Deliverables

- D4.2 Design report of ESPRESSO (**completed)**
- D4.3 Validation of tools by detailed basic experiments (**completed)**

Journal papers

- B.J.Kaaks, D.Lathouwers, M.Rohde, J.L. Kloosterman. Transient freezing of water in a square channel: an experimental investigation, *Experimental Heat Transfer* (2023). *Under review*.
- B.J.Kaaks, S. Couweleers, D. Lathouwers, J.L. Kloosterman, M. Rohde. Non-intrusive temperature measurements for transient freezing in laminar internal flow using laser induced fluorescence, *Experimental Thermal and Fluid Science* (2023). *Under review*.

Relevant experimental and numerical data shared in SAMOSAFER Zenodo community.