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Experimental Investigation of Freezing Phenomena in Forced Convection Internal Flow

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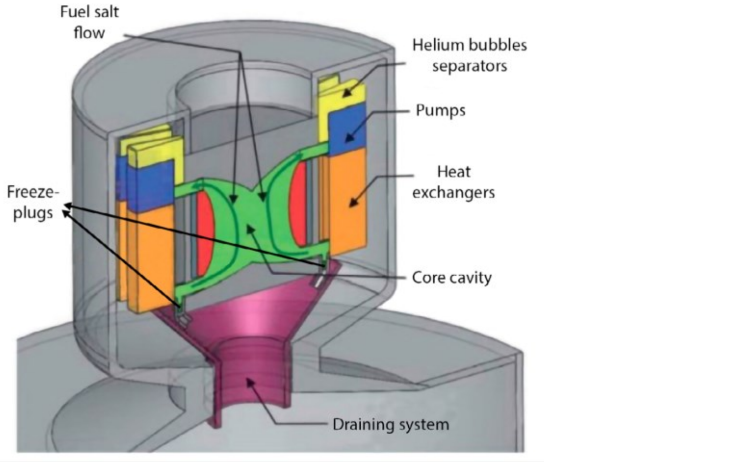
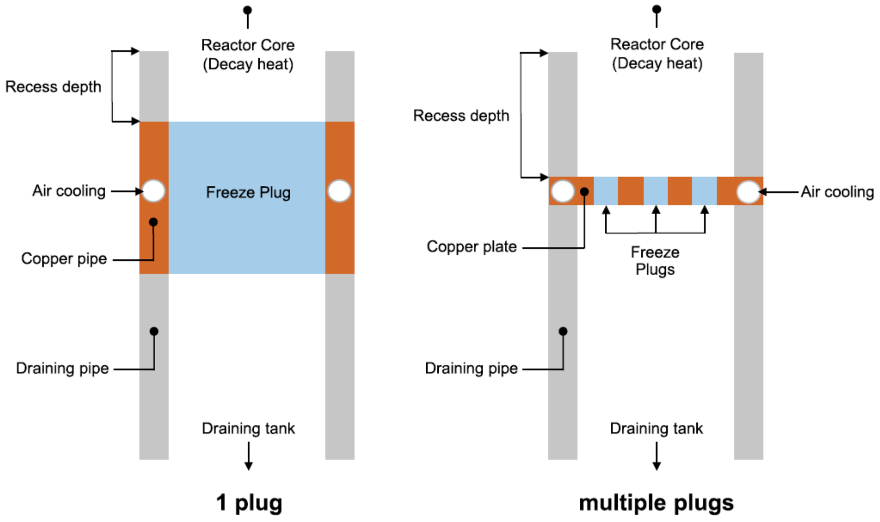
Importance of Melting / Solidification in MSFR

- SAMOSAFER:
  - Develop and demonstrate new safety barriers for the MSFR
  - Ensure compliance with regulations in 30 years time
- Safety considerations regarding melting and solidification:
  - Design of freeze plug
  - Design of passively cooled drain tanks
  - Accident scenario's where solidification may pose a risk (e.g. sudden solidification in the steam generator)



Schematic view of the MSFR fuel circuit and draining system with freeze plugs (Tiberga, 2019)



Schematic of single and multi freeze plug designs (Tiberga, 2019)

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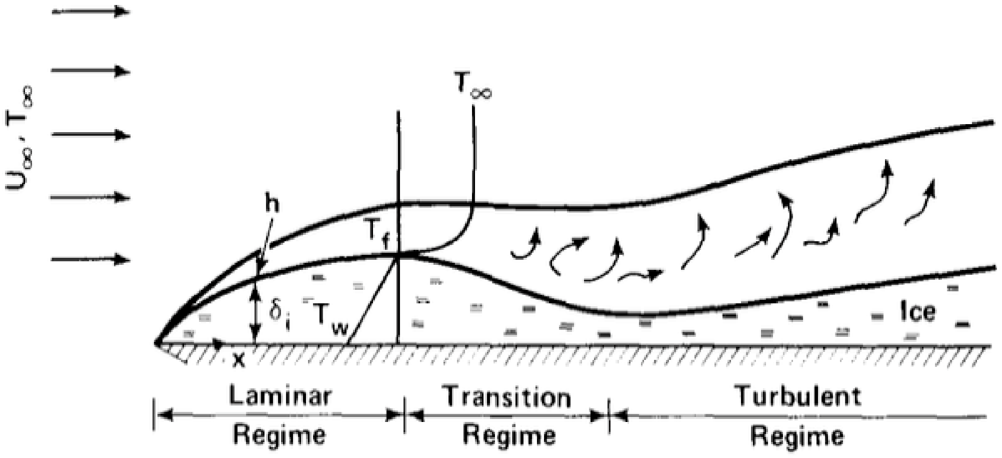
Overview

1. Introduce background and purpose of research:
    - Previous work on freezing in internal flow
    - Objectives of present experimental campaign
2. Description of experimental setup
3. Preliminary results from experimental campaign
4. Conclusion and future outlook

Freezing in Forced Internal Flow

- Comparitively few studies report phase change in forced/mixed convection regime
- Lack of detailed measurements of transient ice-growth suitable for numerical benchmarking purposes



Schematic representation of the ice profile and flow regimes (Hirata, 1979)

Objectives of Present Experimental Campaign

1. Perform benchmark experiments of phase change in laminar forced convection heat transfer regimes:
   - Well defined boundary conditions
   - Non-intrusive experimental techniques
2. Perform whole field measurements of velocity and temperature:
   - PIV & LIF

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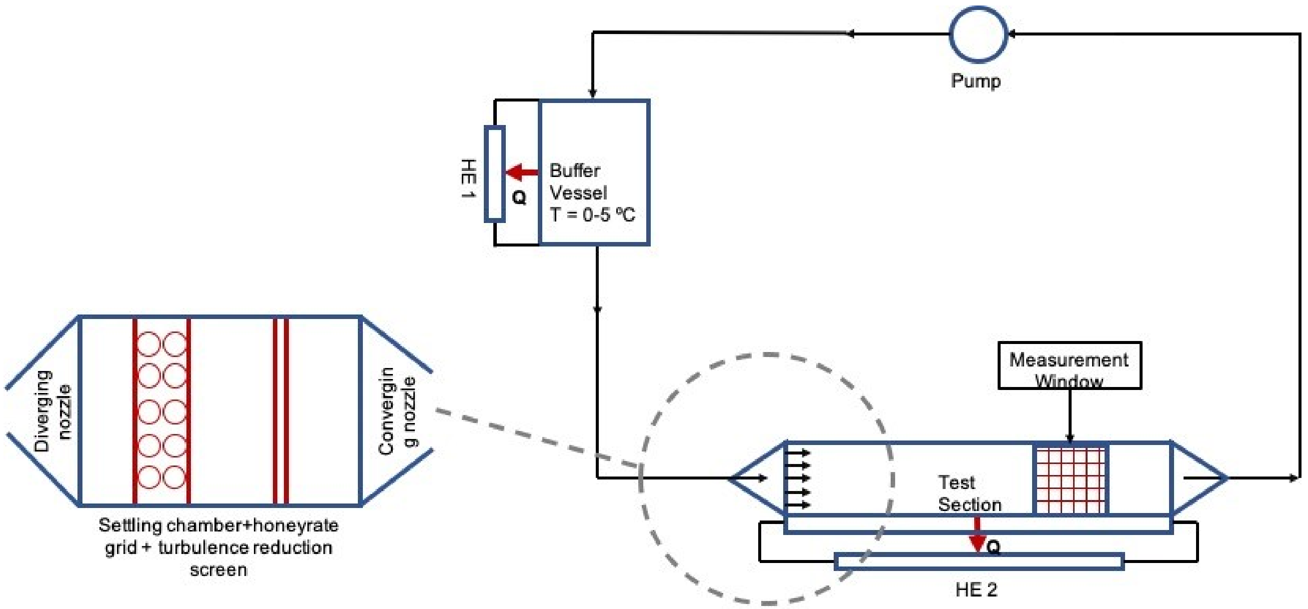
Preliminary Design of Experimental Facility (ESPRESSO)

- Rectangular duct ($h \times b \times l = 5 \times 5 \times 150\ cm$)
- Water loop with Re = 500-10000, $\theta_c = 1 - 30$
- Inlet temperature between 0 and 5 ° C
- Cold plate between -5 and -20 ° C
- Ice-layer grown from cold plate at bottom
- Minimize heat flux through walls of test section: insulation needed
- Converging nozzle for imposing uniform inlet condition, inlet is cooled!



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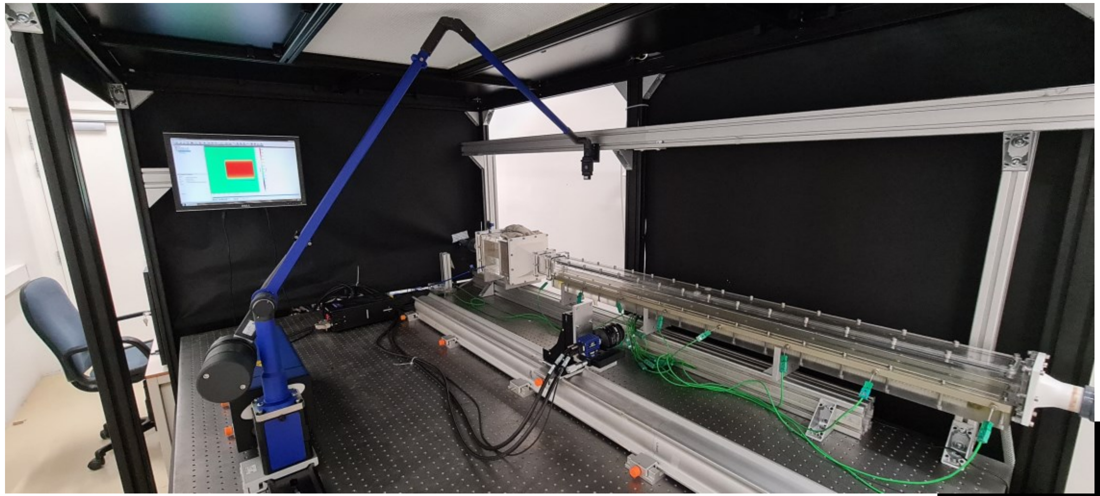
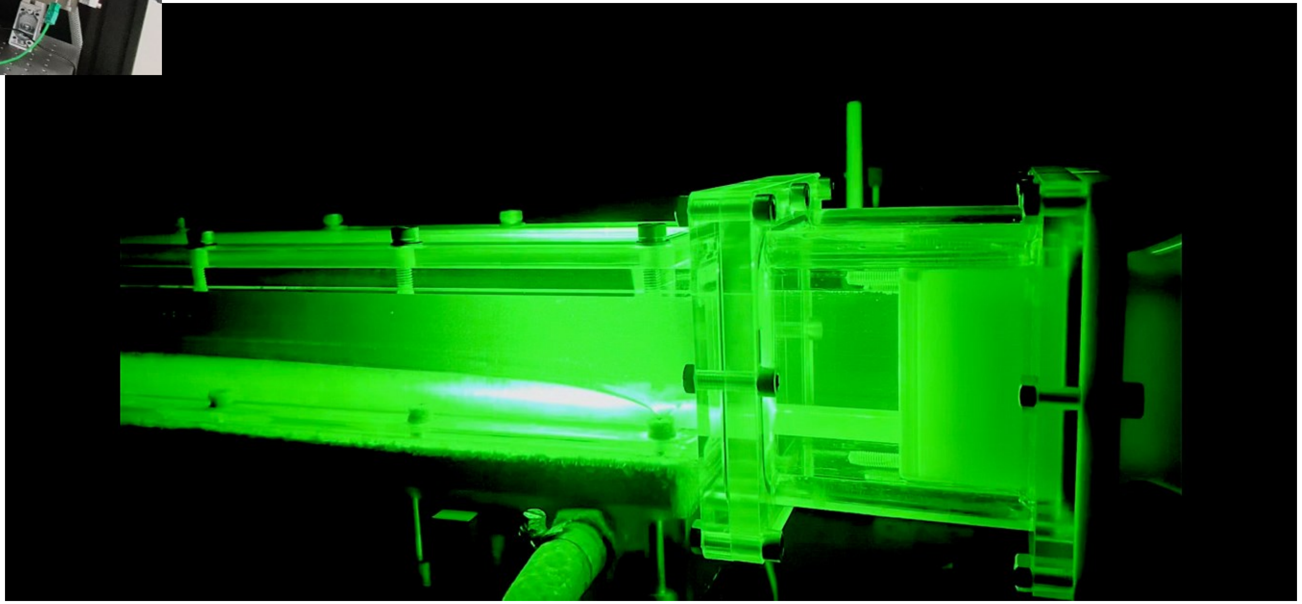
Finalized Design of Experimental Facility (ESPRESSO)



- Planar PIV
- 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)



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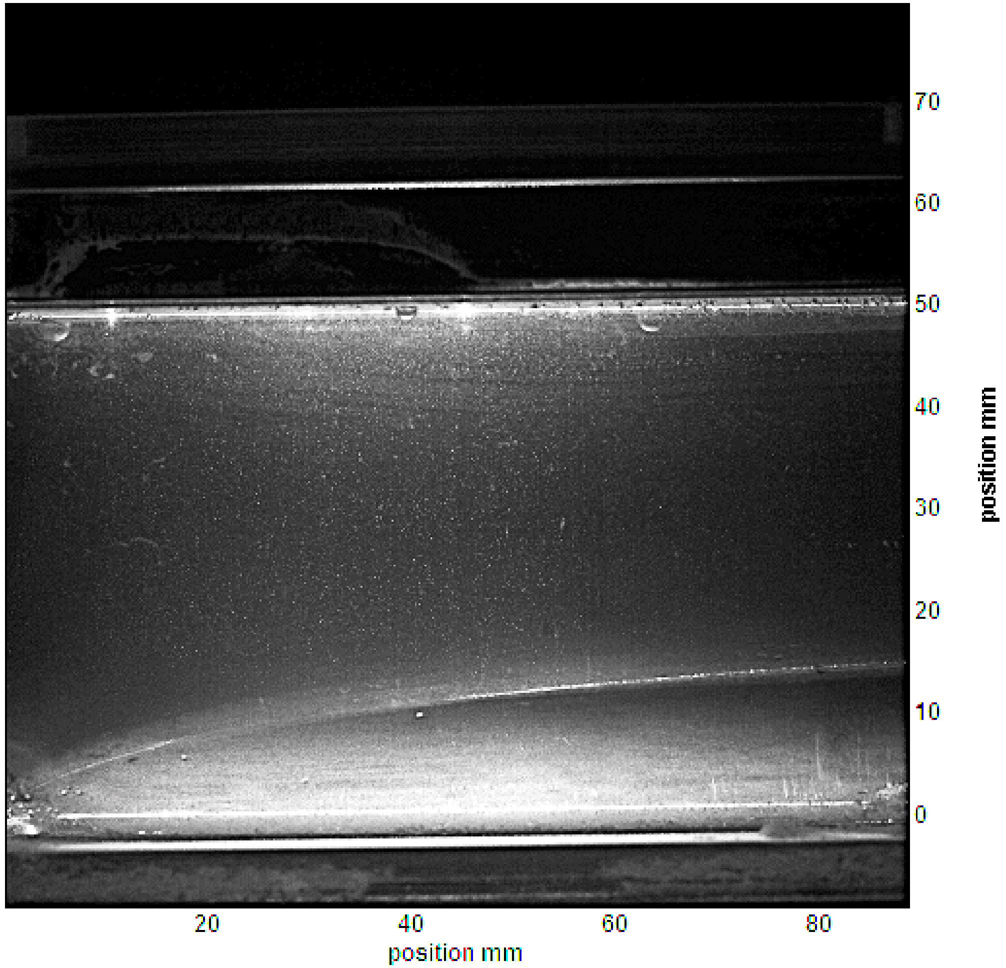
Preliminary Results: Visualization of Ice-Layer

- 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 ≈ 500, T_{in} ≈ 5 °C, T_c ≈ -8 °C

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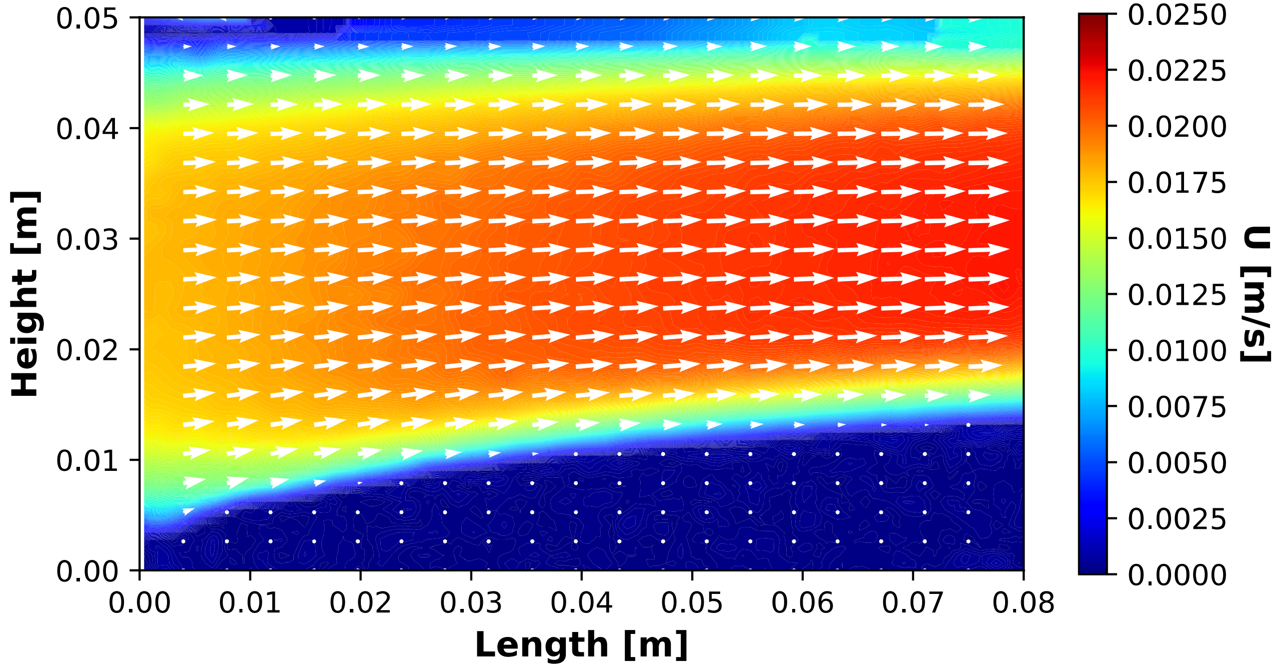
Preliminary Results: Flowfield (1)

- Double-frame PIV with dt = 10 ms
- Image pre-processing:
  1. Sliding background substraction (filter size = 5 pixel)
  2. Butterworth high pass filter for bright field correction
- Postproccessing: sum of cross-correlations.
  1. Multi-pass: 4 x (64 x 64) with 75% overlap, 2 x (32 x 32) with 50% overlap
  2. Remove vectors with $\sigma > 2\sigma$ of neighbours



Flowfield after 90 min for Re ≈ 500, T_{in} ≈ 5 °C, T_c ≈ -8 °C

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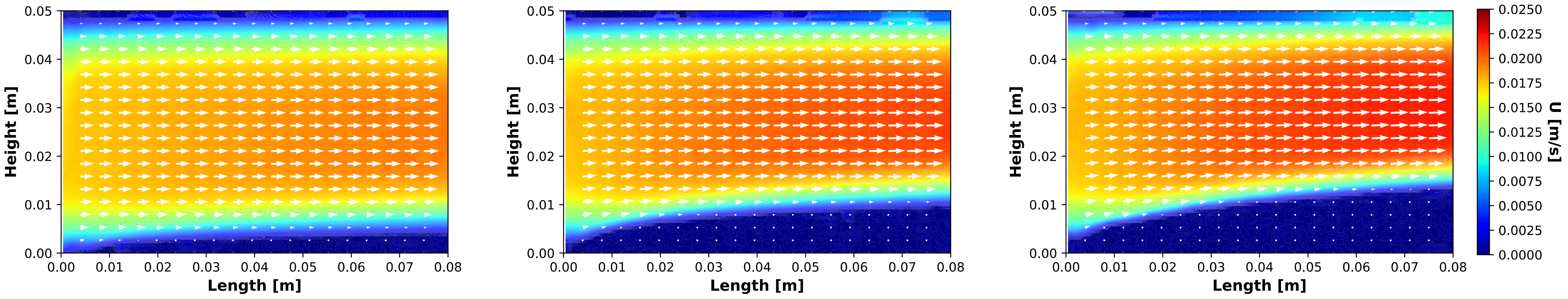
Preliminary Results: Flowfield (2)

- 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. Possible steady state solution?
- No-slip condition on ice-layer: allows a simple algorithm for calculating the ice interface position by interpolating for u = 0 m/s



Flowfield after respectively 10, 30 and 90 min for Re ≈ 500, T_{in} ≈ 5 °C, T_c ≈ -8 °C

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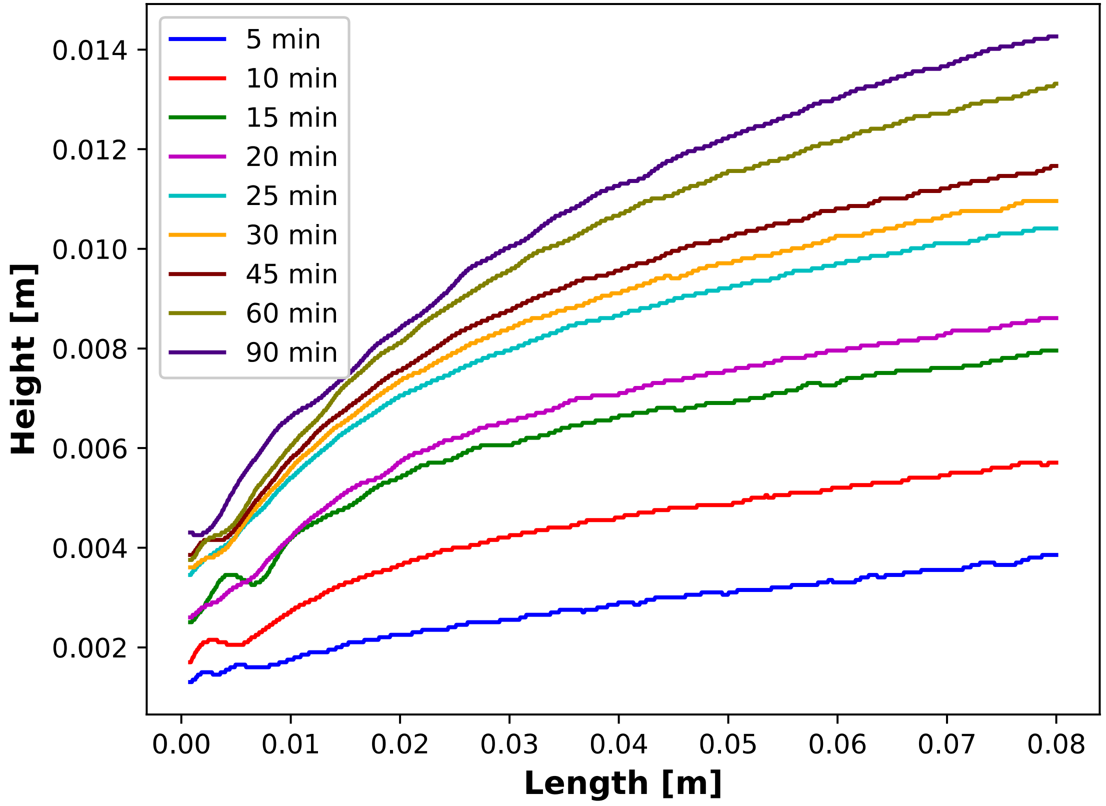
Preliminary Results: Transient Growth of Ice-Layer

- Calculated ice-layer interface positions from algorithm appear to be consistent with the visually observed ice layer from the raw images
- Growth of ice-layer slows down as time progresses
- Uncertainty in interface position yet to be determined: largest uncertainty appears to be near entrance of test section
- Consistent with observations of (*Hirata, 1979*), ice appears to be growing in front of leading edge of plate (more research is needed to confirm this)



Transient growth of the ice-layer for Re ≈ 500, T_{in} ≈ 5 °C, T_c ≈ -8 °C

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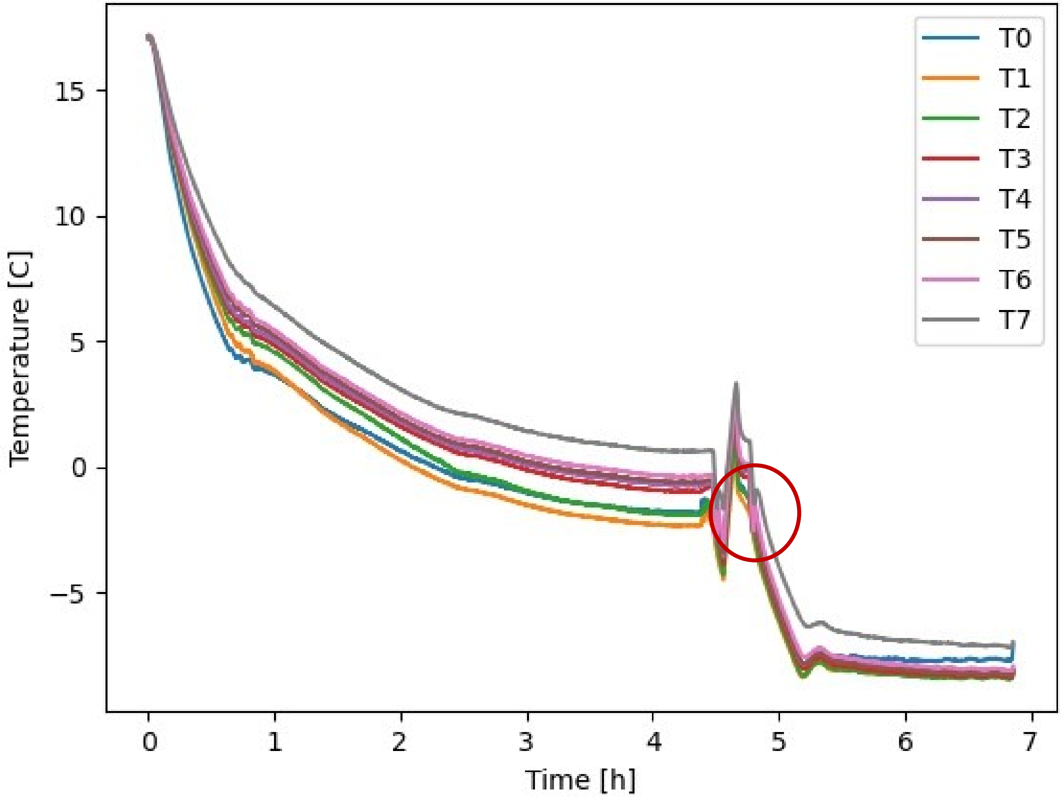
Verification of Boundary Conditions: Coldplate (1)

- Aluminium coldplate with offset fins for maximum heat transfer capacity
- Coolant: ethylene glycol, cooled and recirculated through a recirculating cooler
- 8 equally spaced thermocouples for recording the coldplate temperatures
- Experimental procedure:
  1. Start with high bulk flowrate (Re>10000)
  2. Precool inlet and bring temperature of coldplate down (takes approximately 4 hours)
  3. Reduce flowrate to desired value
- Onset of ice-formation starts after approximately 4h 45 minute (marked by temperature spike, see red circle).
- Subzero cold-plate temperatures at onset of ice-formation may indicate a certain degree of sub-cooling is required. This would be consistent with findings of (*Voulgaropoulos, 2020*).



Time and space dependent temperature distribution of the coldplate for Re ≈ 500, T_{in} ≈ 5 ºC, T_c ≈ -8 ºC

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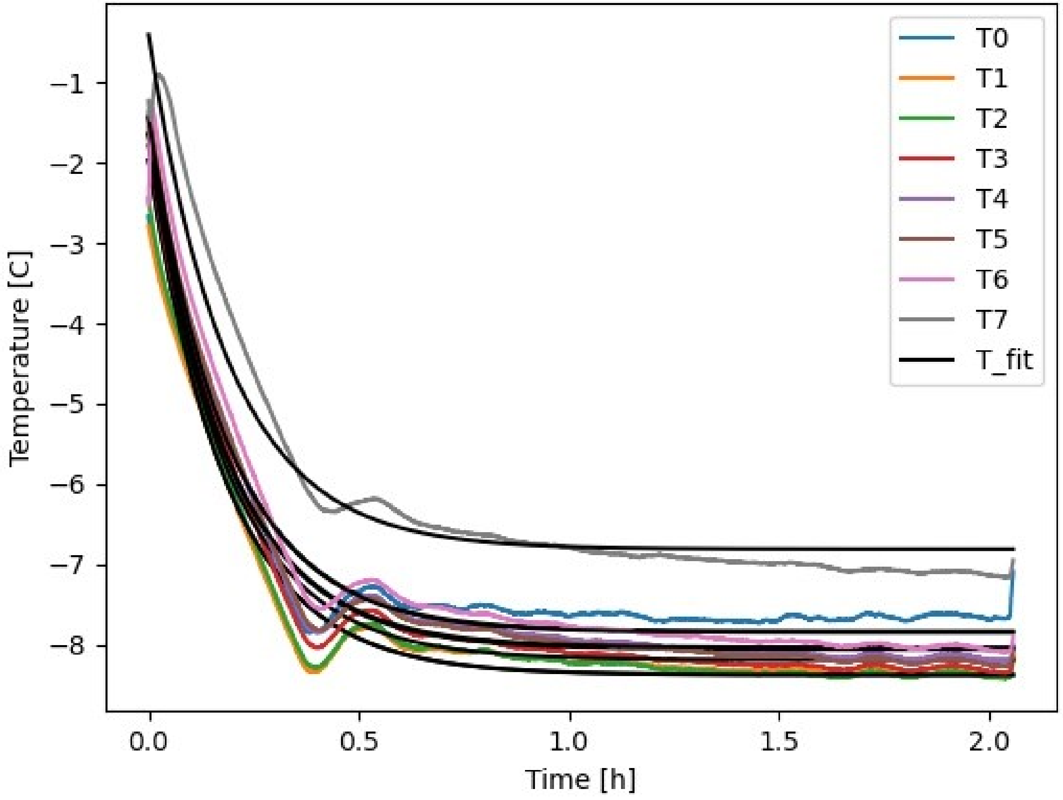
Verification of Boundary Conditions: Coldplate (2)

- Previous literature assumed a constant wall-temperature for the coldplate.
- Thermocouples in cold-plate show that transient behaviour of coldplate (especially during first 30 min of experiment) needs to be taken into account
- Numerical fit (exponential decay in time and 5th order polynomial in space) able to describe behaviour with reasonable accuracy



Time and space dependent temperature distribution of the coldplate after onset of ice-formaton including empirical fit for Re ≈ 500, T_{in} ≈ 5 °C, T_c ≈ -8 °C

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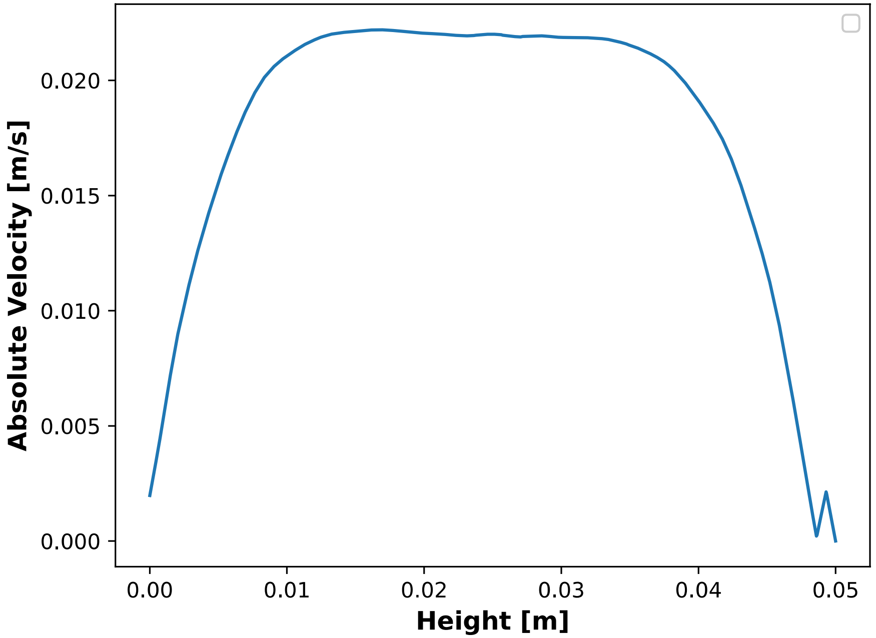
Verification of Boundary Conditions: Inlet Velocity Profile

- Converging nozzle and settling chamber with honeycomb grids and screens to set uniform velocity profile upstream of inlet
- Short development length (circa 1h = 5 cm) before start coldplate due to geometric constraints
- Water enters test-section with partially developed flow



Inlet profile for Re = 500

Summary and Conclusions

- Freezing phenomena in forced convection flow may play an import role in the design and safety analysis of the MSFR
- Detailed experimental data suitable for numerical validation studies is lacking
- To this end, an experimental facility for studying the ice-growth in forced convection internal flow has been designed and built
- First results obtained using planar PIV for the velocity field and transient growth of the ice-layer appear promising
- Unlike previous experimental campaigns, data is provided on the boundary conditions:
  - Suitability for numerical benchmarking
  - Facilitates better understanding of experimental results

Future Outlook

- Finalize experimental database for PIV measurements of ice-growth in forced internal laminar flow
- Perform temperature measurements for ice-growth in forced internal laminar flow:
  - May be very challenging, success is not guaranteed
  - Hope to gain insight in subcooling phenomena and thickness of temperature boundary layer
- Perform experiments database for ice-growth in forced internal **turbulent** flow:
  - Development and formation of ice-layer instabilities
  - Measurement of turbulent (heat) fluxes

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