Recent Ground-based Test Results for the Closed Loop Two-Phase Flow Chilldown Test Module for Future Integration with the Flow Boiling and Condensation Experiment onboard International Space Station

Jayachandran K Narayanan/CWRU, Jason W Hartwig/NASA Glenn, Jeffrey R Mackey/HX5, Mohammad Kassemi/CWRU, Chirag R Kharangate/CWRU

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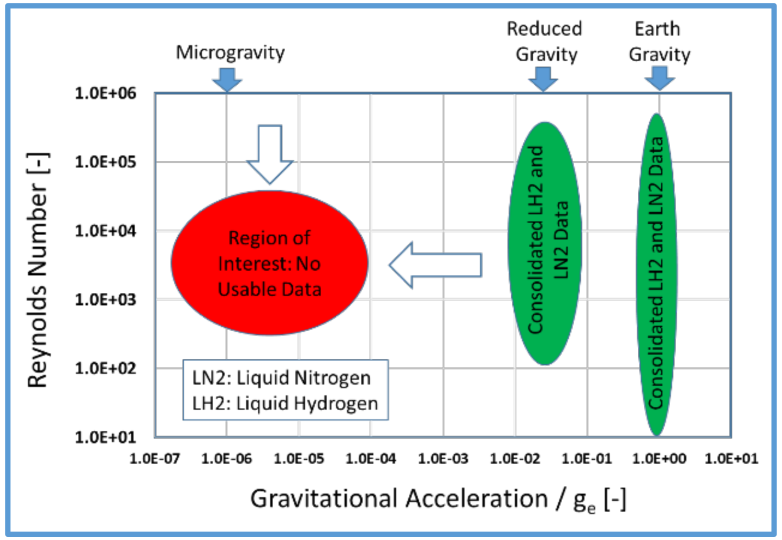
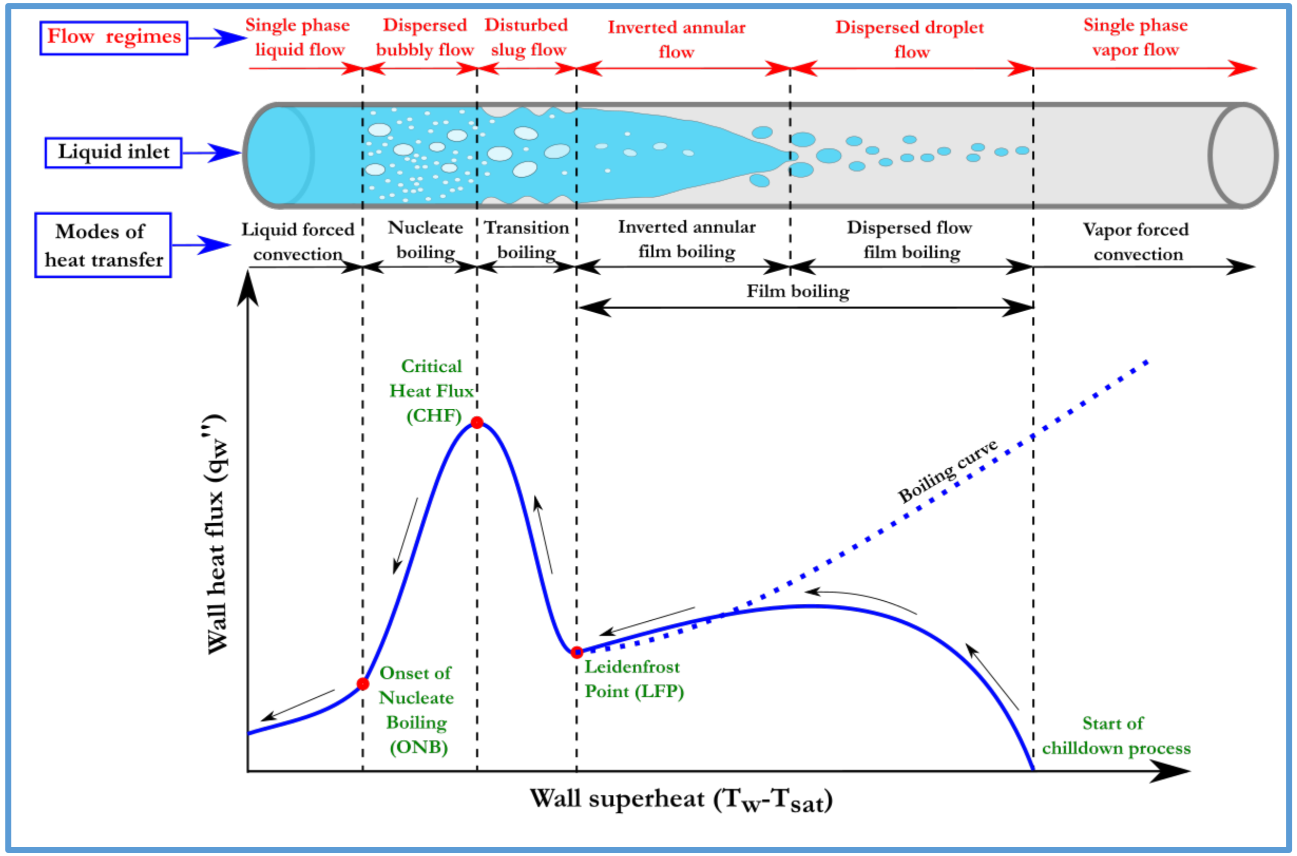
Relevance of Transfer-line Chilldown Data

- Effective cryogenic fluid management - important to the success of future manned and unmanned NASA missions.
- Key technological challenge – Storage and transport of cryogenic fluids in micro-gravity.
- Focus of the present research - line chilldown and transfer process.
- Major gap in research – scarcity of usable data in the low-gravity and low-Reynolds number regimes of interest (Hartwig et al., 2022)



Consolidated line quenching usable data

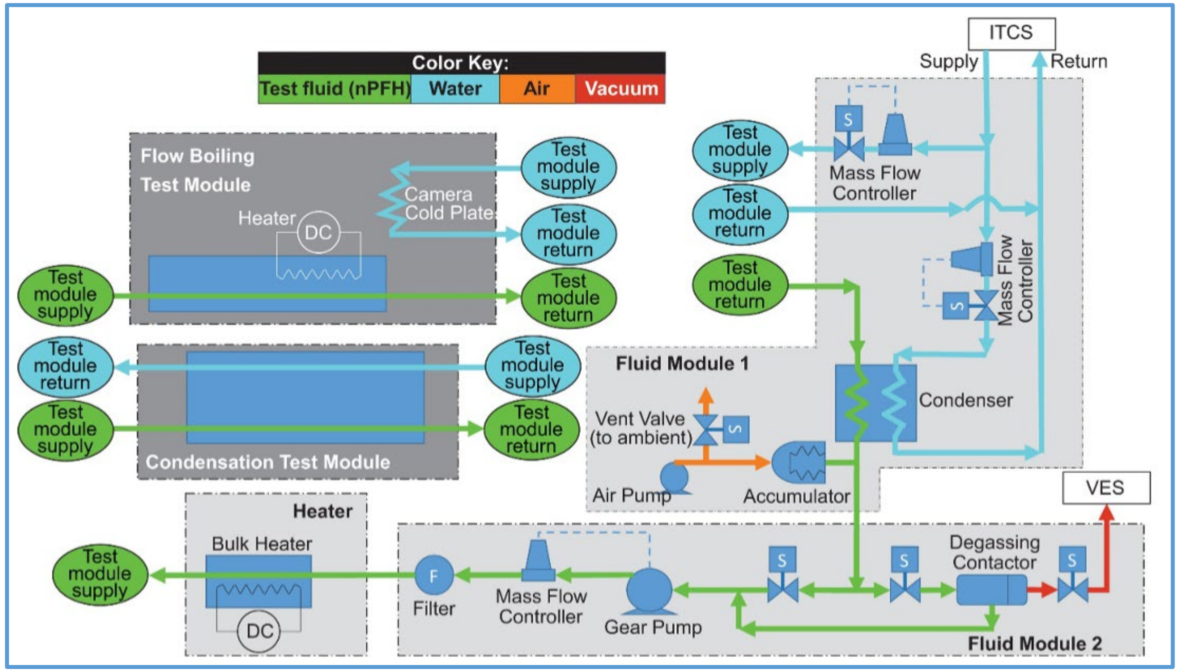


Depiction of the transfer line chilldown process and the quenching curve showing individual flow regimes and corresponding modes of heat transfer

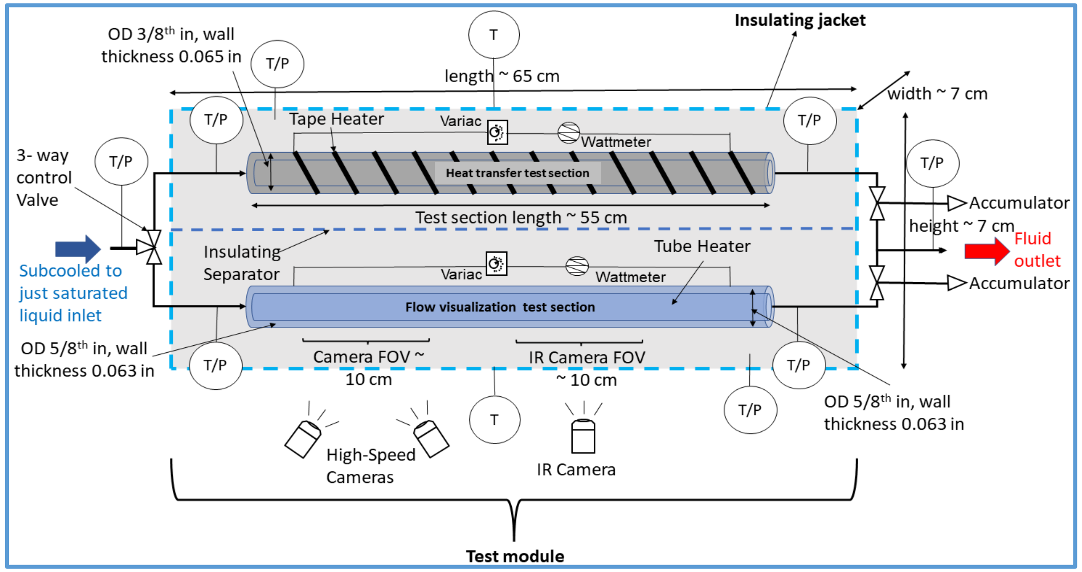
Proposed Flow Boiling Module for the Chilldown Tests at ISS

- Current Flow Boiling and Condensation Experiments (FBCE) Module – Perform flow boiling and condensation tests under microgravity conditions
- Flow boiling module – heated section to obtain data upto CHF.

- We propose a new flow boiling module to replace the current module in the FBCE that will fit in the existing space and be utilized to obtain both terrestrial and long-duration microgravity data for flow boiling occurring during the line chilldown and transfer process.
- Two modules planned – heat transfer and flow visualization

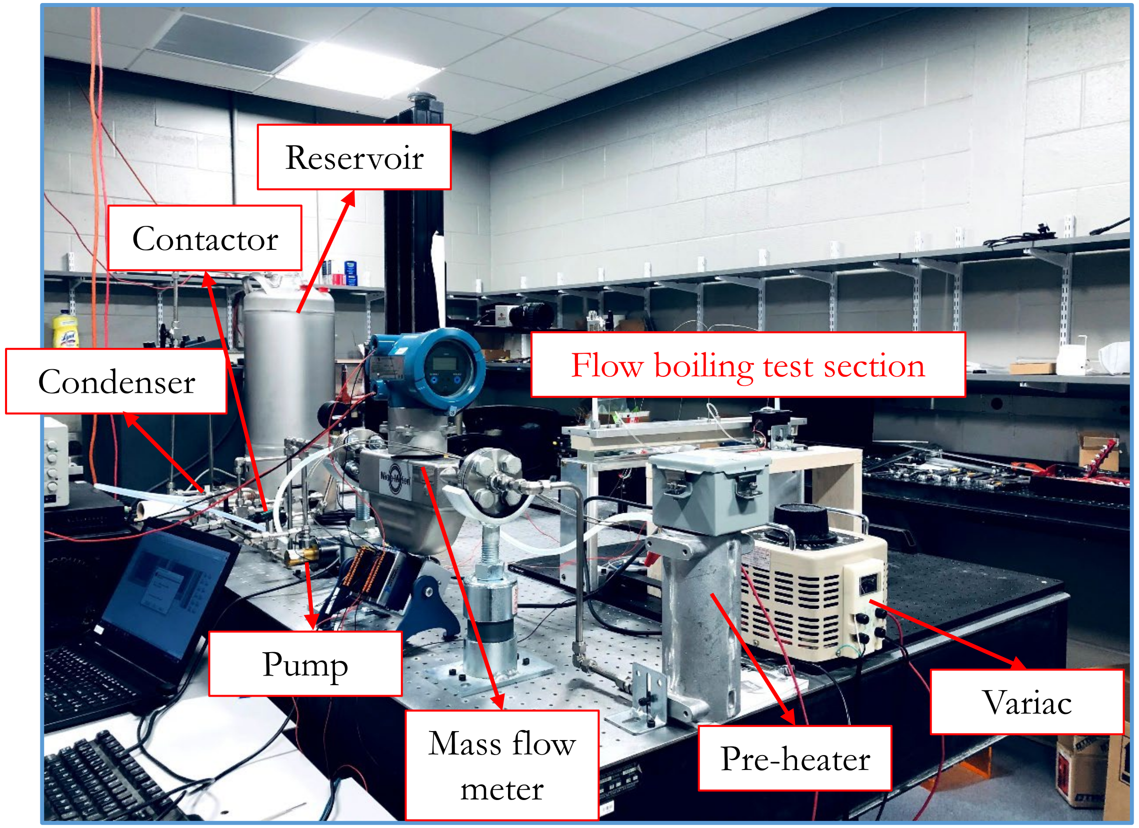


Schematic Representation of Simplified Fluid System for FBCE [Image Courtesy: NASA/TM-20205007641]

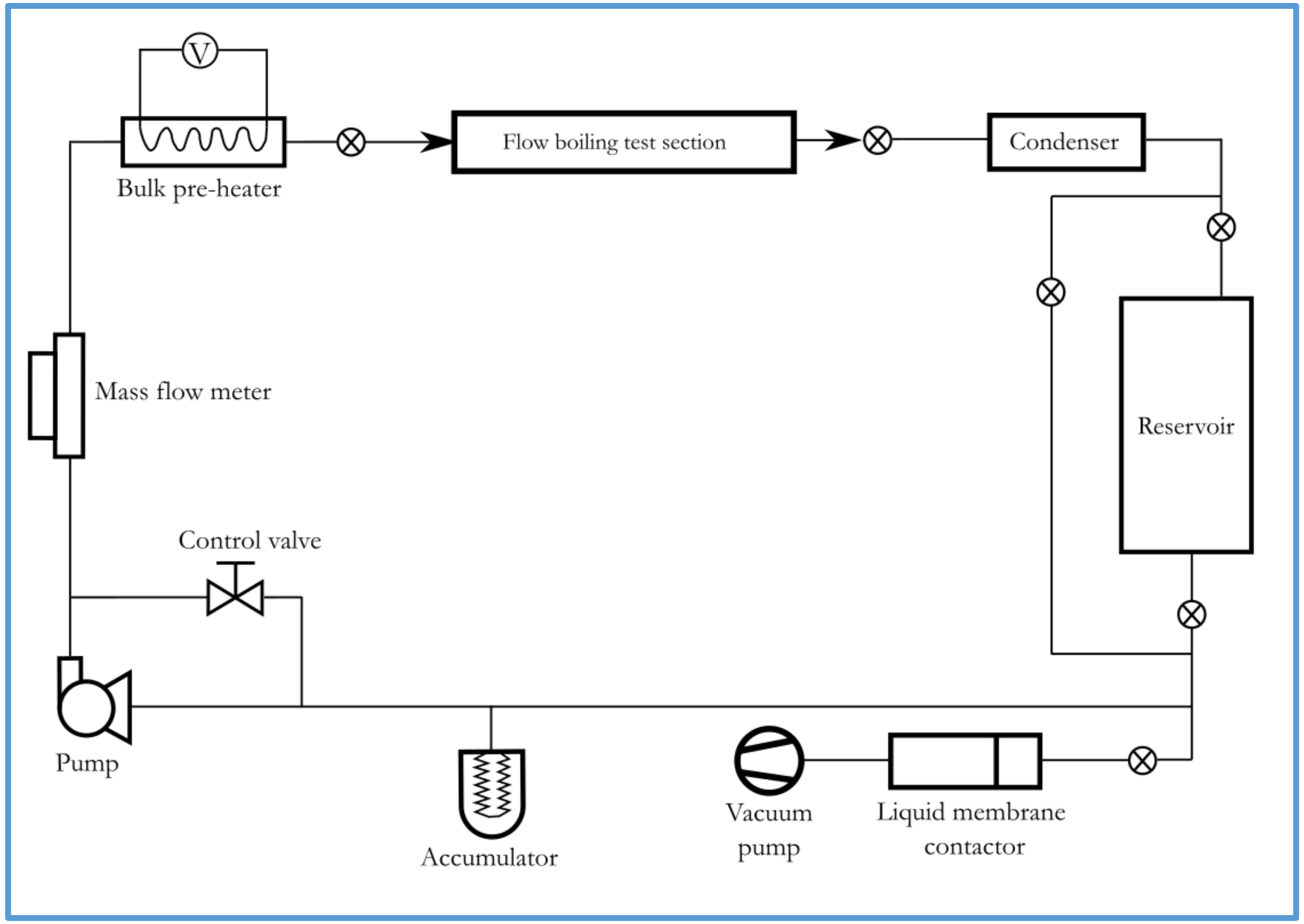


Proposed Flow Boiling Test Module Schematic for Chilldown Tests

Flow Boiling Experiments at TPFTML, CWRU

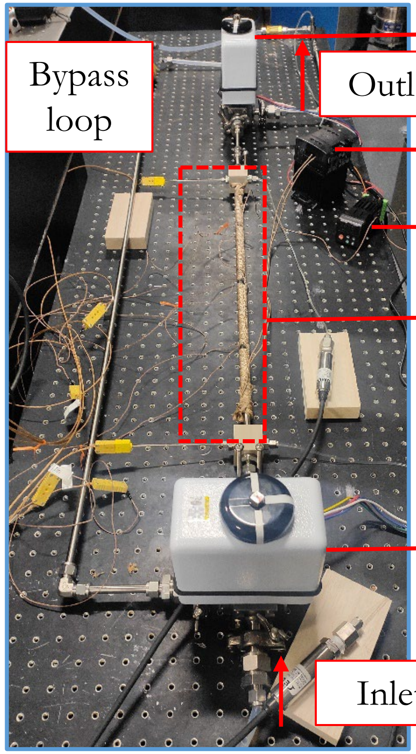


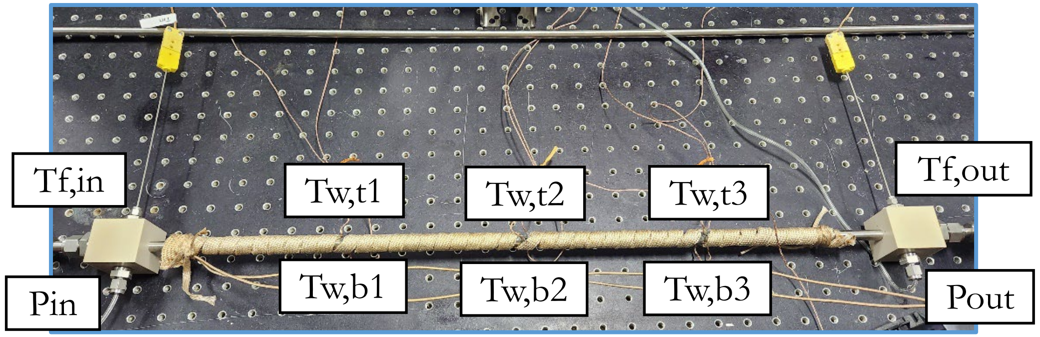
Flow conditioning loop facility at TPFTML, CWRU



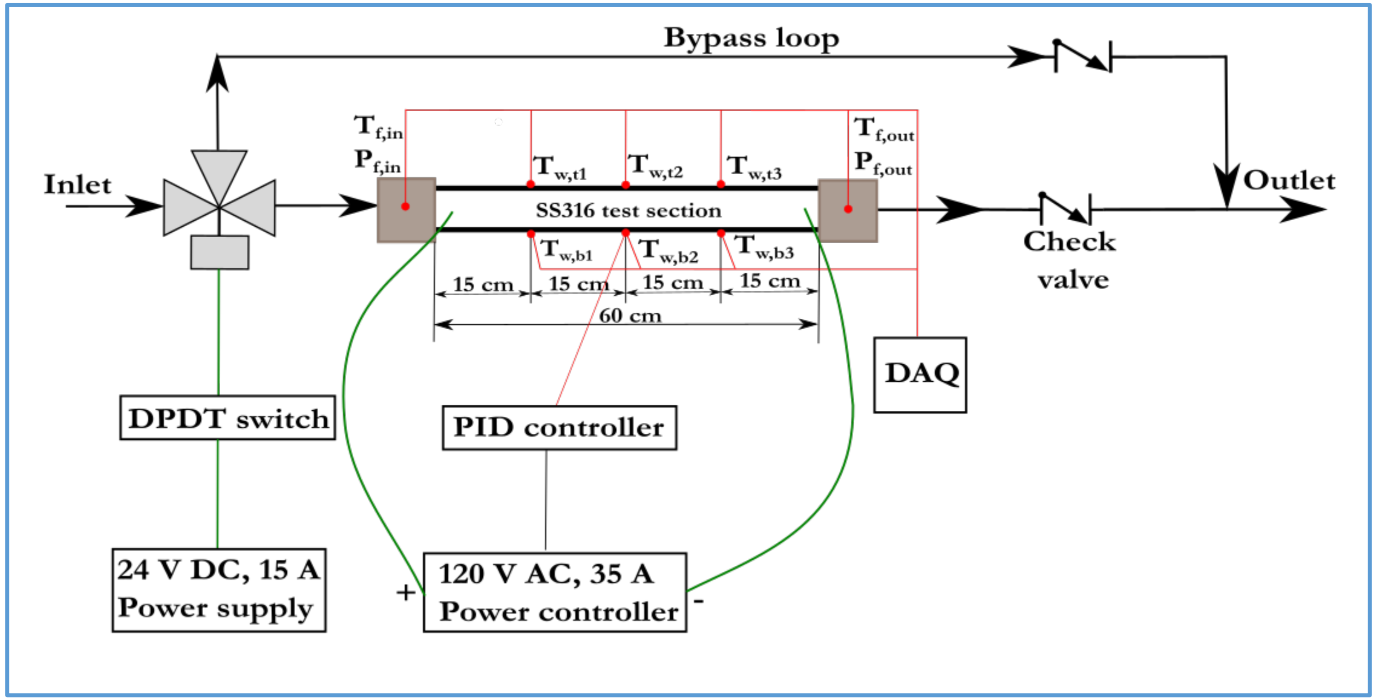
Schematic of the Flow Boiling Facility at TPFTML, CWRU

Development of a Terrestrial Two-phase Flow Chilldown Experimental Setup

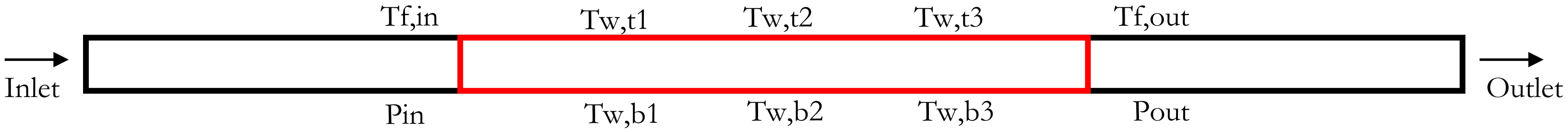


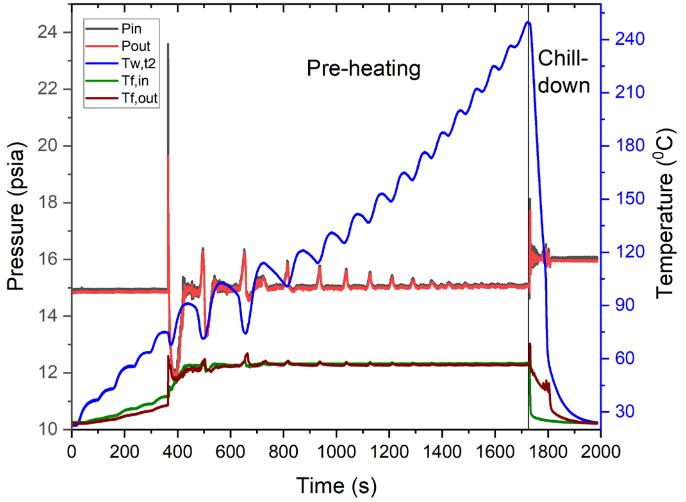


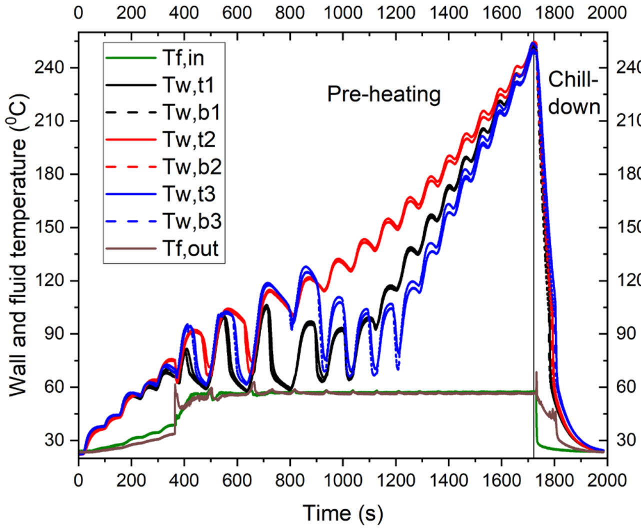
- Additional features required for the chilldown tests,
  - **Pre-heating** – to create the initial wall temperature conditions for the chilldown tests.
  - **Bypass loop** – to stabilize the fluid conditions in the flow loop until the test section is heated to desired wall temperature conditions.

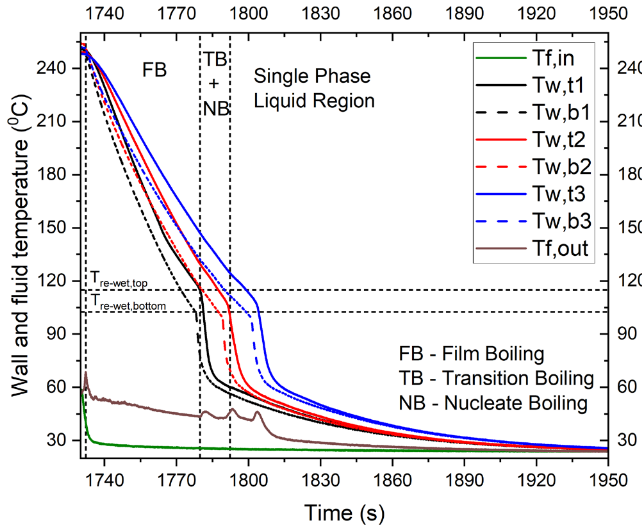


Pre-heating of the Chilldown Test Section





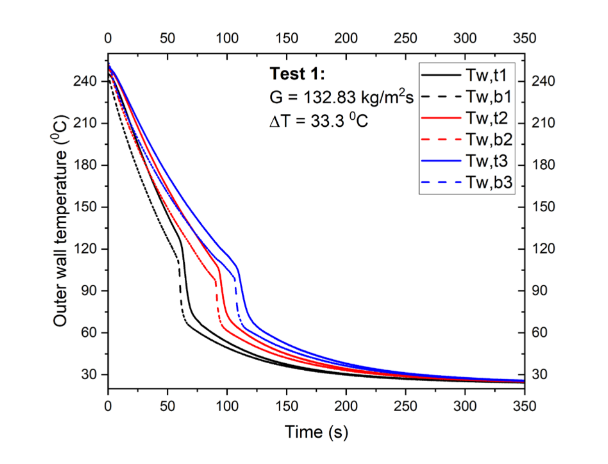


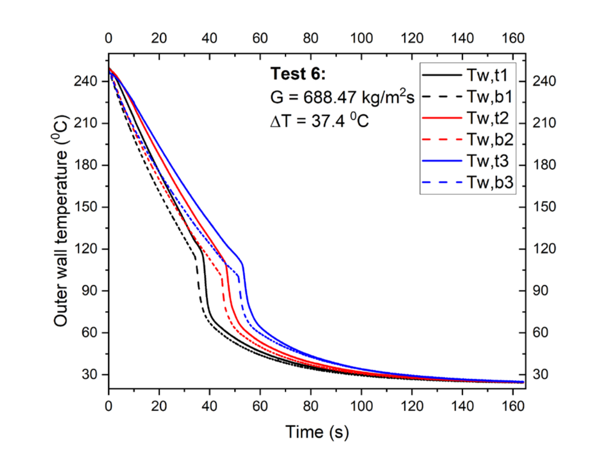


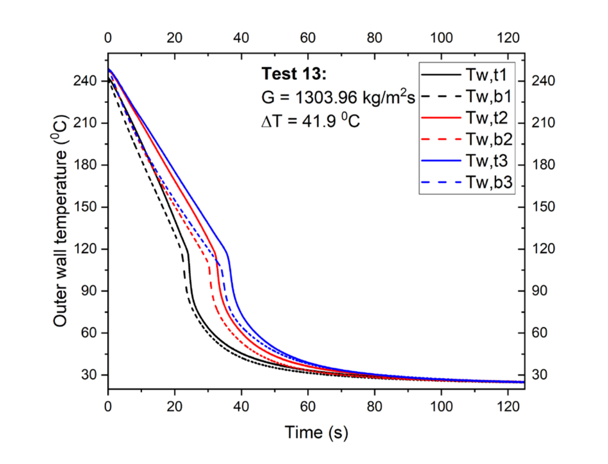
- Preheating of the test section – leads to **pressure spikes when the fluid starts to boil** due to the generation vapor within the test section.
- As the test section pressure increases, the **check valve controls liquid entry** into the flow conditioning loop, while **dampening the pressure oscillations** in the test section.
- **Accumulator designed to hold the liquid** pushed out of the test section.
- **Bulk liquid** remains **saturated** during the preheating phase.
- Tape heater is controlled using the PID controller and hence, the **temperature spikes and dips** during the pre-heating phase.
- The **entire chilldown curve** including the film boiling, transition boiling, nucleate boiling and single phase liquid regimes were captured in the present experiments.

Effect of Inlet Mass Flux – Chilldown Curves

Runs	Inlet mass flux 'G_{in}' [kg/m^2s]	Inlet Re	Inlet pressure 'p_{in}' [kPa]	Inlet temperature 'T_{in}' [°C]	Inlet subcooling '$T_{sub,in}$' [°C]	Initial wall temperature '$T_{w,init}$' [°C]
Test 1	132.83	1291	112.11	26.5	33.3	248.9 ± 4.7
Test 2	265.00	2576	113.14	25.2	34.9	248.6 ± 4.1
Test 3	375.47	3650	114.52	25.0	35.5	248.4 ± 2.1
Test 4	478.70	4654	116.25	24.7	36.2	248.0 ± 2.0
Test 5	582.93	5668	117.90	24.5	36.9	248.2 ± 2.6
Test 6	688.47	6694	119.69	24.4	37.4	248.6 ± 2.2
Test 7	787.43	7656	121.28	24.5	37.9	248.9 ± 3.6
Test 8	887.06	8625	123.83	24.4	38.5	248.8 ± 3.3
Test 9	976.16	9491	126.38	24.3	39.2	249.3 ± 6.0
Test 10	1059.34	10300	128.86	24.3	39.9	249.0 ± 4.2
Test 11	1150.74	11189	131.69	24.2	40.6	248.9 ± 4.3
Test 12	1237.87	12036	134.79	24.3	41.3	248.1 ± 6.8
Test 13	1303.96	12678	137.21	24.2	41.9	246.6 ± 5.3

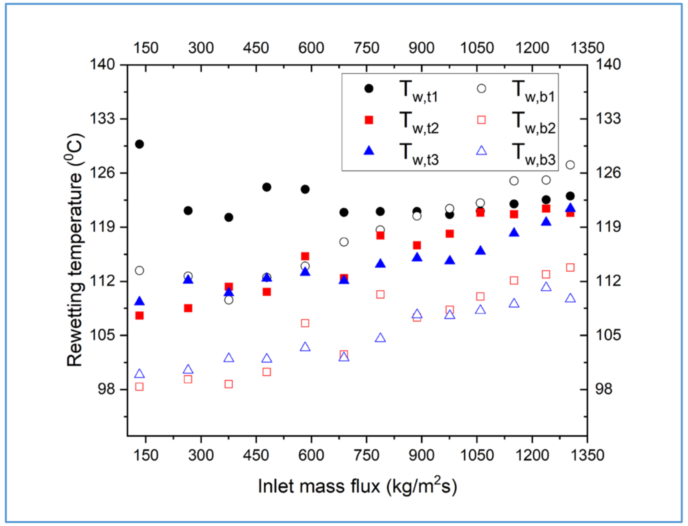


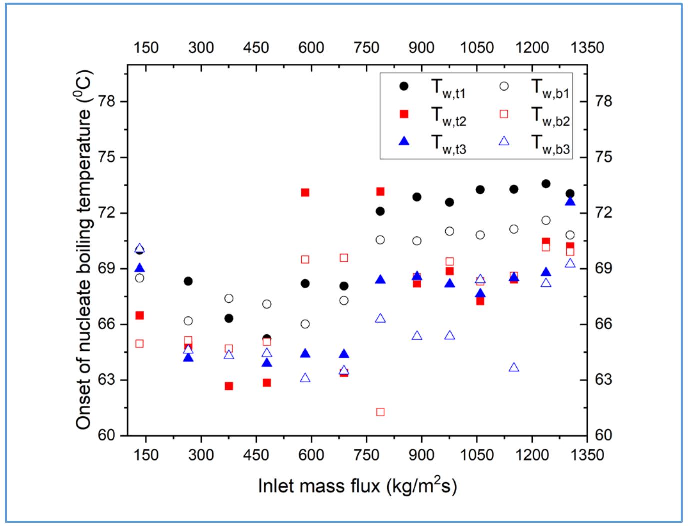


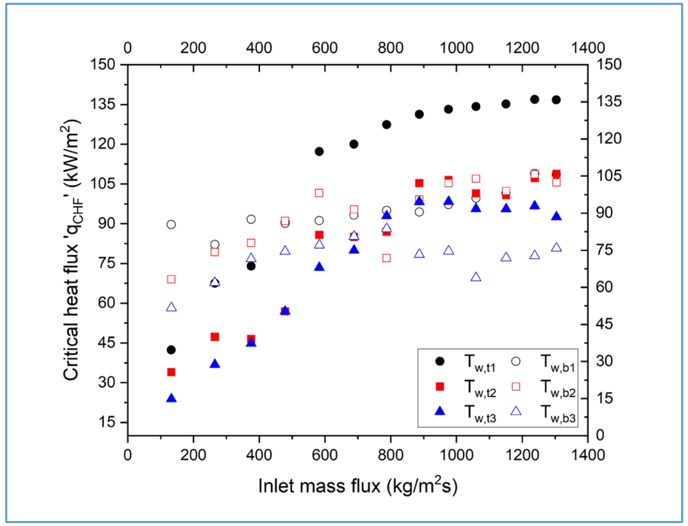


- Chilldown tests are conducted for a wide range of inlet mass fluxes spanning the **entire range of laminar to transition to turbulent** inlet flows.
- The **chilldown curve behavior near the ONB region is different** for different inlet mass flow rates and the slope changes are gradual as mass flow rate increases.

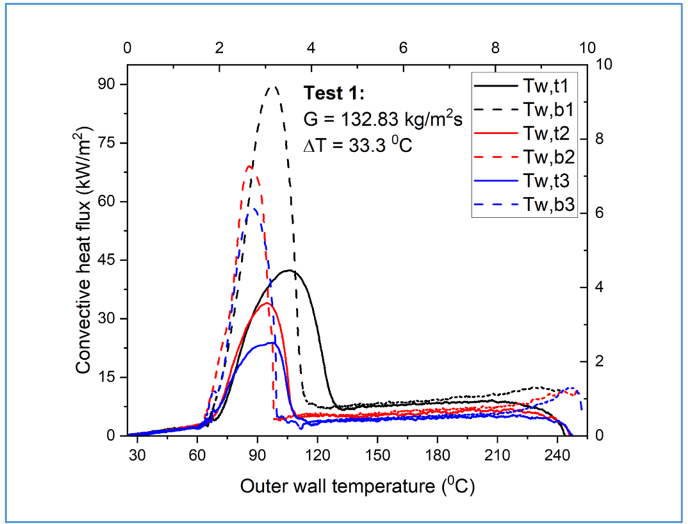
Effect of Inlet Mass Flux – Temperature Transition Points, CHF and Quenching Curve

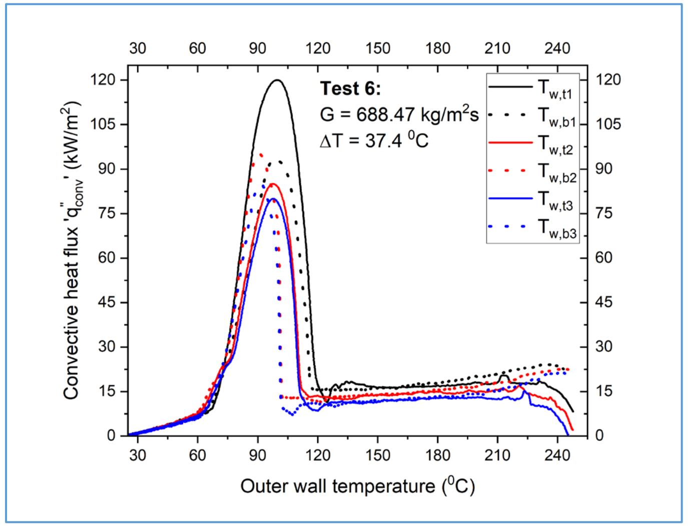


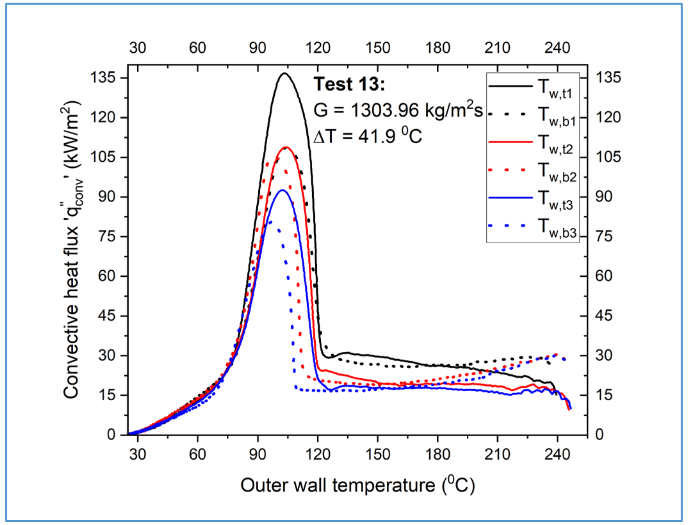




- ➢ T_{rewet} – increases with increase in G_{in} except for $T_{w,t1}$
- ➢ T_{ONB} – no definitive trend – overall trend is increasing with increase in G_{in}
- ➢ q_{CHF} - increases till around 700 kg/m²s – no definitive trend at higher mass fluxes.

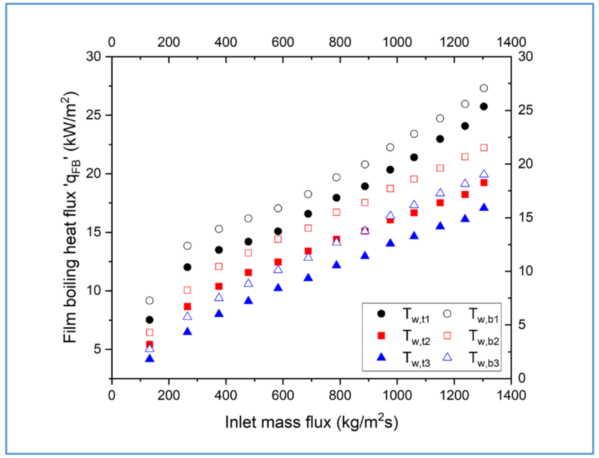


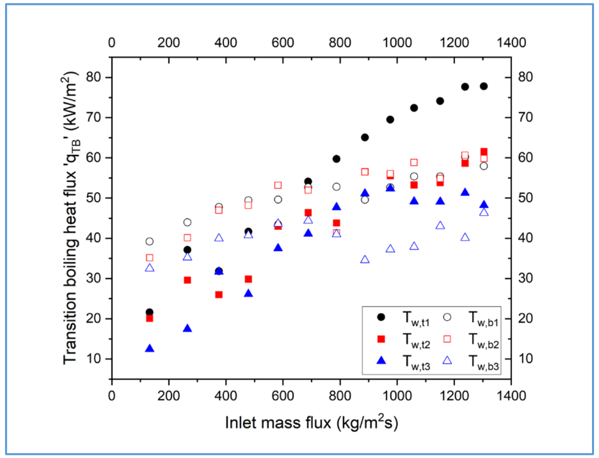


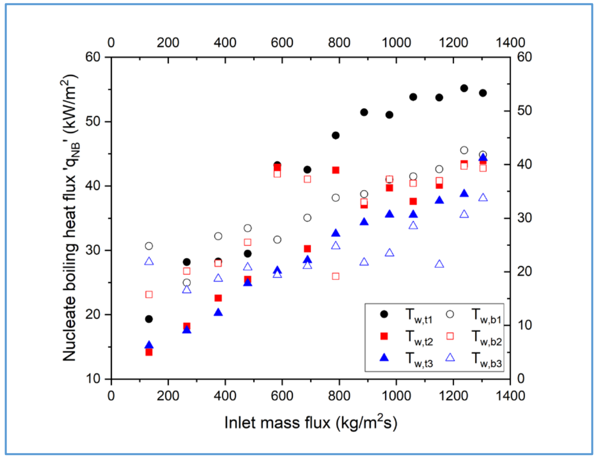


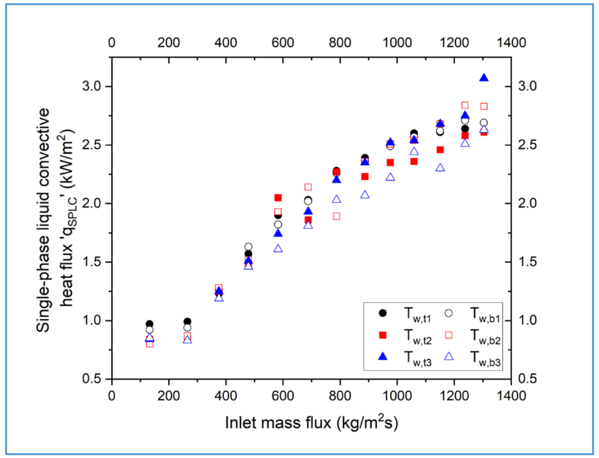
- ➢ Top wall quenching curve includes dispersed flow film boiling regime for most of the tests.
- ➢ Bottom wall heat fluxes higher than top wall heat fluxes except for upstream location where the trend reverses at higher mass fluxes.

Effect of Inlet Mass Flux – Regime Specific Heat Fluxes and Heat Transfer Coefficients

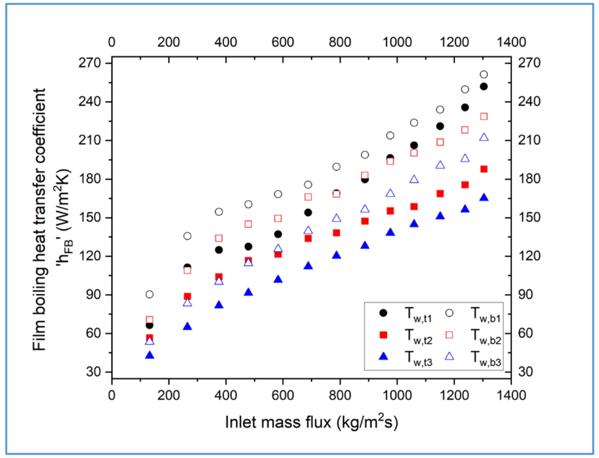


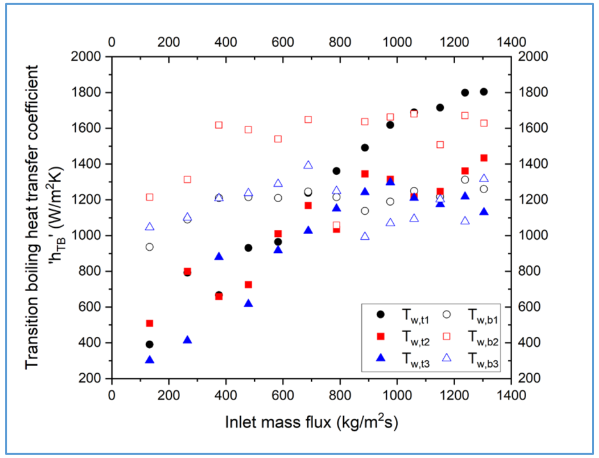


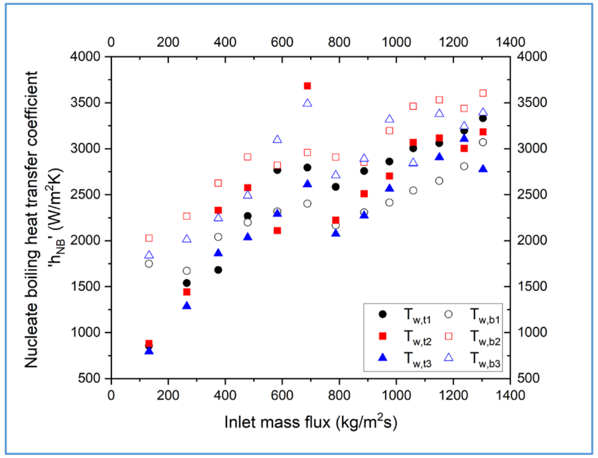


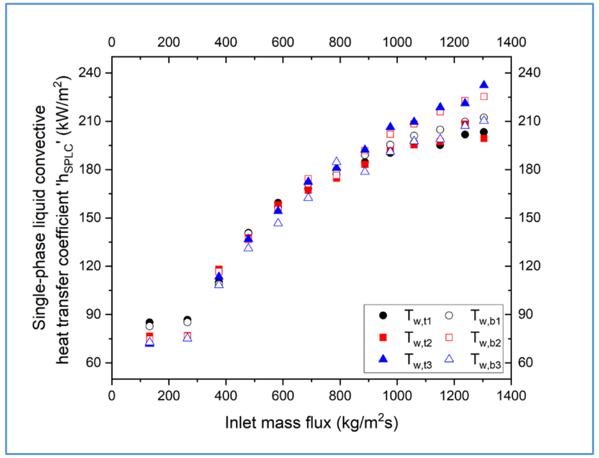


- Film boiling and single phase liquid convective heat fluxes – increases with increases in inlet mass flux.
- Transition and nucleate boiling heat fluxes – definitive increase till around 700 kg/m^{2}s – slight increase after that except for the downstream location.



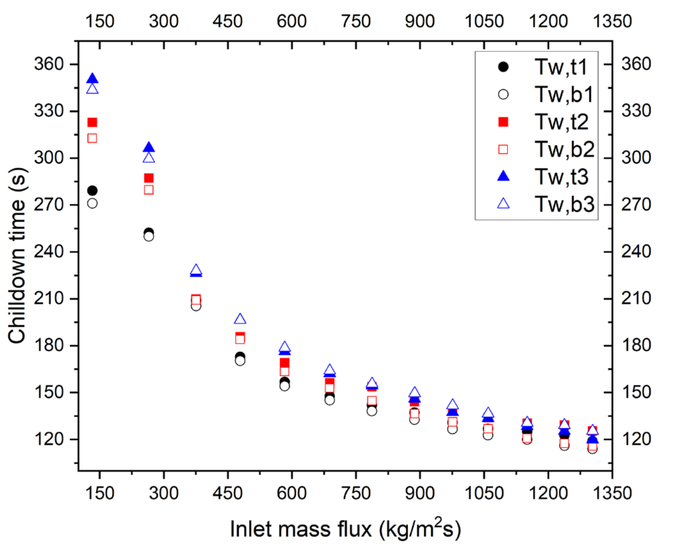


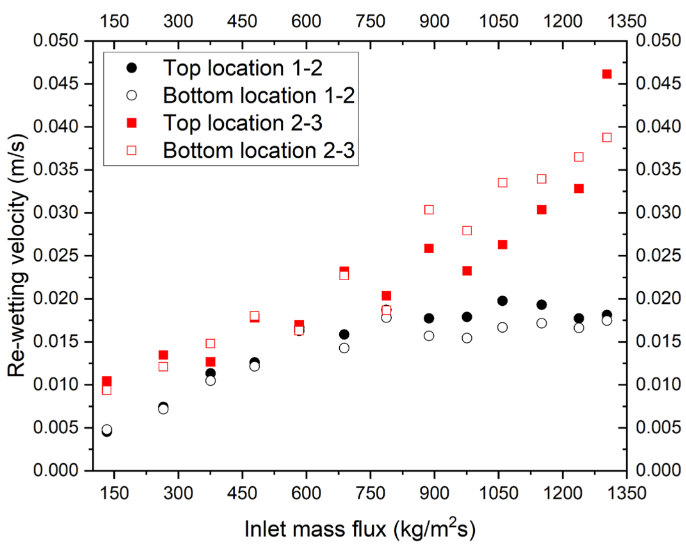


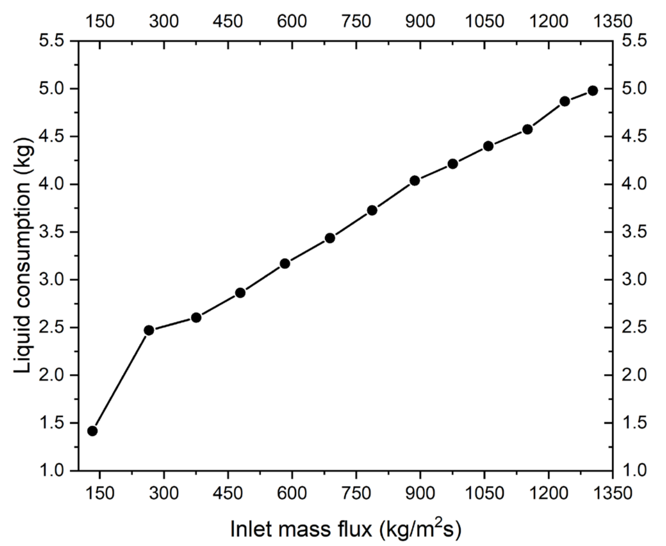


- Film boiling and single phase liquid convective heat transfer coefficients – increases with increases in inlet mass flux.
- Transition and nucleate boiling heat transfer coefficients – definitive increase till around 700 kg/m^{2}s – slight increase after that except for the downstream location.

Effect of Inlet Mass Flux – Chilldown Performance Parameters







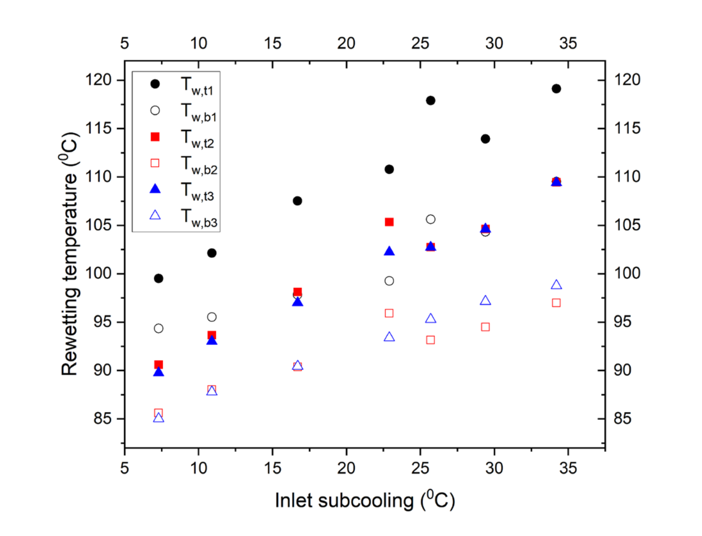
- Major chilldown performance parameters
  - Chilldown time
  - Rewetting/quench front propagation velocity
  - Liquid consumption

- Chilldown time decreases with increase in inlet mass flux.
- At the upstream location – rewetting velocity increases at low mass fluxes and nearly constant at higher mass fluxes. At the downstream location – rewetting velocity increases with increase in inlet mass flux.
- Liquid consumption increases with increase in inlet mass flux.

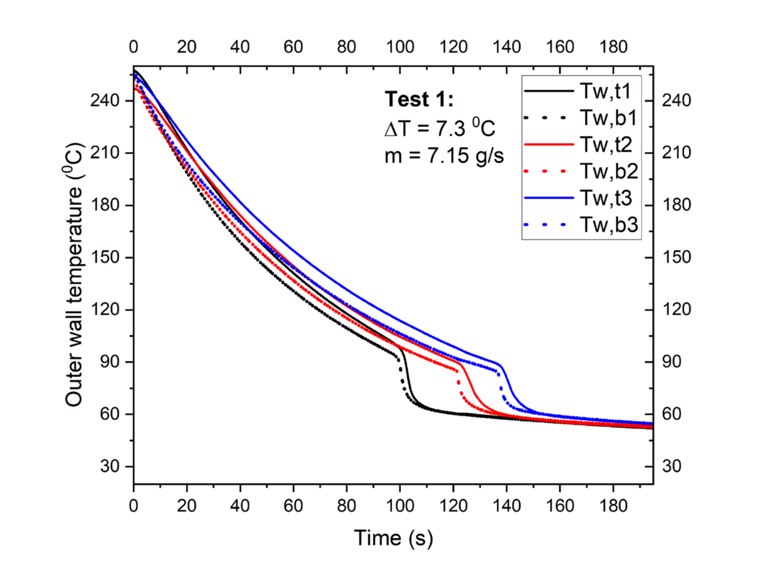
- Future directions with the effect of inlet mass flux test cases
  - Accumulator needs to be dynamically controlled to decouple the inlet mass flux and inlet subcooling effects.
  - Direct heating of the SS-316 test section to avoid the uncertainties in the wall heat flux calculations.
  - Averaging for regime specific heat flux and heat transfer coefficients at higher inlet mass flux – leads to uncertainties which needs to be investigated further.
  - Detailed flow visualization studies needed to understand the flow behavior and elucidate the heat transfer results from the present study.

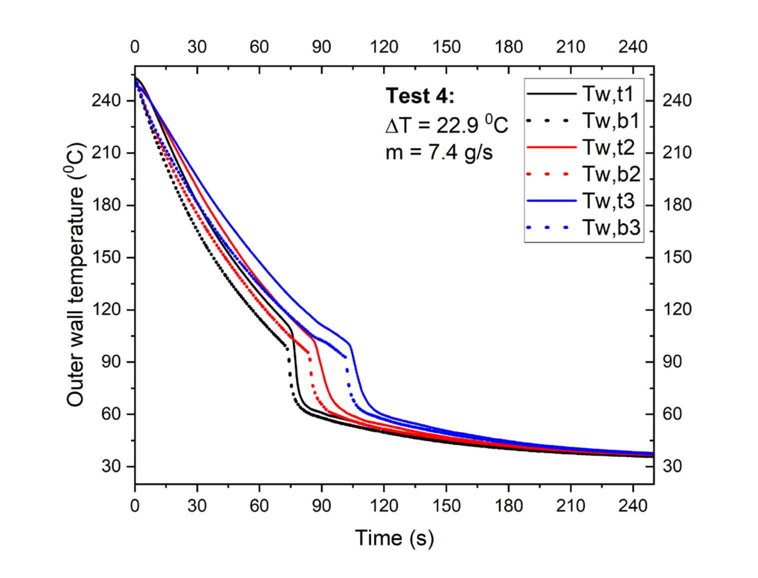
Effect of Inlet Subcooling – Chilldown Curves and Rewetting points

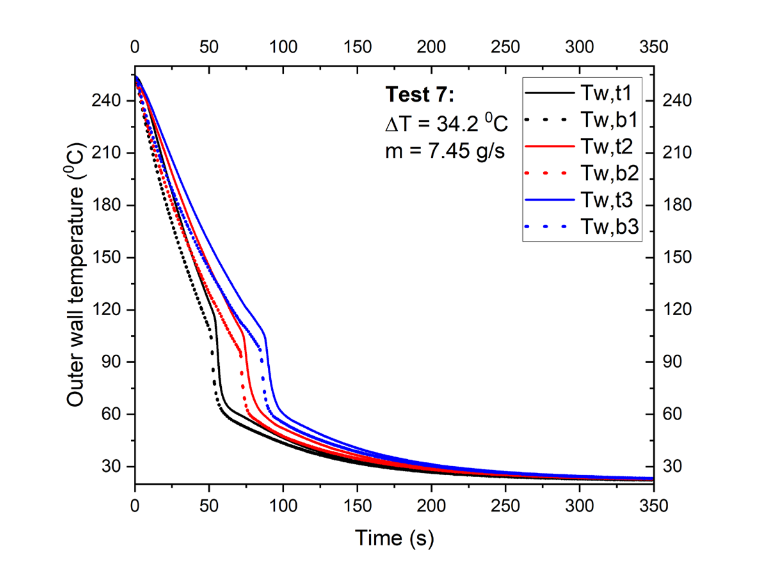
Runs	Inlet mass flow rate ‘m_{in}’ [g/s]	Inlet pressure ‘p_{in}’ [kPa]	Inlet temperature ‘T_{in}’ [◦C]	Inlet subcooling ‘$T_{sub,in}$’ [◦C]
Test 1	7.15	109.35	51.9	7.3
Test 2	7.32	113.14	49.3	10.9
Test 3	7.48	111.56	43.1	16.7
Test 4	7.4	109.9	36.4	22.9
Test 5	7.46	105.83	32.5	25.7
Test 6	7.49	105.01	28.6	29.4
Test 7	7.45	103.63	23.4	34.2



- Rewetting temperatures increase with increase in inlet liquid subcooling.
- Chilldown time increases with increase in inlet liquid subcooling.
- Bottom wall thermocouples show a lower rewetting temperature than top wall thermocouples.







Summary and Conclusions

- Chilldown experiments are performed on a 0.375" OD, 0.065" thickness SS-316 tube in a horizontal flow configuration with PF-5060 as the working fluid.

- Tests are conducted at 13 different inlet mass fluxes ranging from 132.83 kg/m^2s - 1303.96 kg/m^2s covering the entire inlet regime of laminar to transition to turbulent inlet flows.

- The chilldown tests captured the entire regime of the boiling curve *viz.,* film boiling, Liedenfrost point, transition boiling, critical heat flux, nucleate boiling, onset of nucleate boiling and single-phase liquid flow regions.

- The effect of inlet mass flux on the temperature transition points, *viz.,* rewetting and onset of nucleate boiling (ONB) points, critical heat flux and regime specific heat fluxes and heat transfer coefficients investigated in detail.

- The chilldown performance parameters *viz.,* chilldown time, rewetting/quench front propagation velocity and liquid consumption evaluated at different inlet mass fluxes.

- Some preliminary results with the varying inlet liquid subcooling presented.

Acknowledgement

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References

[1] Hartwig, J.W., Meyerhofer, P., Stiegemeier, B., and Morehead, R. "Liquid Methane and Liquid Oxygen Horizontal Chilldown Experiments of a 3.5 and 10.2 cm Transfer Line" Applied Thermal Engineering 205, 118042. 2022.

THANK YOU