EPFL Thesis 6993 public defence

Innovative low-mass cooling systems for the ALICE ITS Upgrade detector at CERN

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Doctoral Programme in Energy (EDEY)

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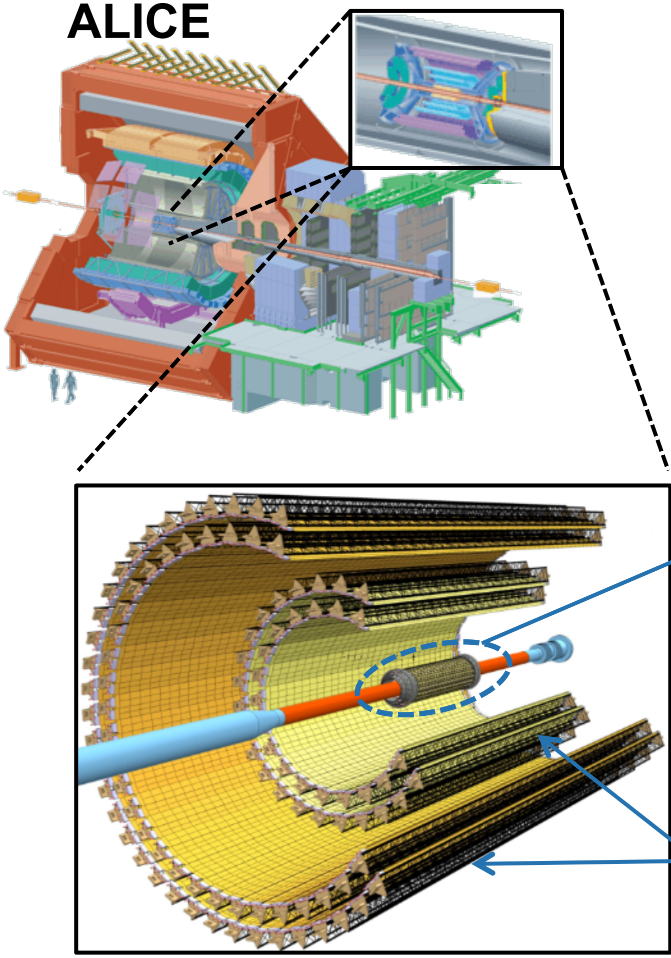
Goals

1. Lightweight cooling system for ALICE ITS Upgrade
   - Design parameters
   - Experimental setup & methodology
   - Cooling performance results

2. Flow boiling heat transfer in a polyimide channel

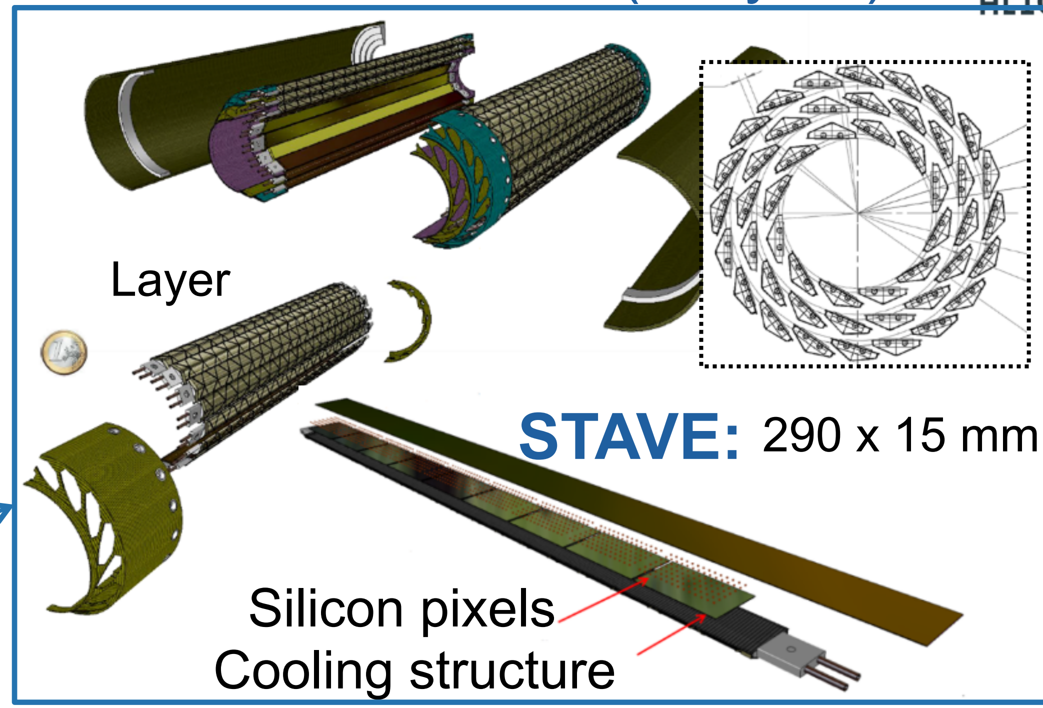
ALICE ITS Upgrade

ALICE

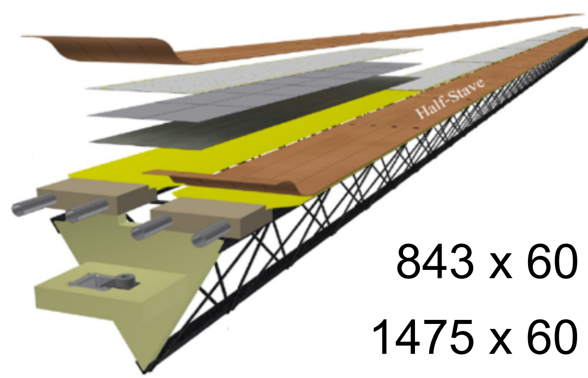


ITS Upgrade (2019)

Inner Barrel (3 layers)



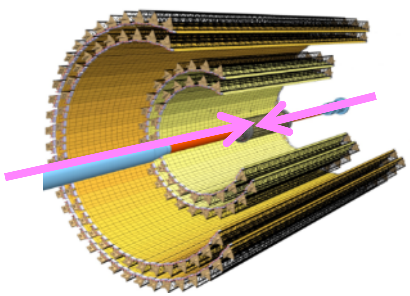
Middle & Outer Barrel (2+2 layers)

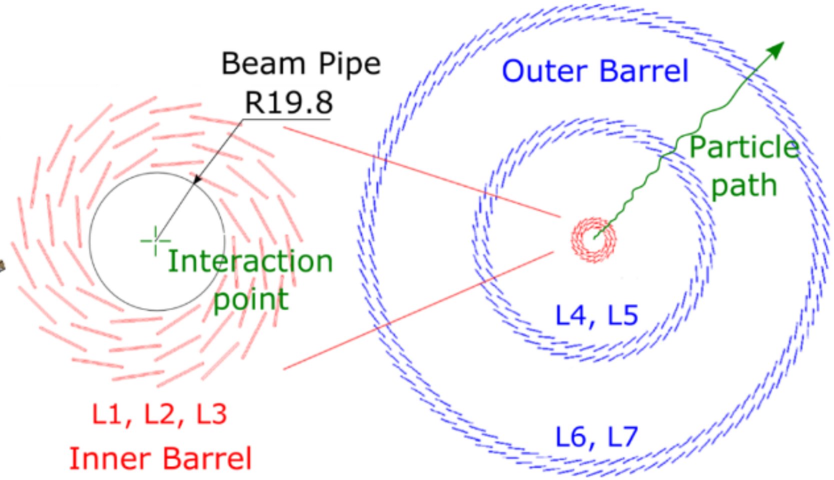


843 x 60 mm

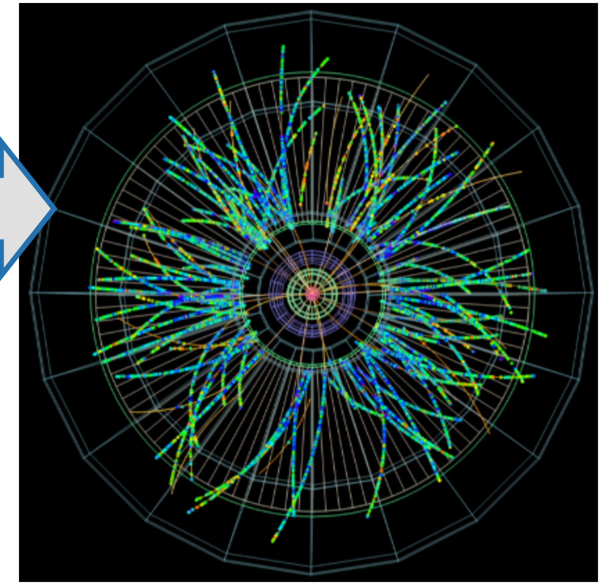
1475 x 60 mm

Power dissipation





ITS Upgrade sectional view



12.5 GPix “camera”
100-400 kHz

Charged and neutral particles cross detector chips:

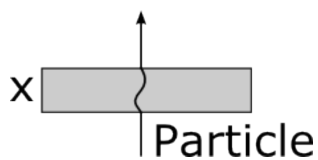
1. **Ionizing current:** signal
2. **Non-ionizing current:** radiation damage → **power dissipation**

➢ If T_{chip} ↑ 7 K, **2x** radiation damage *(irreparable!!)*

Design parameters

Power dissipation	0.10 W cm^{-2} *(2015)* 0.15 W cm^{-2} *(1.5 FS)*
Chip temperature	< 30°C
Temperature non-uniformity	5-10 K
Global material budget	IB: $x/X_0 \leq$ **0.3%** per layer MB/OB: $x/X_0 \leq$ **1.0%** per layer

$$\frac{x}{X_0} 100\ [\%]$$

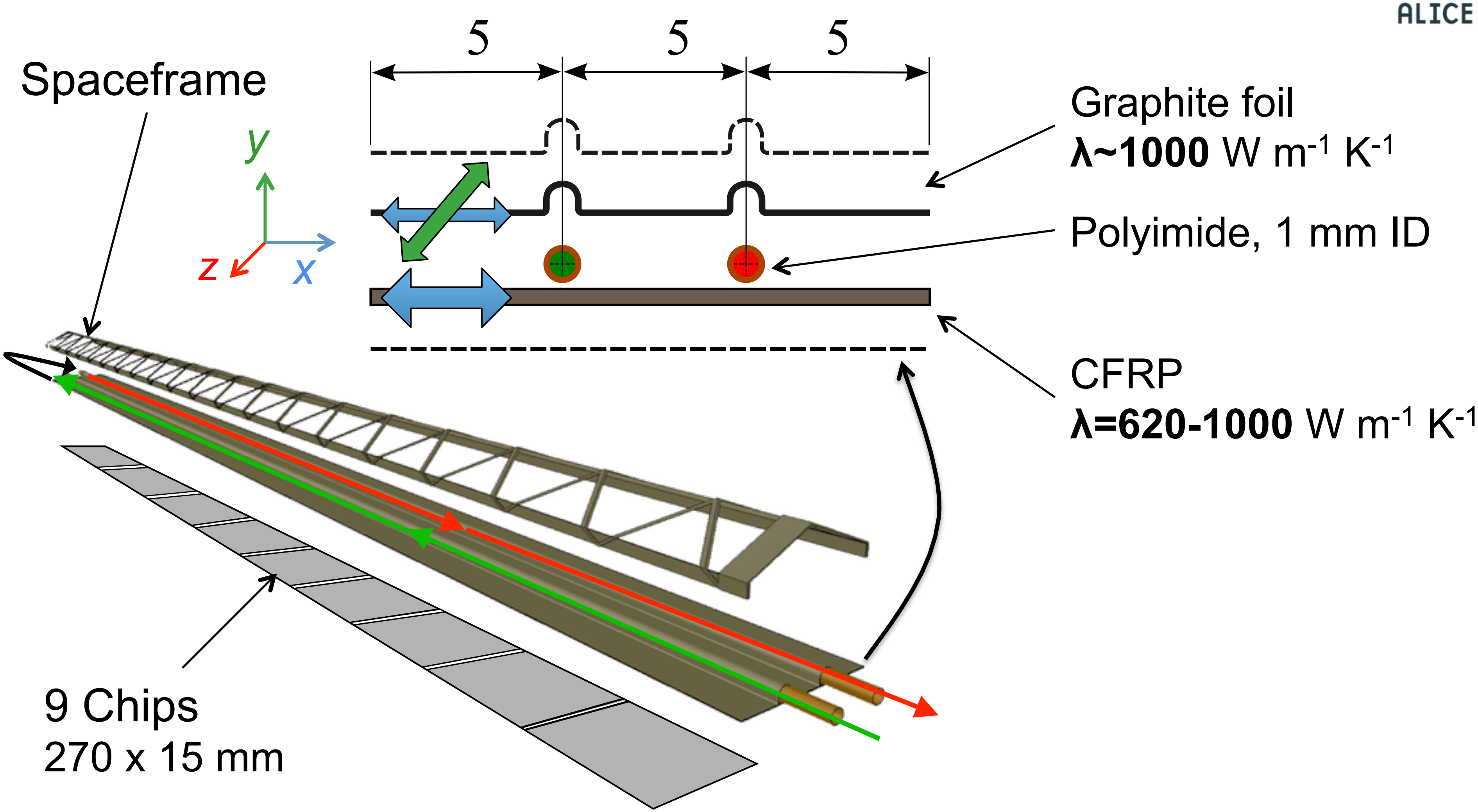


$$X_0 = \frac{716.4 \cdot A_N}{Z(Z+1)\ln\frac{287}{\sqrt{Z}}\rho}\ [\text{cm}]$$

x=1 mm of material	x/X_0 [%]
Copper	6.94
Polymide (Kapton®)	0.34
CFRP (K13D2U-2K)	0.42
Water (liquid)	0.28
Two-phase R245fa	0.06*

*** *ε = 0.85***

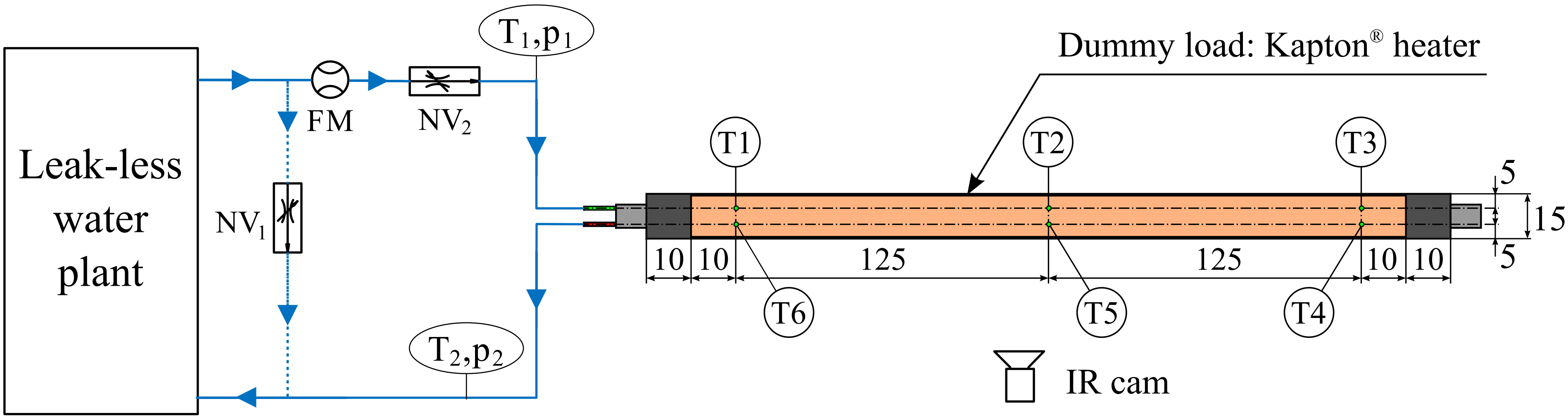
Ultra-light cooling concept



[1] Gómez Marzoa et al., ExHFT8, Lisbon, 2013.

Single-phase **water**

- + Radiation hard
- + Loop simplicity
- – Leak-less ($\Delta p < 0.3$ bar)
- – Liquid: ↑ x/X_0



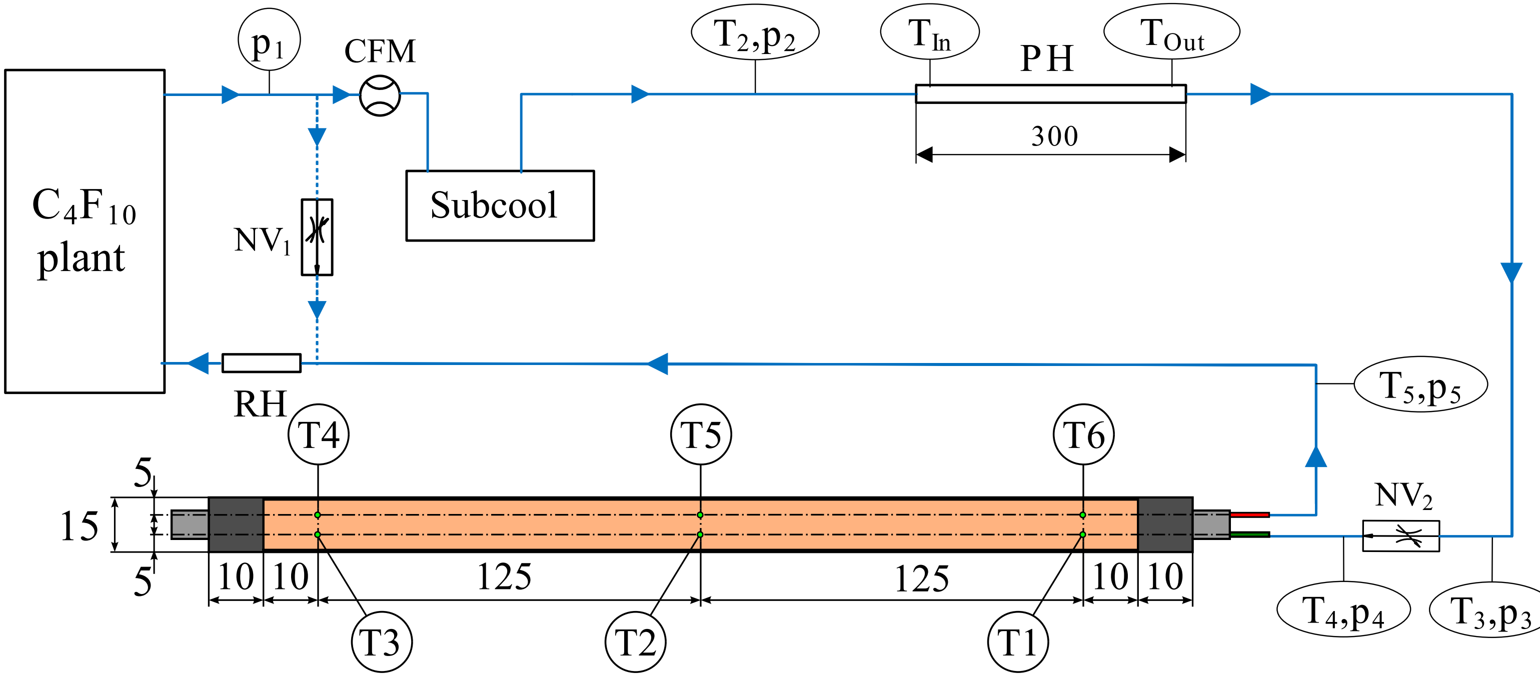
Cooling performance:

$$\Delta T_{heater\text{-}coolant} = \frac{1}{6}\sum_{i=1}^{6} T_{NTCi} - \frac{T_{coolant,out} + T_{coolant,in}}{2} < 15\ \mathrm{K}$$

Two-phase C_4F_{10} loop

+ Radiation hard, dielectric
+ p_{sat} =1.9 bar @15°C
+ ↓ x/X_0

– More complex loop
– Flow distribution (346 staves)

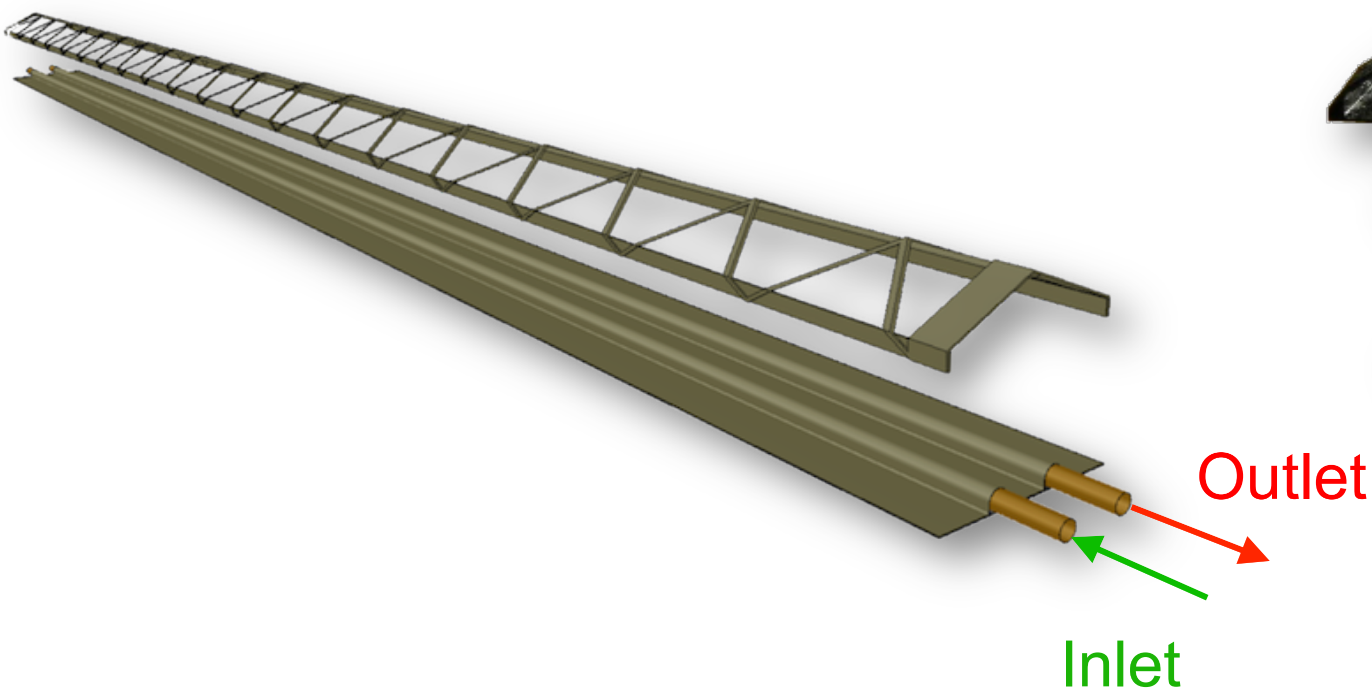


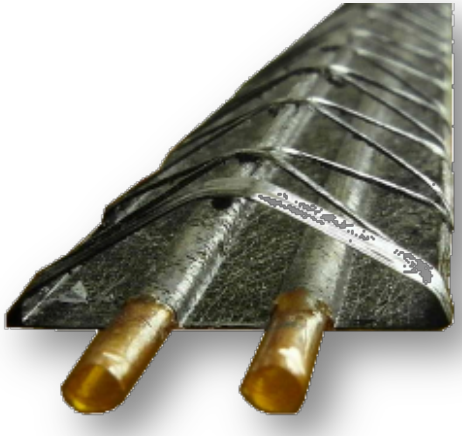
$$G = \frac{E_{heater}}{i_{lv}\Delta x_{in\text{-}out}} \frac{1}{A_i}$$

$$x_4 = f(p_4, i_4)$$

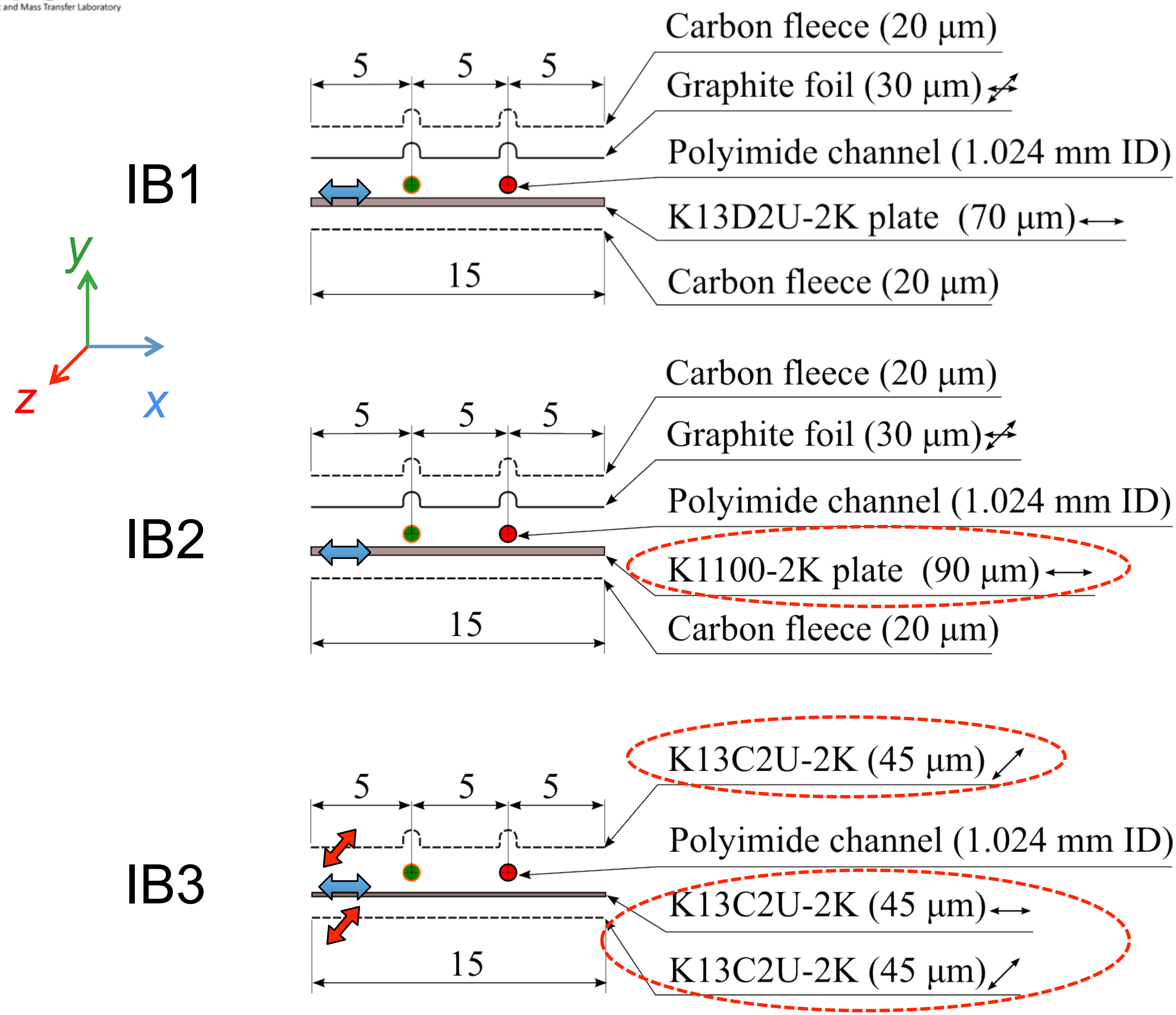
$$x_5 = \frac{\frac{E_{heater} - E_{air}}{G A_i} + i_4 - i_{5,l}}{i_{5,lv}}$$

Inner Barrel staves





Inner Barrel: stave layouts



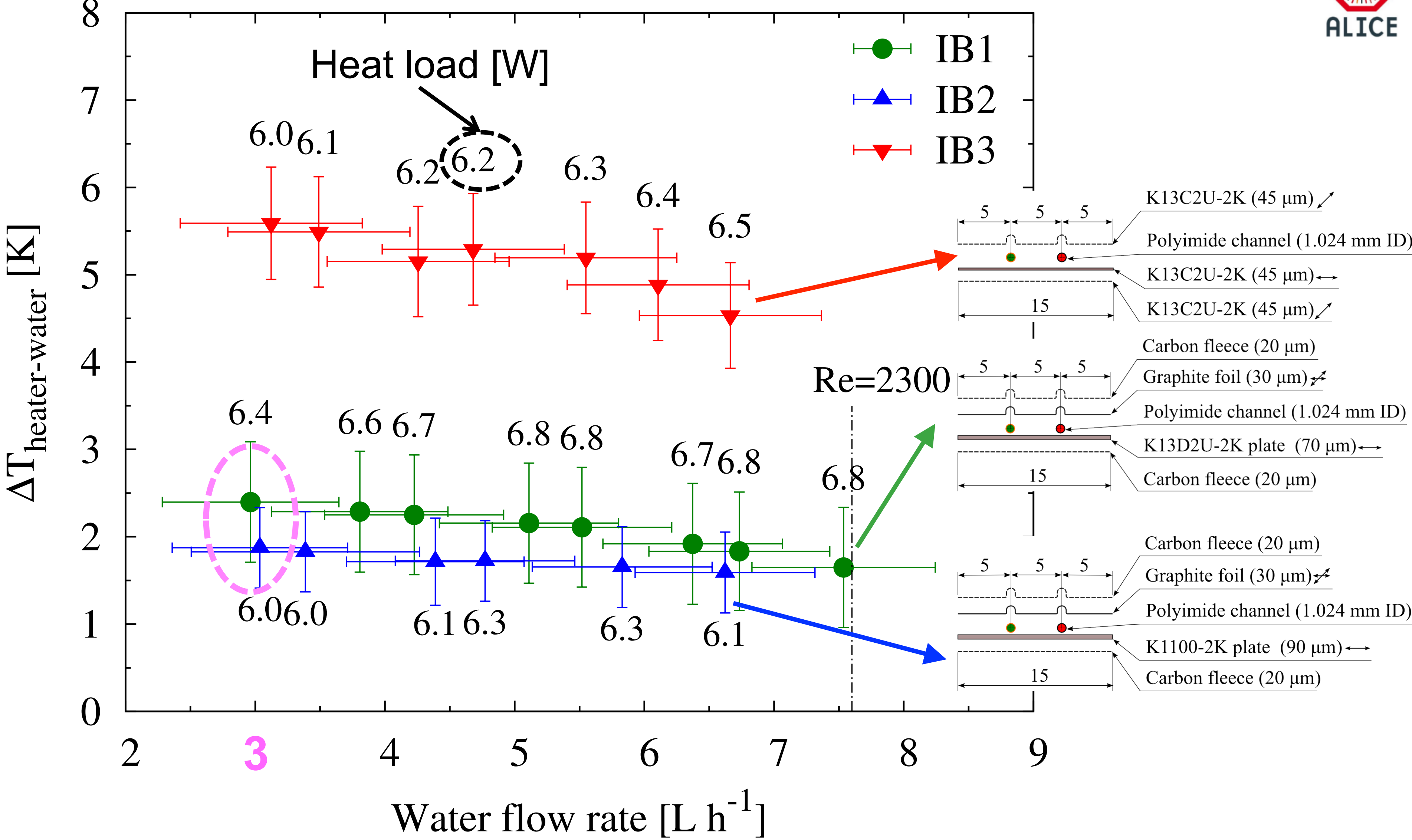
IB1: 1.4 g

IB2: 1.8 g

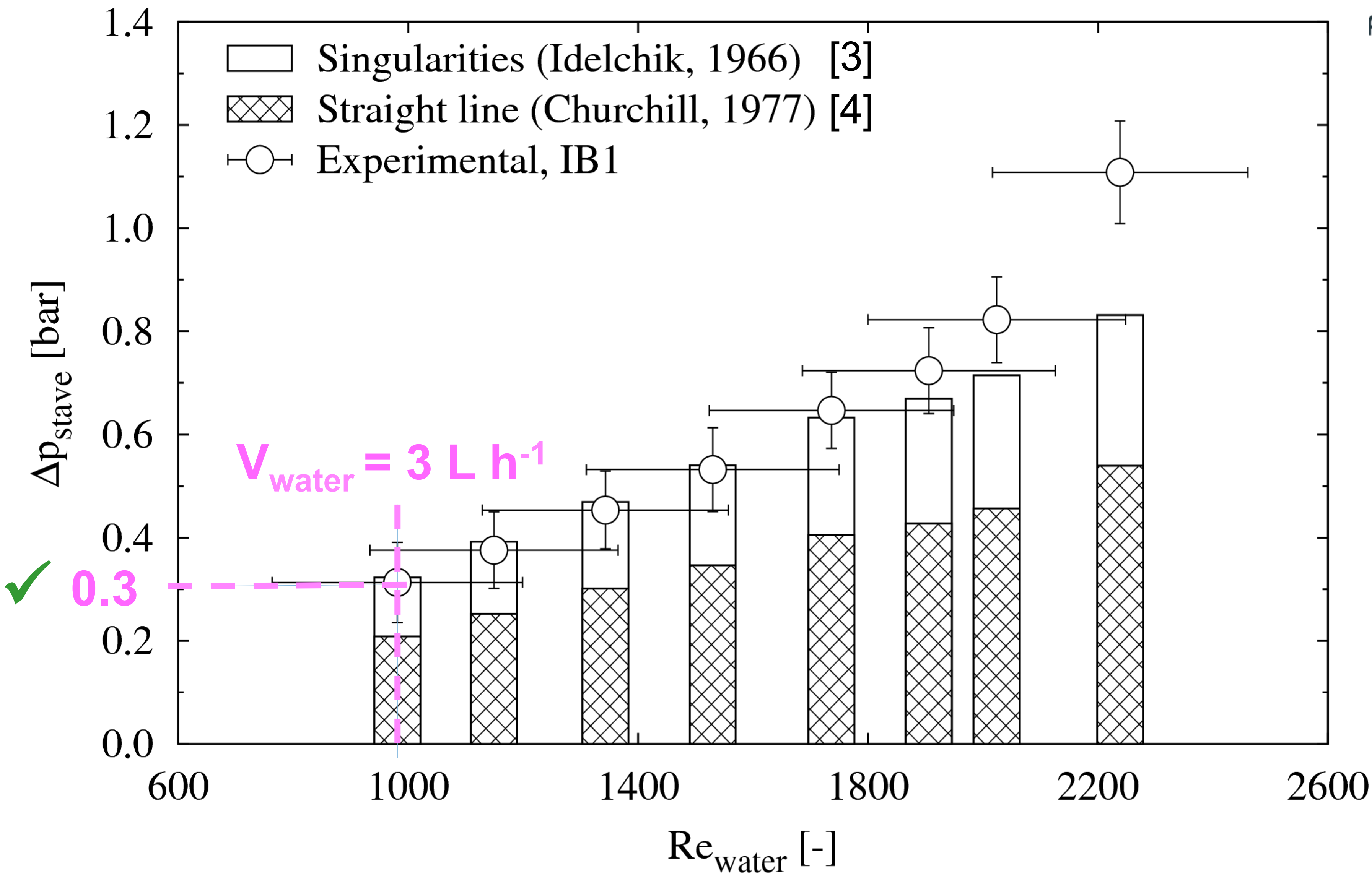
IB3: 1.7 g

Total x/X_0=0.29%
(water, services included [2])

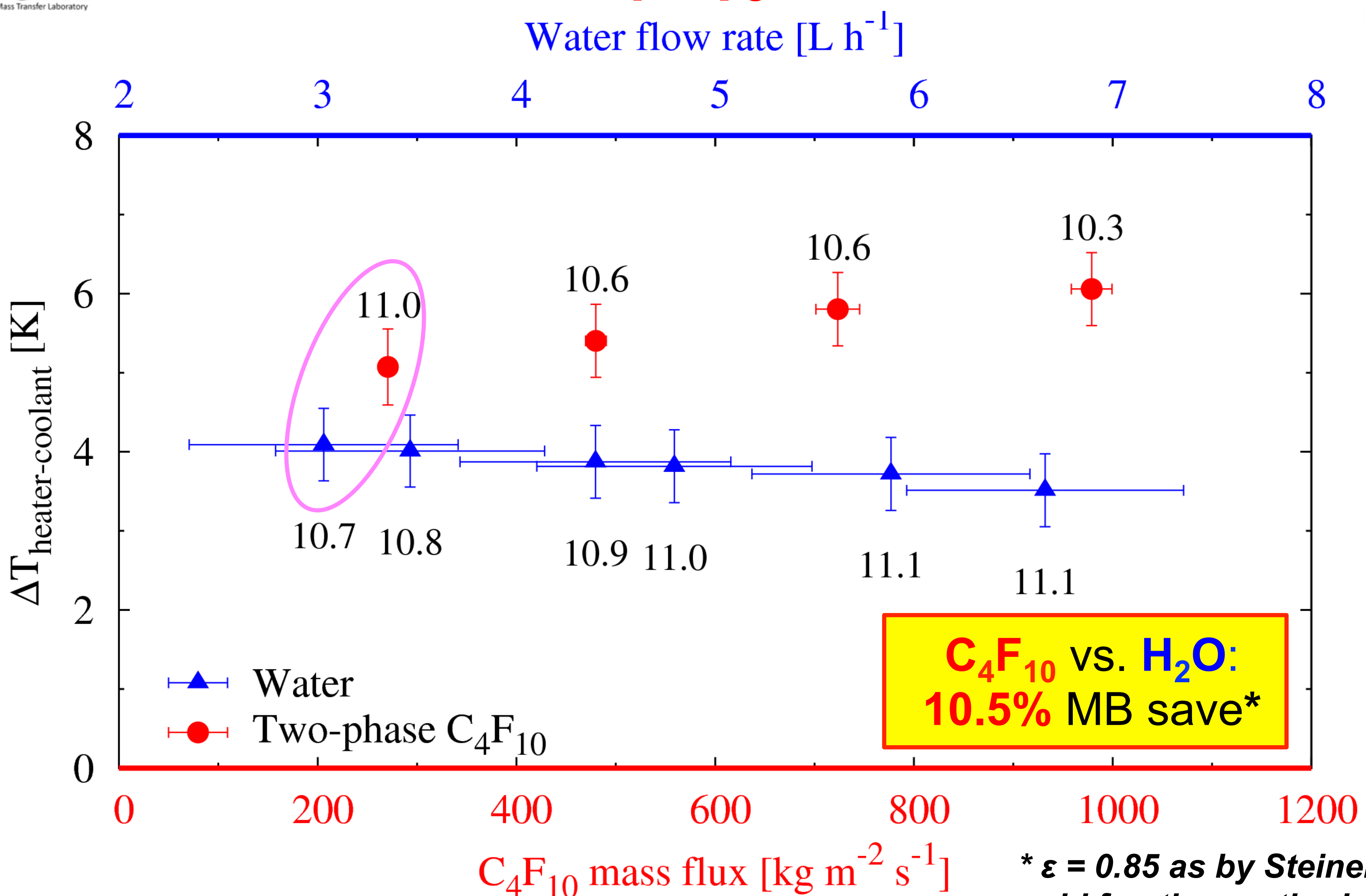
Water: $\Delta T_{heater-water}$, 0.15 W cm^{-2}



Water: total Δp (inc. singularities)



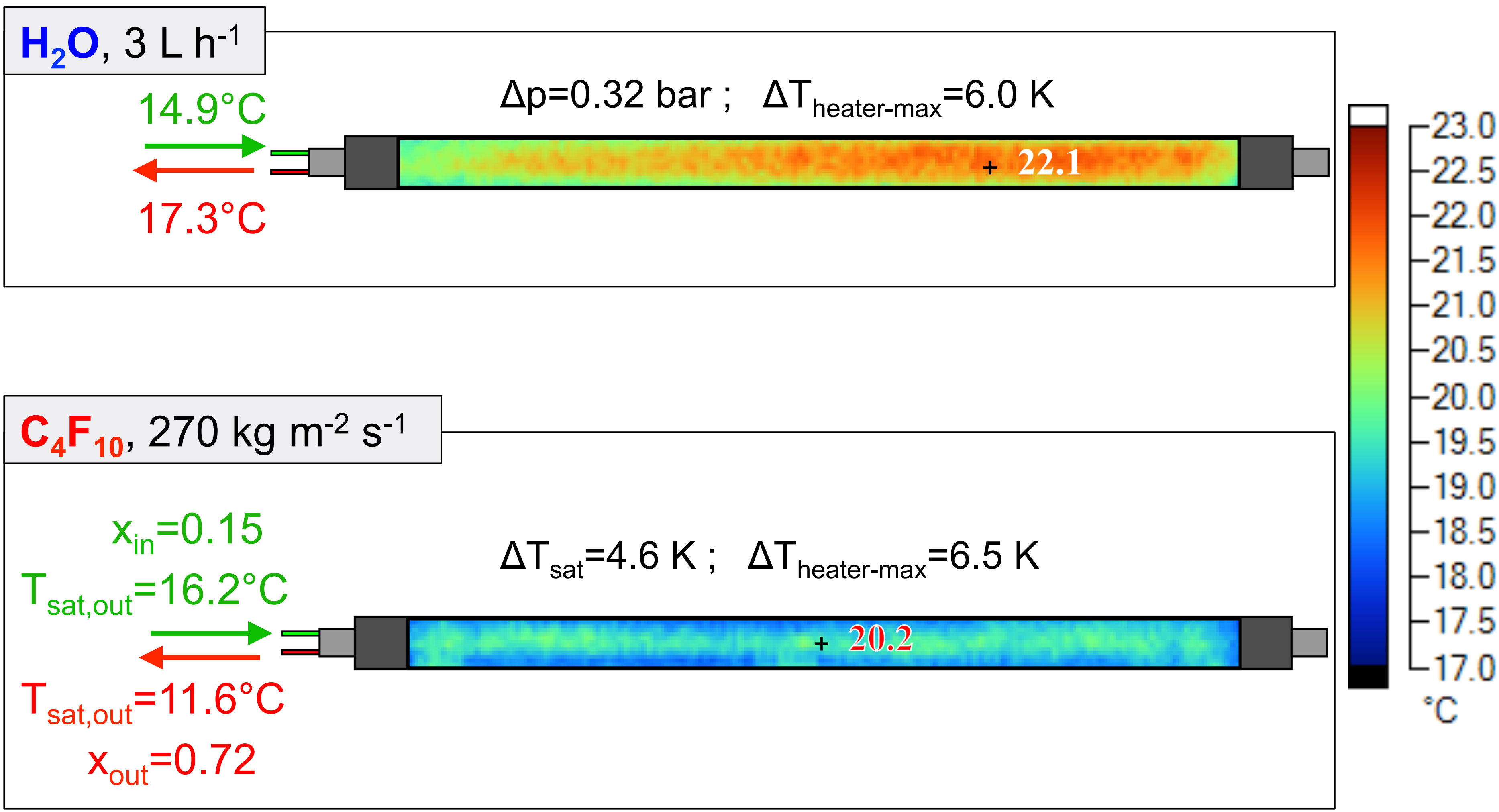
IB2: 2-Ph C_4F_{10}, 0.30 W cm^{-2}



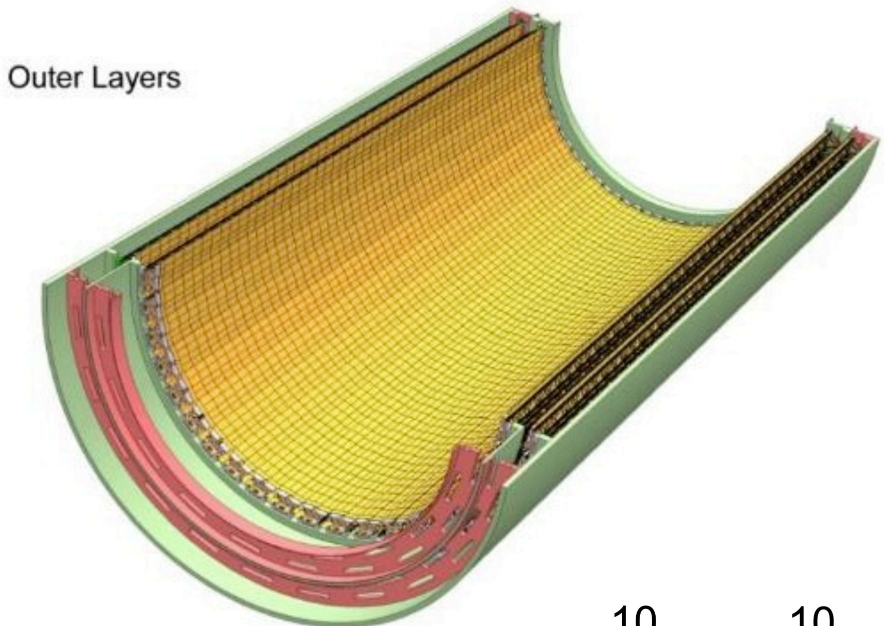
C_4F_{10} vs. H_2O: 10.5% MB save*

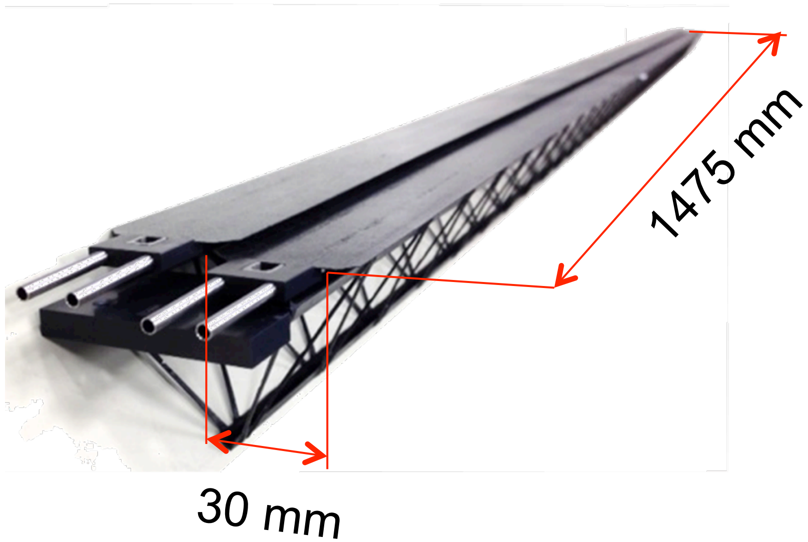
**** ε = 0.85 as by Steiner [5] void fraction method***

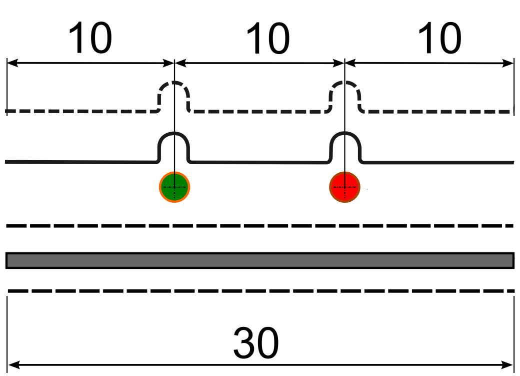
IB2: Water vs. C_4F_{10}, 0.30 W cm^{-2}

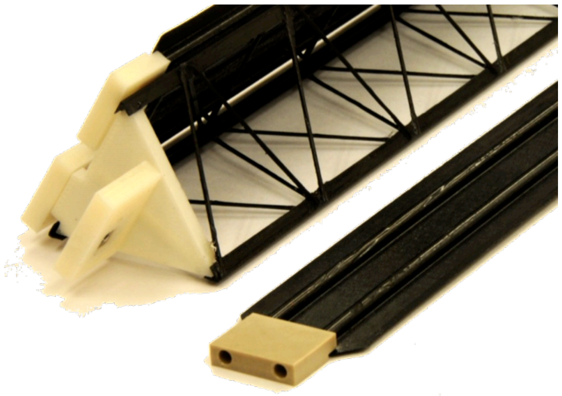


Outer Barrel staves

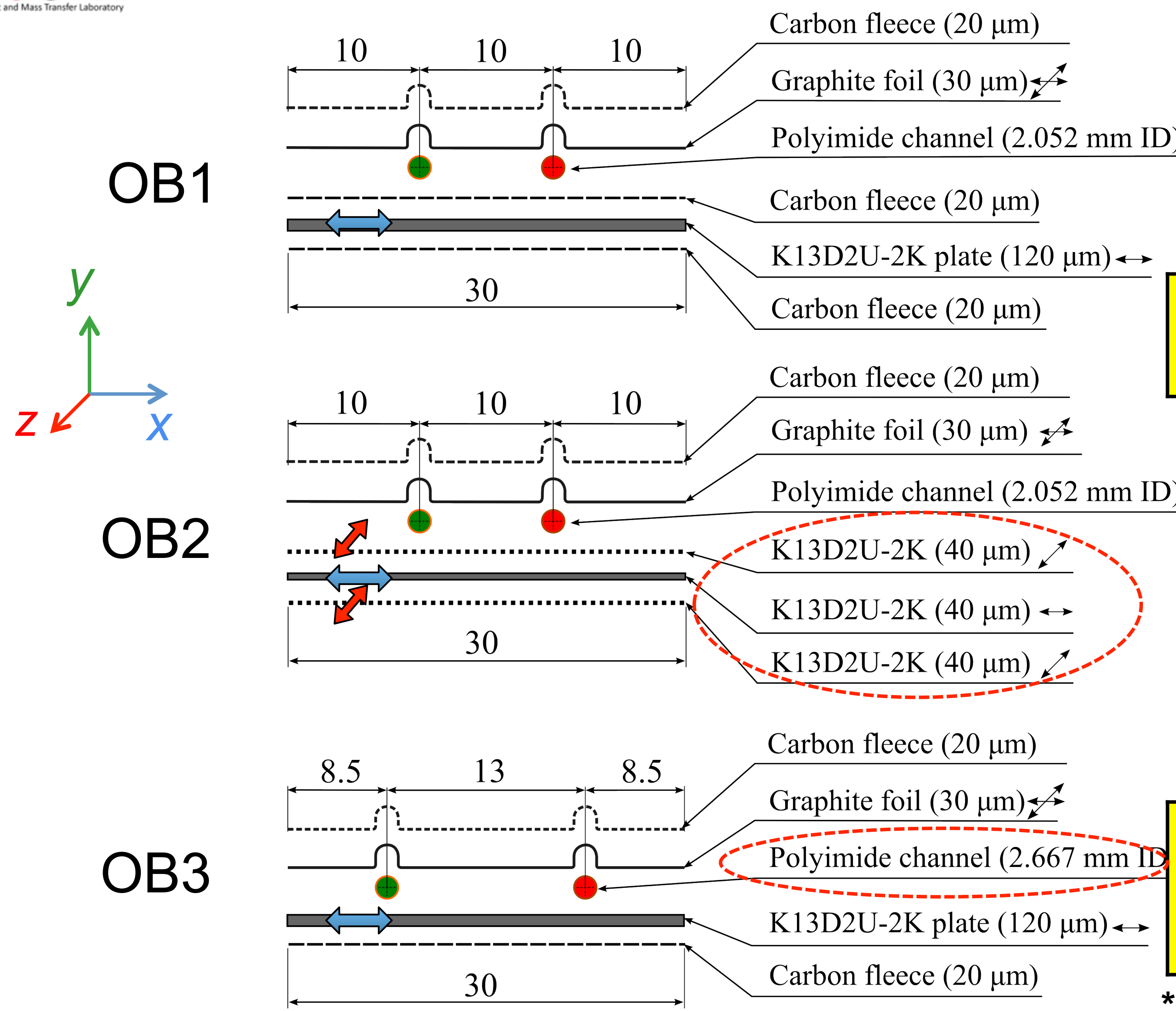








Outer Barrel: half-stave layouts



20.4 g

Total x/X_0=0.770%
(inc. water, services)

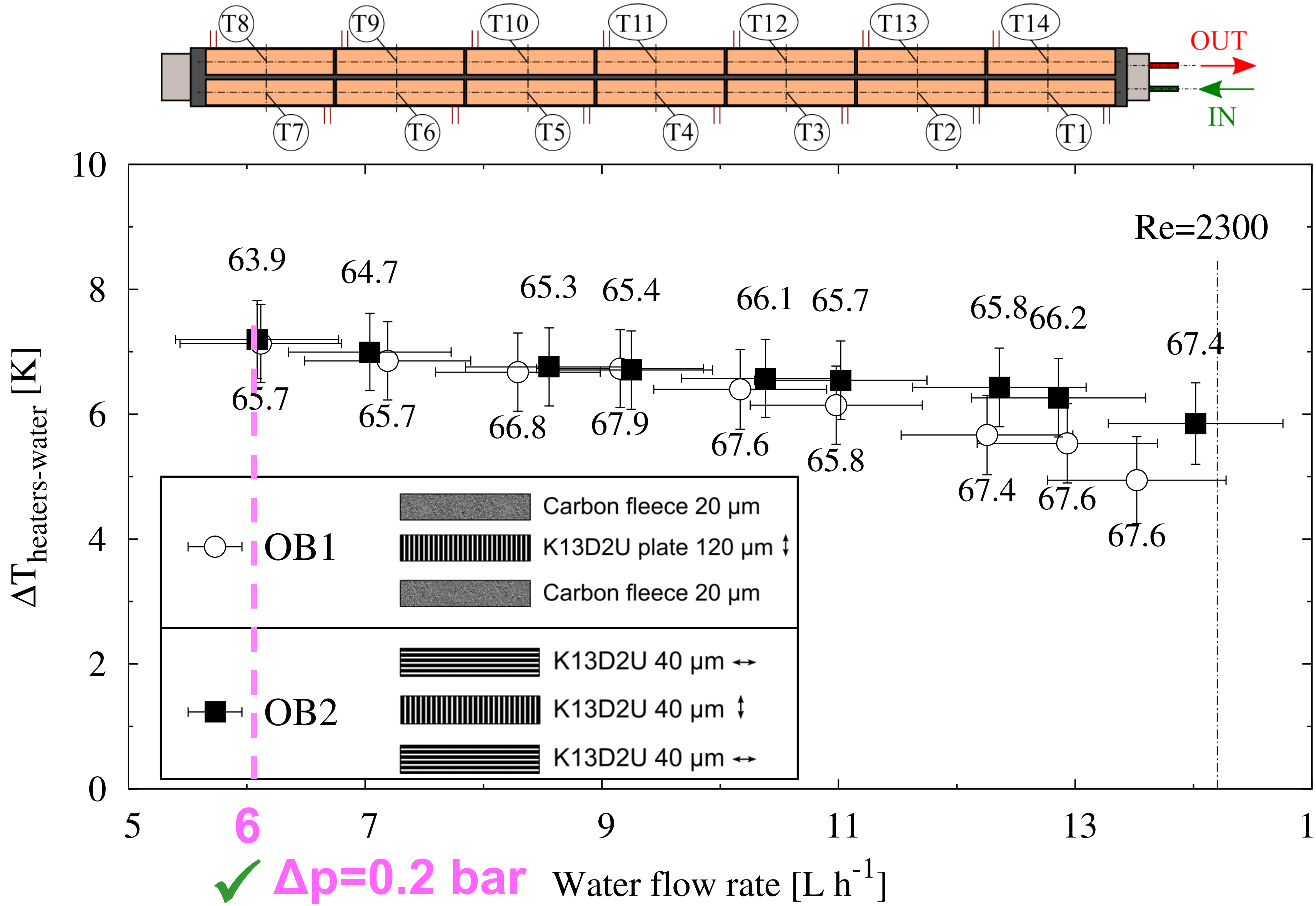
20.7 g

22.0 g

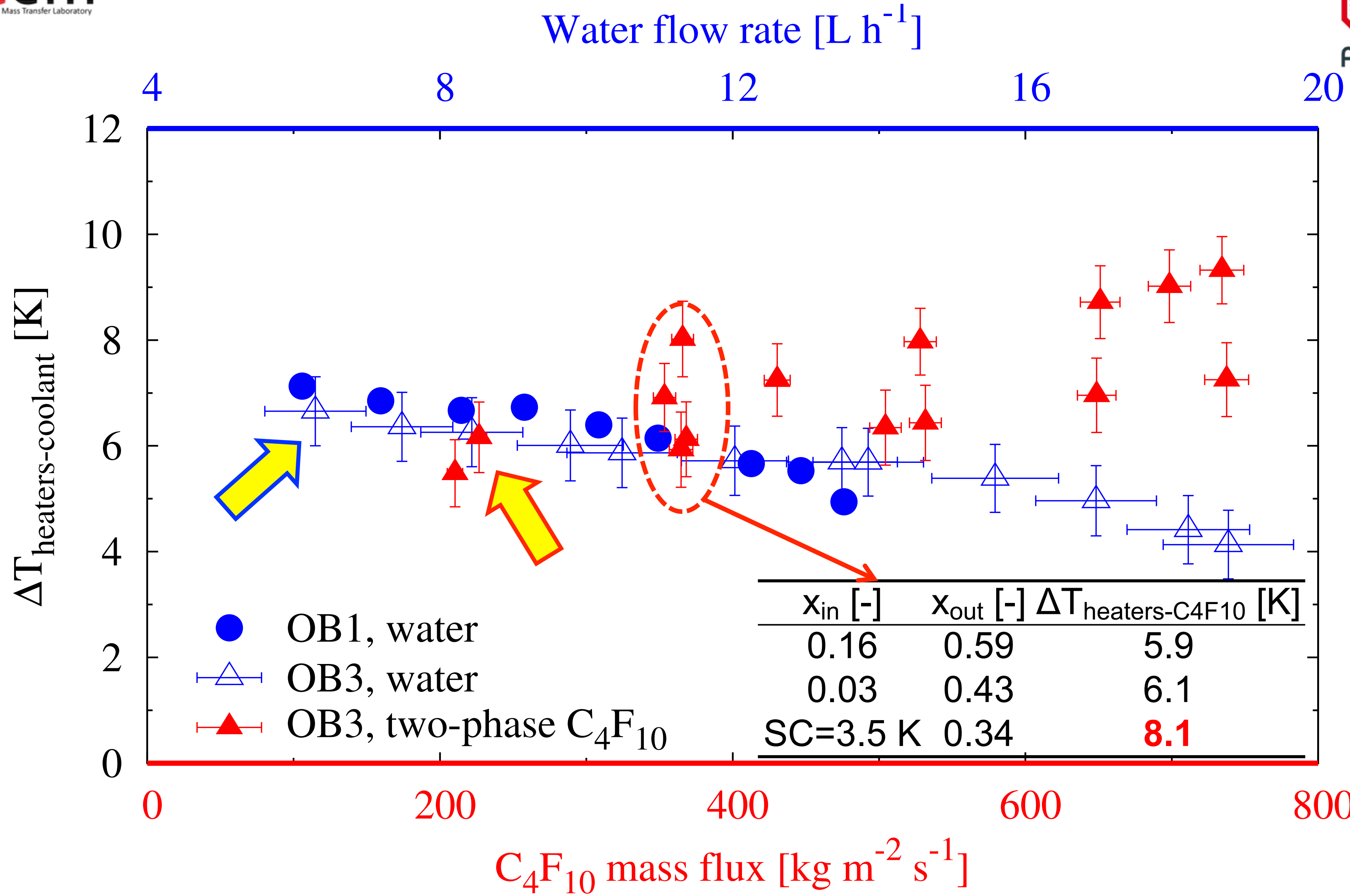
Total x/X_0=0.741%*
(two-phase C_4F_{10}, services included)

*** ε = 0.85 as by Steiner [5] void fraction method**

Water: $\Delta T_{heaters\text{-}water}$, 0.15 W cm^{-2}

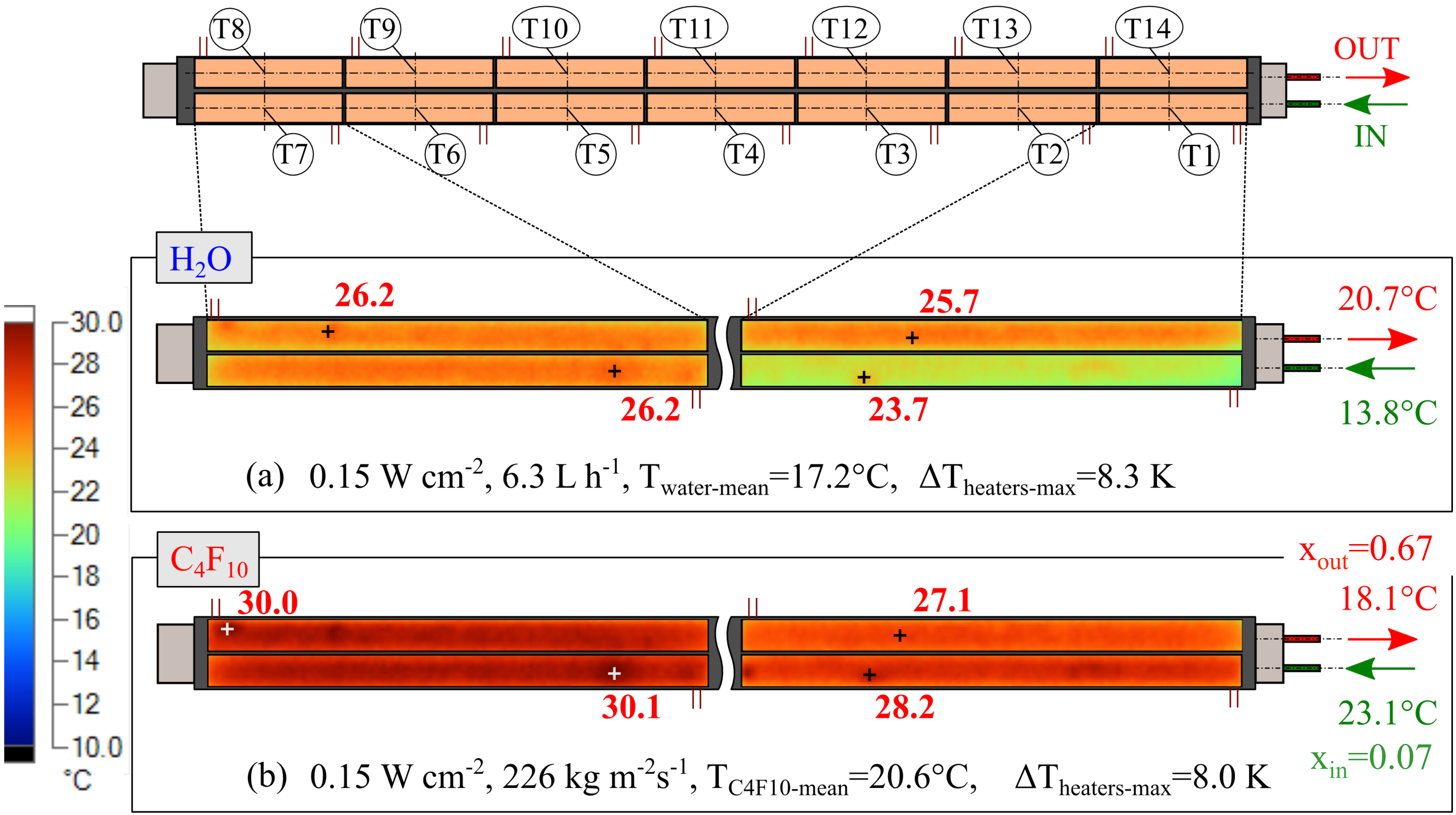


OB3: 2-Ph C_4F_{10}: 0.15 W cm^{-2}



x_{in} [-]	x_{out} [-]	$\Delta T_{heaters-C4F10}$ [K]
0.16	0.59	5.9
0.03	0.43	6.1
SC=3.5 K	0.34	**8.1**

OB3: Water vs. C_4F_{10}, 0.15 W cm^{-2}



Goals

1. Lightweight cooling system for ALICE ITS Upgrade
   - ✓ Innovative solutions: plastic tubing & CFRPs.
   - ✓ Robust, low material budget.
   - ✓ $\Delta T_{heater\text{-}coolant} < 7$ K @0.15 W cm^{-2}. Water or two-phase C_4F_{10}.
     - ➢ No data in literature on flow boiling in plastic channels
     - ➢ HTC vs. G, q, T_{sat} ??

2. Flow boiling heat transfer of R245fa in a polyimide channel

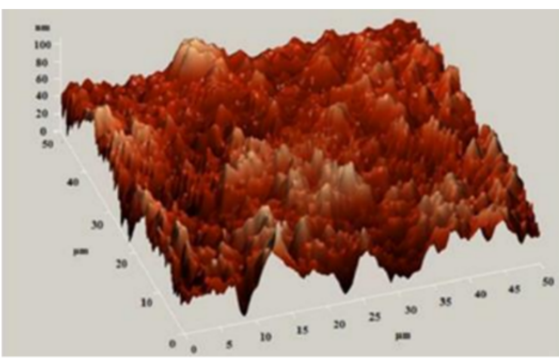
Heat Transfer Research Group (Prof. Ribatski), Escola de Engenharia de São Carlos, USP.

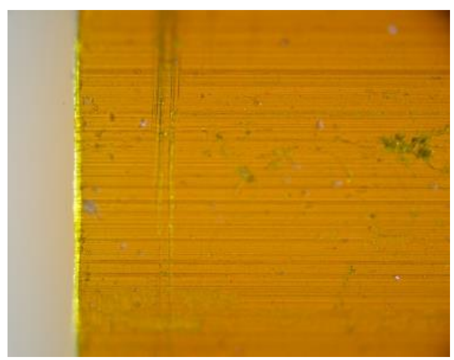
9-month project funded by the Swiss National Science Foundation (SNSF)
Doc.Mobility Project no. 155264

Polyimide channel

- Dimensions measured in microscope:
  - ID=2.689±0.025 mm
  - w=0.063±0.011 mm

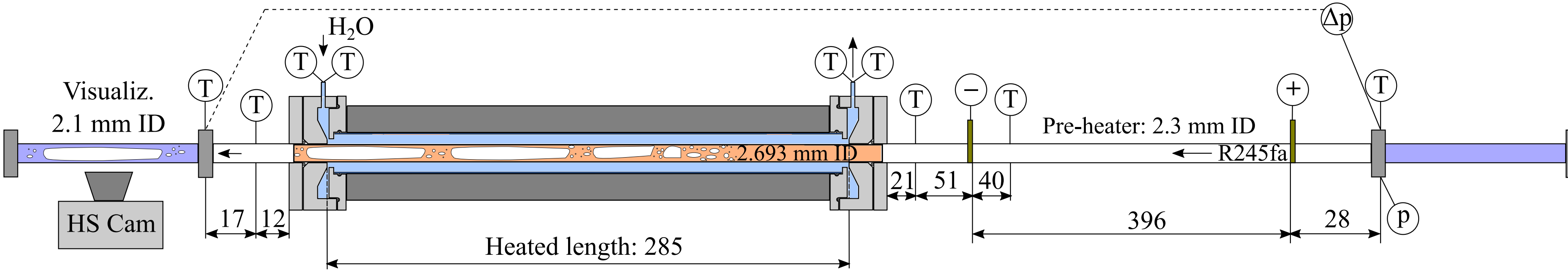
- Statistical aver. roughness: **12 nm**, AFM (Fiorenza *et al.* [6])





- $\lambda_{Polyimide}$= **0.12** W m^{-1} K^{-1}

Test rig



4. Visualisation

Quartz, 2.1 mm ID

4000 fps High-speed camera

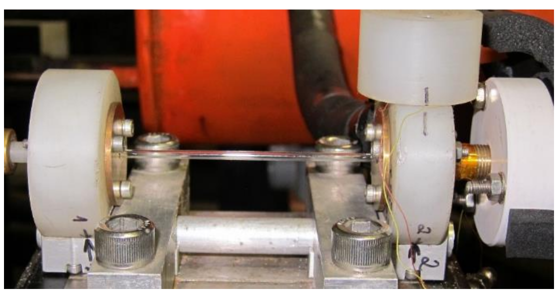
3. Polyimide channel

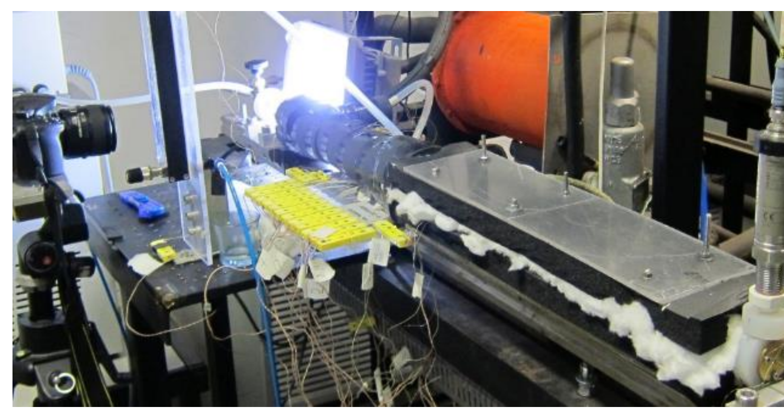
2. SS Preheater (PH)

2.3 mm ID

1. SC R245fa

SC=10-20 K



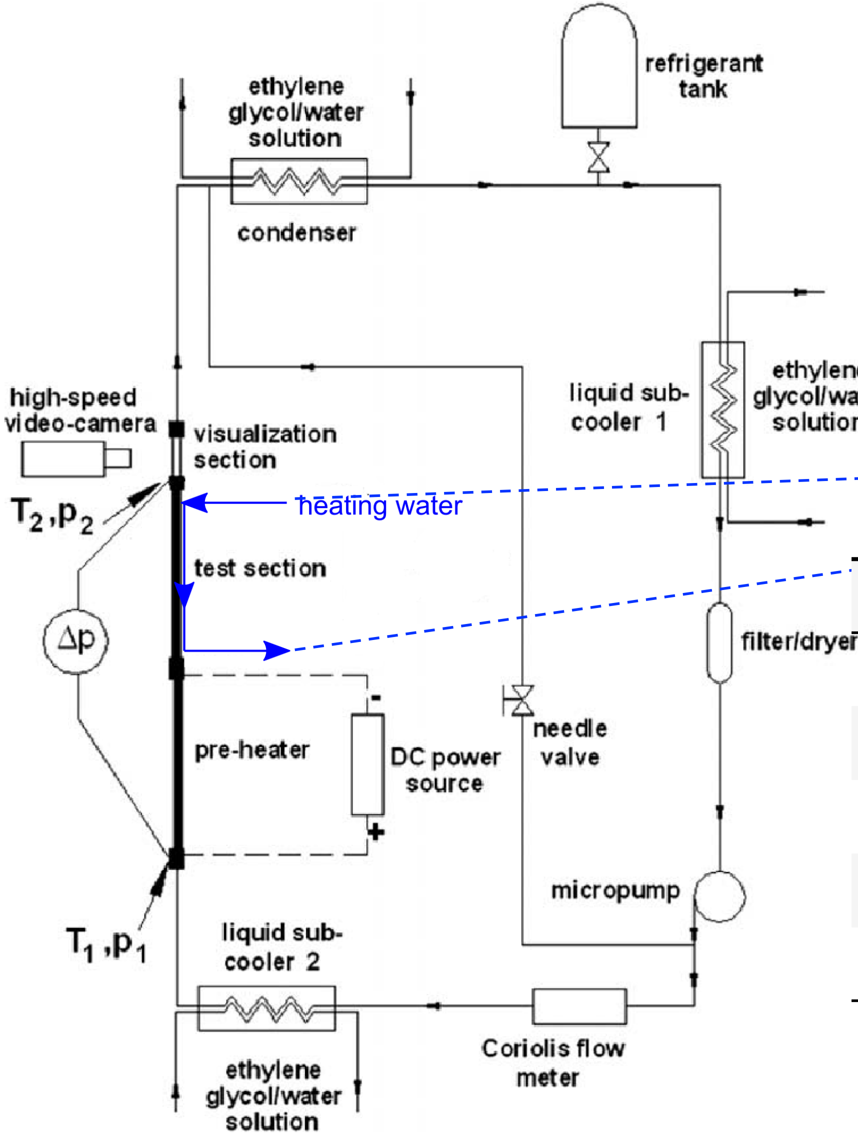


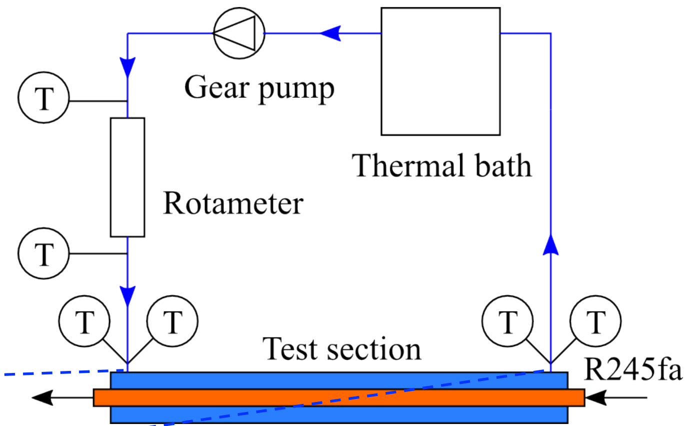
$$Q = \dot{m} c_p \Delta T_{water}$$

- ΔT_{water} = 0.9-2.5 K
- Re_{water} = 3500-5500
- Glass ID = 4.925 mm

Experimental apparatus

Facility: Tibiriçá and Ribatski (2010) [7]



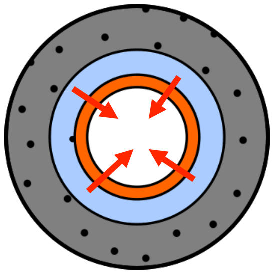


Parameter	Uncertainty
T (type K) 23-79°C	0.10-0.11 K
Water flow rate 40-80°C	0.031 L min^{-1}
Δp (differential)	150 Pa
P transducer	4.5 kPa
Coriolis flow meter	0.1% g s^{-1}
$h_{ts,mean}$	**13-39%**
$x_{ts,mean}$	**~ 4%**

Two-phase tests: data reduction

- Mean **HTC** ($h_{ts,m}$):

$$h_{ts,m} = \frac{1}{R_{conv,int}(\pi L_{heated} D_i)}$$



$$R_{conv,int} = \frac{T_{water,m} - T_{R245fa,m}}{E_{net}} - R_{cond,wall} - R_{conv,ann} \left[\frac{K}{W}\right]$$

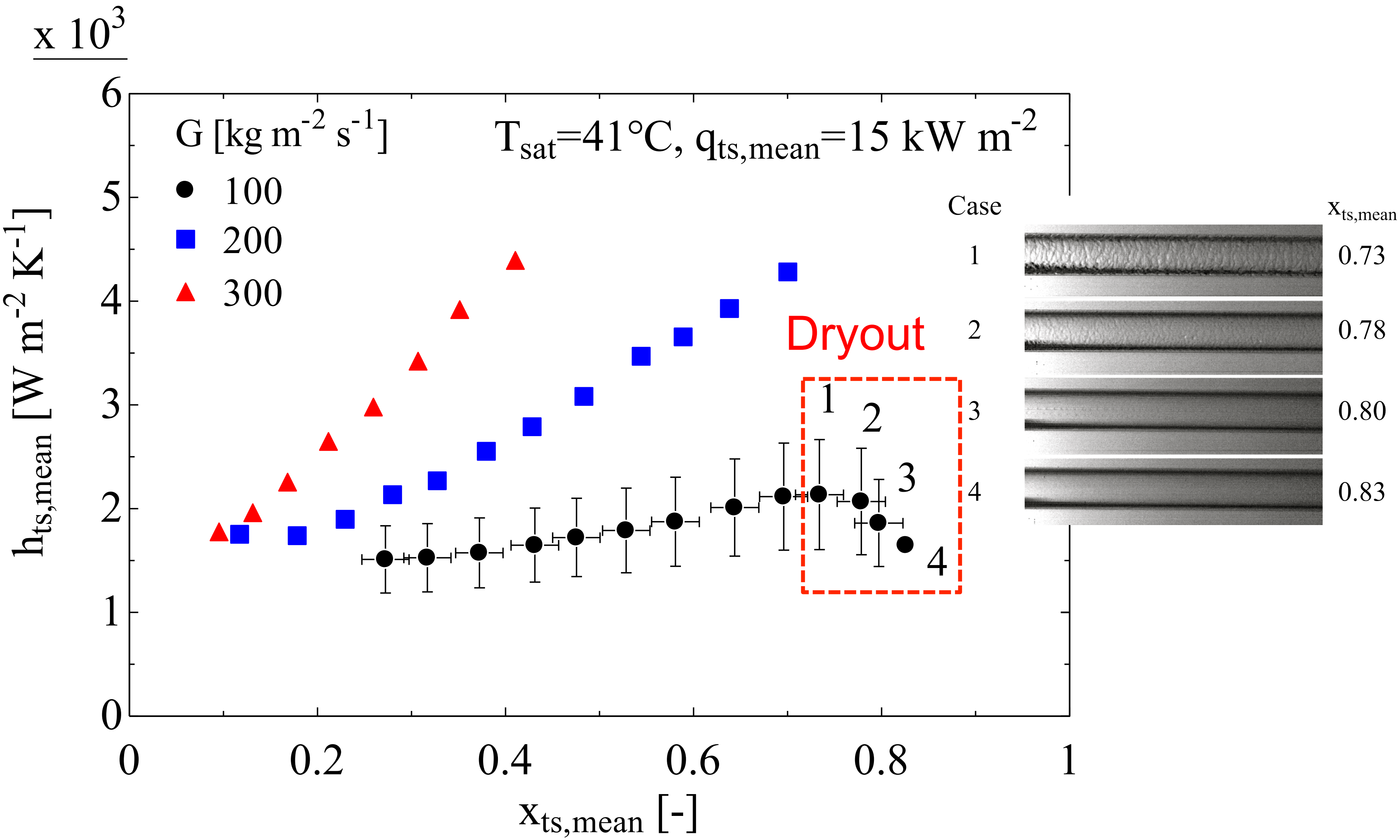
Water-water tests ($R_{cond,wall}$)   Petukhov [8] (validated) ($R_{conv,ann}$)

- Mean **vapour quality** ($x_{ts,m}$):

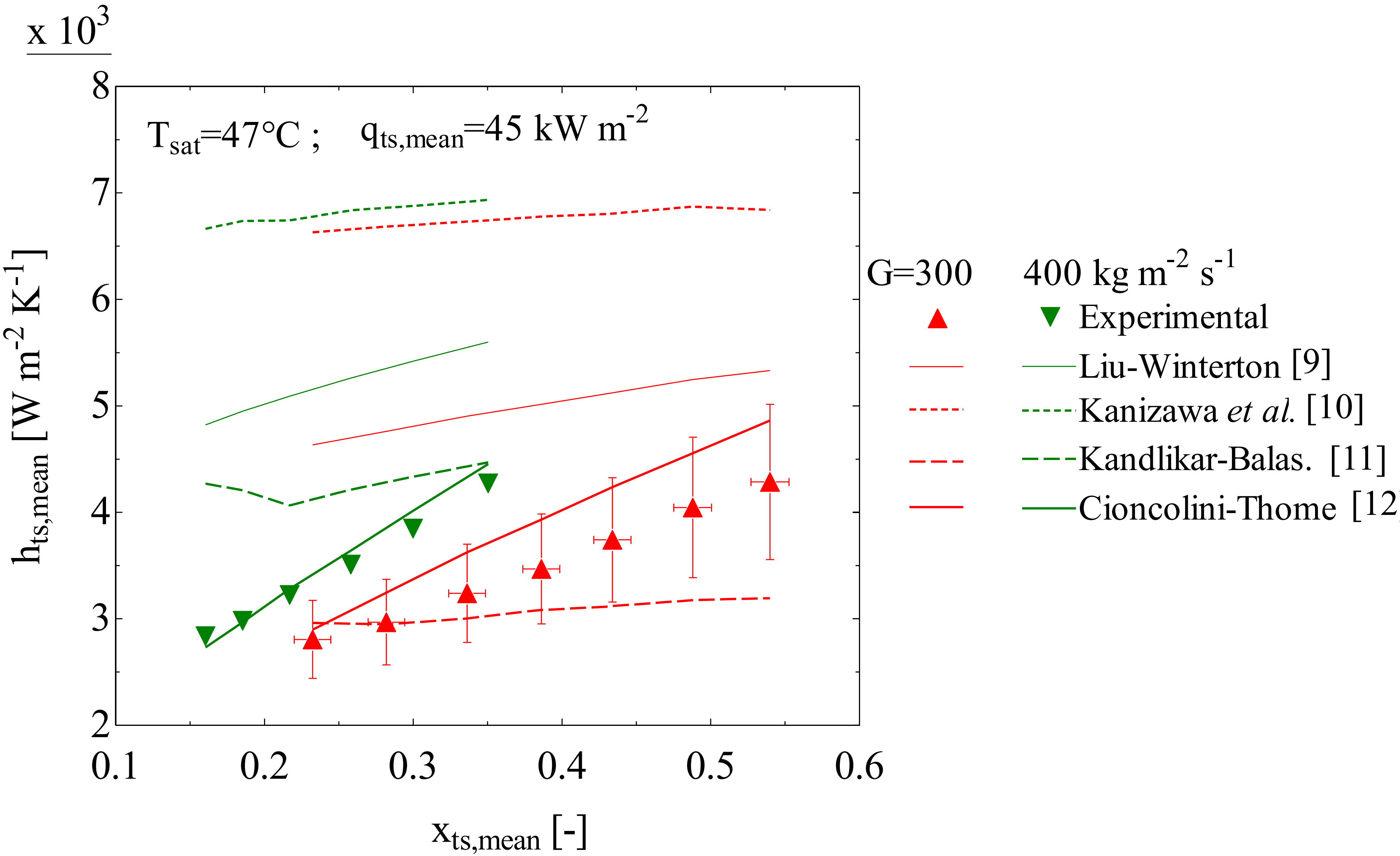
$$x_{ts,in} = \frac{\left(\frac{Q_{ph}}{G_{ph} A_{i,ph}} + i_{ph,in}\right) - i_{l,ts,in}}{i_{lv,ts,in}} \qquad x_{ts,out} = \frac{\left(\frac{Q_{ph}}{G_{ph} A_{i,ph}} + \frac{Q_{net}}{G_{ts} A_{i,ts}} + i_{ph,in}\right) - i_{l,ts,out}}{i_{lv,ts,out}}$$

G [kg m^{-2} s^{-1}]	q [kW m^{-2}]	T_{sat} [°C]	x_{mean} [-]
100-500	15-55	35, 41, 47	0.1-0.9

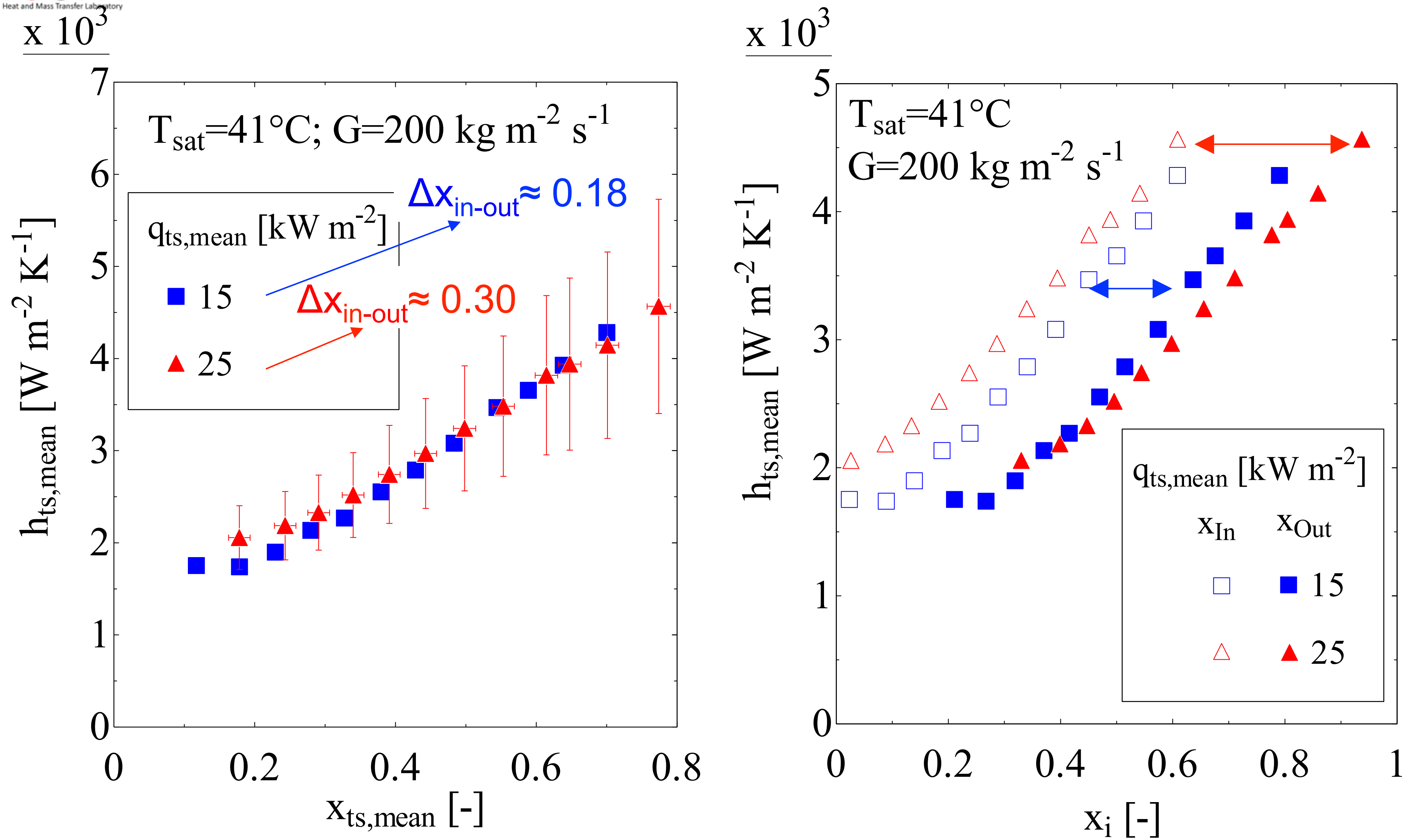
Results: influence of **G**



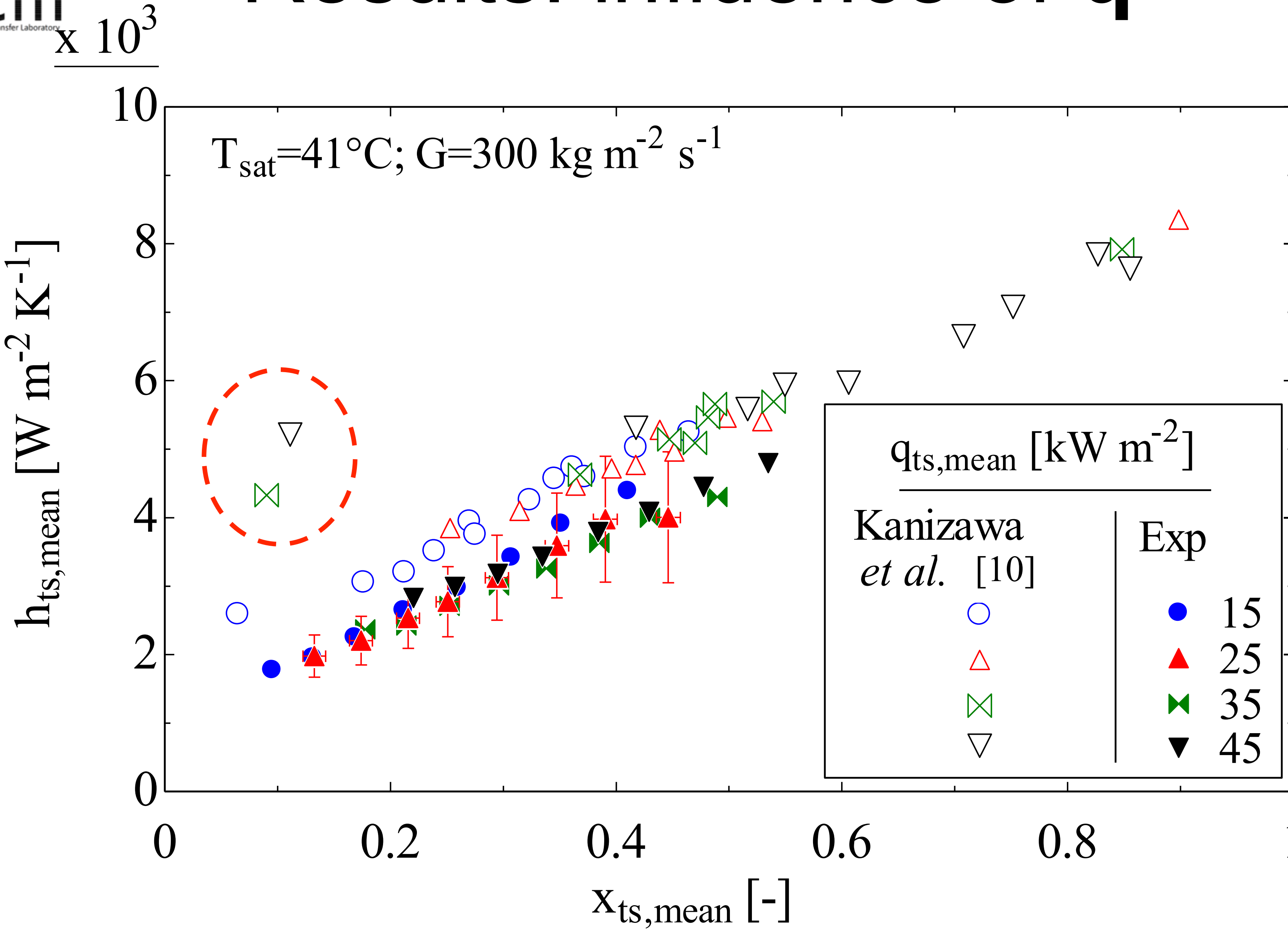
Results: influence of G



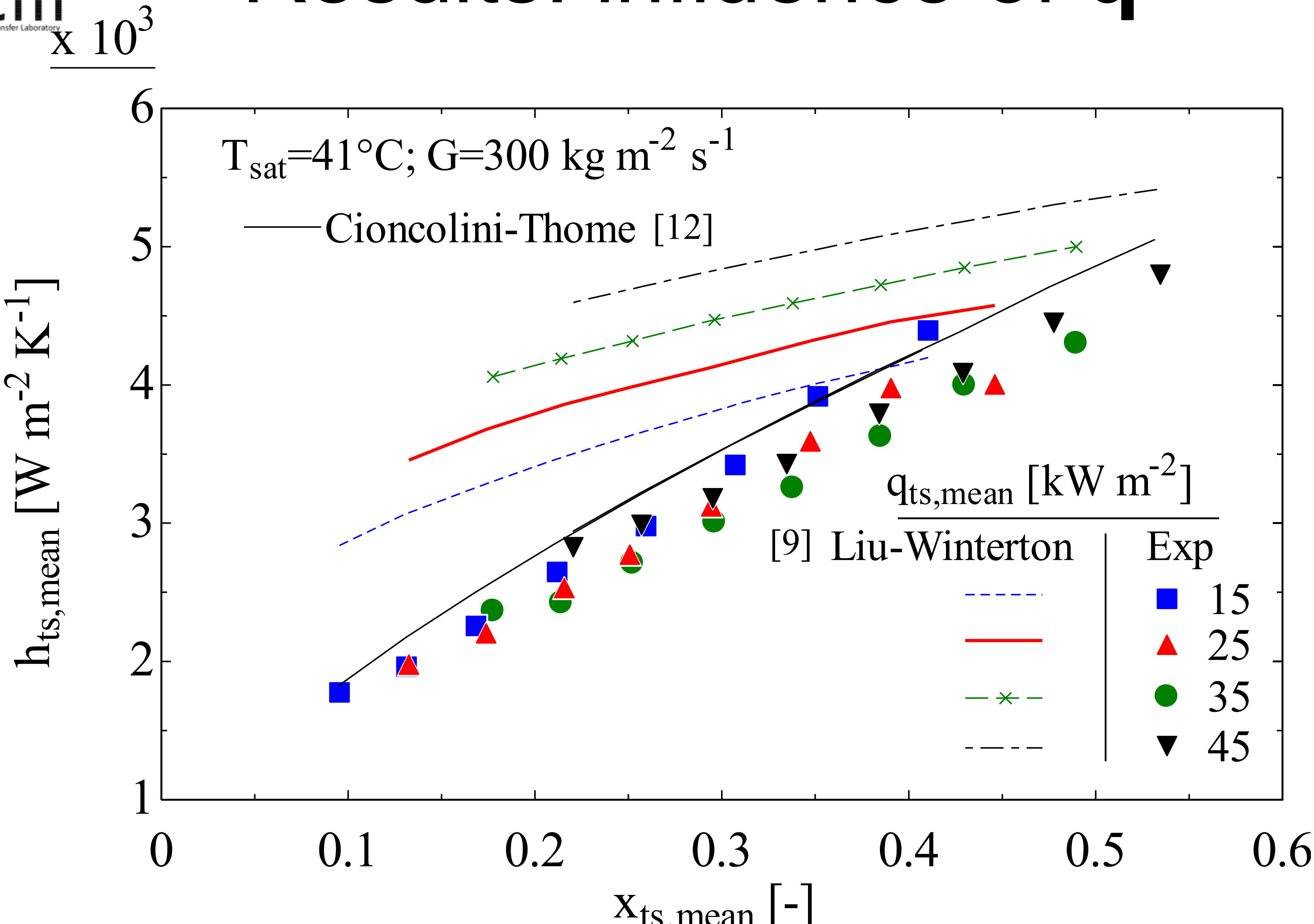
Results: influence of **q**



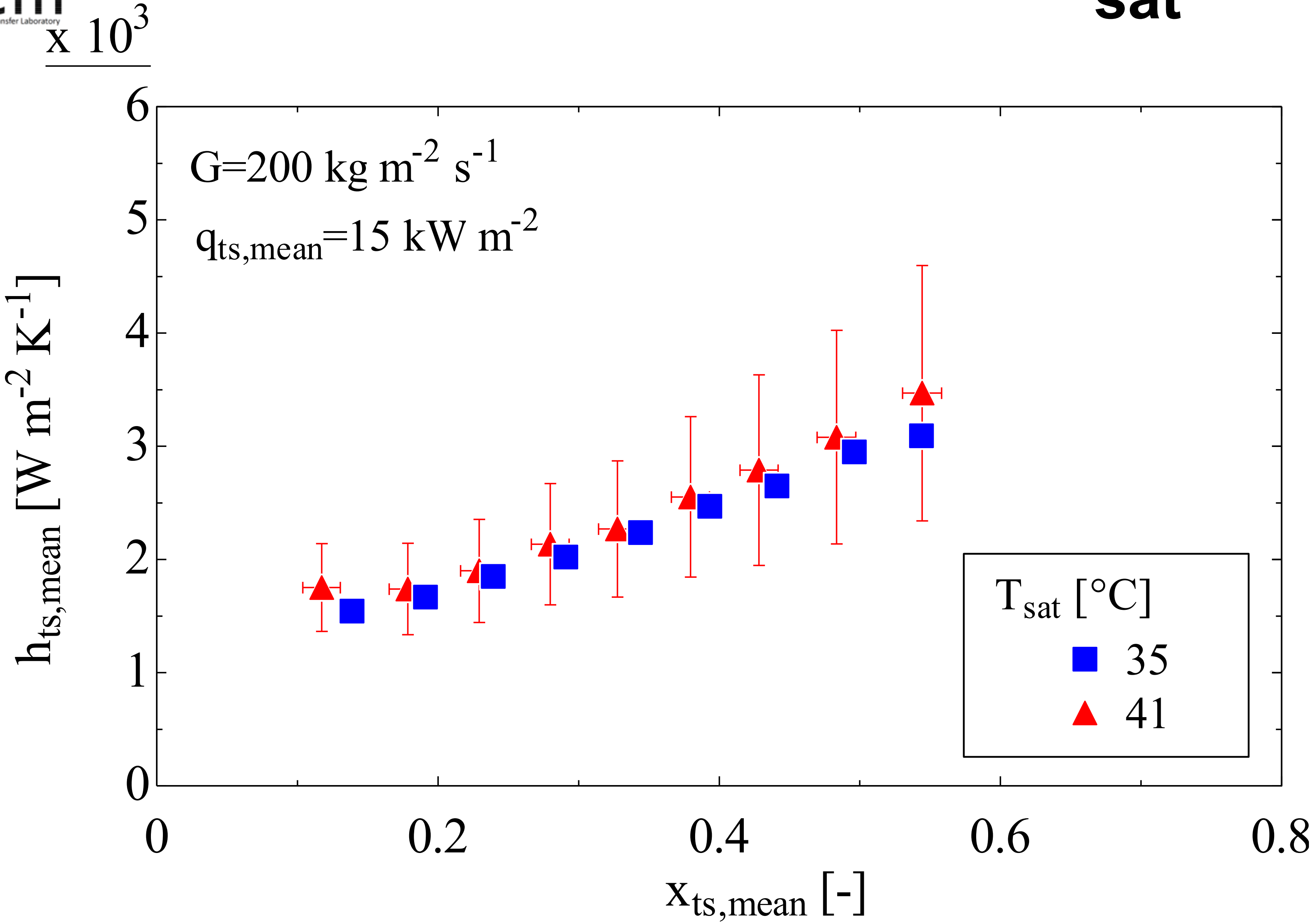
Results: influence of q



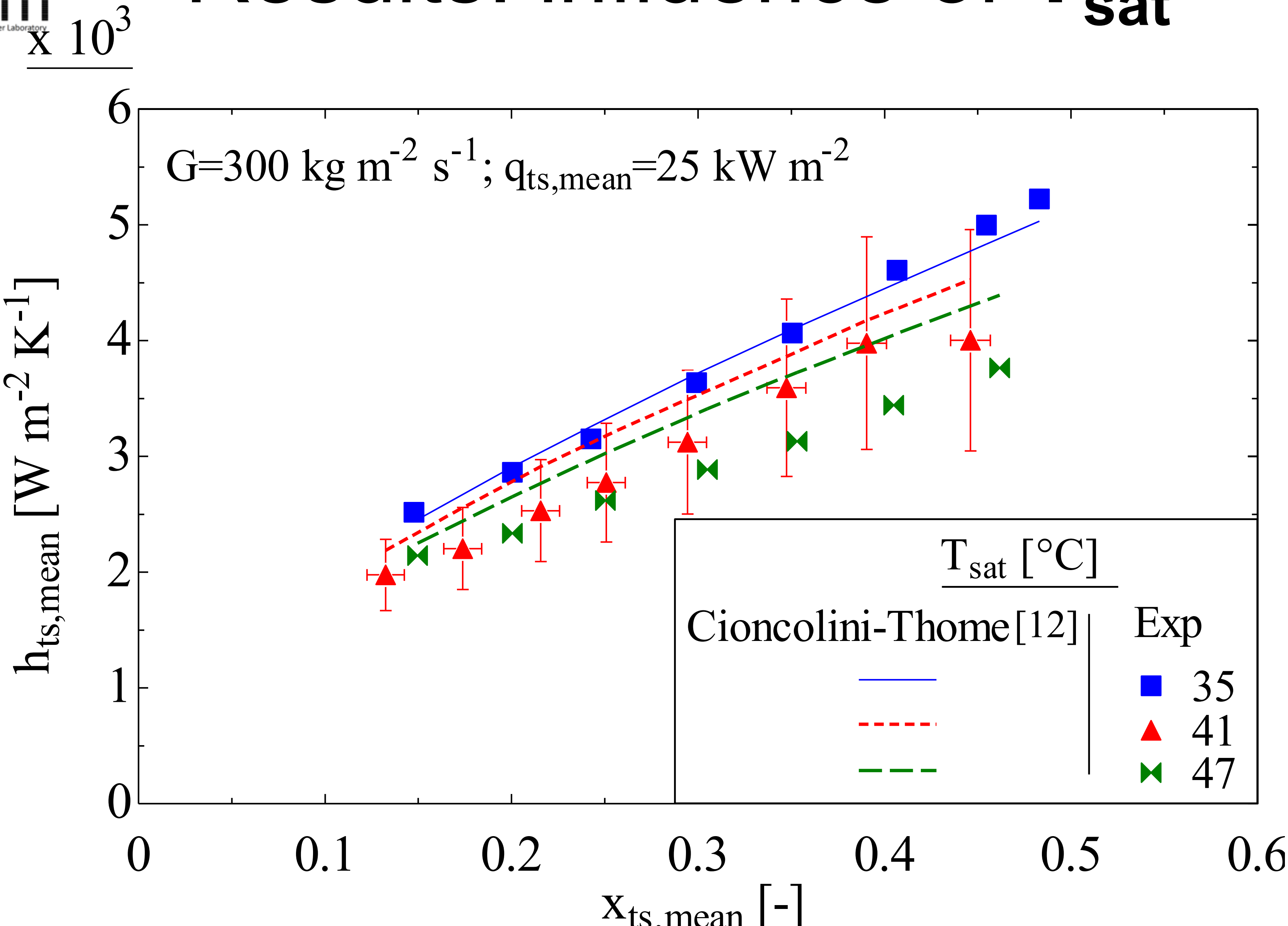
Results: influence of q



Results: influence of T_{sat}



Results: influence of T_{sat}



Concluding remarks

1. Lightweight cooling system for ALICE ITS Upgrade
   - ✓ Innovative solutions: plastic tubing & CFRPs.
   - ✓ Robust, low material budget.
   - ✓ $\Delta T_{heater\text{-}coolant} < 7$ K @0.15 W cm^{-2}. Water or two-phase C_4F_{10}.

2. Flow boiling heat transfer in a polyimide channel
   - ✓ ↑ HTC with ↓ T_{sat} at high G, high q.
   - ✓ ↑ HTC with ↑G, ↑x_{mean}
   - ✓ HTC not depending on q

   } **Convective boiling**

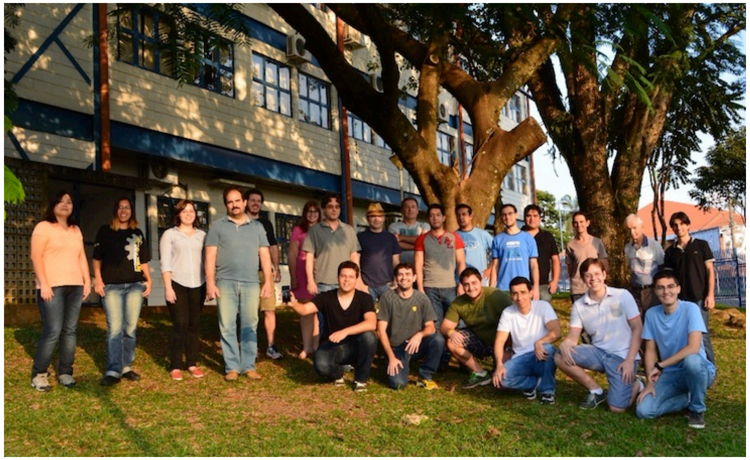
   - ✓ Cioncolini-Thome [12] convective method fits experimental data.

Next steps

- ALICE ITS Upgrade
  - Cooling tests on fully assembled staves (chips, glue, FPC, power bus).
  - Cooling test full staves assembled IB, OB layer.
  - Loop design (water).

- Flow boiling heat transfer in a polyimide channel
  - Influence of diameter (1.024, 2.052 mm ID), fluid (R134a).
  - Direct flow visualisation (transparent Kapton® tube).
  - Improve test section: thermopile, local HTC measurements.
  - Condensation tests.

Thank you!



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Swiss National Science Foundation (SNSF)

Heat Transfer Research Group, EESC-USP

Prof. G. Ribatski

LTCM

Prof. J. R. Thome

Lucia & my family

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

CERN

ALICE

USP

NETeF Núcleo de engenharia térmica e fluidos

ltcm Heat and Mass Transfer Laboratory

EN

FNSNF

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