Experiments on Thermohydraulics of Stratified Melt Pool – SIMECO-II and LIVE2D Tests

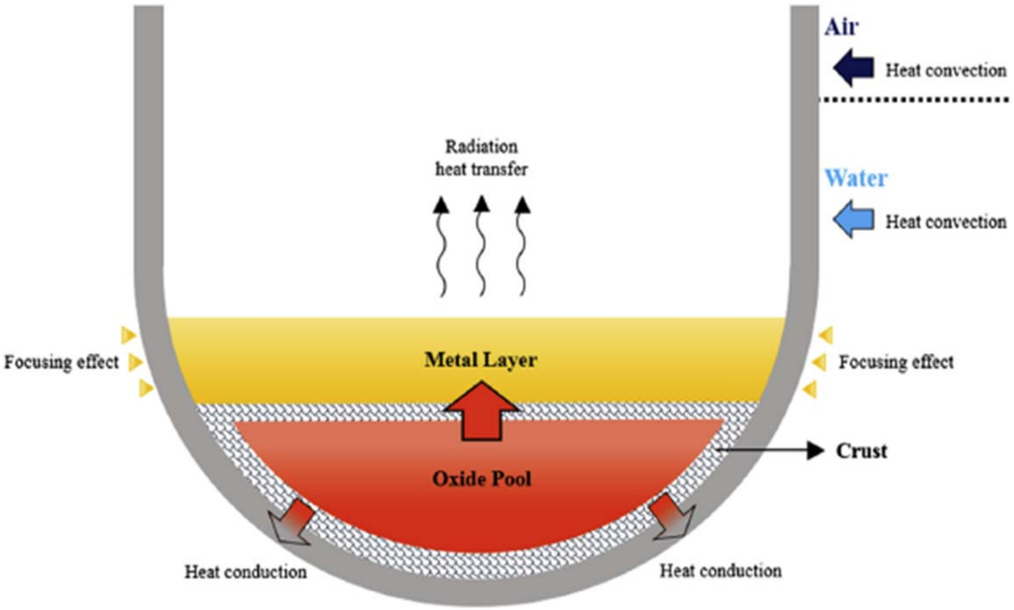
X. Gaus-Liu, T. Cron, B. Fluhrer (KIT)

A. Komlev, W. Ma, S. Bechta (KTH)

Outline

- Objectives
- Experimental setups
  - SIMECO-II
  - LIVE2D
- Performance of LIVE2D test series
- Results of LIVE2D test series
- Summary and Outlook

Objectives



Objectives

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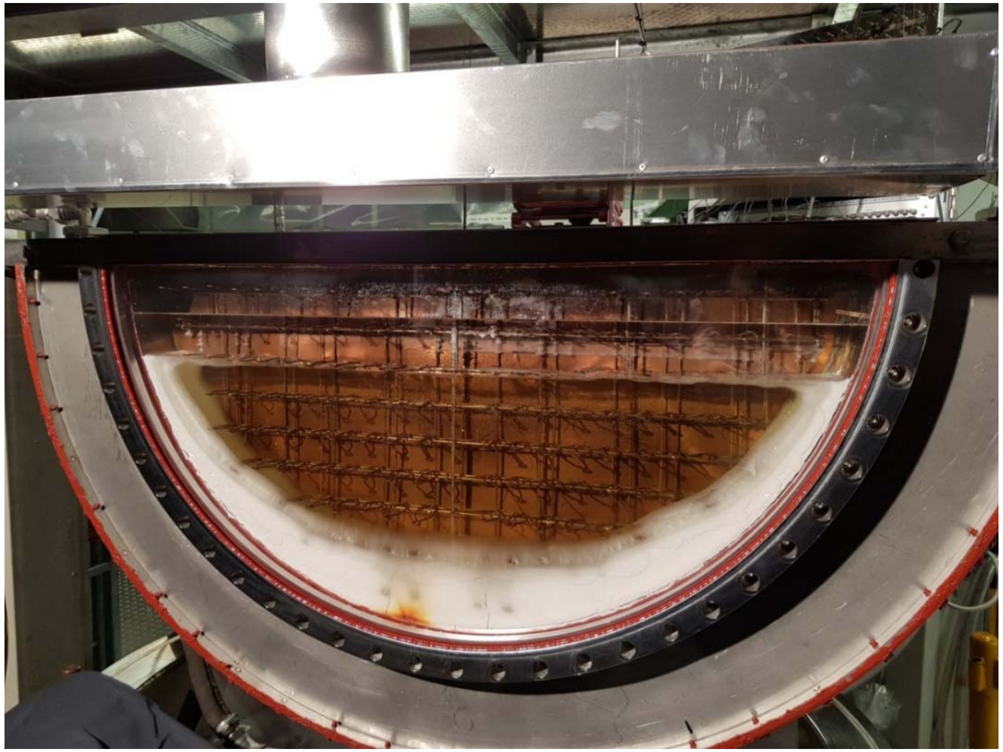
- In-vessel melt retention by external cooling
- High risk of thermal load on the vessel wall in the metallic layer due to the heat flux focusing effect influenced by:
  - Interlayer crust
  - Upper layer thickness
  - Upper boundary cooling condition

Experimental Setup – SIMECO-II facility

LIVE2D Experimental Setup



- Slice geometry:
  1 m in diameter, 12 cm in width,
- Transparent front wall and insulated back wall,
- Nine layers of evenly distributed electrical heating cables in the vessel,
- External boundary rigid cooled; upper surface either rigid cooled or under hot air atmosphere.

Performance of LIVE2D test series

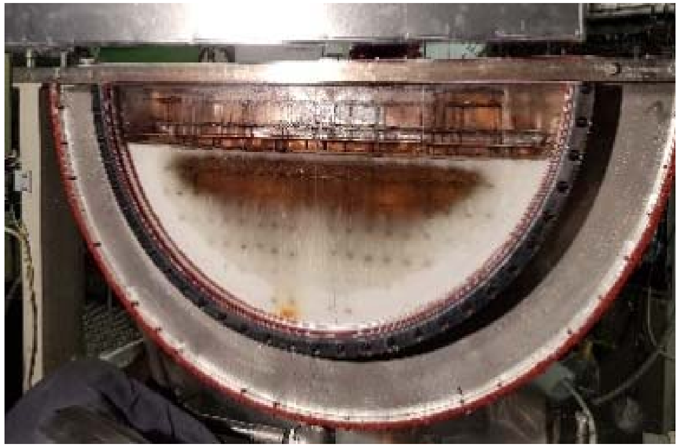
Test	Simulant material		Heigh of layer, mm		Heating phase, W	Boundary condition	
	Upper layer	Lower layer	Upper layer	Lower layer	heating only in lower layer	Top surface	Vessel wall
SO1	Thermal oil	eutectic $NaKNO_3$	35	340	1300 – 940 – 1040 – 1310 – 1400 – 900	Hot air (metal plate covers the vessel)	Water cooled
			75	340	1300 – 1800- 1150		
			110	340	2200 – 1800 – 1400 – 1600		
			75	340	1600		
SOTC	Thermal oil	eutectic $NaKNO_3$	110	340	3000 – 3600 - 4250	Rigid cooling (Water cooled lid)	Water cooled
			75	375	4230 – 3000 - 3600		
			35	415	3600 – 3000 – 4300 – 3400 –2400 – 1800		

Material properties in LIVE2D tests

Material properties	unit	Lower layer: 50% KNO_3-50% $NaNO_3$		Upper layer: Thermal oil	
		at 224 °C	*at 260 °C*	*at 140 °C*	*at 220 °C*
density	*kg/m³*	1964	1937	755	540
kinematic viscosity	*mm²/s*	2.76	2.23	11	9
thermal conductivity	*W/(mK)*	0.48	0.47	0.15	0.15
thermal capacity	*J/(gK)*	1.29	1.31	1.7	1.83
Pr		14.5	12.0	94	59

LIVE2D test interlayer crust behaviour

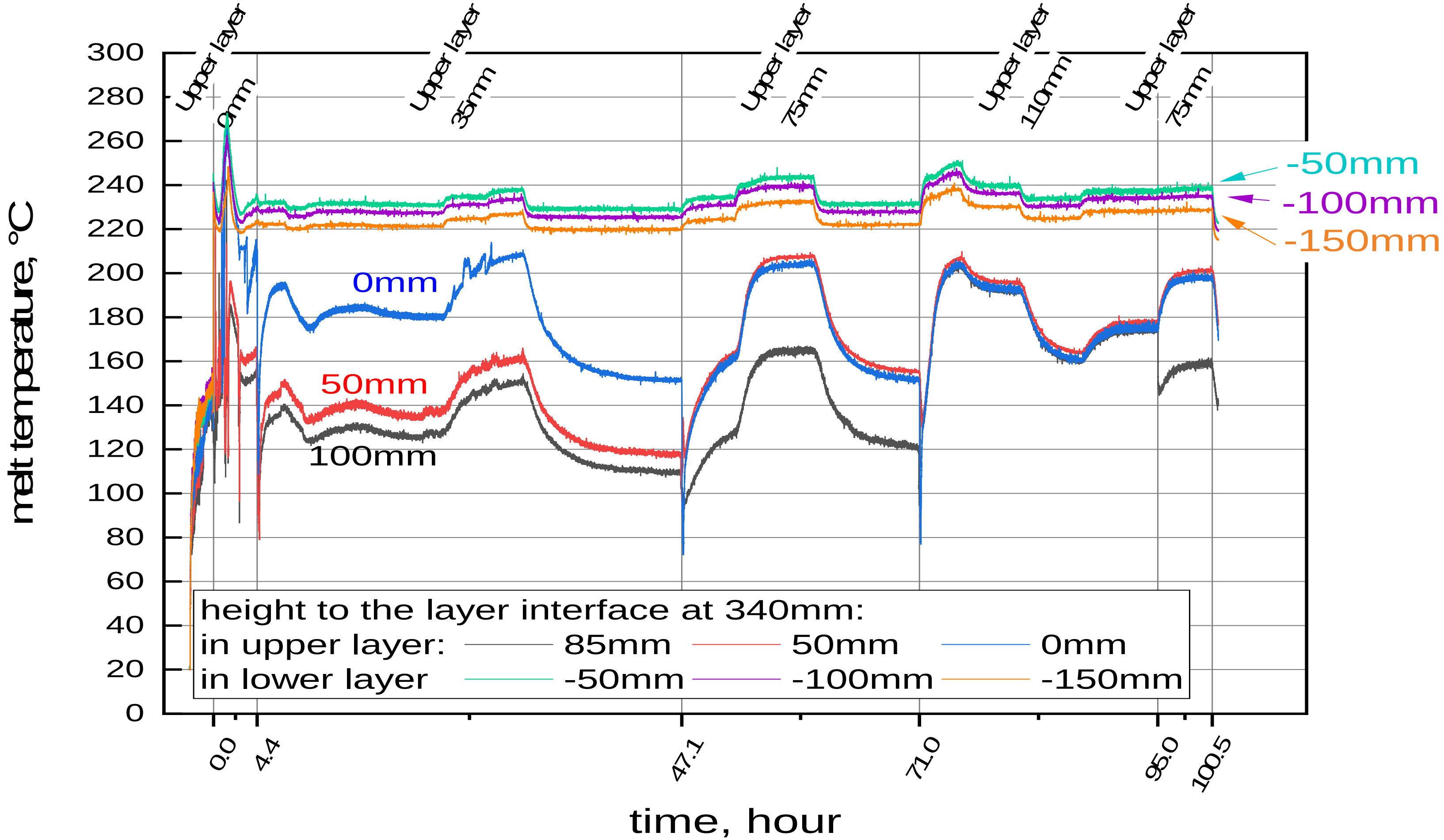
Compact crust



Almost no crust

Half crust

Result - Transient process in SO1 test

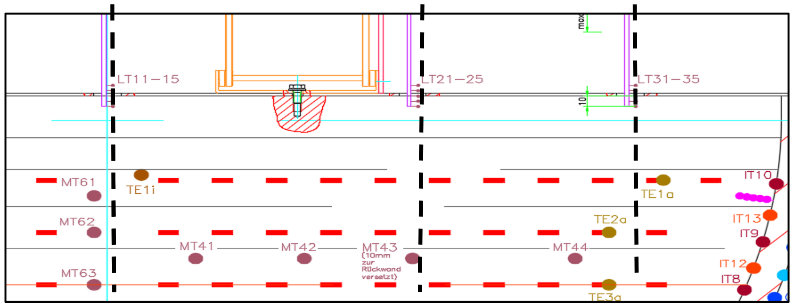


LIVE2D Results - upper layer melt flow pattern

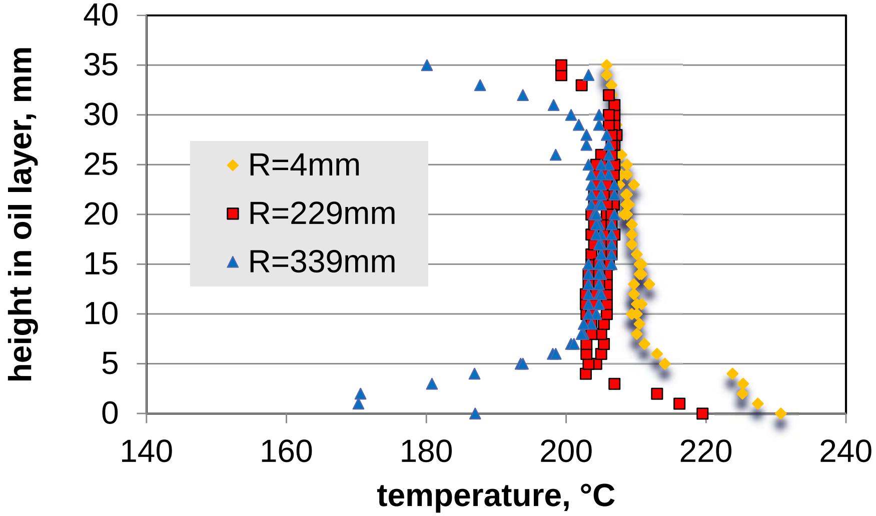
SO1 test: hot atmosphere at the upper surface: global circulation

SOTC test: rigid cooled upper surface. Raleigh-Bernard convection

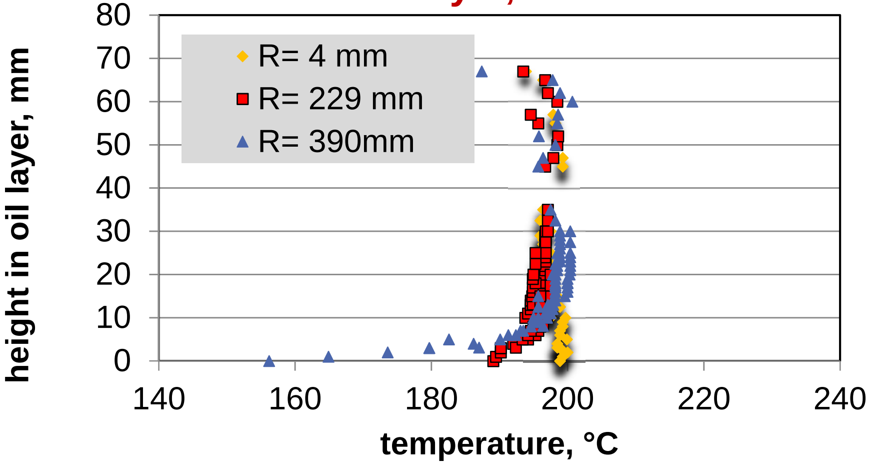
Results - Upper layer temperature profiles in SO1 test



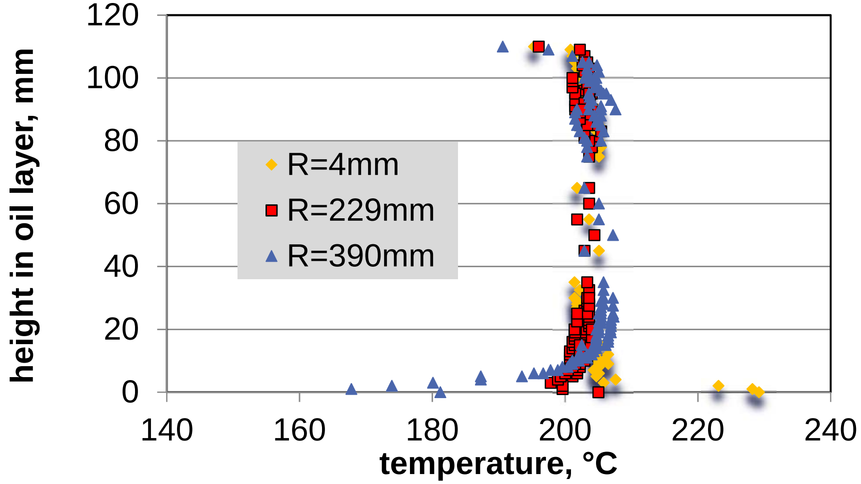
35 mm layer, 1400 W



75 mm layer, 1600 W



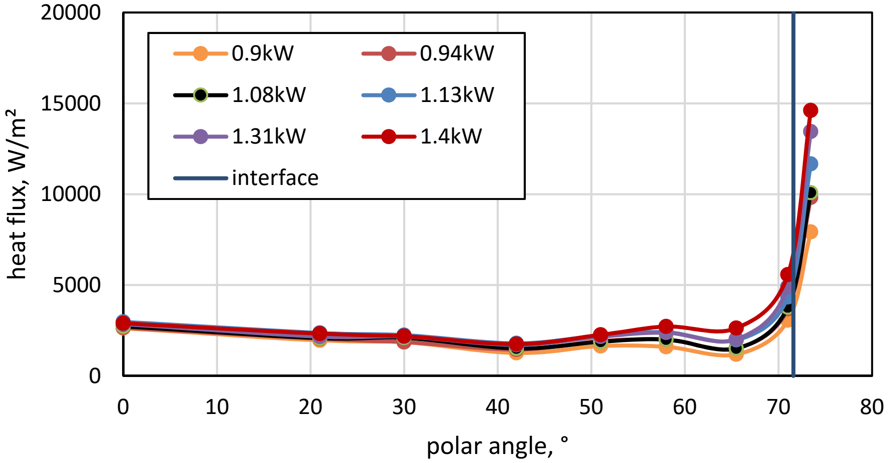
110 mm layer, 2200 W



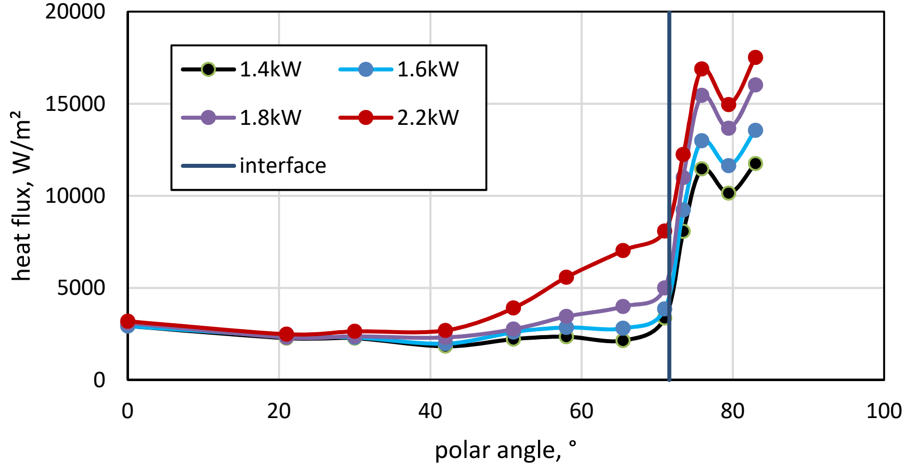
Results - LIVE2D Heat fluxes (1)

SO1 test: hot atmosphere at the upper surface

upper layer 35mm

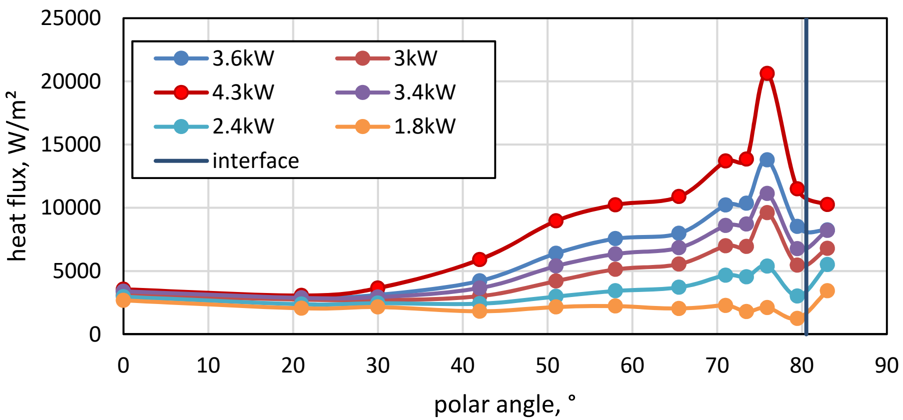


upper layer 110mm

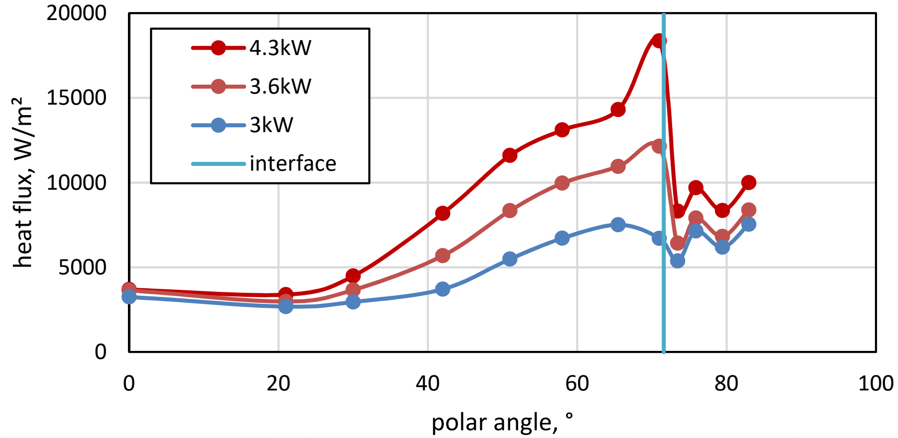


SOTC test: rigid cooled upper surface

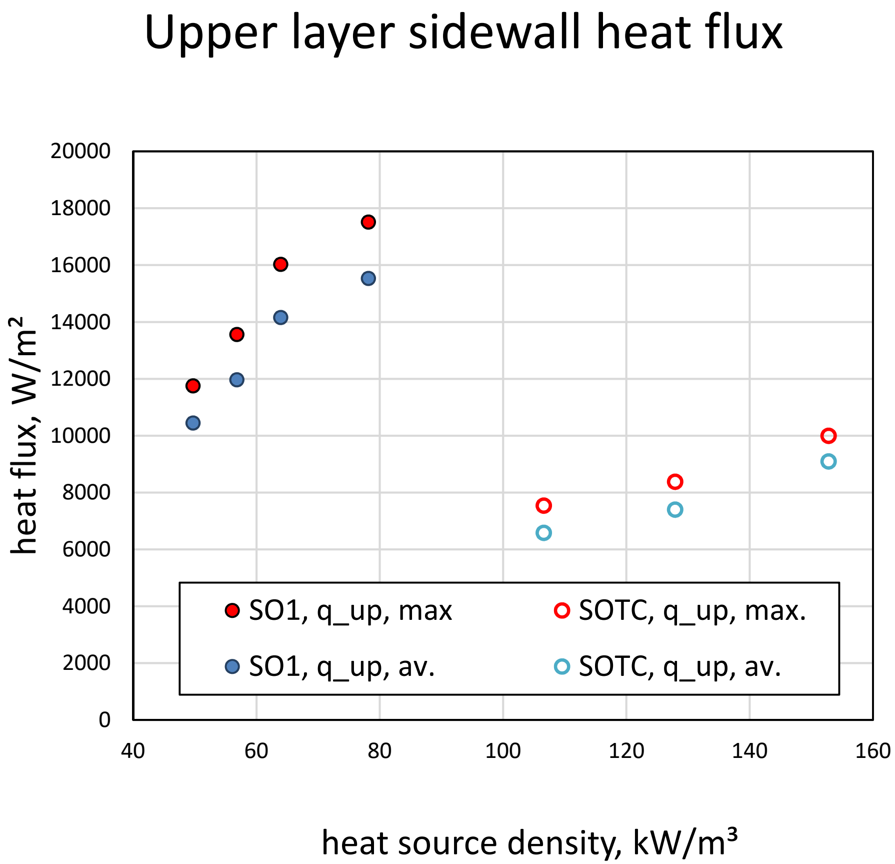
upper layer 37mm

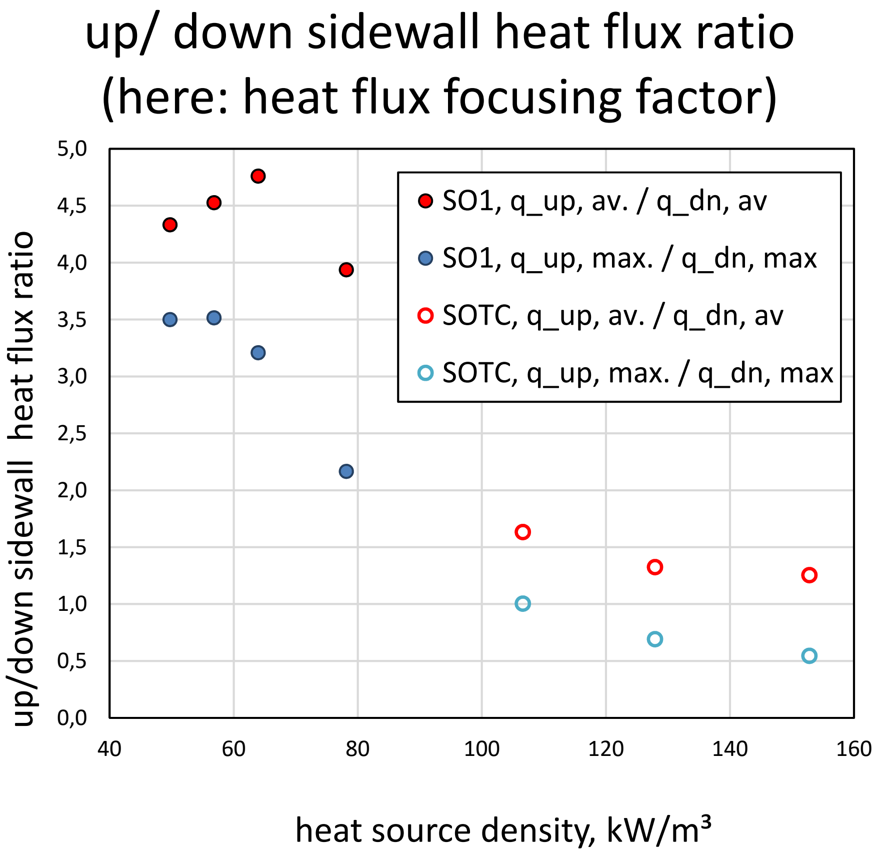


upper layer 112mm



Results - Heat flux focusing effect





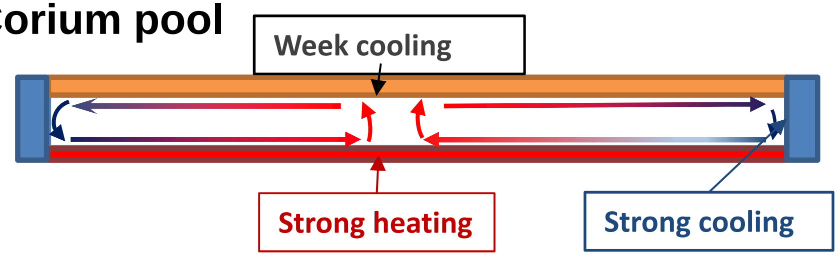
- Heat flux focusing factor reduces strongly under rigid surface cooling,
- Heat flux focusing factor decreases gradually when the interlayer crust melts down and the layer interface temperature increases.

Results - Nu and Ra of the upper layer sidewall heat transfer (theory)

- $Ra_{up,sd} = \frac{g\beta\Delta T L^3}{\lambda\nu}$
- $Nu_{up,sd} = \frac{q}{\Delta T \lambda L}$
- $L = H_{up}$
- $\Delta T = T_{bulk,up} - \bar{T}_{w,up}$

Reference Temperauture of parameter is T_{film} : (T_{bulk} + $T_{w,\,up}$) /2

Upper layer boundary conditions in Corium pool



- Downward flow on cooled vertical plate
- confined cavity with heated bottom boundary

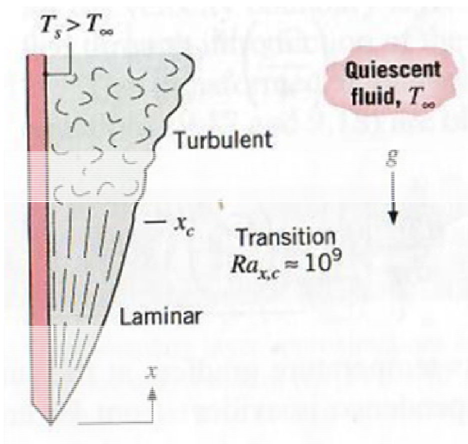
Churchill&Chu correlation and boundary conditions

Laminar flow, Ra<10⁹

$$Nu_{sd,lam} = 0.68 + \frac{0.67 Ra^{\frac{1}{4}}}{\left[1 + \left(\frac{0.492}{pr}\right)^{\frac{9}{16}}\right]^{\frac{4}{9}}} \qquad Nu_{sd} \sim Ra^{\frac{1}{4}} Pr^{\frac{1}{4}}$$

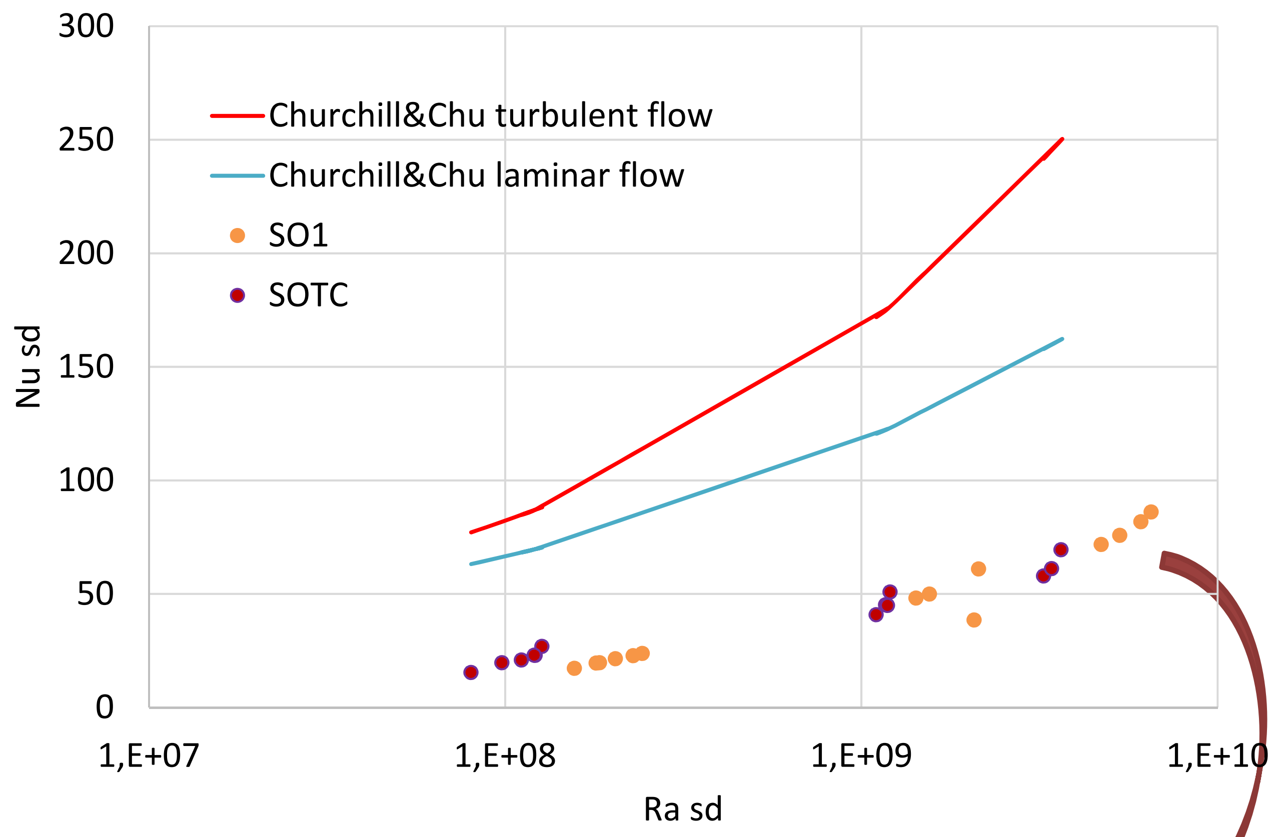
Turbulent Flow: Ra>10⁹

$$Nu_{sd} = \left\{0.825 + \frac{0.387 Ra^{\frac{1}{6}}}{\left[1 + \left(\frac{0.492}{\mathrm{Pr}}\right)^{9/16)}\right]^{\frac{8}{27}}}\right\}^2 \qquad Nu_{sd} \sim Ra^{\frac{1}{3}} Pr^{\frac{1}{3}}$$



- Isothermal heated plate
- Upward flow
- Non-confined cavity
- For all Pr values

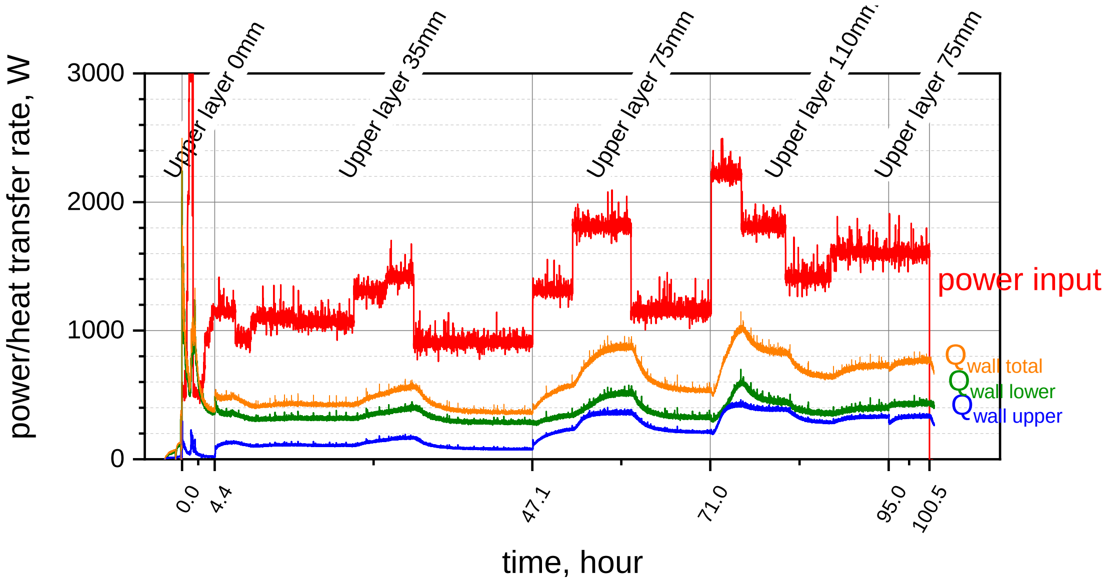
Results - Nu and Ra in LIVE2D tests



$$Nu_{sd} = 0.0282\ Ra_{sd}^{\ 0.35}$$

$$R^2 = 0.945$$

Heat Balance in LIVE2D tests

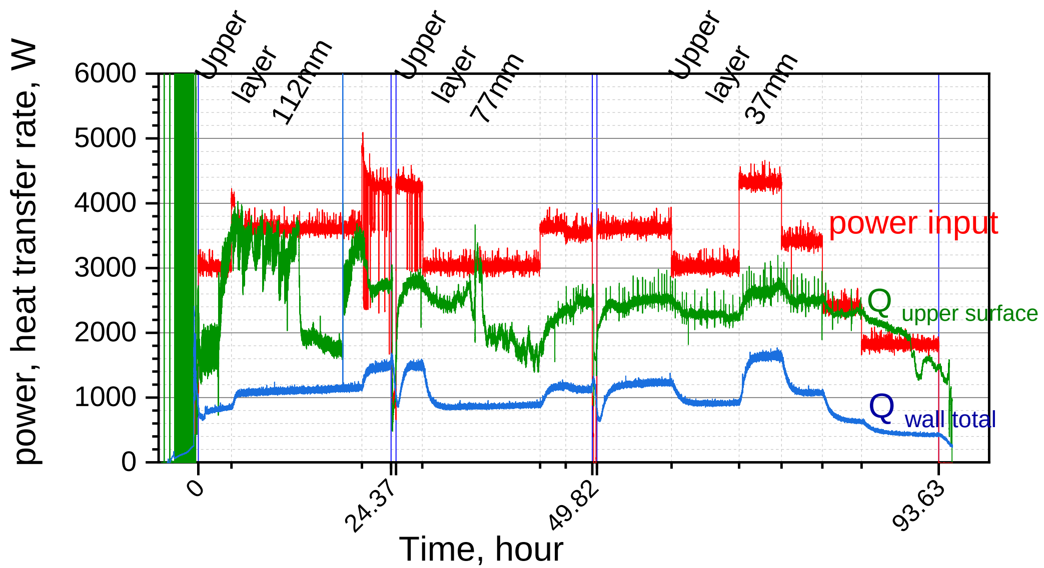


SO1 test

$Q_{wall}/Q_{in} \sim 0.37\text{-}0.46$

Main heat losses via

- Front wall (radiation)
- Cooled sidewall above the melt
- Hot air above the melt



SOTC test

- $Q_{wall}/Q_{in} \sim 0.21\text{-}0.31$
- Waterside heat transfer measurements at the sidewall and at the upper surface were not reliable due to the low water pressure and low flow rate.

Summary

- SIMECO-II and LIVE2D test facilities were designed for the thermal hydraulic studies of a stratified melt pool in large geometry,
- SIMECO-II test will apply metallic simulant material in the upper layer, whereas LIVE2D applied thermal oil for the upper melt layer,
- Two series of LIVE2D test with 3 upper-layer thicknesses were performed,
- The transient process of the upper layer is longer than that of the lower layer, and it reflects the time period of interlayer crust change,
- Strong heat flux focusing effect was observed when the heat transfer at the melt upper surface was poor; whereas upper surface rigid cooling can effectively minimize the heat flux focusing effect,
- The experimental results of Nu of upper layer sidewall heat transfer is considerably lower than the Churchill & Chu correlations.

Outlook

- SIMECO-II plans?

This work is funded by the IVMR grant agreement number 662157 (H2020) and national governments