西安交通大學
XI'AN JIAOTONG UNIVERSITY

EXPERIMENTAL AND NUMERICAL STUDY ON THE HEAT TRANSFER CHARACTERISTICS OF MELT POOL

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Contents

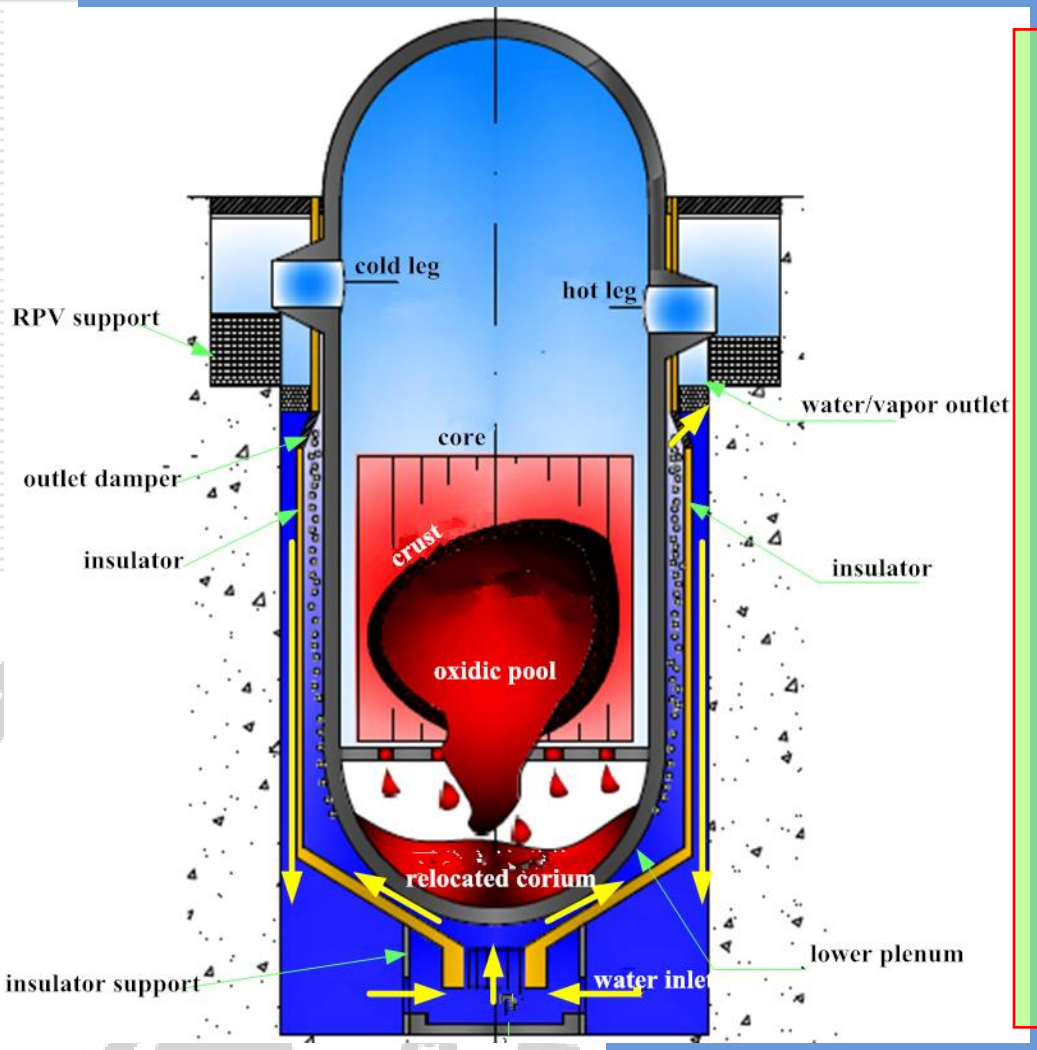
1 COPRA Experiments

2 Preliminary Numerical study on COPRA

3 International cooperation tests on COPRA

4 Conclusions

Background



- During severe accidents, core may melt and relocate into the lower head to form corium pools.
- **In-Vessel Retention(IVR)** of core melt is a key severe accident management strategy, which has been implemented to advanced reactors.
- **Natural convection** in corium pool plays an important role in determining the thermal load on the vessel wall, which is directly relevant to the problem of IVR.

Review

	Geometry	Scale	Simulant	Heating	Ra’
COPO	2D Semi-elliptical slice Length: 1.77 m Depth: 0.8 m Thickness: 0.1 m	1:2	H_2O-$ZnSO_4$	Joule heating	**10^{14}-10^{16}**
UCLA	3D Hemisphere Radius: 0.2183 m and 0.3005 m	1:10	Freon-113	Magnetron	**10^{10}-10^{14}**
ACOPO	3D Hemisphere Radius: 0.2 m	1:2	Water	No heating	**10^{12}-10^{16}**
BALI	2D 1/4 circular slice Radius: 2 m Thickness:15 cm	1:1	Salt water	Joule heating	**10^{13}-10^{17}**
RASPLAV	2D Semicircular slice Radius: 0.2 m Thickness:16.7 cm	1:10	UO_2–ZrO_2–Zr; NaF-$NaBF_4$	Side wall heating Direct electrical heating	**10^{11}-10^{13}**
SIMECO	2D Semicircular slice Radius: 0.25 m Thickness:9 cm	1:8	$NaNO_3$-KNO_3; Paraffin-water-Chlorobenzene	Cable-type heaters	**10^{12}-10^{13}**
SIGMA-SP	3D Hemisphere Radius: 0.25 m	1:8	Water	Cable-type heaters	**10^{8}-10^{11}**
LIVE	3D Hemisphere Radius: 0.5 m	1:5	Water	Cable-type heaters	**10^{12}-10^{13}**

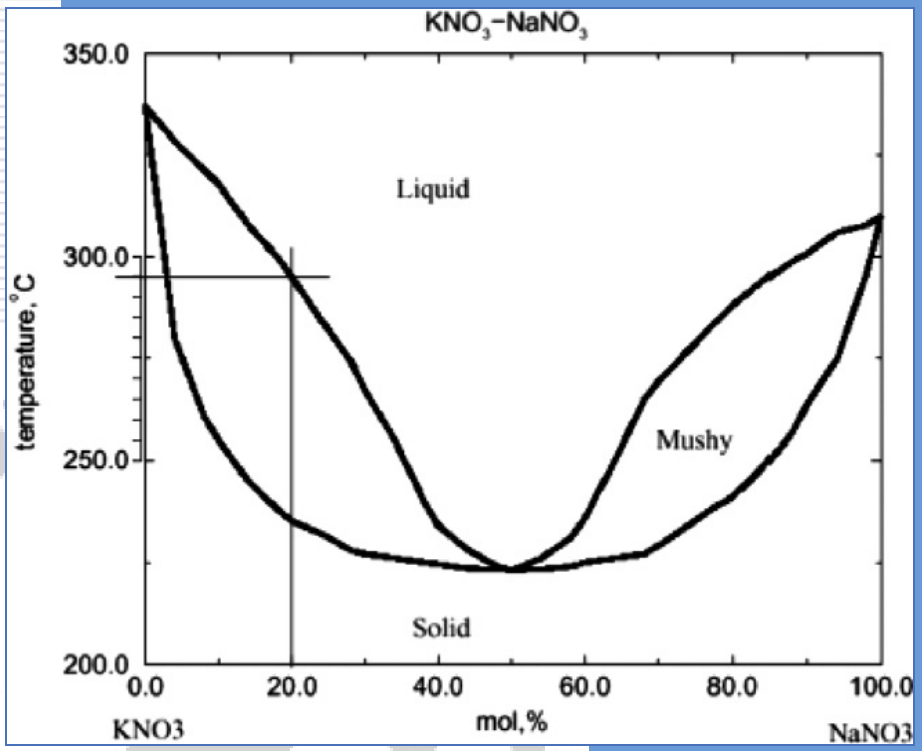
Facility Description

COPRA (COrium Pool Research Apparatus)

Geometry	2D 1/4 circular pool Radius 2.2m Width 20cm
Scale	1:1 for ACP1000
Simulant	Water 20%$NaNO_3$-80%KNO_3
Heating	Electrical heating rod
Boundary	Insulated or isothermal top wall and isothermal bottom wall
Ra’	10^{16}

Simulant Material

1. Non-eutectic mixture
2. Distinctive solidus-liquidus temperature gap
3. Similar solidification behavior
4. Unaggressive to vessel and easy for technical handling

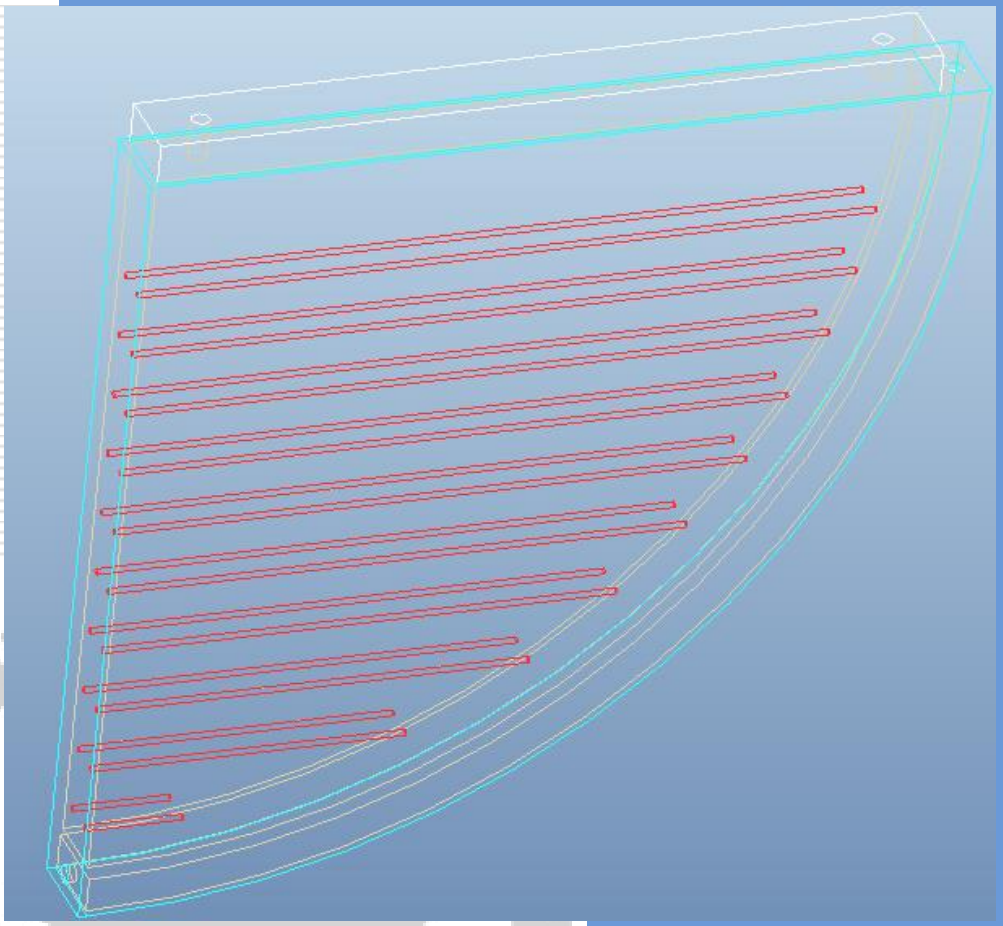


Material	$20\%NaNO_3$-$80\%KNO_3$	
t, ℃	300℃	350℃
c_p, J/(g·K)	1.332	1.346
ρ, kg/m^3	1902	1866
ν, m^2/s×10^{-6}	1.75	1.35
λ, W/(m·K)	0.439	0.422
α, m^2/s×10^{-7}	1.69	1.65
Pr	10.36	8.18

- **Largest S-L temperature gap ~ 60℃ ($20\%NaNO_3$-$80\%KNO_3$)**
- **Pool temperature range 284℃ (liquidus) ~ 370℃ (decomposition)**

Pham Q.T. et al. Modeling of heat transfer and solidification in LIVE L3A experiment[J]. International Journal of Heat and Mass Transfer, 2013. 58(1): 691-701.

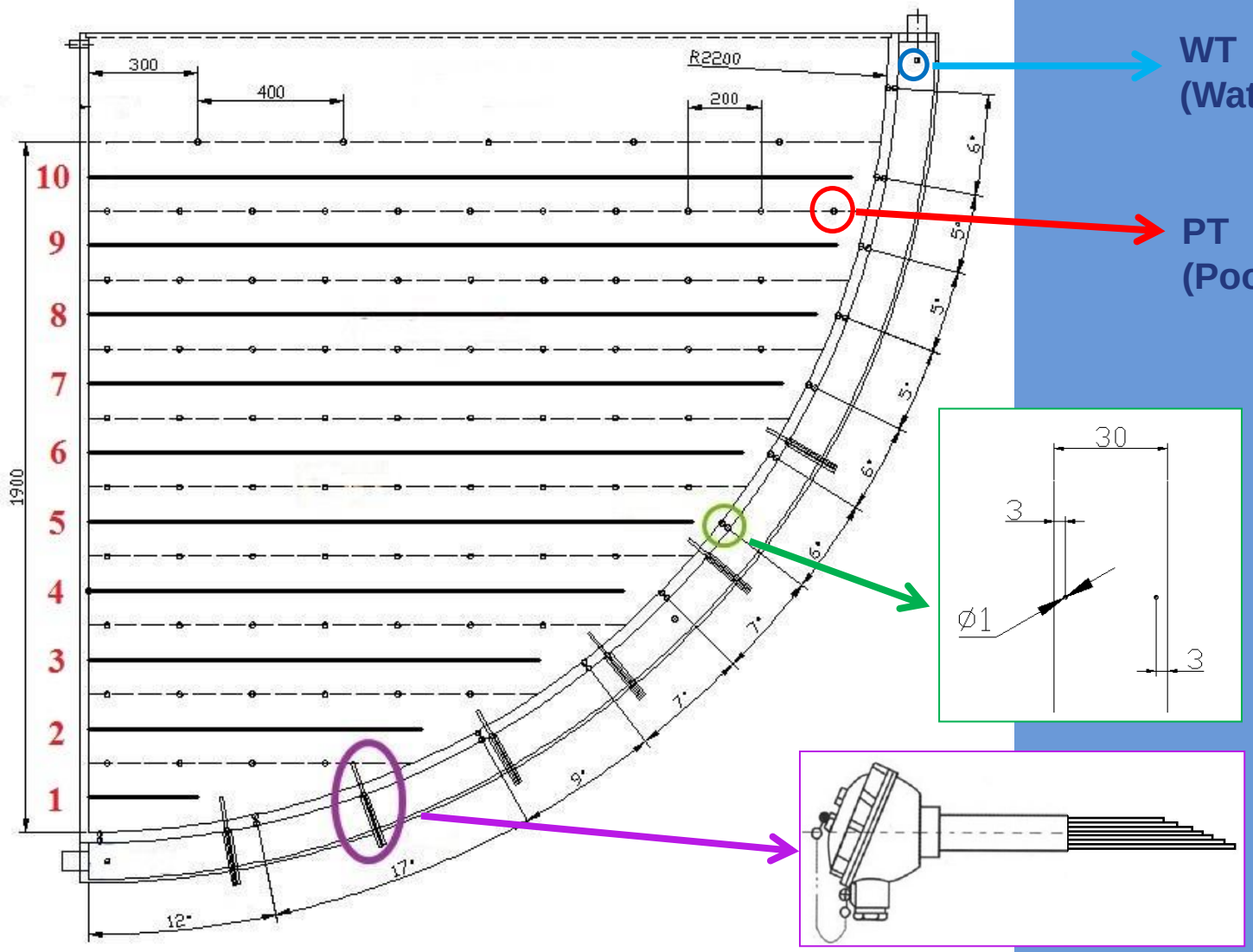
Heating System



Heating rods arrangement

- pool height: 1900mm
  pool volume: 0.63m^3
- The melt pool is divided into 10 heating zones, each with a height of 190mm
- 20 electrical heating rods
  diameter of 16mm
  uniformly distributed
  individually controlled
- At heating power of 15kW, and flow rate of 5kg/s, the temperature change of cooling water could be kept within 1 ℃ to create an isothermal boundary

Temperature Measurement



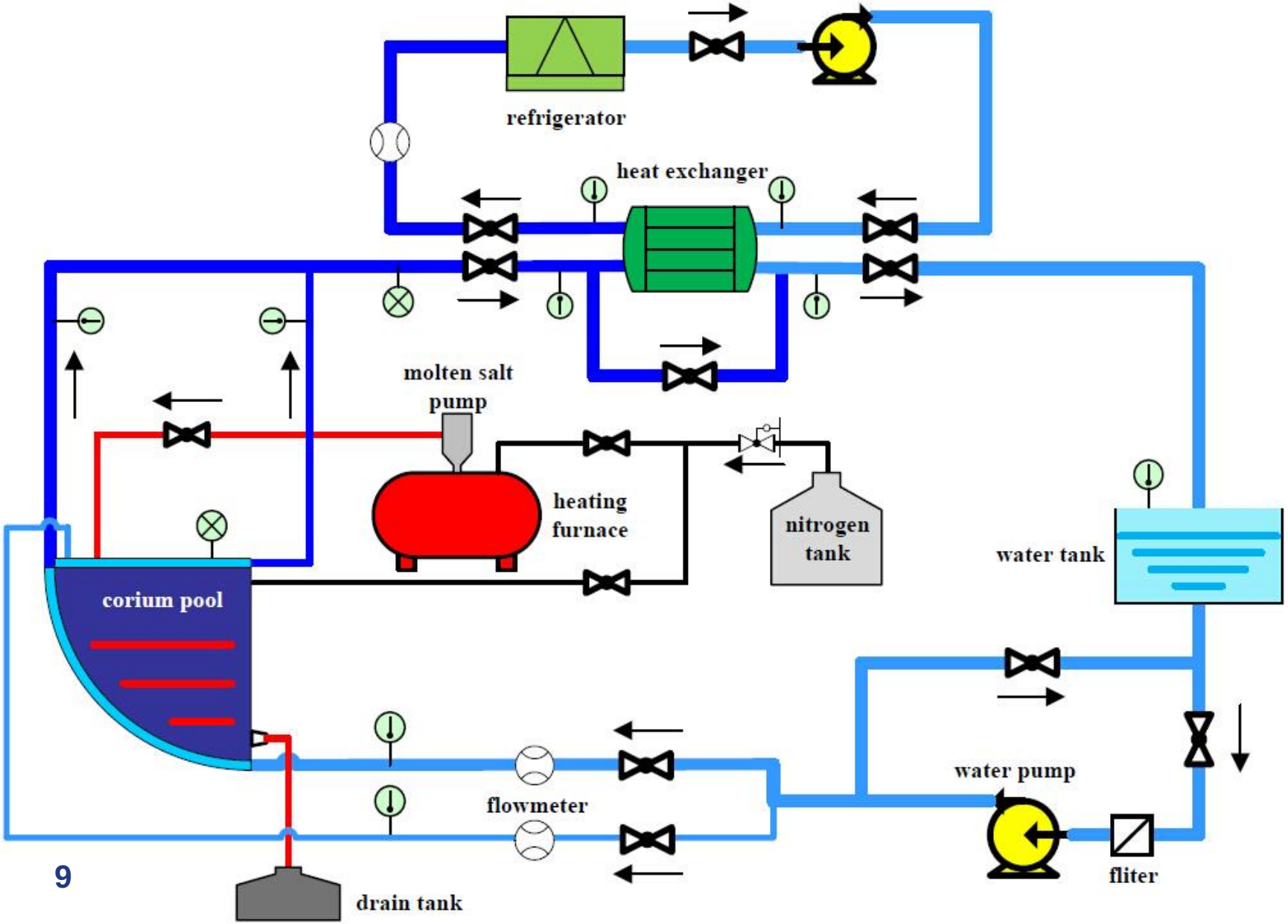
WT
(Water Thermocouple)

PT
(Pool Thermocouple)

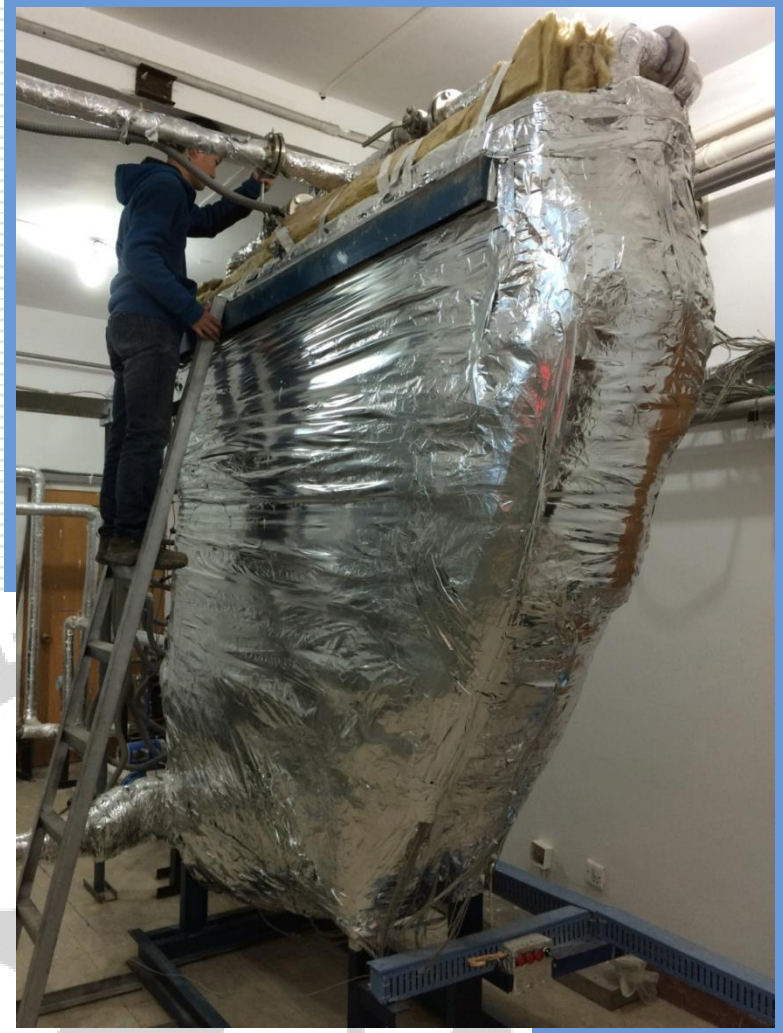
IT/OT
(Inner/Outer
Thermocouple)

CT
(Crust
Thermocouple)

COPRA Loop


refrigerator
heat exchanger
molten salt
pump
heating
furnace
nitrogen
tank
water tank
corium pool
water pump
flowmeter
fliter
drain tank

COPRA Photo



Test vessel

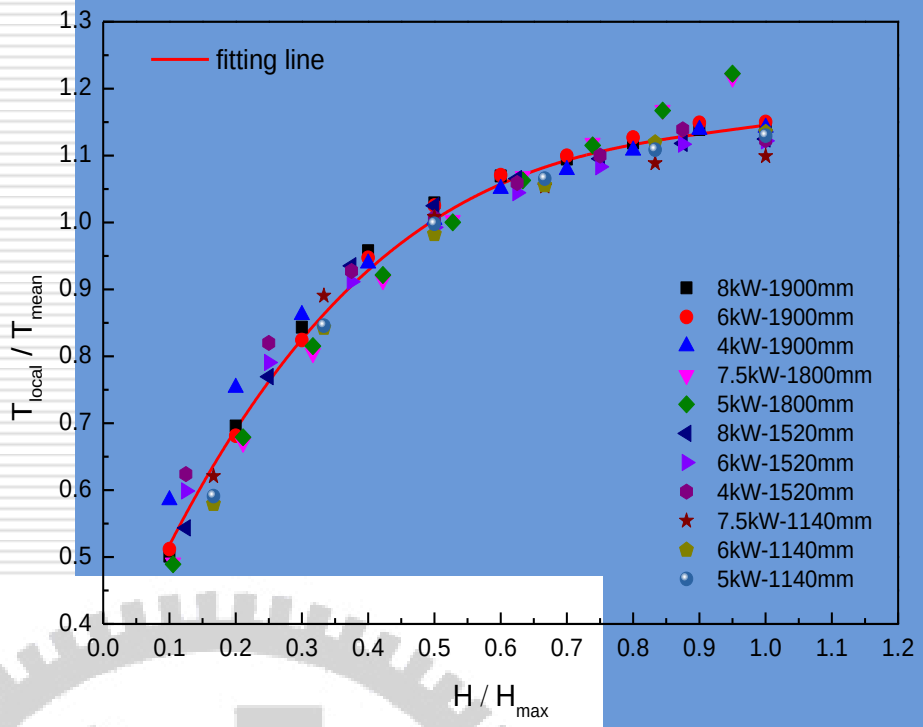
Lab view

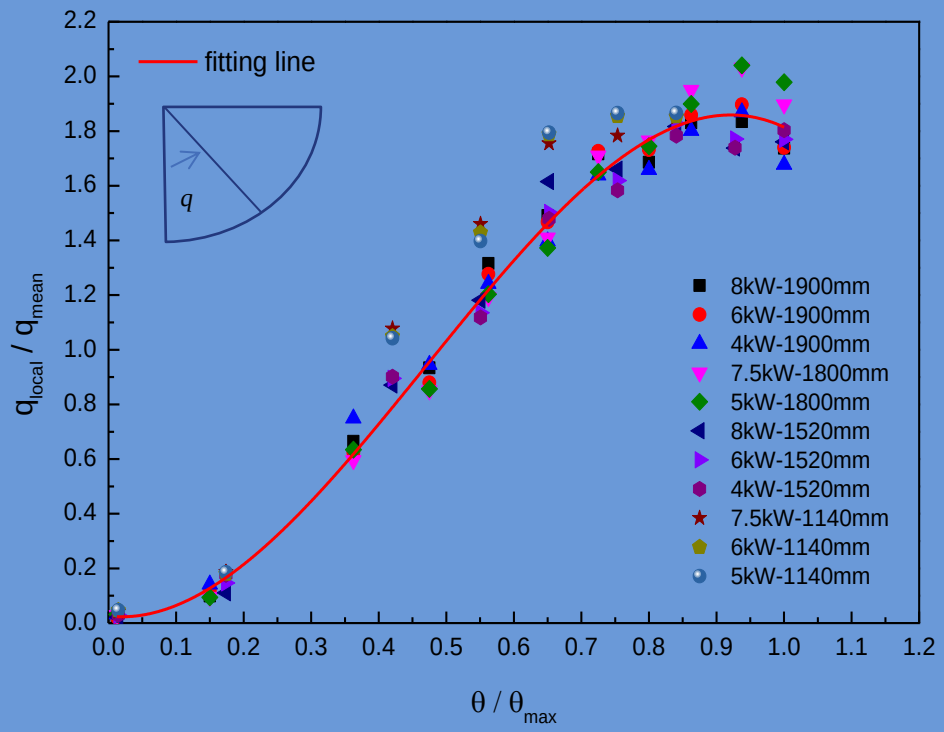
Molten salt heating furnace

Water Test Matrix

No.	Pool Height/ mm	Pool Volume/ m^3	Heating Power/ kW
1	1140	0.313	5
2		0.313	6
3		0.313	7.5
4	1520	0.466	4
5		0.466	6
6		0.466	8
7	1800	0.589	5
8		0.589	7.5
9	1900	0.629	4
10		0.629	6
11		0.629	8

Water Test Results





dimensionless temperature distribution

$$T_{local}/T_{mean} \sim H/H_{max}$$

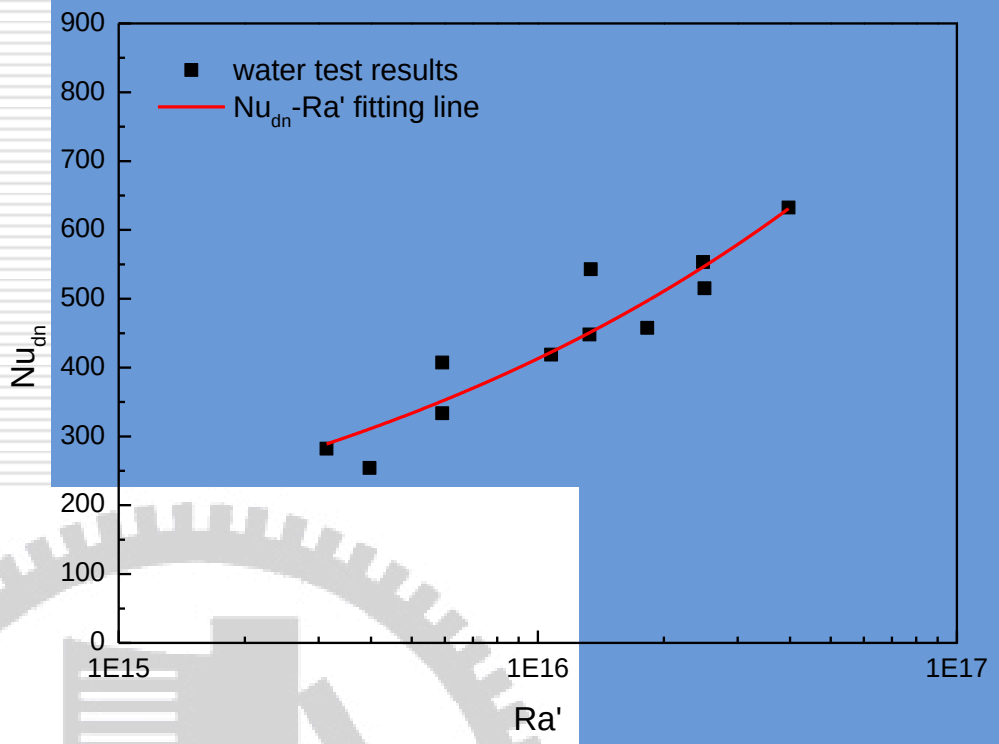
$$\frac{T_{local}}{T_{mean}} = 0.30281 + 2.37675\left(\frac{H}{H_{max}}\right) - 2.3635\left(\frac{H}{H_{max}}\right)^2 + 0.82949\left(\frac{H}{H_{max}}\right)^3$$

dimensionless heat flux distribution

$$q_{local}/q_{mean} \sim \theta/\theta_{max}$$

$$\frac{Nu(\theta)}{Nu_{mean}} = 0.02563 - 0.2679\left(\frac{\theta}{\theta_{max}}\right) + 7.06417\left(\frac{\theta}{\theta_{max}}\right)^2 - 5.00761\left(\frac{\theta}{\theta_{max}}\right)^3$$

Water Test Results



Nu_{dn}–Ra′ relation

- **Ra′ range : 3.134×10^{15}~3.966×10^{16}**
- **Nu_{dn} range : 249.274~616.834**
- **Nu_{dn} increases with increasing Ra′**
- **IVR relation from COPRA water tests :**

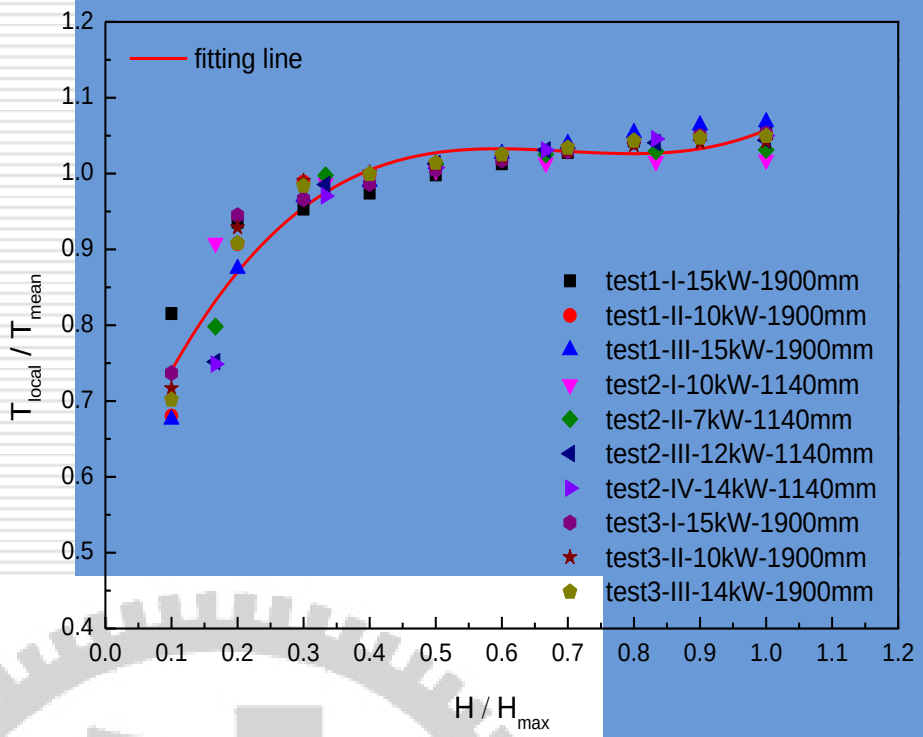
$$Nu_{dn} = 0.00495 Ra'^{0.30761}$$

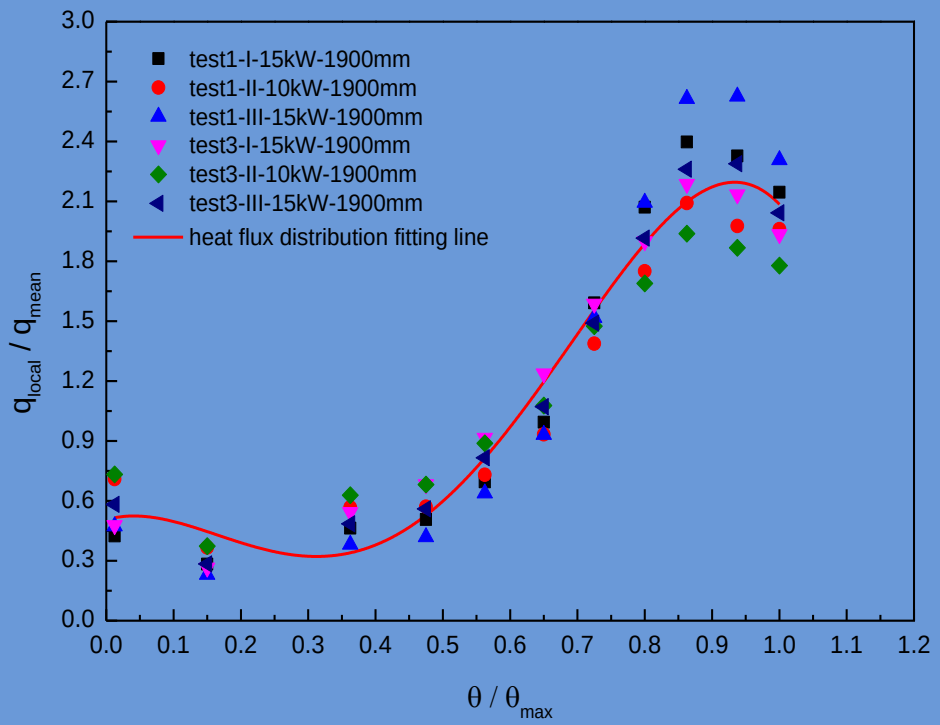
$$Nu_{dn} = 0.425 Ra'^{0.191} \left(\frac{H}{R}\right)^{0.457}$$

Molten Salt Test Matrix

No.	Upper cooling	Relocation position	Pool Height	Heating Power
1	no	lateral	1900mm	8kW, 18kW-15kW-10kW-15kW
2		central	1140mm	10kW-7kW-12kW-14kW
3			1140→1900mm	14kW→15kW-10kW-14kW
4	yes	lateral	1140mm	12kW-8kW-12kW
5			1140→1520mm	12kW→13kW-9kW-13kW
6			1520→1900mm	13kW→15kW-10kW-15kW

Molten Salt Test Results





dimensionless temperature distribution

$$T_{local}/T_{mean} \sim H/H_{max}$$

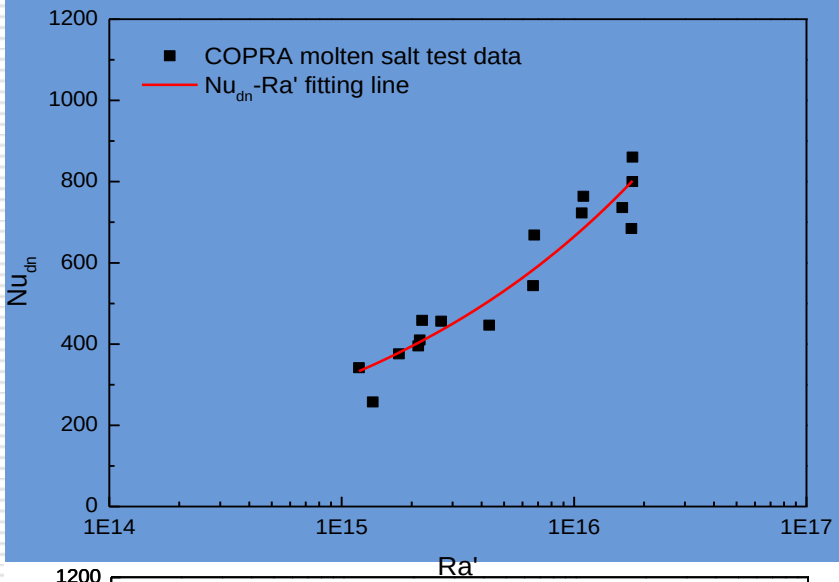
$$\frac{T_{local}}{T_{mean}} = 0.55664 + 2.13347\left(\frac{H}{H_{max}}\right) - 3.13473\left(\frac{H}{H_{max}}\right)^2 + 1.50215\left(\frac{H}{H_{max}}\right)^3$$

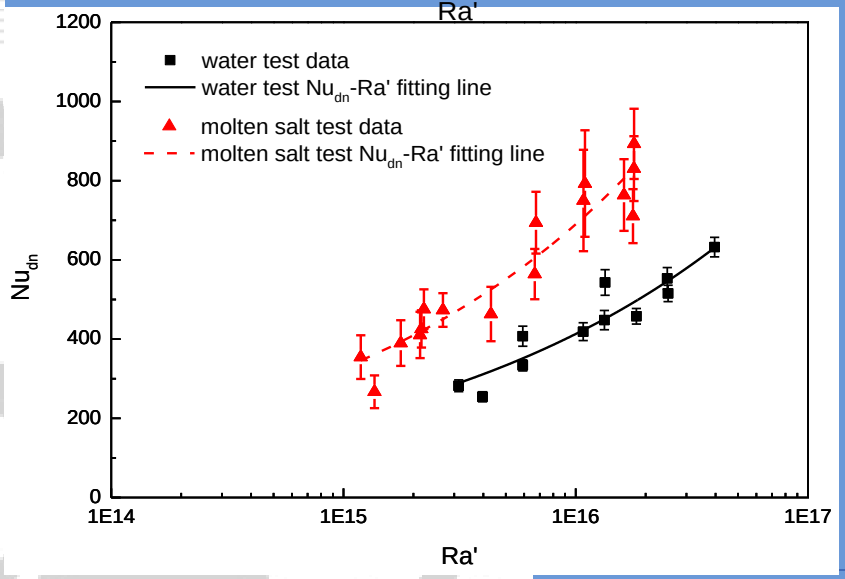
dimensionless heat flux distribution

$$q_{local}/q_{mean} \sim \theta/\theta_{max}$$

$$\frac{Nu(\theta)}{Nu_{mean}} = 0.50579 + 0.96132\left(\frac{\theta}{\theta_{max}}\right) - 13.78669\left(\frac{\theta}{\theta_{max}}\right)^2 + 34.52997\left(\frac{\theta}{\theta_{max}}\right)^3 - 20.12502\left(\frac{\theta}{\theta_{max}}\right)^4$$

Molten Salt Test Results





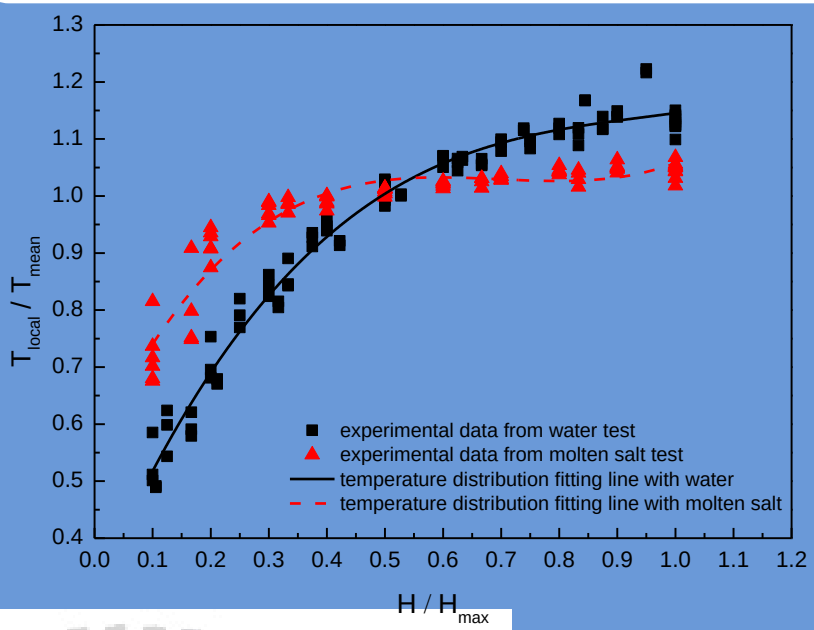
- **Ra` range: $1.188\times10^{15}\sim1.784\times10^{16}$**
- **Nu_{dn} range: 267.155~893.092**
- **Nu_{dn} increases with larger Ra`**
- **IVR relation from COPRA water tests :**

$$Nu_{dn} = 0.00453Ra'^{0.32393}$$

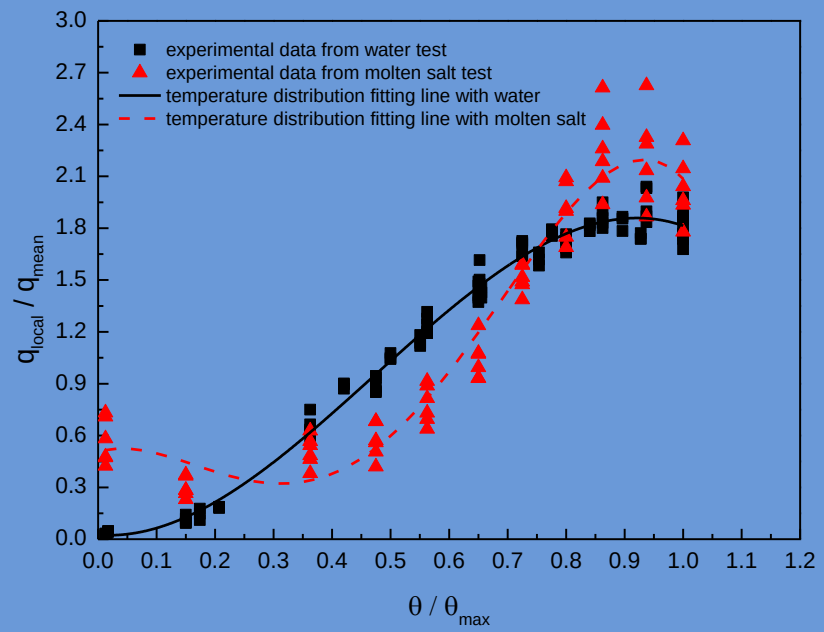
$$Nu_{dn} = 0.14707Ra'^{0.23205}\left(\frac{H}{R}\right)^{0.39542}$$

- **Error within 10% for water test and 20% for molten salt test**

Comparison between water and molten salt tests



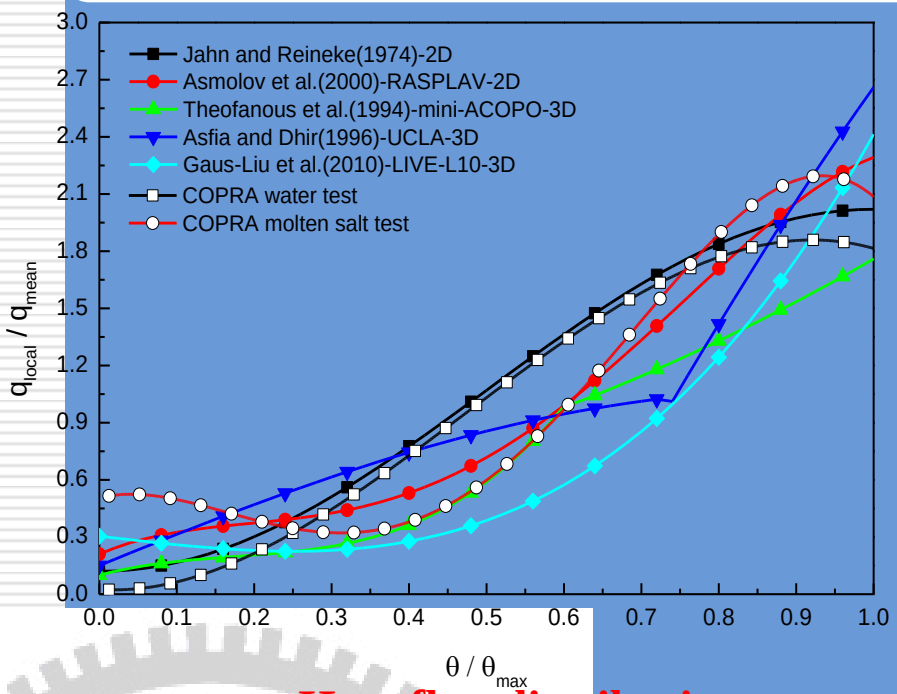
Temperature distribution



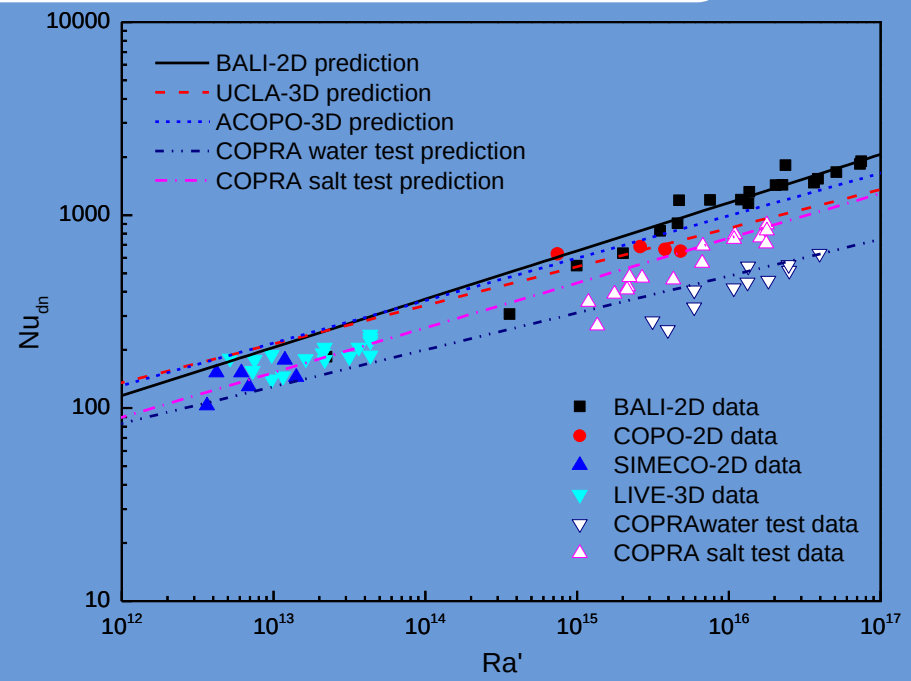
Heat flux distribution

- Compared to the water tests, the crust formation in the salt tests suppressed the thermal stratification. The pool temperatures in the bottom were much lower than those in the upper part with nearly uniform temperature distribution.
- The heat flux from water tests increased appropriately linearly and reached to its peak at θ/θ_{max} = 0.9 about 2.0. Whereas in the molten salt experiments, the heat transfers were smaller in the middle part and larger at the top, leading to the lager q_{max}/q_{mean} of about 2.7.

Comparison with other experiments



Heat flux distribution



Nu_{dn}–Ra′ relation

- Heat flux distribution from COPRA water tests were in good agreement with Jahn-Reineke water test, and the results from COPRA molten salt tests agreed well with those from RASPLAV NaF-$NaBF_4$ experiments.
- Comparison with previous experiments showed that the downward heat transfer Nu_{dn} from COPRA experiments were lower than those from ACOPO and BALI water experimental predictions, but were in good agreement with SIMECO and LIVE salt experimental results.

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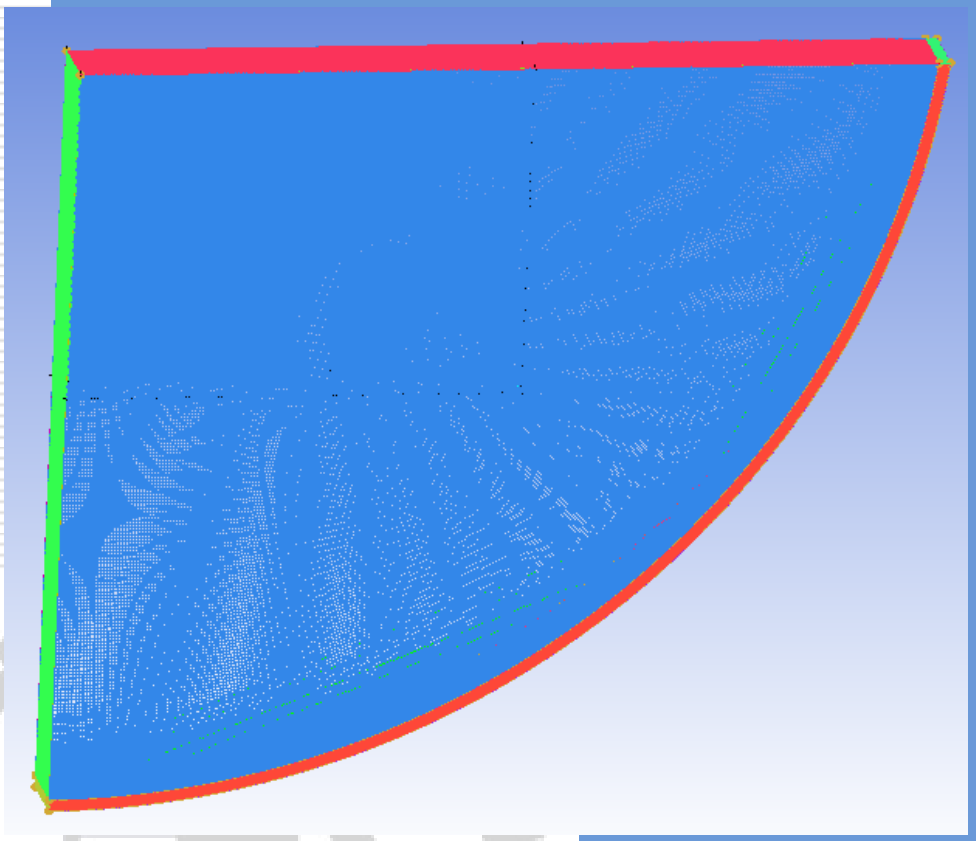
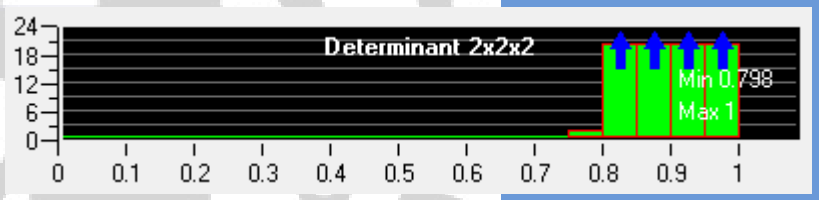
FLUENT simulation - COPRA water test

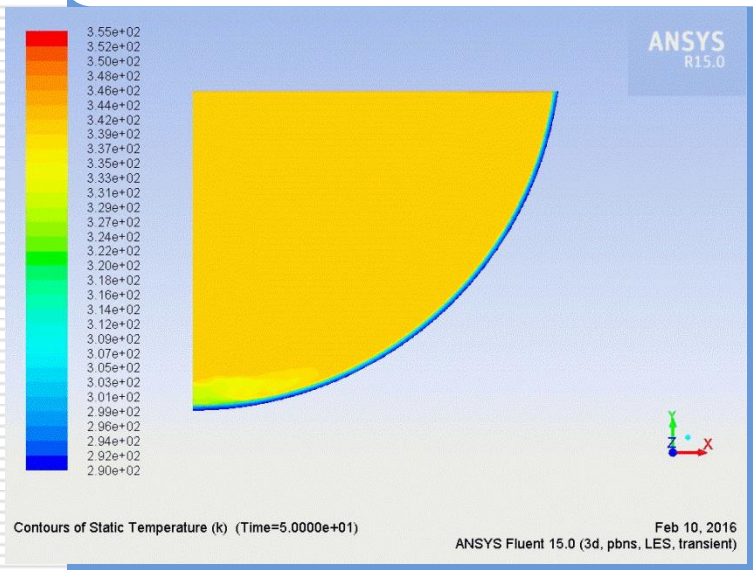




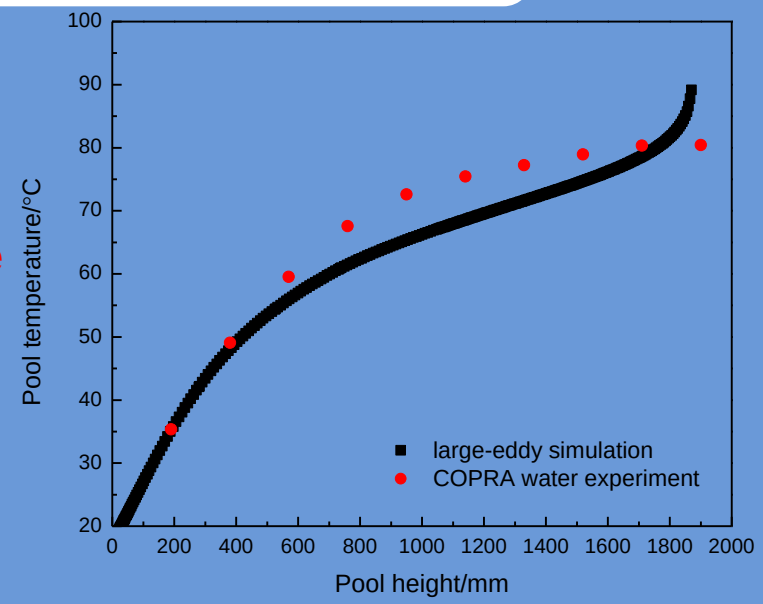
Boundary setup (8kW water test)

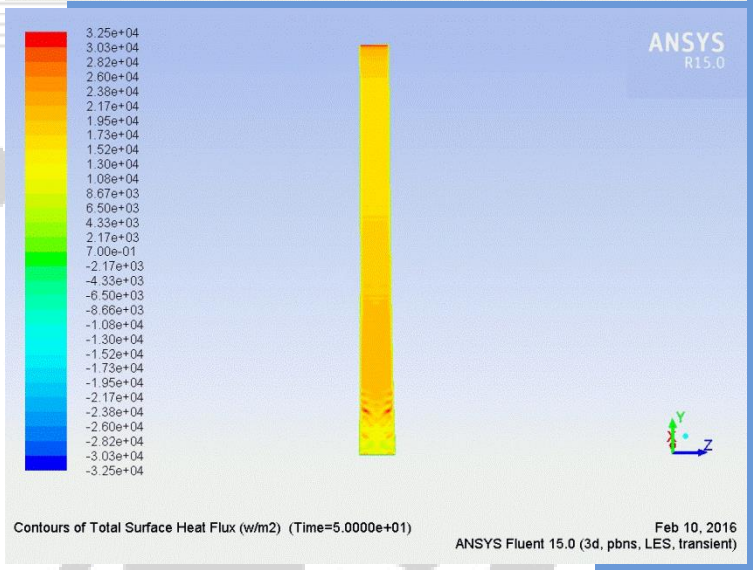
- ✓ 180w+ hexahedral mesh
- ✓ more fined boundary mesh
- ✓ insulated vertical wall
- ✓ initial water pool temperature 340K
- ✓ internal heating density 8500 W/m^3
- ✓ outside of curved wall 290K
- ✓ upwall radiation loss 2000W/m^2
- ✓ large eddy simulation (WMLES)

FLUENT simulation - COPRA water test

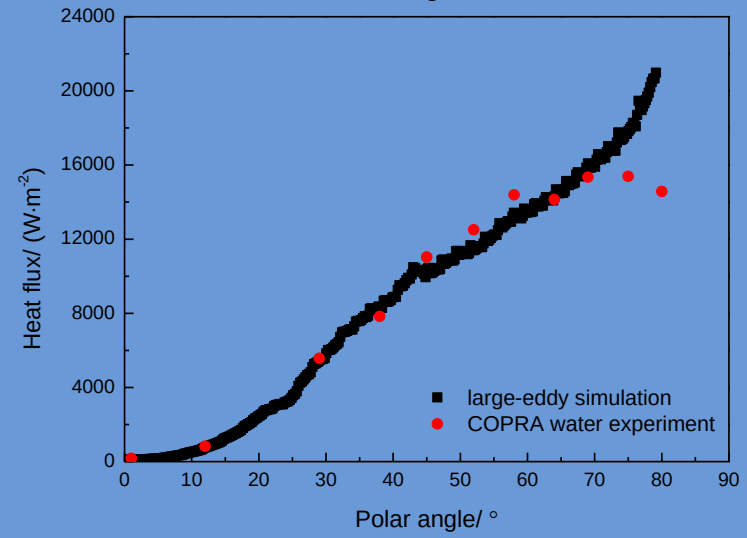


pool temperature distribution

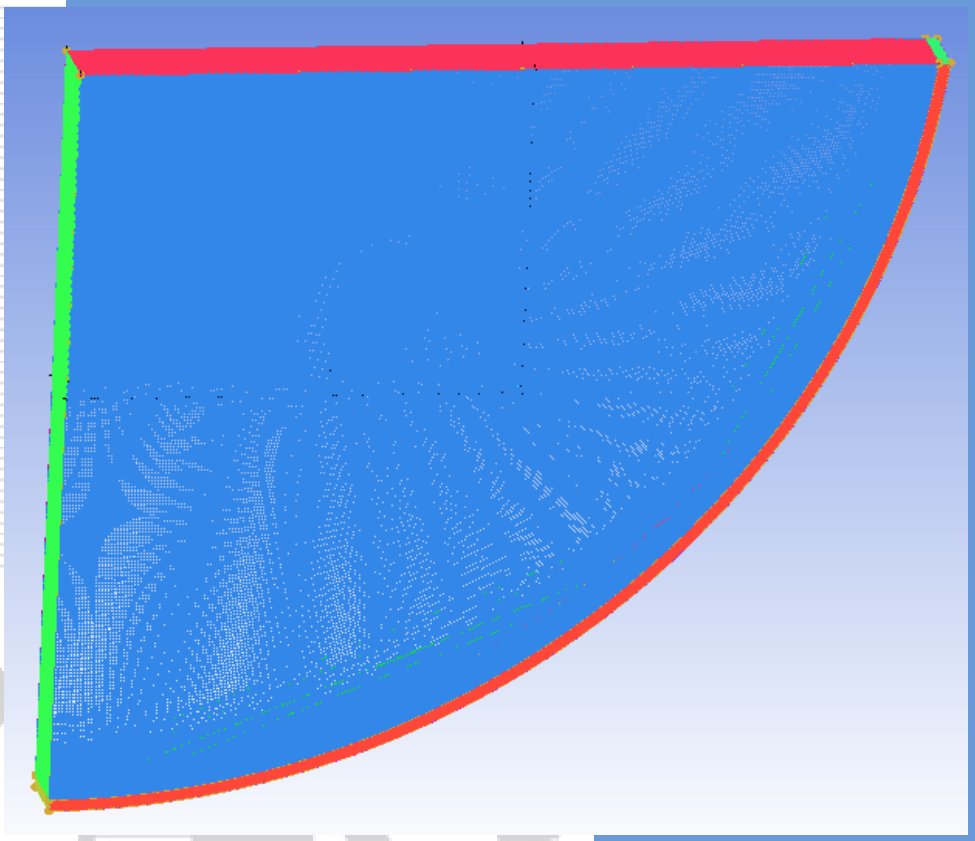


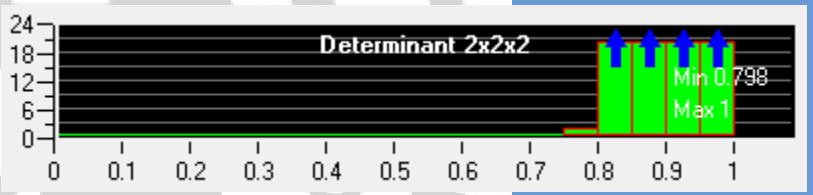


Curved wall heat flux distribution



FLUENT simulation - COPRA salt test

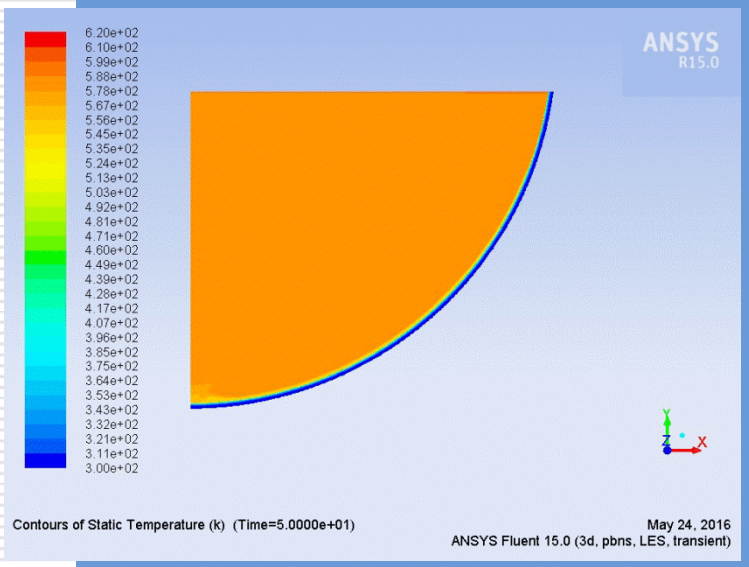




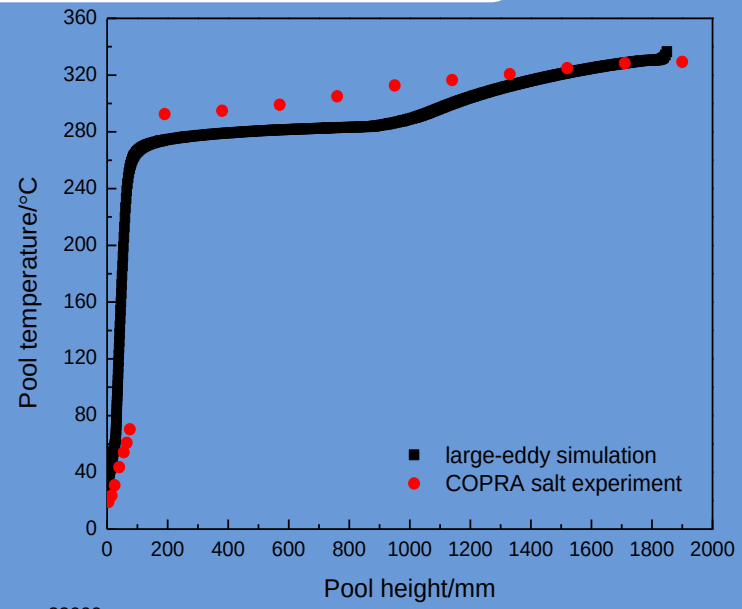
Boundary setup (15kW salt test)

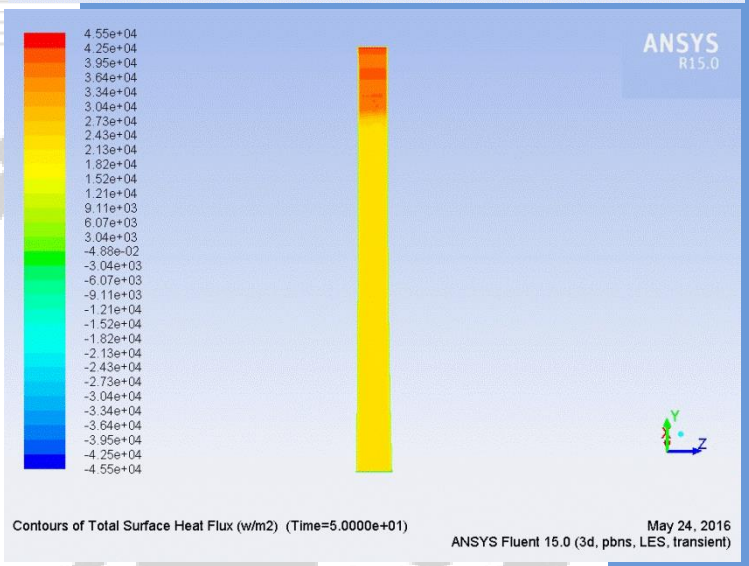
- ✓ 180w+ hexahedral mesh
- ✓ more fined boundary mesh
- ✓ insulated vertical wall
- ✓ initial salt pool temperature 585K
- ✓ internal heating density 8500 W/m^3
- ✓ outside of curved wall 300K
- ✓ upwall radiation loss 3000W/m^2
- ✓ large eddy simulation (WMLES)
- ✓ 0.5mm crust gap thermal resistance

FLUENT simulation - COPRA salt test

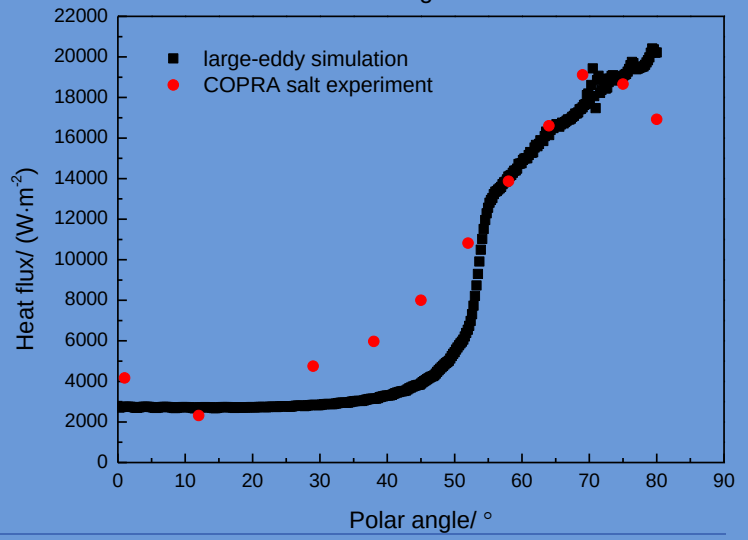


pool temperature distribution

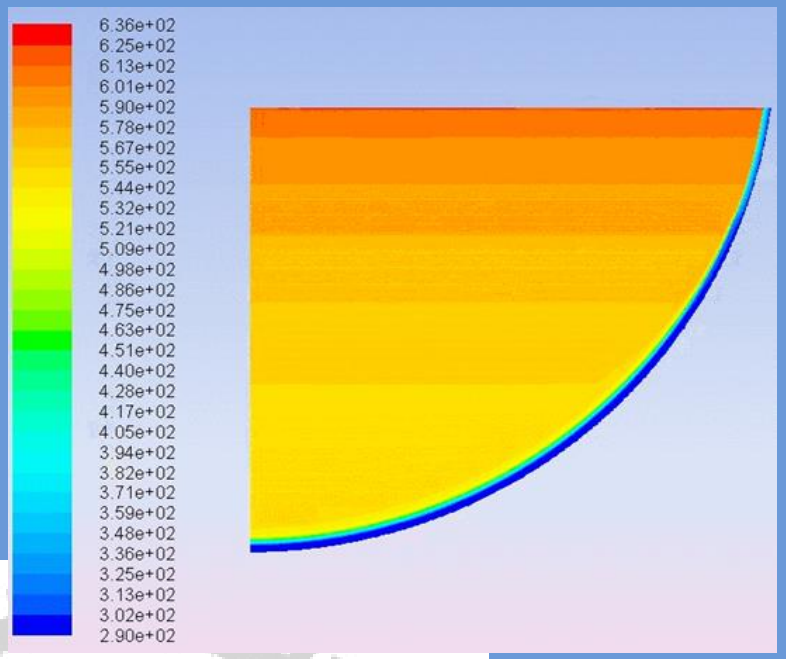




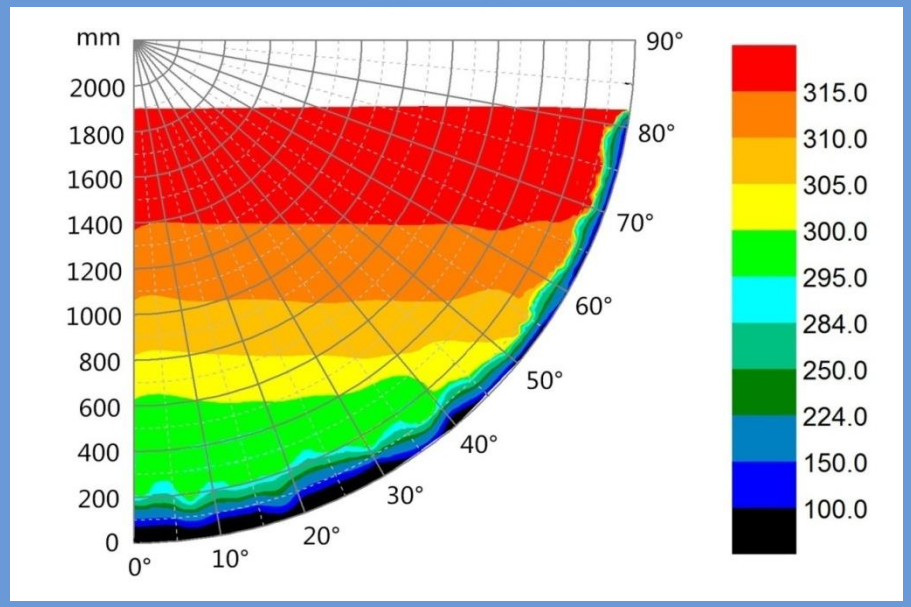
Curved wall heat flux distribution



FLUENT simulation - COPRA salt test



Calculation results by FLUENT

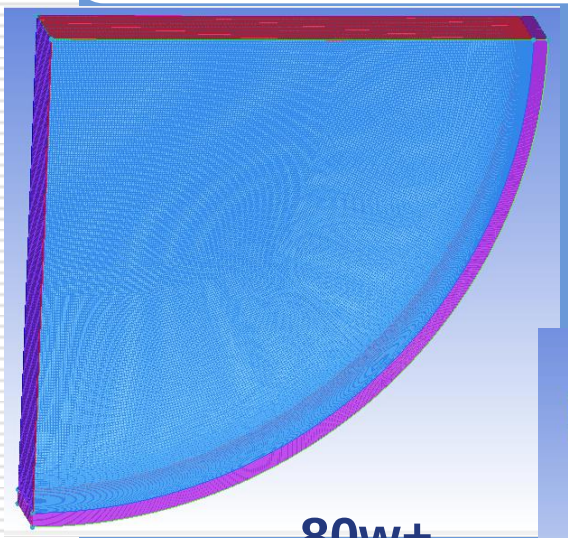


COPRA data

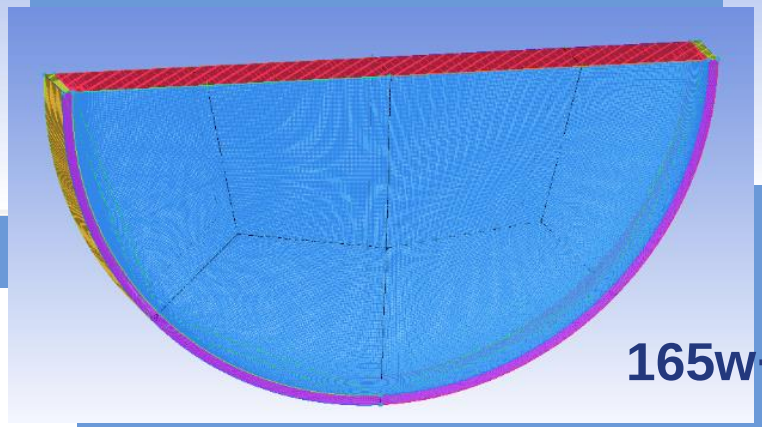
Next work:

- Modified solidification model by using UDF
- Modified properties by using UDF

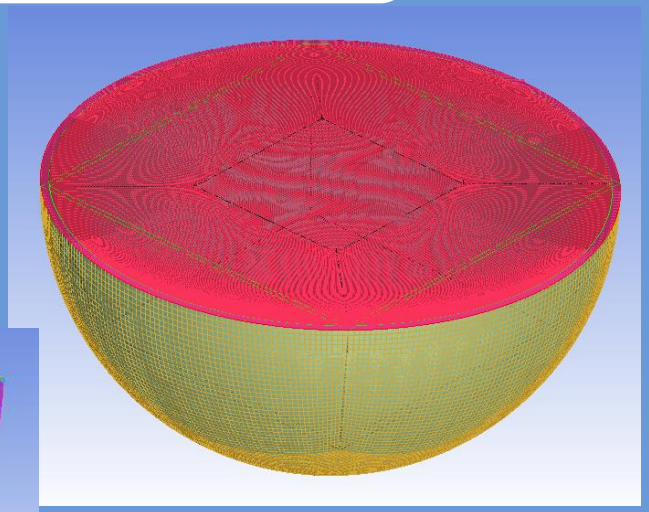
FLUENT simulation – geometry effect



80w+



165w+



200w+

same boundary setup

fined boundary mesh

internal heating density 16000 W/m^3

upwall radiation loss 2000W/m^2

inner radius 1m

initial water pool temperature 340K

outside of curved wall 290K

large eddy simulation (WMLES)

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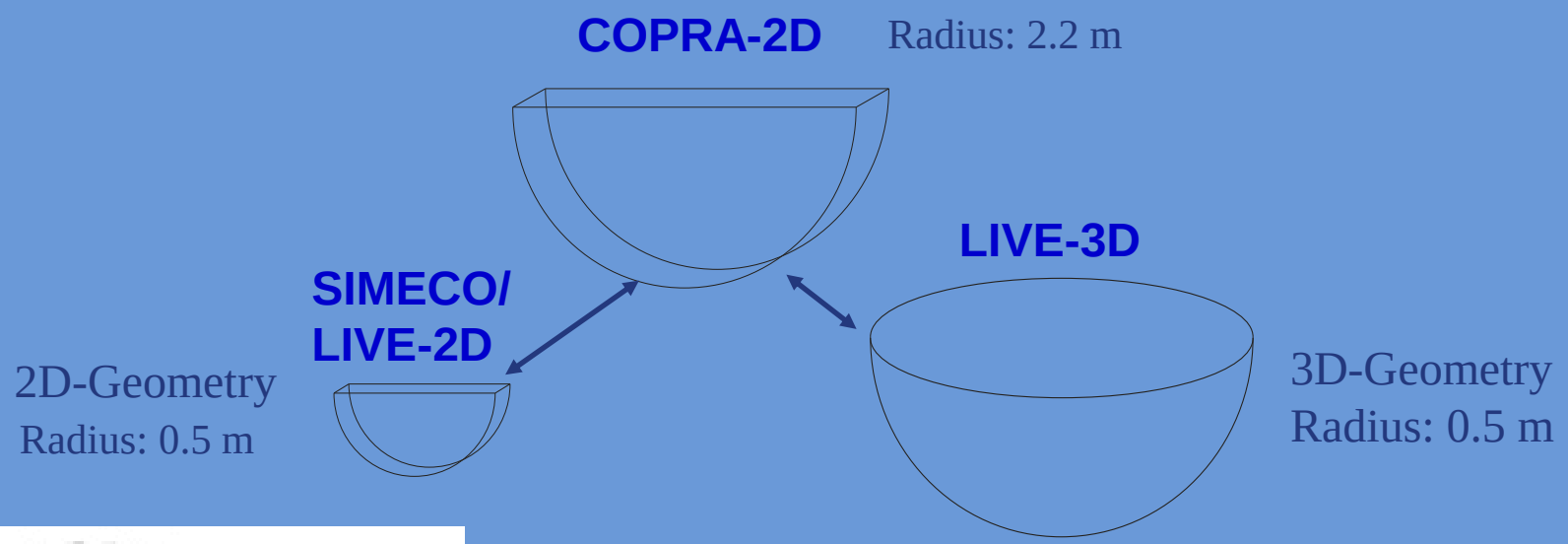
Purpose and Goals



- What is the influence of the length scale?
- What is the influence of the dimension?
- Can one infer 3D behavior from 2D experiments?

核反应堆热工水力研究室
Nuclear thermal-hydraulic lab.

ALISA projects - COPRA

ALISA（Access to Large Infrastructures for Severe Accidents between China and Europe）

XJTU-COPRA

严重事故机理与处置大型实验研究

ALISA

Access to Large Infrastructures for Severe Accidents

http://alisa.xjtu.edu.cn/

China

- Xi' an Jiao Tong University — Shared Device
- State Nuclear Power Technology Corporation
- China Nuclear Power Technology Research Institute — Shared Device
- Shanghai Jiao Tong University — Shared Device

Europe

- Karlsruhe Institute of Technology (KIT) — Shared Device
- COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES — Shared Device

Cooperation Organization

西安交通大學 XI'AN JIAOTONG UNIVERSITY

KIT Karlsruher Institut für Technologie

中广核 CGN

上海交通大學 SHANGHAI JIAO TONG UNIVERSITY

cea

国核软件技术中心 STATE NUCLEAR POWER SOFTWARE DEVELOPMENT CENTER

ALISA projects - COPRA

- **1. Proposal from KIT: COPRA-LIVE tests**
  - ✓ One **with top insulation** and external cooling condition
  - ✓ One **with top cooling** and external cooling condition
- **2. Proposal from EDF: Impact of a convective transient on the heat flux from a molten pool**

- in order to "merge" KIT and French partners proposals into a single one, we agree on a two-test procedure: one with the insulated upper lid, one with the water-cooled lid.
- in both tests, the melt is poured while the lateral curved wall is not cooled; after the melt has been poured and a steady-state has been reached, water is injected to cool down the lateral surface and the test is carried until steady-state.
- in these tests, the temperature of the upper surface of the melt will be measured ; the upper insulation lid will be instrumented by two rows of TCs so that the power lost through the lid can be obtained.
- regarding the water flow along the curved wall, the inlet and outlet temperature are measured and, as suggested by Xiaoyang, the mass flow rate has to be selected so that the temperature difference is sufficiently high (~10°) to have an accurate evaluation of the power extracted by the water.

XJTU & KIT – COPRA & LIVE

Similarities

- Simulant materials: non-eutectic binary nitrate salt
- Heating method: direct electrical heating
- similar vessel wall material and thickness
- Relocation: central and lateral position
- External cooling: water
- Crust formation can be realized with salt simulants

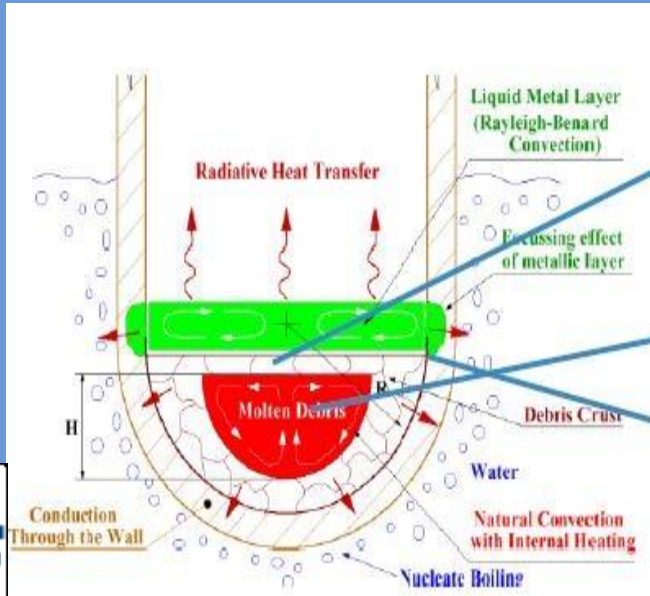
Difference

	LIVE	COPRA
Dimension	3D	2D
Ra_{in}	10^{14}	10^{16}

To answer the questions of

- Melt/debris transient behavior
- Influence of dimension (dimension effect)
- Influence of crust formation
- Influence of Ra number (Scaling effect)

XJTU & EDF (China) - COPRA



Under which height of metallic pool does the convective cells (responsible for focusing effect) disappear ? What is the characteristic time of convection establishment regime ?

➔ European IVMR project

Are the heat transfer correlations in the oxidic pool still valid in transient regimes ?

➔ ALISA project

Can the thin metallic melt be entrained by the hightly convective oxidic melt (Ra ~ 10^{18}) ?

➔ EDF-XJTU agreement

- **Phenomenological Study for Two-fluid Configuration of Corium Pool**
  - Mechanical dynamics, oscillation instability
  - Thermal effects, vortex entrainment

Contents

1 COPRA Experiments

2 Preliminary Numerical study on COPRA

3 International cooperation tests on COPRA

4 Conclusions

Conclusions

- **Experiments:** The large scale COPRA experiments have been performed to study the natural convection heat transfer in corium pools with high Rayleigh numbers up to 10^{16}.
- **CFD simulation:** Preliminary CFD simulation results showed that the solidification model of FLUENT should be modified.
- **International cooperation:** Further research work on melt pool heat transfer should focus on influence of dimension and scaling effect to reduce uncertainty of correlations used for IVR analysis.

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Thank you for your attention!

西安交通大學
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