Comparison of 2D and 3D Experiments for IVR

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Introduction

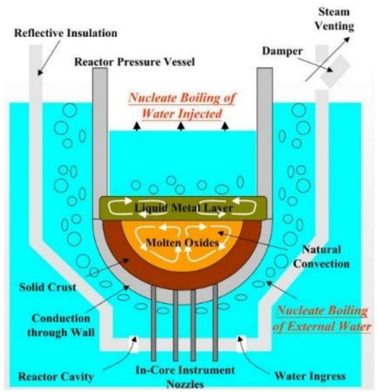
No one is sure actually what happens in the reactor vessel in a severe accident

Introduction

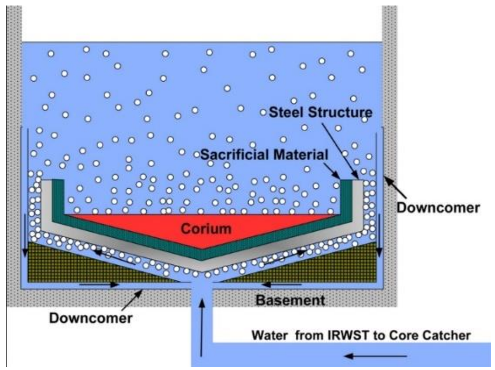
2 representative strategies for mitigation of severe accident

- In-Vessel Retention – External Reactor Vessel Cooling (IVR-ERVC)
  - ✓ Applied to a 1000 MW class
- External core catcher cooling
  - ✓ Applied to a 1800 MW class

➡ APR1400?



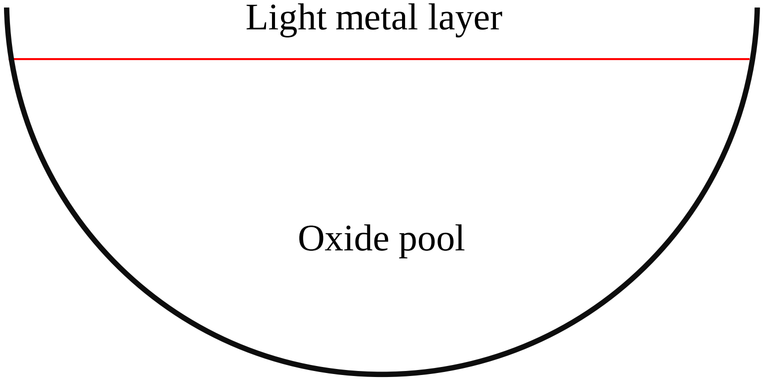
IVR-ERVC



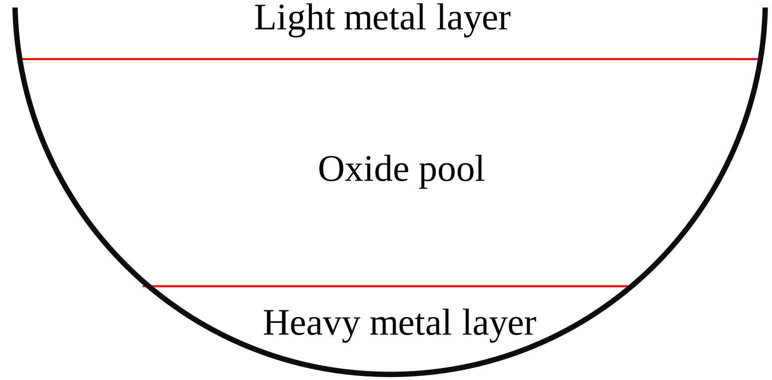
External core catcher cooling

Introduction

Nuclear fuels melt in a severe accident condition

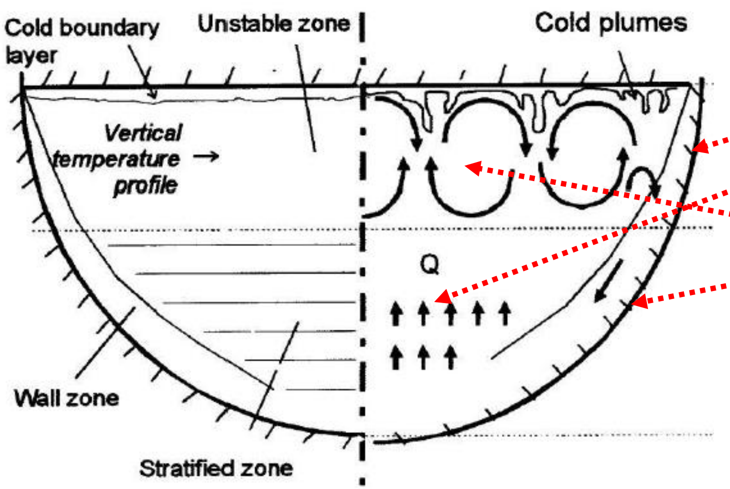


2-layer model



3-layer model

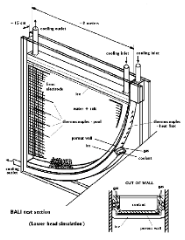
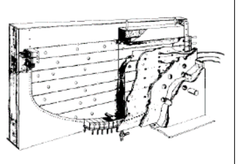
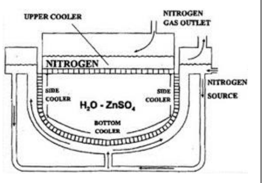
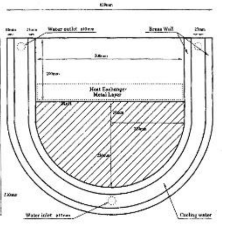
Technical issues on oxide pool (2 layer model)



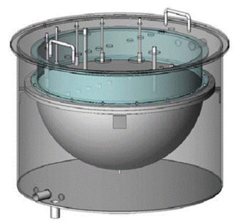
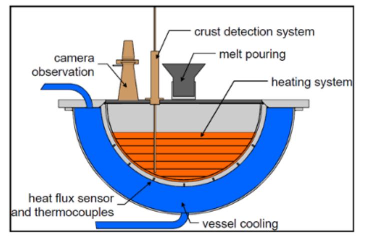
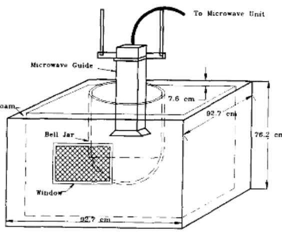
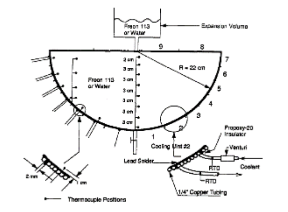
- **Natural convection phenomena**
  - The corium descends along the curvature
  - The concentrated corium at the bottom rises to the top
  - Unstable flow in the vicinity of the top
  - Isothermal condition on inner walls by ERVC

- **Technical issues**
  - High *Ra'*
  - Angle dependent heat flux

Summary of existing studies (2-Dimensioanl)

Facilities	BALI	COPO Ⅰ	COPO Ⅱ	SIMECO	SIGMA CP
Geometry					
Working fluids	Water	$ZnSO_4$-H_2O	$ZnSO_4$-H_2O	$NaNO_3$-KNO_3	Air and water
Volumetric heat source	Joule heating (Lattice shaped)	Joule heating (Horizontal)	Joule heating (Horizontal)	Joule heating (Horizontal)	Joule heating (Bend shaped)
Ra'_H	$10^{13} – 10^{17}$	1.24×10^{14} – 1.61×10^{15}	$8\times10^{14} – 1.4\times10^{15}$	1.51×10^{13} – 3.14×10^{13}	5.71×10^{6} – 7.04×10^{11}
Nu_{up}	-	-	Uniform	-	Scattered
Nu_{dn}	Maximum at the top	Maximum at the top	Maximum at the top	Peak at lower curve	Peak at lower curve

Summary of existing studies (3-Dimensioanl)

Facilities	SIGMA-3D	LIVE	UCLA	ACOPO
Geometry				
Working fluids	Air	Water	Freon-113	Water
Volumetric heat source	Joule heating (Bend shaped)	Joule heating (Ring array)	Microwave	Pre-heating
Ra' Ra'_H	4.46×10^{8}	1.2×10^{14}	$5\times10^{11}-8\times10^{13}$	$1\times10^{14}-2\times10^{15}$
Nu_{up}	Scattered	-	-	-
Nu_{dn}	Peak value at lower curve	-	Peak value at lower curve	Maximum at the top

Objective of study

To investigate….

- Angle dependent heat flux
- Dimensional effect (2D vs. 3D)
- Influence of the modified Rayleigh numbers
- Phenomenological analyses (Poorly conducted in previous studies)

Experimental Methodology

- Analogy between heat transfer and mass transfer

< Governing equations >

Heat transfer	Mass transfer
$\frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} = 0$	
$\rho \frac{Du}{Dt} = -\frac{\partial P}{\partial x} + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) + X$	
$\frac{DT}{Dt} = \alpha \nabla^2 T$	$\frac{DC}{Dt} = D \nabla^2 C$

< Dimensionless numbers >

Heat transfer		Mass transfer	
Nu	$\frac{hL}{k}$	Sh	$\frac{h_m L}{D_m}$
Pr	$\frac{\nu}{\alpha}$	Sc	$\frac{\nu}{D_m}$
Ra	$\frac{g \beta \Delta T L^3}{\alpha \nu}$	Ra	$\frac{g L^3}{D_m \nu} \frac{\Delta \rho}{\rho}$

Heat Transfer Problem → Mass Transfer Problem

Analogy concept

Mass Transfer Problem ↓ Mass Transfer Solution

Heat Transfer Solution ← Mass Transfer Solution

Similarity

From the volumetrically heating phenomenon point of view,

Rayleigh number (Ra) → Modified Rayleigh number (Ra')

$$Ra'_H = Ra_H \times Da \text{ , where Damköhler number } (Da) = \frac{q'''H^2}{k\Delta T}$$

$$Ra'_H = \frac{g\beta \Delta T H^3}{\alpha \nu} \times \frac{q'''H^2}{k\Delta T} = \frac{g\beta q''' H^5}{\alpha \nu k}.$$

Similarity

Heat flux (q), temperature (T), thermal conductivity (k)

↓

Current (I), concentration (C), mass diffusivity (D_m)

$$Da = \frac{q''' H^2}{k \Delta T} \quad \Rightarrow \quad Da_m = \frac{(1 - t_{Cu^{2+}}) I''' H^2}{nFD_m \Delta C}$$

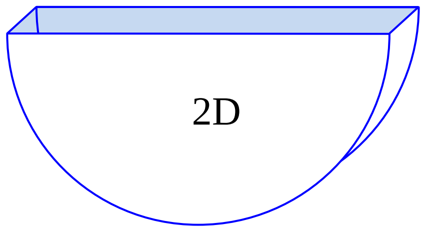
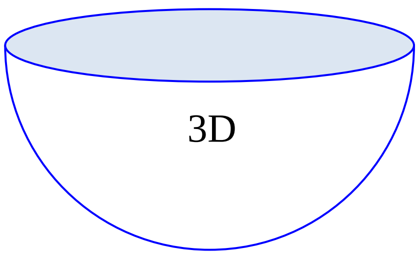
Similarity

Thus, the *Ra'* in mass transfer system can be expressed by

$$Ra_H = \frac{gH^3\Delta\rho}{D_m\mu} = 128.5\frac{gH^3\Delta C}{D_m\mu}, \text{ where } \frac{\Delta\rho}{\Delta C} \sim 128.5$$

$$Ra'_H = Da_m \times Ra_H = \frac{(1-t_{Cu^{2+}})I'''H^2}{nFD_m\Delta C} \times 128.5\frac{gH^3\Delta C}{D_m\mu} = 128.5\frac{(1-t_{Cu^{2+}})gI'''H^5}{nFD_m{}^2\nu\rho}$$

Test matrix

Dimension	Ra'	H (cm)
 2D	5.00×10^{12}	4.2
	1.21×10^{14}	10.0
	9.86×10^{14}	16.7
 3D	8.63×10^{12}	4.2
	2.02×10^{14}	10.0
	1.45×10^{15}	16.7

$Sc(Pr)$ = 2,014 (Fixed)

Method

Isothermal heating condition → Using electroplating mass transfer system

- Decrease of the copper ion concentration, the working fluid becomes lighter

Isothermal cooling condition → Reactor vessel inner wall (Existing experiments)

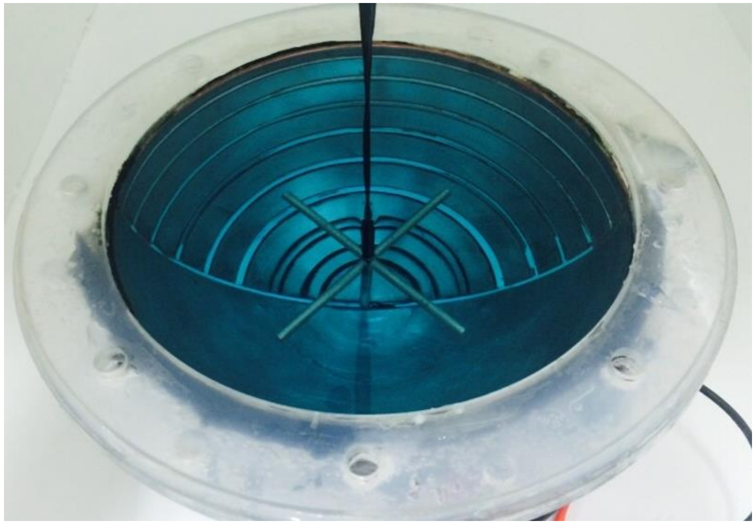
- Corium becomes heavier, due to the ERVC system

In order to establish cooling condition using mass transfer system.
the direction of gravity need to be inverted

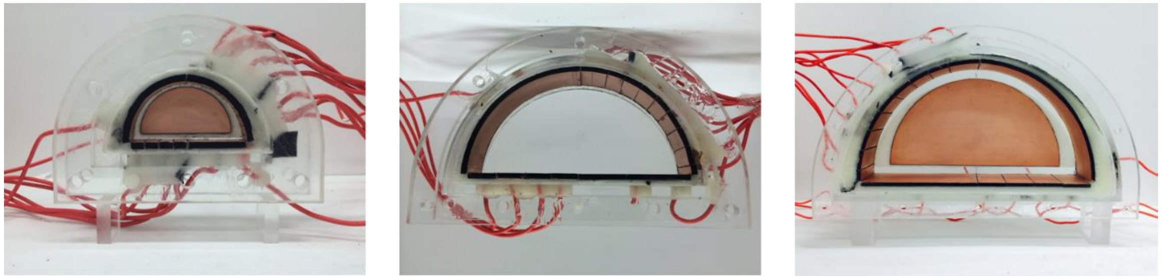
Method

Inverted test rig was designed to simulate oxide pool using mass transfer system

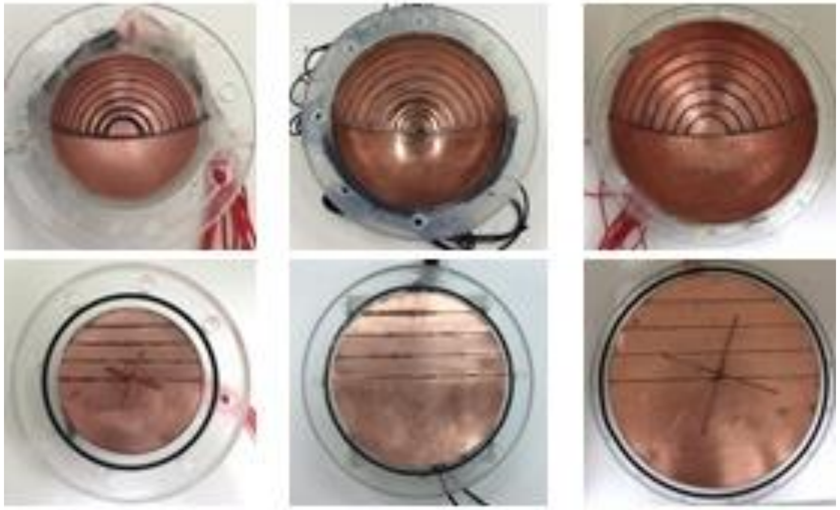
➡ Mass Transfer Experimental Rig for Oxide Pool (MassTER-OP)



MassTER-OP

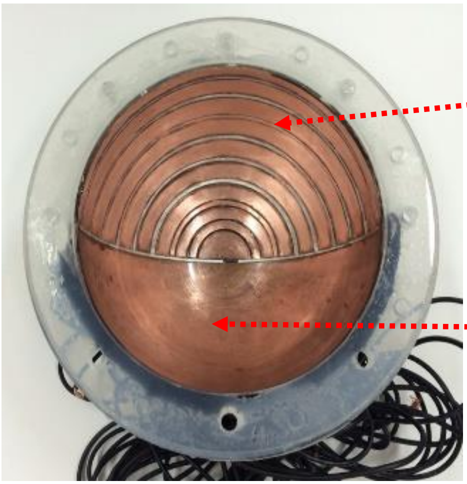


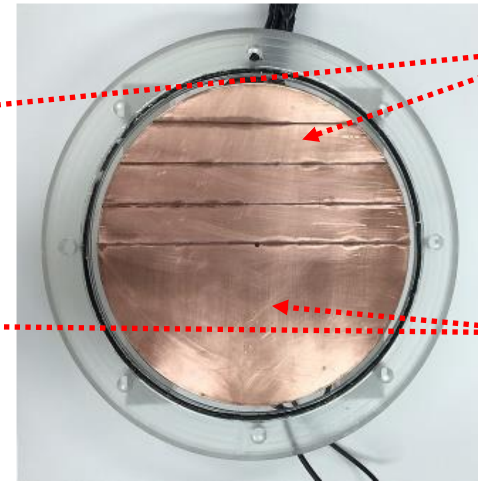
MassTER-OP2



MassTER-OP3

Measurement Verification





Piecewise electrodes
- To measure local value

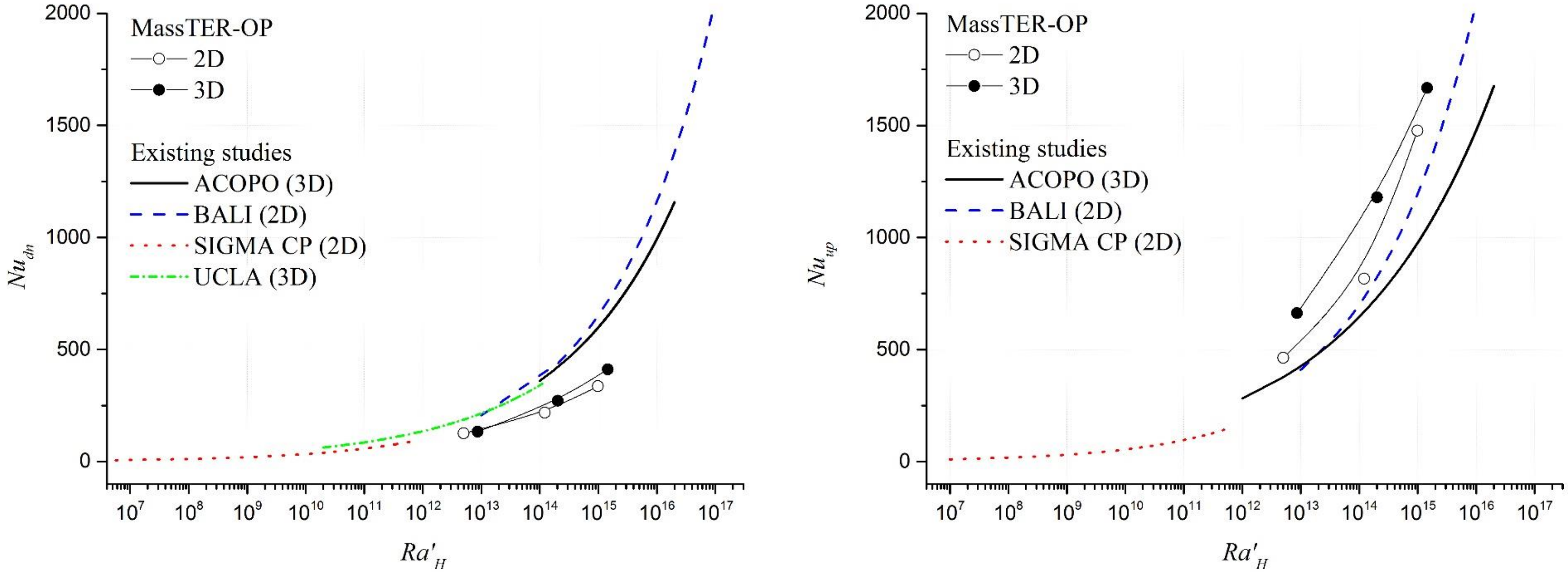
One-piece electrodes
- To compare with piecewise electrodes

Average discrepancies between piecewise and one-piece

- Lower head < 4.2 %
- Top plate < 7.4 %

Existing results Vs. MassTER-OP results

Comparisons of existing results with MassTER-OP results



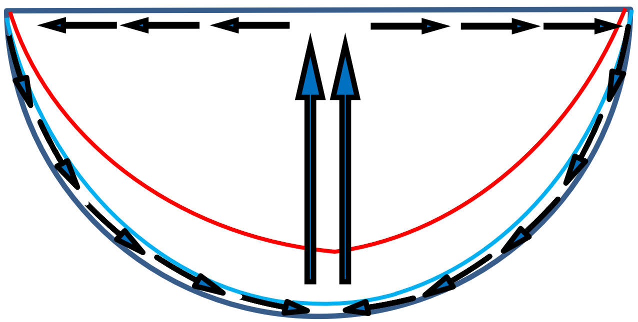
- Nu_{dn} was measured 40 % lower than existing results
- Nu_{up} was measured 40 – 60 % higher than existing results

Existing results Vs. MassTER-OP results

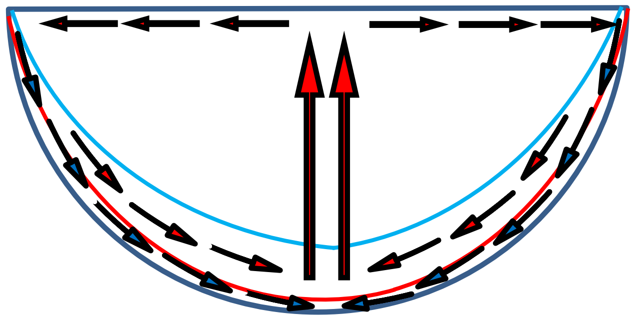
- *Pr* ~ or << 1
  - ✓ Momentum BL, towards the top plate can not cover bulk fluids

Nu_{up} **Enhances**

- *Pr* >> 1
  - ✓ Momentum BL, towards the top plate covers bulk fluids



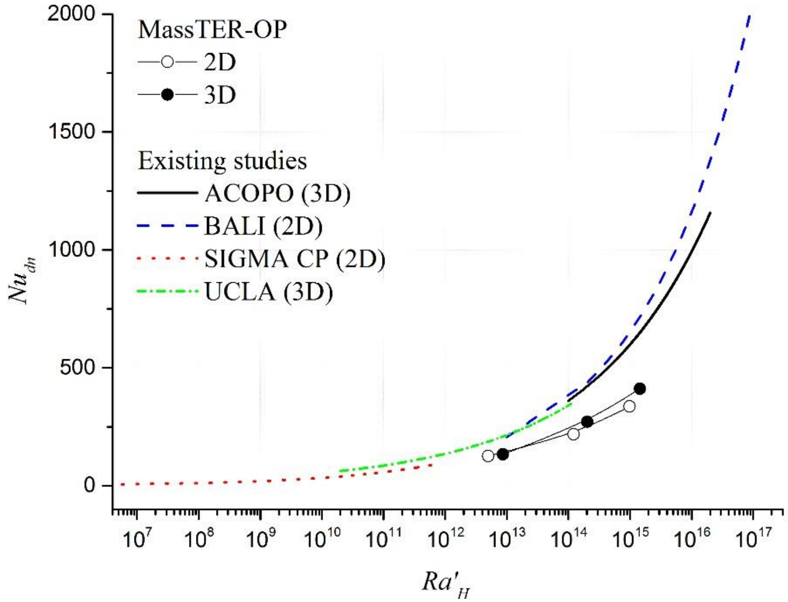
$Pr << 1$

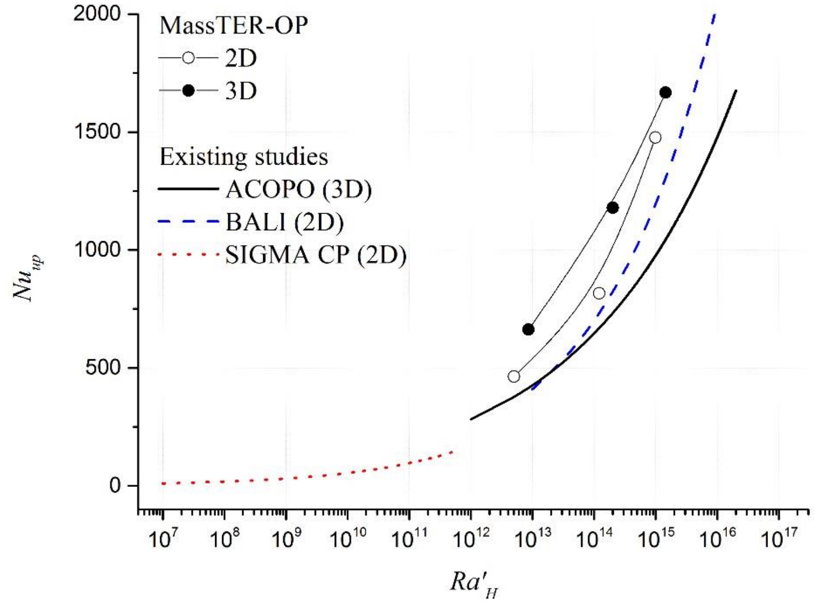


$Pr >> 1$

Existing results Vs. MassTER-OP results

Comparisons of existing results with MassTER-OP results

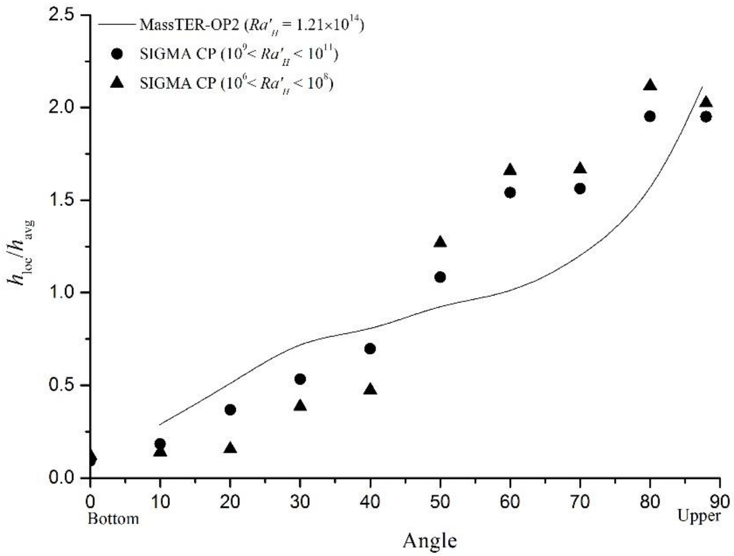


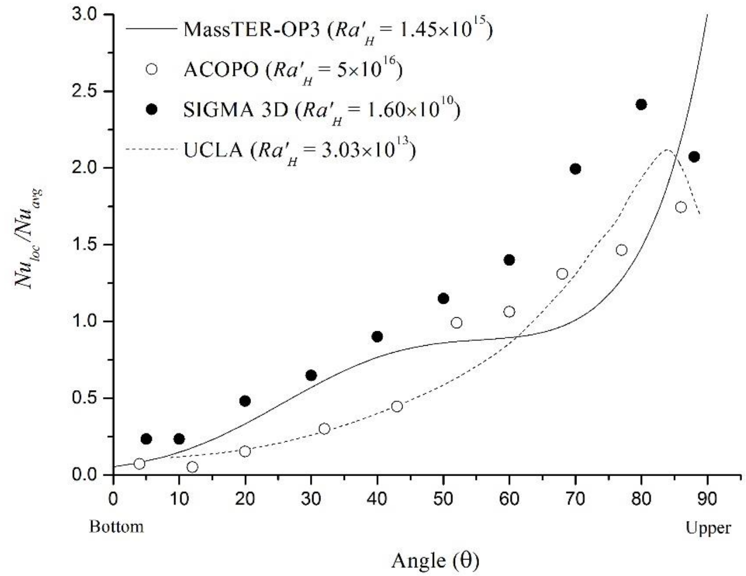


$$Nu_{dn} = 0.46\, Ra'^{\,0.19}\ \text{(2D)}$$
$$= 0.20\, Ra'^{\,0.22}\ \text{(3D)}$$

$$Nu_{up} = 0.37\, Ra'^{\,0.24}\ \text{(2D)}$$
$$= 3.19\, Ra'^{\,0.18}\ \text{(3D)}$$

Existing results Vs. MassTER-OP results



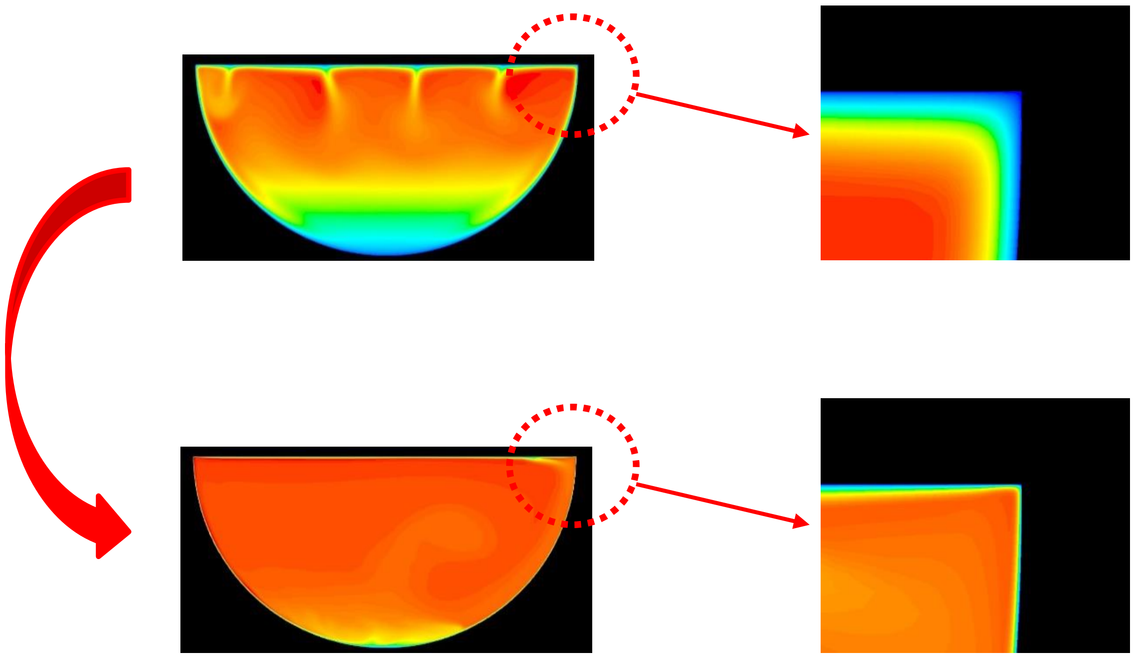


- Heat flux increased as angle increased in both 2D and 3D cases
- But, heat fluxes of the 90 degrees were showed different trend

Existing results Vs. MassTER-OP results

- Roughly simulated results using FLUENT (2D)

Ra' or *Pr* increased



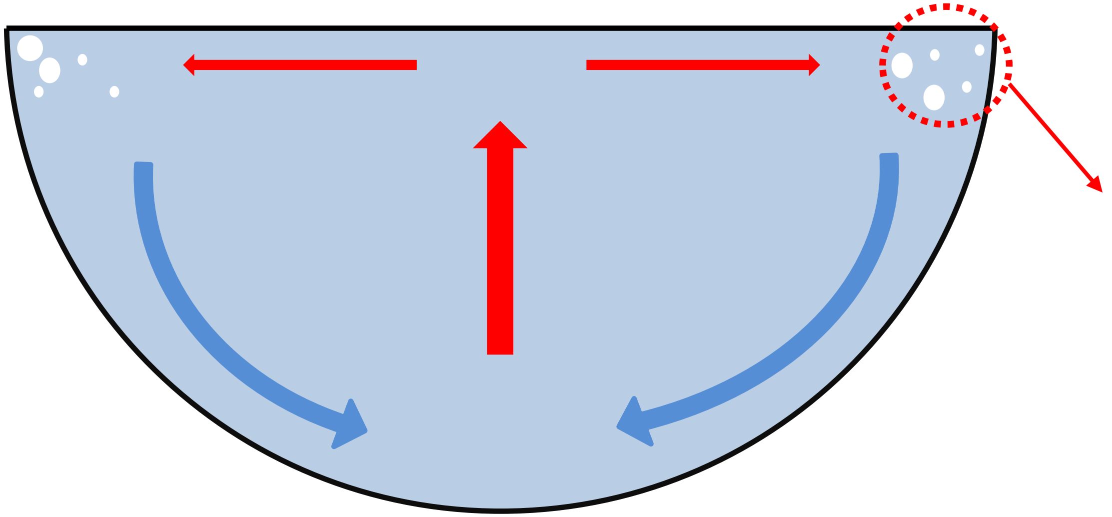
- Boundary layer overlap → Impair the heat transfer

Existing results Vs. MassTER-OP results

- Unwanted voids may formed in the bulk when filling up the test rig
- And the voids will move to the edge due to the main stream

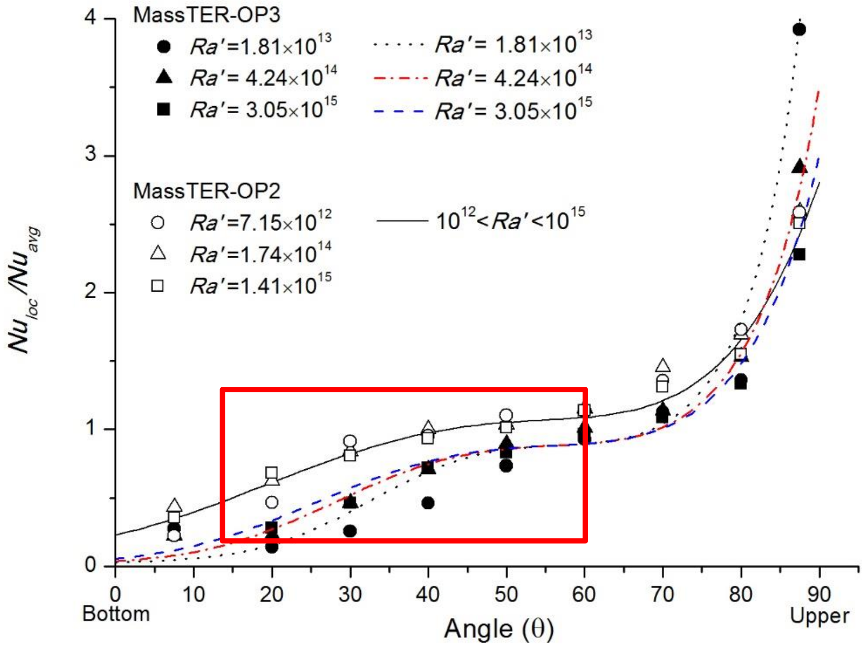
↓

- Heat transfer in the vicinity of the 90 degrees may impaired by the voids



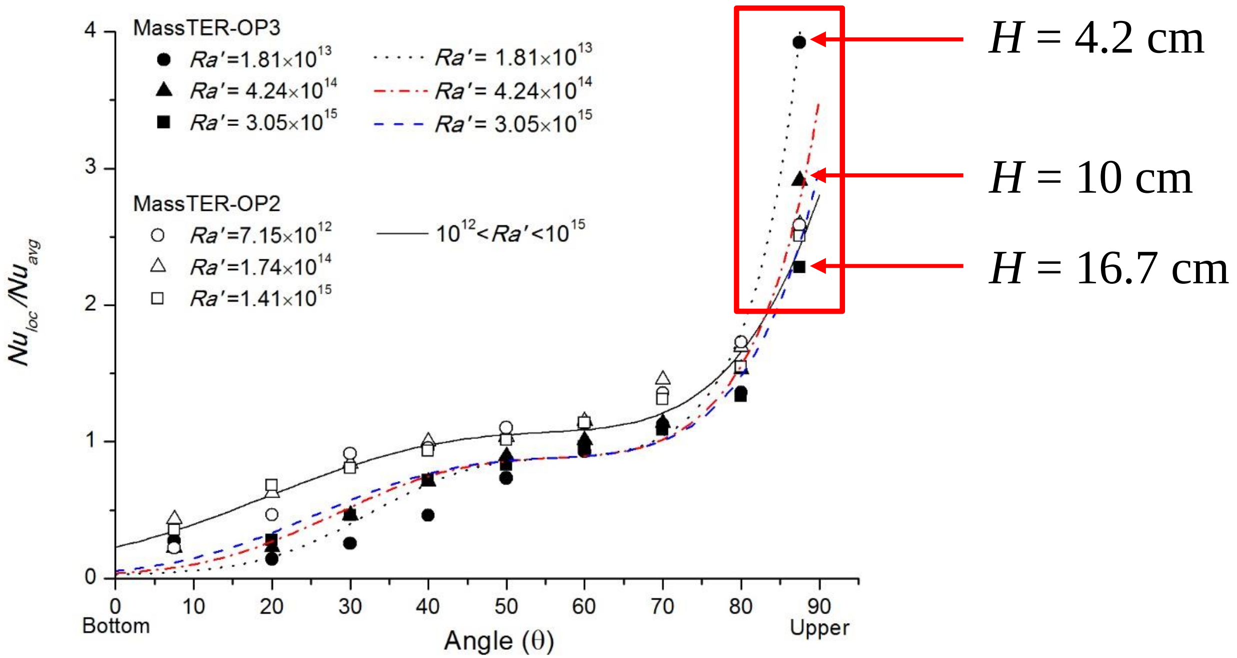
80-90 degrees

Comparisons of the 2D and 3D results



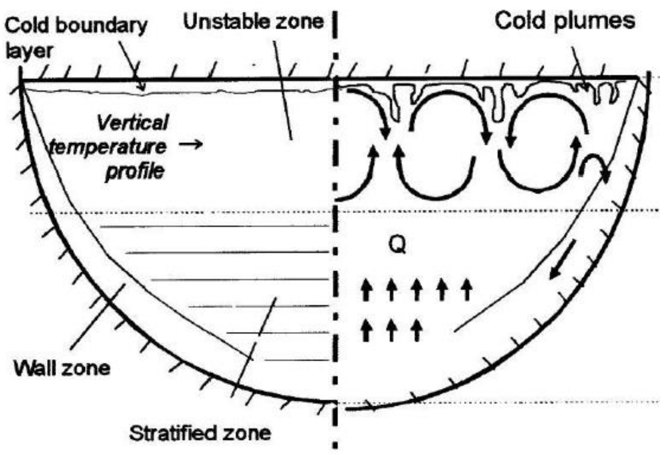
- 2D results showed higher *Nu* ratio than 3D results
- Thermal boundary layer was overlapped along the curvature in the 3D cases

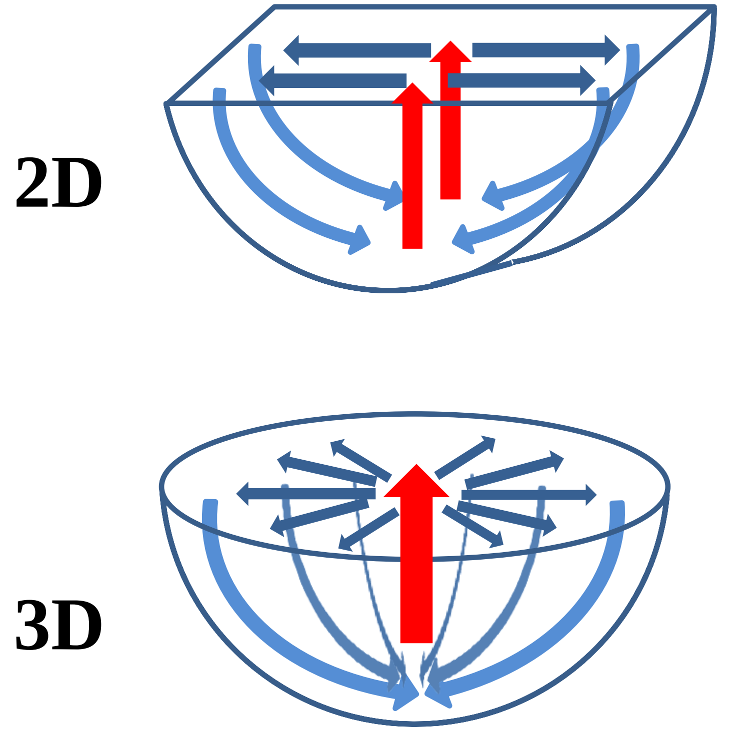
Comparisons of the 2D and 3D results



- 2D results showed similar trend regardless of the *Ra'*
- But, 3D results affected by the *Ra'* in the vicinity of the 90 degrees

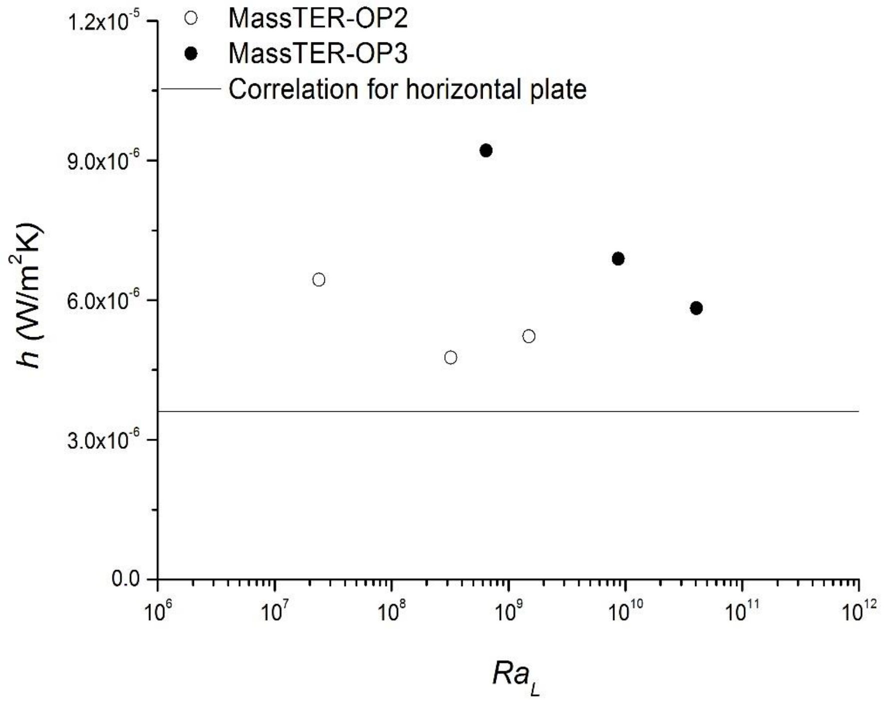
Comparisons of the 2D and 3D results





- Rising flow force at the center is different due to the geometrical feature
- Flows at the top plate, either

Comparisons of the 2D and 3D results



- Heat transfer of the top plate was enhanced by rising flow
- Outstanding trend is shown in the 3D cases

Comparisons of the 2D and 3D results

- Correlations for 2D and 3D angular *Nu* ratio were developed

$$Nu_{Ratio(dn)} = A + B\,\theta + C\,\theta^2 + D\,\theta^3 + E\,\theta^4 + F\,\theta^5$$

	2D	3D		
Ra'_H	-	10^{13}	10^{14}	10^{15}
A	2.28×10^{-1}	3.23×10^{-2}	7.17×10^{-2}	11.40×10^{-2}
B	1.32×10^{-2}	2.40×10^{-2}	4.12×10^{-2}	2.91×10^{-2}
C	4.02×10^{-4}	-2.97×10^{-3}	-4.00×10^{-3}	-2.61×10^{-3}
D	-1.56×10^{-6}	1.486×10^{-4}	1.672×10^{-4}	1.125×10^{-4}
E	-2.19×10^{-7}	-2.607×10^{-6}	-2.647×10^{-6}	-1.797×10^{-6}
F	2.31×10^{-9}	1.514×10^{-8}	1.423×10^{-8}	9.672×10^{-9}

Comparisons of the 2D and 3D results

- Multiplier was developed

$$Nu_{3D} = Nu_{2D} \times \phi$$

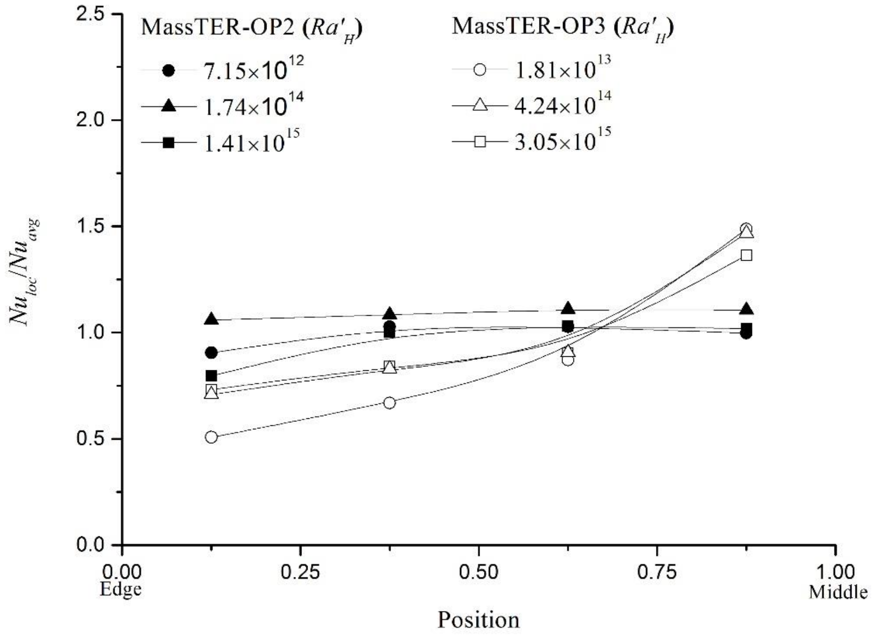
where,

$$\phi = 0.7e^{A}$$

$$A = 10^{-5}(\theta - 57.95)^{3}\left(\frac{1.81\times10^{13}}{Ra'}\right)^{0.24} + 0.122$$

- Thus, 2D result is able to substitutes those of the 3D case

Comparisons of the 2D and 3D results



- Almost similar *Nu* ratios were measured at 2D cases
- But, maximum *Nu* ratios were measured at 3D cases
- Enhanced rising flow causes the results

Conclusion

- Natural convection of 2-layer model oxide pool was investigated by mass transfer experimental test rig
  - ✓ High *Ra'* with compact test rig (simple and cheap)
  - ✓ 2D and 3D experiments
  - ✓ *Ra''s* were varied (varying height of the test rig)

- Nu_{dn}'s were 40 % lower but Nu_{up}'s were 40 to 60 % higher than existing studies, but total *Nu* were measured within 20 %

- Angular heat fluxes
  - ✓ 2D: Not affected by *Ra'*
  - ✓ 3D: Affected by *Ra'* in the vicinity of the 90 degrees

- Top plate heat fluxes
  - ✓ 2D: Measured in an almost identical trend at all position
  - ✓ 3D: Maximum value at the center due to the strong rising flow

Conclusion

- Local heat fluxes were measured in different characteristics between 2D and 3D cases
  - ✓ The multiplier was developed
  - ✓ Mean *Nu* trends were similar in 2D and 3D cases due to the compensated those local heat transfer results

- Thus, 2D experiment is able to substitutes 3D experiment