Investigation of Natural Convection Heat Transfer of Oxide Pool using 2D and 3D Experimental Facilities: MassTER-OP2 and OP3

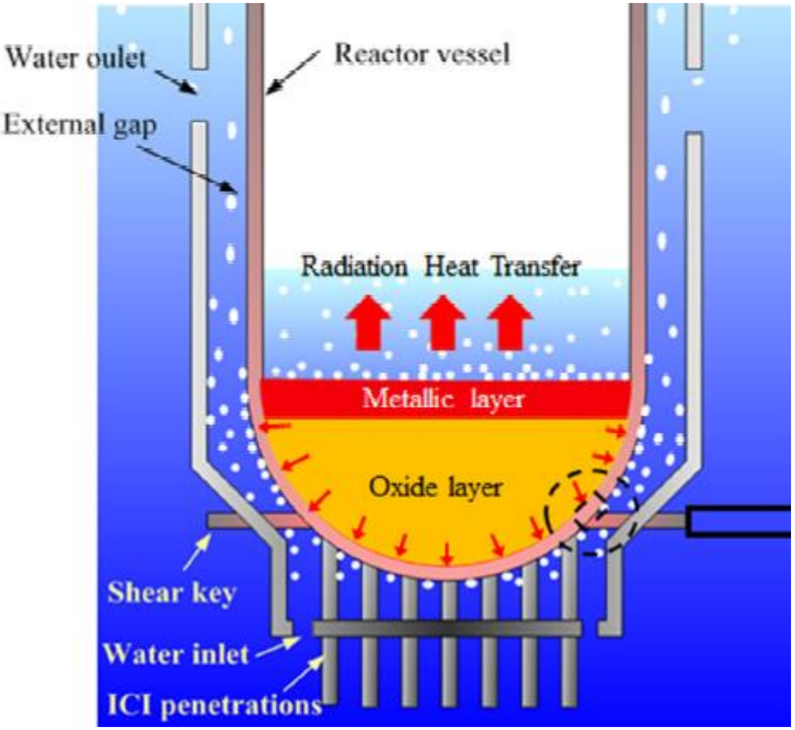
2016. 5. 13

Su-Hyeon Kim, Hae-Kyun Park, Bum-Jin Chung

Kyung Hee University

Introduction

- Core catcher
- IVR-ERVC (In-Vessel Retention – External Reactor Vessel Cooling)



IVR-ERVC

Objective of study

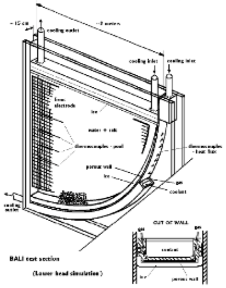
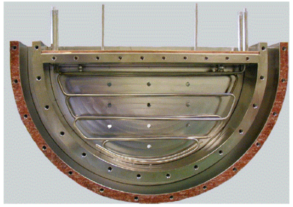
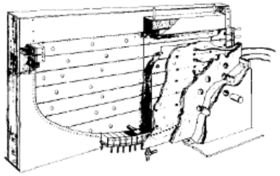
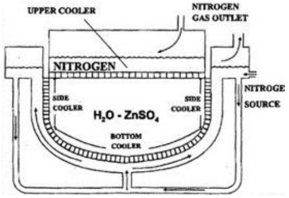
1. Specification of Modified Rayleigh number (Ra') for 2D facility

2. Comparison between 2D and 3D geometries

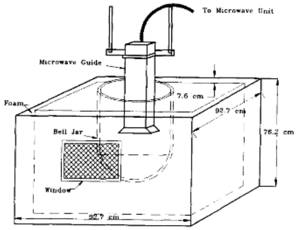
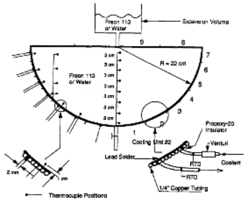
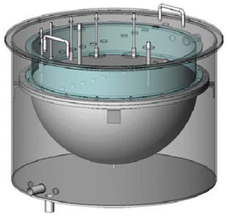
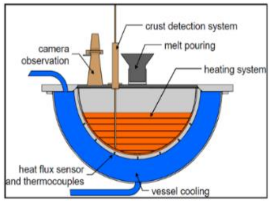
3. Development of correlation between 2D and 3D results
   - 2D correlation × Multiplier → 3D correlation

4. Inference of 3D results from 2D results

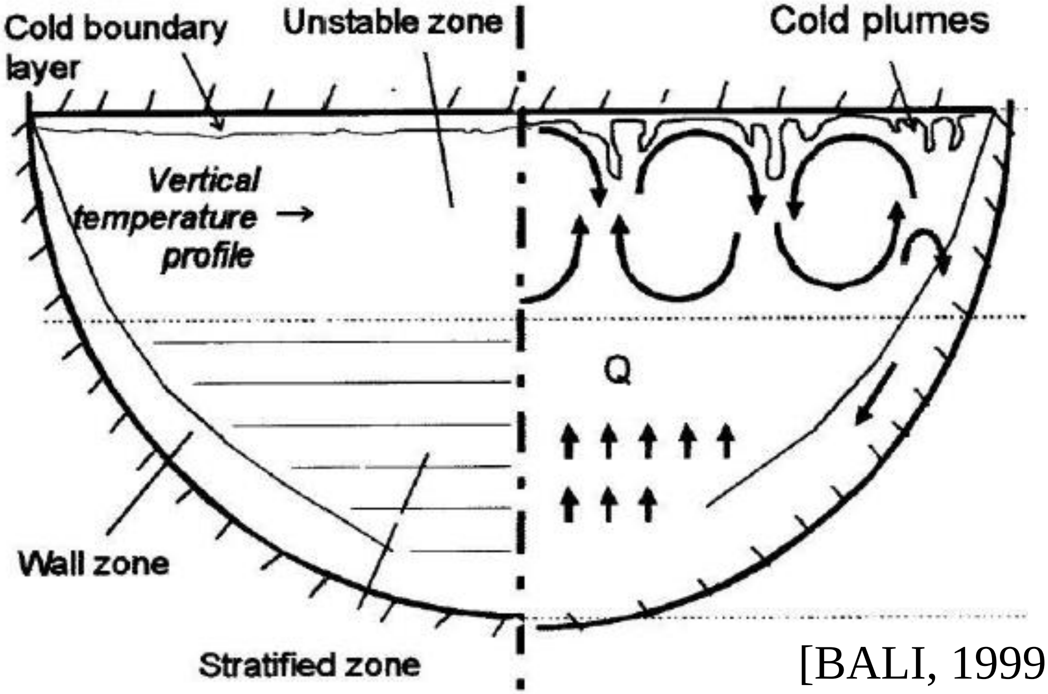
Summary of previous studies (2D)

	BALI	**SIGMA CP**	**COPOI**	**COPOII**
Pool shape	Semicircular		Torispherical	
Ra_H'	10^{13}–10^{17}	5×10^{6}–7×10^{11}	10^{14}–10^{15}	8×10^{14}–10^{15}
Correlations	$Nu_{up}=0.383Ra'_H{}^{0.233}$ $Nu_{dn}=0.116Ra'_H{}^{0.25}$	$Nu_{up}=0.31(Ra'_H Pr^{-0.36})^{0.245}$ $Nu_{dn}=0.31(Ra'_H Pr^{-0.215})^{0.235}$	-	-
Nu_{dn}	Maximum at uppermost curve	Peak at lower curve	Maximum at uppermost curve	Maximum at uppermost curve
Nu_{up}	-	Scattered	-	-
Image				

Summary of previous studies (3D)

	UCLA	ACOPO	SIGMA 3D	LIVE
Pool shape	Hemispherical			
Ra'_H	5×10^{11}–8×10^{13}	1×10^{14}–2×10^{16}	4×10^{14}–3×10^{15}	1.2×10^{14}
Correlations	$Nu_{dn}=0.54(Ra'_H)^{0.2}(H/R_e)^{0.25}$	$Nu_{up}=1.95Ra'^{\,0.18}_H$ $Nu_{dn}=0.3Ra'^{\,0.22}_H$	-	-
Nu_{dn}	Peak at lower curve	Maximum at uppermost curve	Peak at lower curve	-
Nu_{up}	-	-	Scattered	-
Image				

Phenomena



[BALI, 1999]

- **Main flow :** The downward flows run down along the curved surface and merge at the bottom. Then, it move upward and disperse at the top plate.

- **Second flow :** There is also natural convective flow underneath the top plate.

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	$\frac{hH}{k}$	Sh	$\frac{h_m H}{D_m}$
Pr	$\frac{\nu}{\alpha}$	Sc	$\frac{\nu}{D_m}$
Ra	$\frac{g\beta\Delta TH^3}{\alpha\nu}$	Ra	$\frac{gH^3}{D_m\nu}\frac{\Delta\rho}{\rho}$

Heat Transfer Problem

Mass Transfer Problem

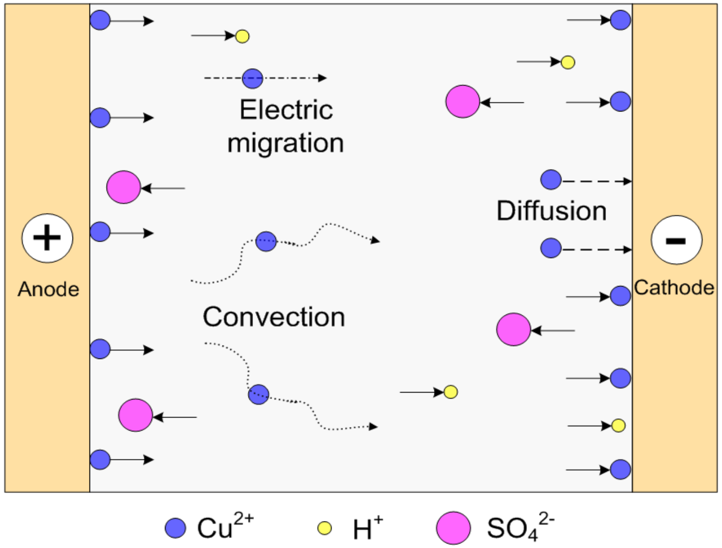
Analogy concept

Heat Transfer Solution

Mass Transfer Solution

Copper electroplating system

- **Mass transfer in a cupric acid-copper sulfate**



$$h_m = \frac{(1-t_n)I_{lim}}{nF(C_b - C_s)}$$

1. Electric migration (N_m) → not in heat transfer system (H_2SO_4)
2. Diffusion (N_d)
3. Convection (N_c)

$$N_t - N_m = N_d + N_c = \frac{(1-t_n)I_{lim}}{nF} = h_m(C_b - C_s)$$

Modified Rayleigh number

To incorporate the decay heat emitted in the mixture layer, the expression for internal heat generation is needed replacing the temperature difference expression for traditional *Ra*.

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

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

Modified Rayleigh number in mass transfer

[Heat transfer] **[Mass transfer]**

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

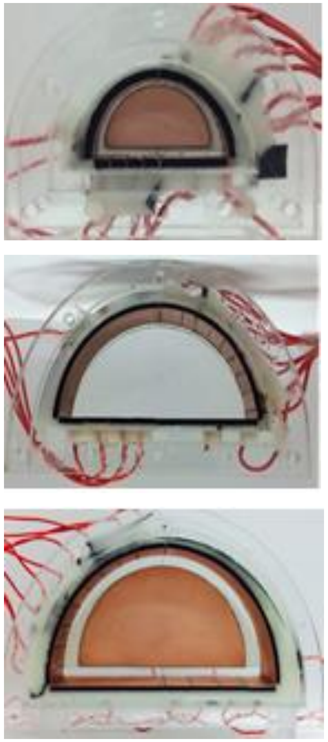
$$\boxed{Ra' = \frac{g\beta q'''H^5}{\alpha\nu k}} \rightarrow \boxed{Ra' = 128.5\frac{(1-t_{Cu^{2+}})gI'''H^5}{nFD_m^2\nu\rho}}$$

q''' (Volumetric heat generation)	***I '''*** (Volumetric current)
T (Temperature)	***C*** (Concentration)
k (Thermal conductivity)	***D_m*** (Mass diffusivity)

Test apparatus

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

[MassTER-OP2]



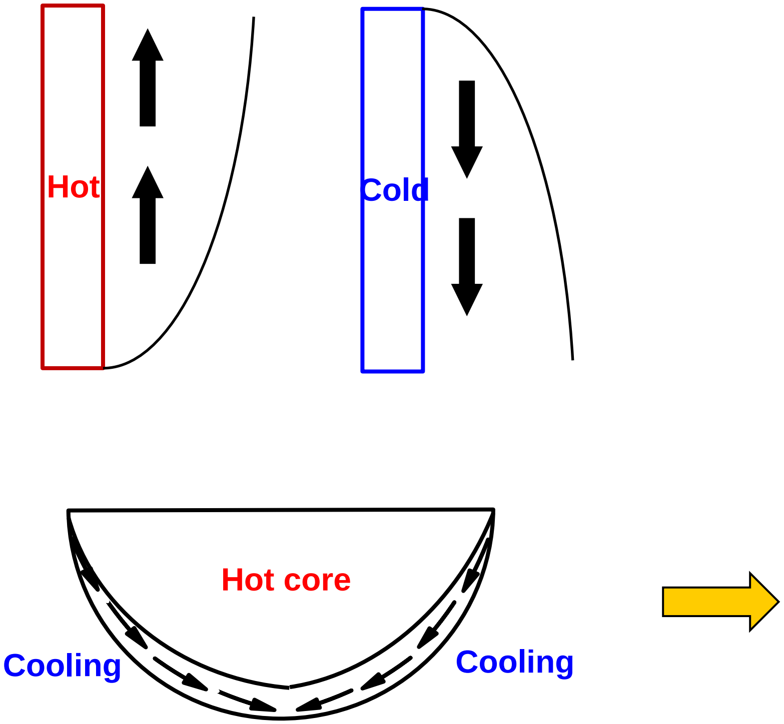
[MassTER-OP3]

Single electrode

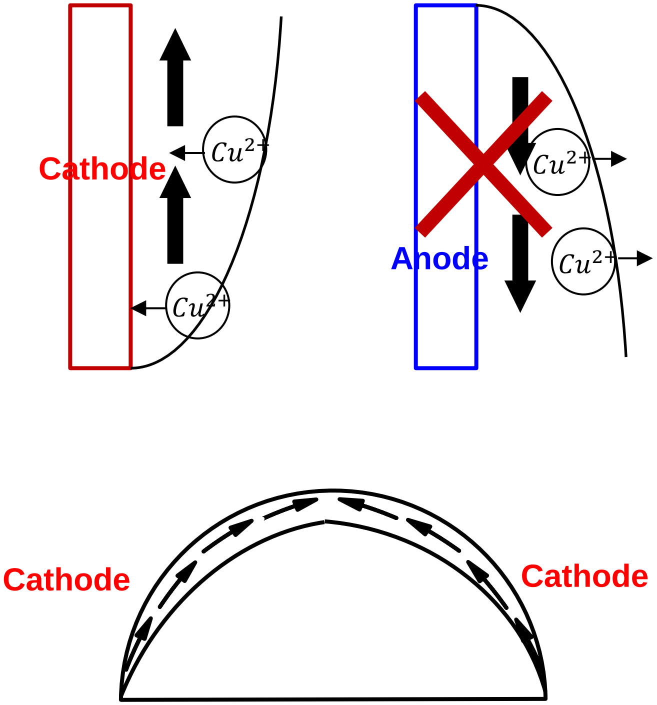
Piecewise electrodes

Test method

[Heat transfer]

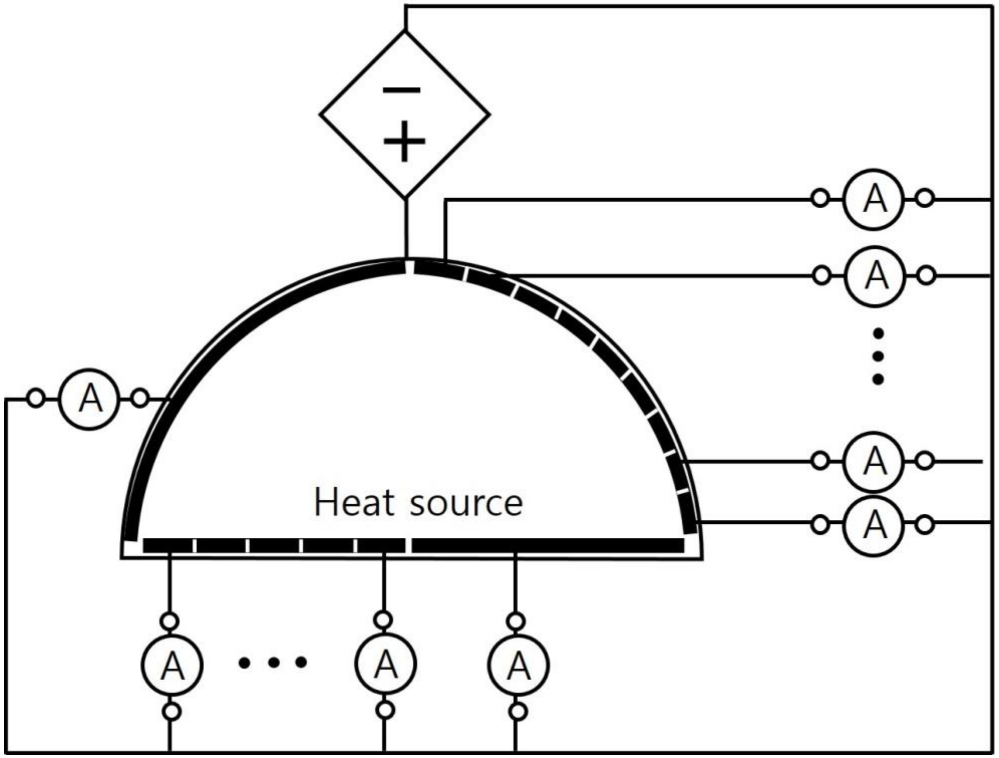


[Mass transfer]



→ **Inverted against gravity direction**

Test circuit



Test matrix

	H (m)	Ra'_H	Pr
MassTER-OP2	0.042	4.55×10^{12}	2,014
	0.100	1.11×10^{14}	
	0.167	8.99×10^{14}	
MassTER-OP3	0.042	8.64×10^{12}	
	0.100	2.02×10^{14}	
	0.167	1.46×10^{15}	

Specification of Ra'_H for 2D geometry

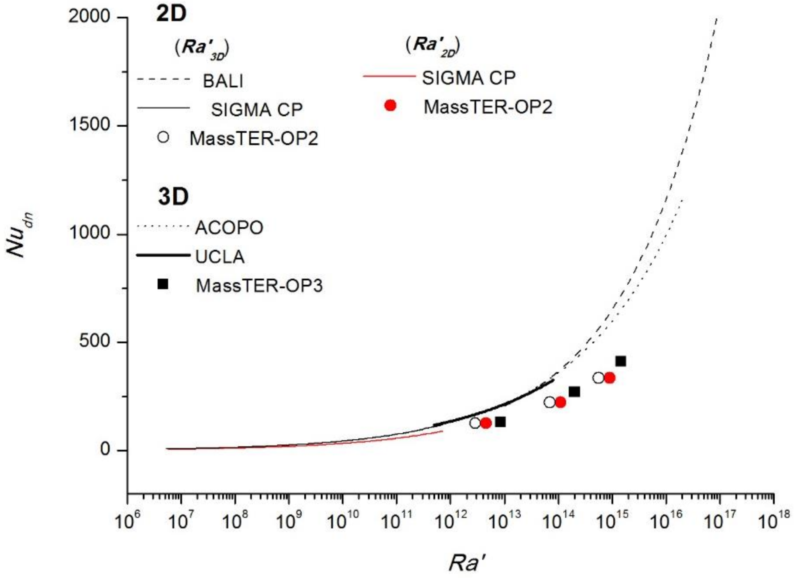
$$Ra'_H = \frac{g\beta q''' H^5}{\alpha \nu k}$$

	Volumetric heat generation (q''') (In previous studies, no exact definition)	
3D	$\frac{q}{H^3}$ $\leftrightarrow$	$\frac{q}{V}$
2D	$\frac{q}{H^3}$ $\cancel{\leftrightarrow}$ **Width**	$\frac{q}{V}$

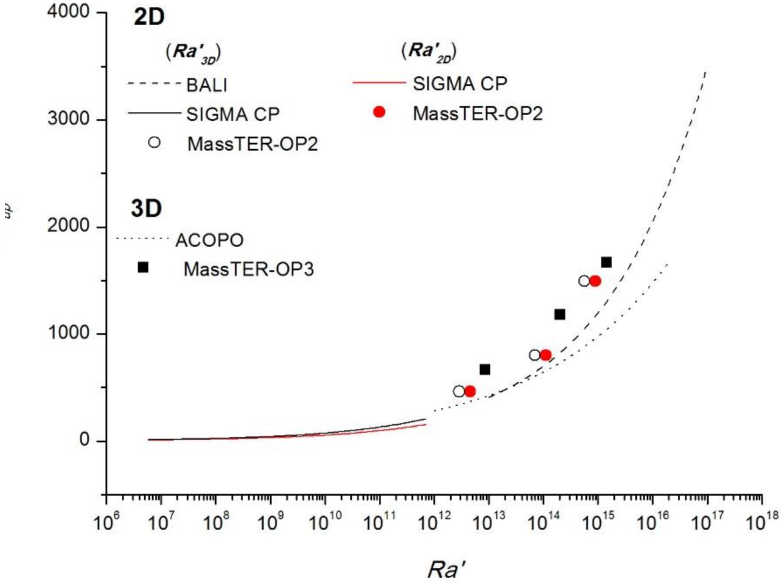
Specification of *Ra′* for 2D geometry

- **Comparison of the 2D results between different definition of volumetric heat generation (q''')**

[Curved surface]



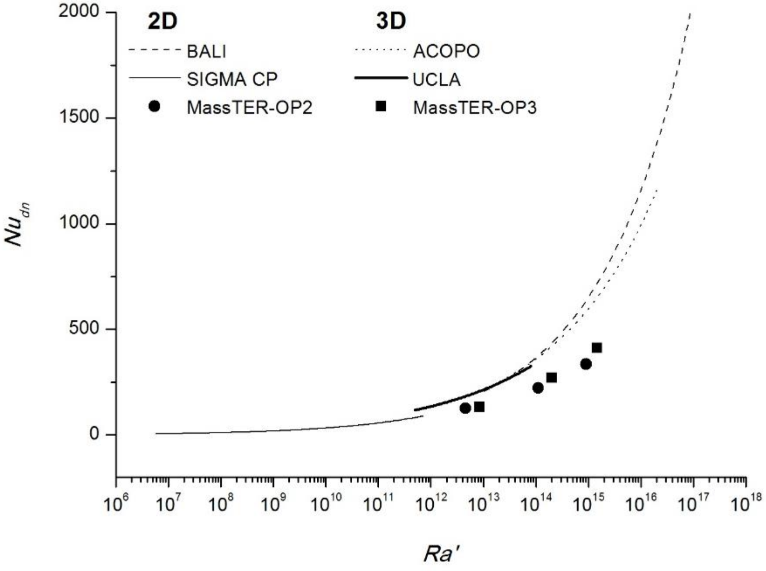
[Top plate]



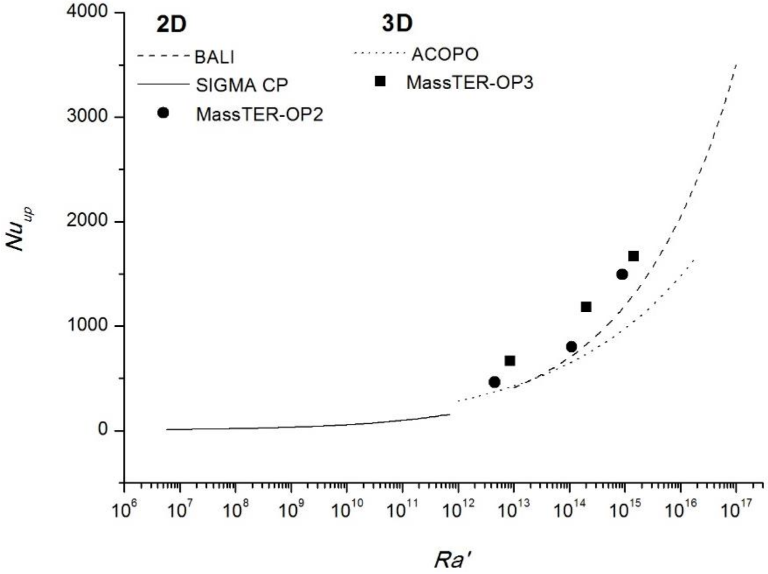
Mean Nu – MassTER-OP vs. Existing studies

- **Comparison of the existing heat transfer correlation with the results**

[Curved surface]



[Top plate]

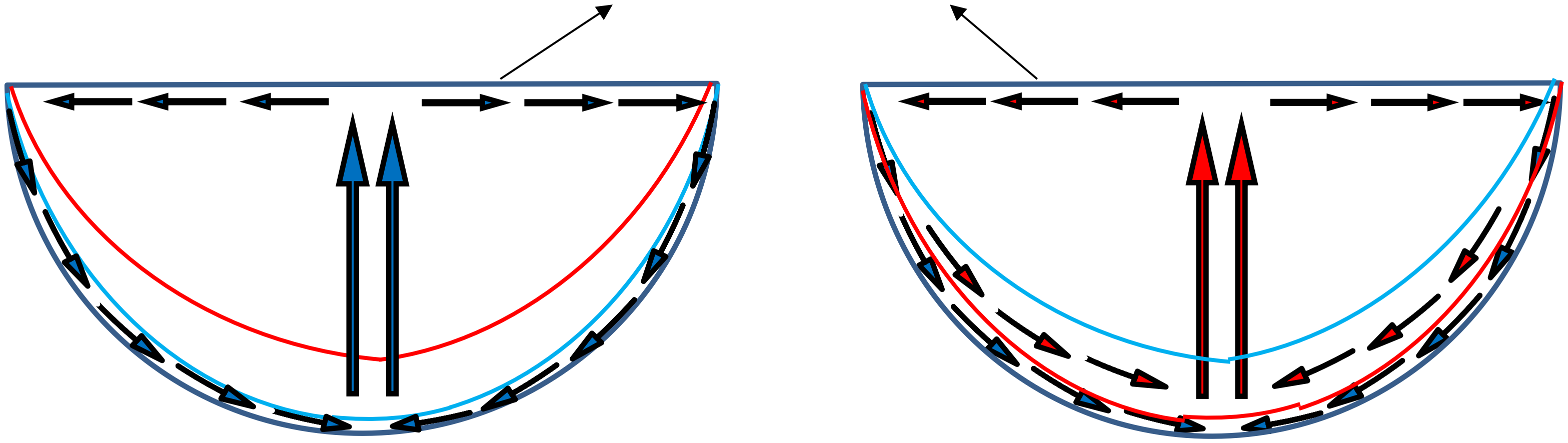


→ In the curved surface, MassTER-OP results showed the lower Nu_{dn} than the existing correlations.

→ In the top plate, MassTER-OP results showed the higher Nu_{up} than the existing correlations.

Mean Nu – MassTER-OP vs. Existing studies

$$(T_\infty - T_S) \quad < \quad (T_\infty - T_S)$$



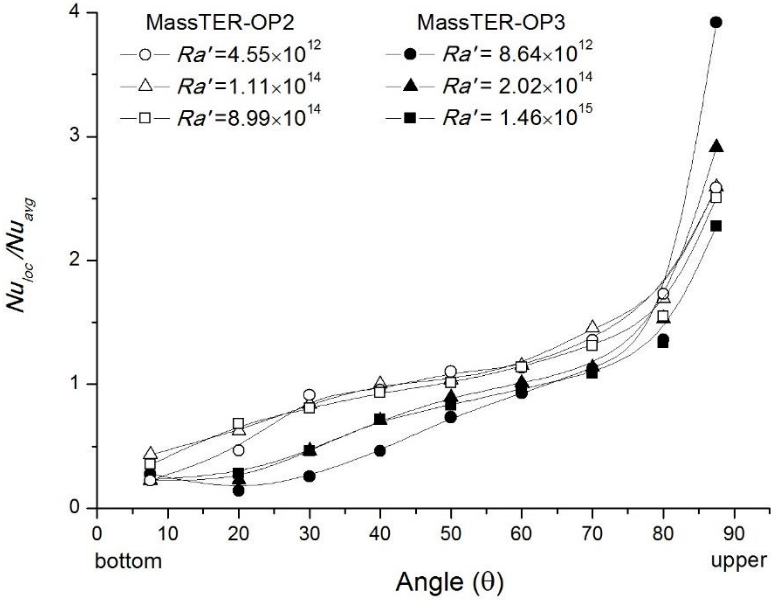
***Pr* << 1**

***Pr* >> 1**

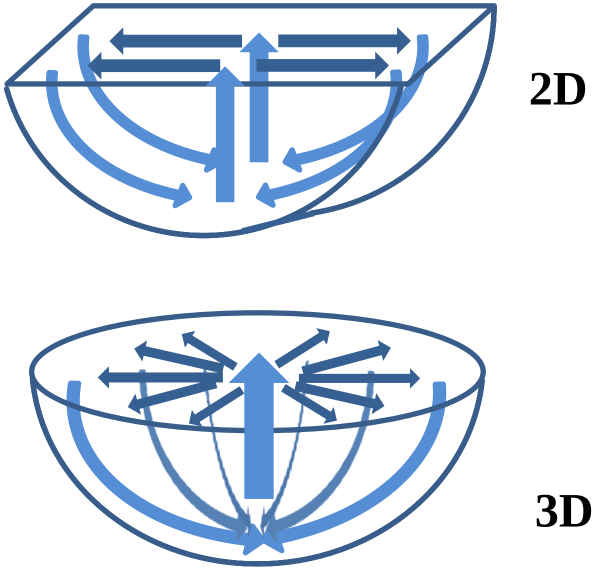
Existing studies	$Pr < 10$
MassTER-OP	$Pr = 2{,}014$

Local *Nu* – 2D vs. 3D

- **Comparison of *Nu* ratio (Nu_{loc}/Nu_{avg}) between MassTER-OP2 and OP3**



[Curved surface]

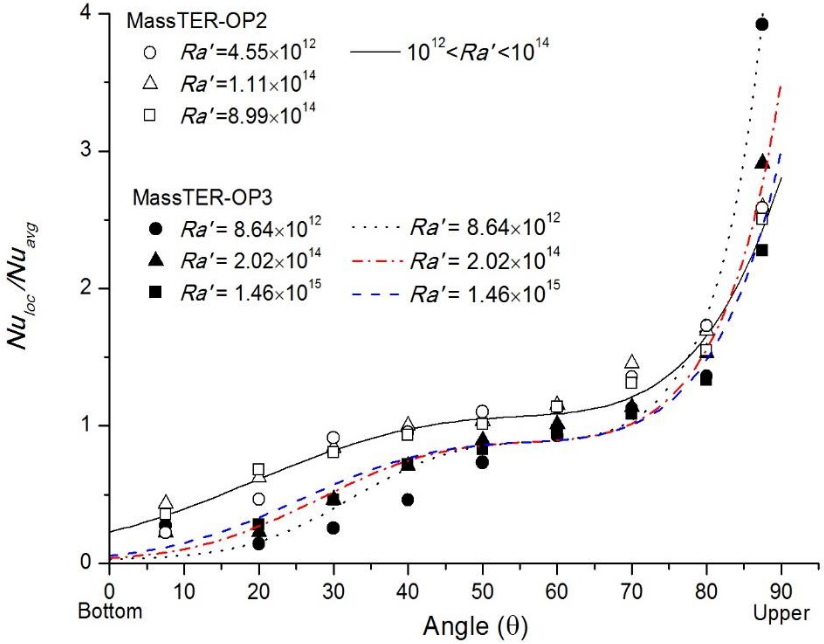


→ In the lower section, 2D results was higher than the 3D results

→ In the upper section (80˚- 90˚), 2D results were similar regardless of *Ra'* but 3D results were different depending on *Ra'*

Local *Nu* – 2D vs. 3D

- **Correlation between MassTER-OP2 and OP3**



- **Correlation for MassTER-OP2**

$$Nu_{2D} = 0.228 + 0.0132\theta + 0.000402\theta^2 - 0.00000156\theta^3 - 0.000000219\theta^4 + 0.00000000231\theta^5$$

- **Multiplier**

$$\Phi = 0.7e^{0.00001(\theta-57.95)^3\left(\frac{1.81\times10^{13}}{Ra'}\right)^{0.24}} + 0.122$$

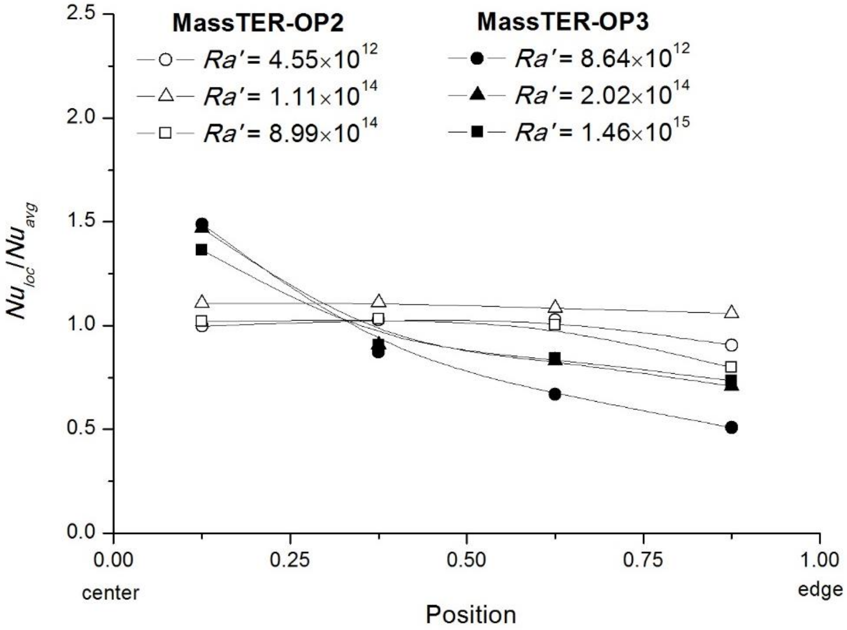
- **Correlation between MassTER-OP2 and OP3**

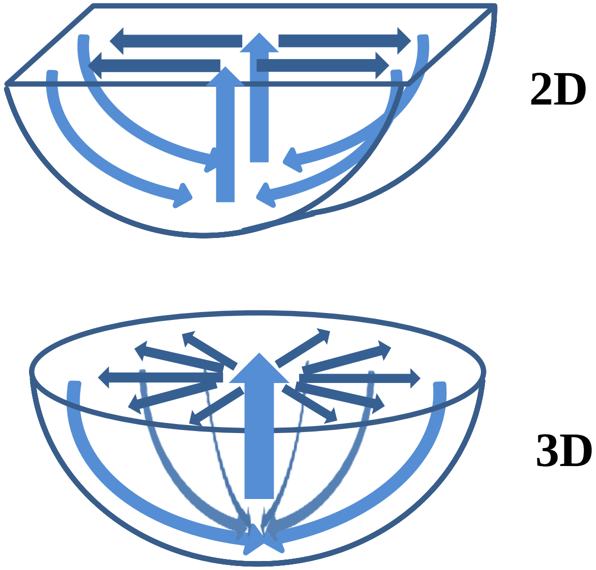
$$Nu_{3D} = Nu_{2D} \times \Phi$$
$$= Nu_{2D} \times [0.7e^{0.00001(\theta-57.95)^3\left(\frac{1.81\times10^{13}}{Ra'}\right)^{0.24}} + 0.122]$$

Local *Nu* – 2D vs. 3D

- **Comparison of *Nu* ratio (Nu_{loc}/Nu_{avg}) between MassTER-OP2 and OP3**

[Top plate]





→ 3D results decrease consistently from center to edge

→ But, 2D results was uniform until 0.6 position and decrease at the edge

Conclusions

- Natural convection heat transfer experiments were performed by mass transfer
  → **High Ra'_H with small facilities**

- Specification of Ra'_H definition for 2D geometries
  → **Volumetric heat generation(q''') = $\frac{q}{V}$**

- Nu_{dn}'s were lower and Nu_{up}'s were higher than the existing studies
  → **Difference of *Pr***

- Local *Nu* ratios were different between MassTER-OP2 and OP-3
  → **Difference of flow patterns between 2D and 3D geometries**

- Comparing between 2D and 3D results, local *Nu* was different but mean *Nu* was identical. The correlation between 2D and 3D results was developed
  → **3D results could be inferred from 2D results**

Thank you for your attention !