Natural convection heat transfer of two heating spheres with pitch-to-diameter ratio

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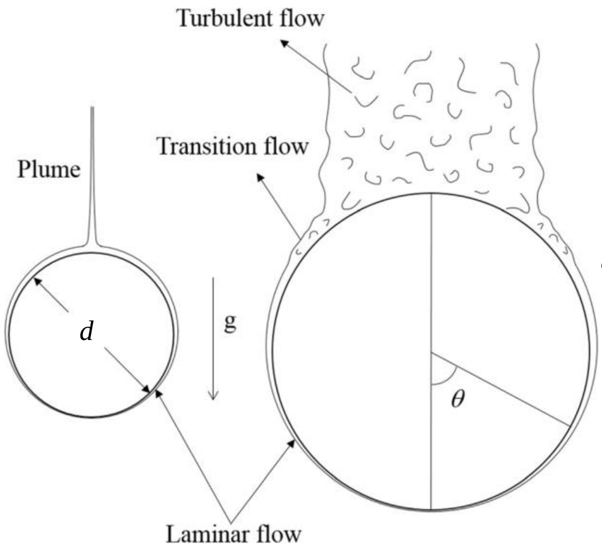
Introduction

- **Applications of packed bed**
  - ➢ Pebble fuel of nuclear reactors, thermal energy storage, catalytic reactors, heat exchanger, etc.
- **The investigation on the interaction between adjacent spheres in the packed bed for natural convective flow is needed.**
- **In this study,**
  - ➢ Measurement of natural convection heat transfer of two heating spheres with different arrangement.
  - ➢ Visualization experiment of plating patterns appearing on two spheres.

Natural convection of a single heating sphere



Natural convection on a sphere
[Lee et al., 2017]

- **Natural convection of a single heating sphere**
  - ➢ The buoyant flow starts at the bottom along the surface of the sphere.
  - ➢ It separates the plume from the upper part of the sphere.

- **For small Ra_d**
  - ➢ For low Ra_d, the laminar boundary layer is formed.
  - ➢ The plume rises from the uppermost part

- **For large Ra_d**
  - ➢ For high Ra_d, the transition to turbulence occurs.
  - ➢ The plume rises from at the upper part of the sphere which is relatively lower.
  - ➢ Critical $Ra_d = 3 \times 10^8$

Experimental Methodology

- **Analogy between heat transfer and mass transfer**

[Governing equations]

<table>
<tr><th>Heat transfer</th><th>Mass transfer</th></tr>
<tr><td colspan="2">$\frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} = 0$</td></tr>
<tr><td colspan="2">$\rho \frac{Du}{Dt} = -\frac{\partial P}{\partial x} + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) + X$</td></tr>
<tr><td>$\frac{DT}{Dt} = \alpha \nabla^2 T$</td><td>$\frac{DC}{Dt} = D \nabla^2 C$</td></tr>
</table>

[Dimensionless numbers]

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

Heat Transfer Problem → Mass Transfer Problem

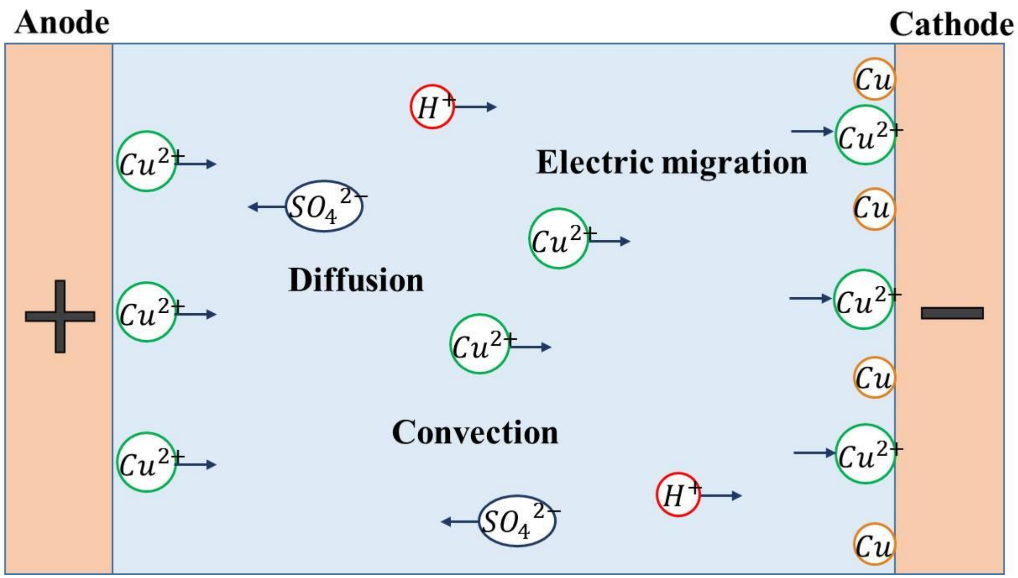
↓

Mass Transfer Solution → Heat Transfer Solution

Analogy concept

Copper electroplating system

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



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

0

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

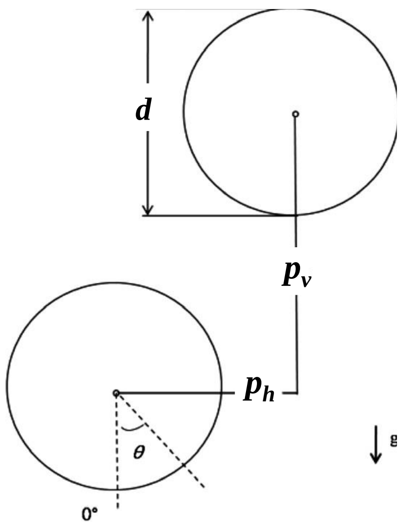
$$N_t - N_m = N_d + N_c = \frac{(1-t_n)I_{lim}}{nF} = h_m(C_b - C_s)$$

Test matrix

Test matrix

Sc	d (mm)	Ra_d	Position	
			P_h/d	P_v/d
2,014	6, 15.8, 25	1.83×10^7, 3.35×10^8, 1.33×10^9	0	1.06, 1.5, 2, 3, 5, 7
			0.47	1.06, 1.5, 2, 3, 5, 7
			0.76	1.06, 1.5, 2
			1.06	1.06, 1.5, 2

P_h/d : Horizontal pitch-to-diameter
P_v/d : Vertical pitch-to-diameter



Arrangement of two spheres

Varying P_h/d

P_h/d = 0

P_h/d = 0.47

P_h/d = 0.76

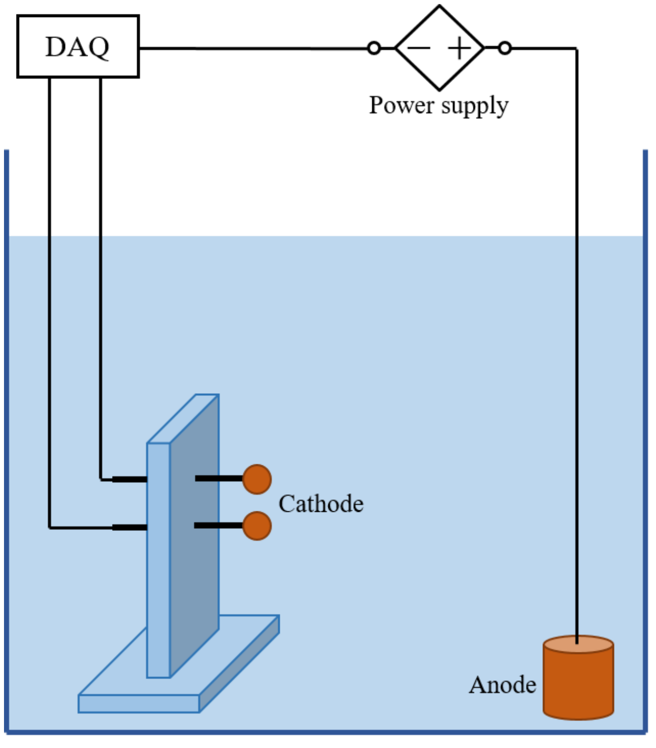
Varying P_v/d

P_v/d = 1.06

P_h/d = 1.5

P_h/d = 3

Experimental setup

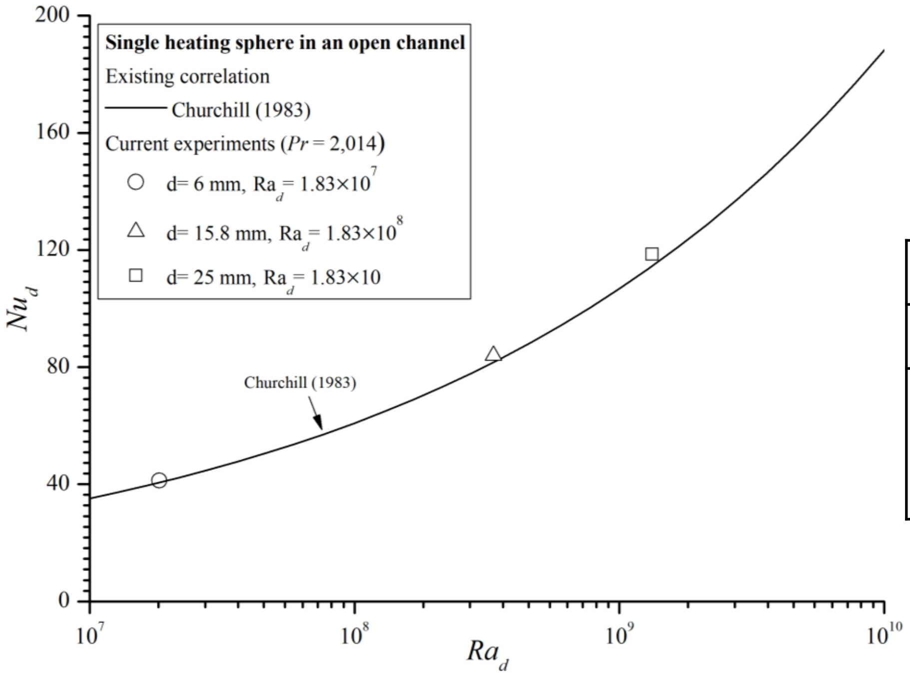


Schematic electric circuit

Front view

Side view

Results : Single sphere

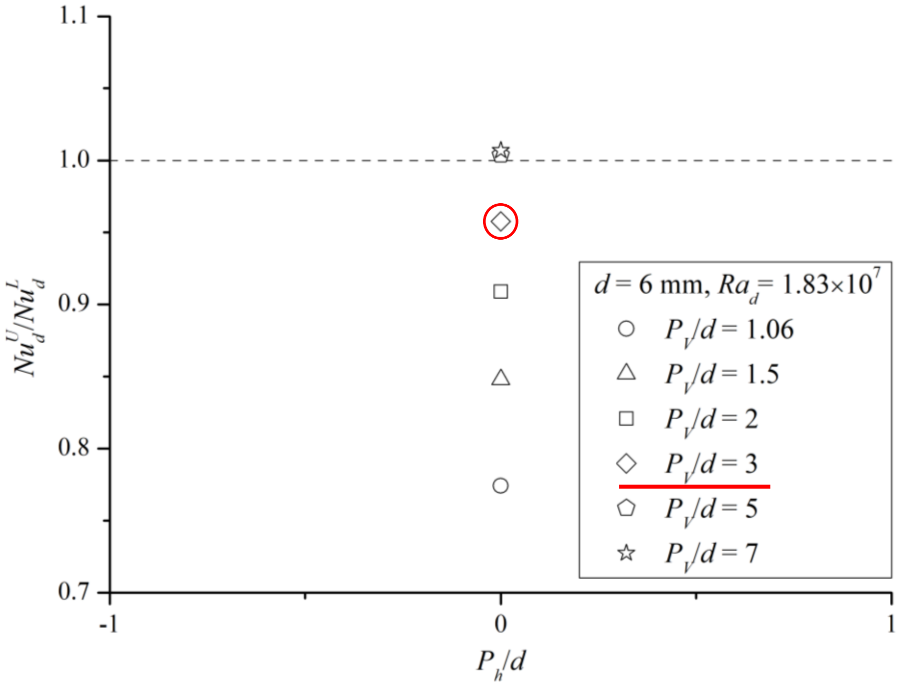


Comparison of experimental results with existing correlation

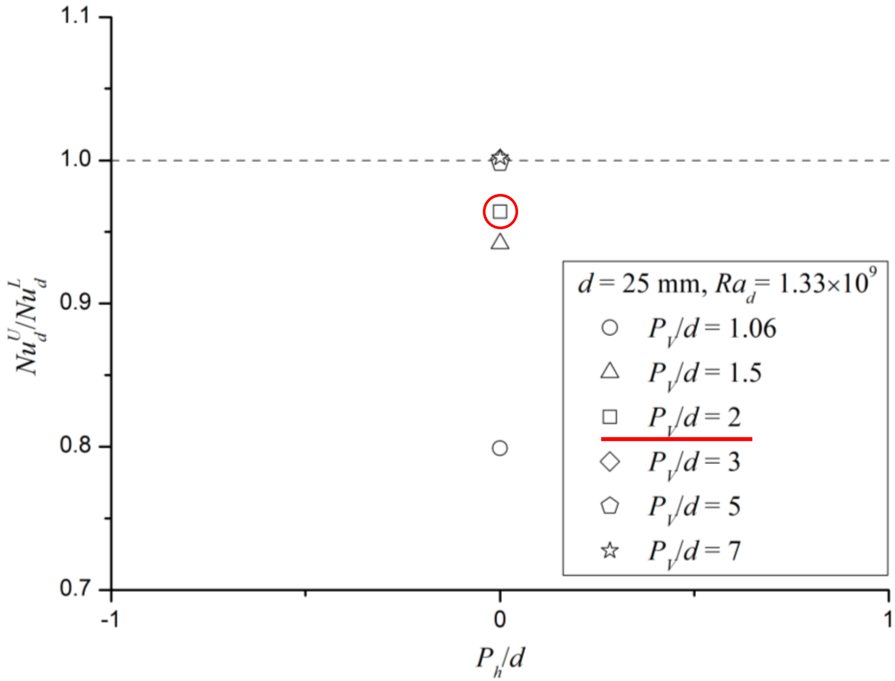
Churchill (1983)	
Correlation	**Range**
$Nu_d = 2 + \frac{0.589 Ra_d^{0.25}}{[1 + (0.469 / Pr)^{9/16}]^{4/9}}$	$Ra_d < 10^{11}$

- The experimental results were compared with correlation of Churchill (1983).
  - ➢ Average error = 2.7 %

Results : Two inline spheres



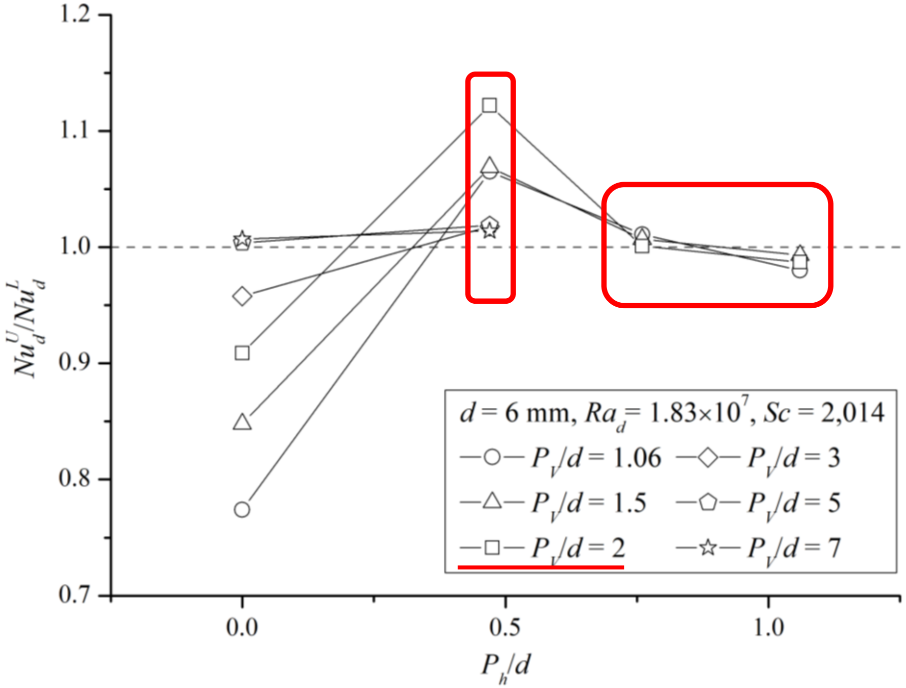
***d* = 6 mm**



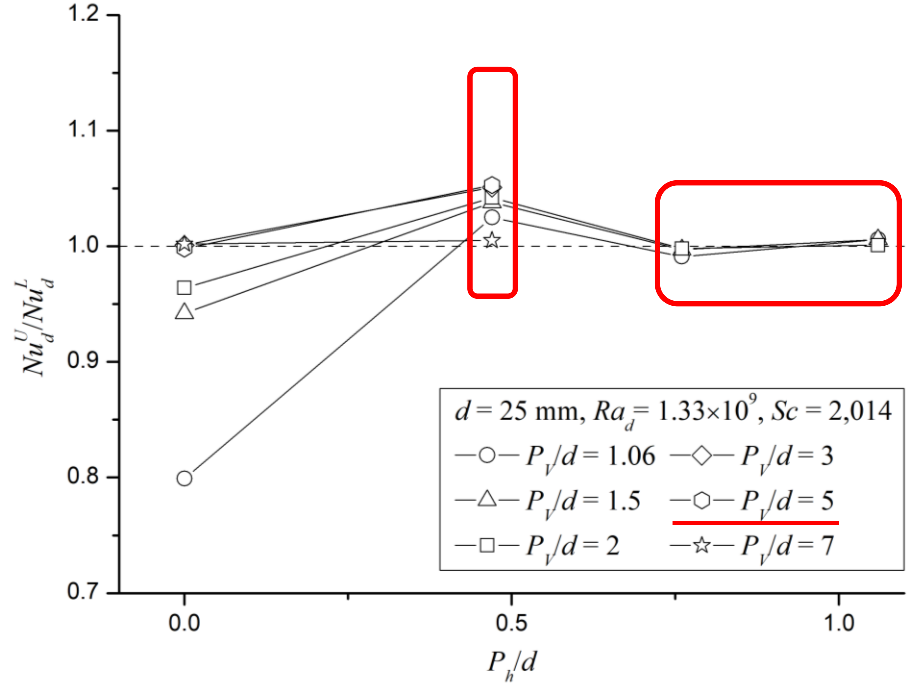
***d* = 25 mm**

- The heat transfer of the upper sphere was declined by the decrease of the P_v/d.
  - This is due to preheating effect and stagnant flow effect.
  - Up to P_v/d = 3 (6 mm, 15.8 mm), up to 2 (25 mm).

Results : Two staggered spheres



***d* = 6 mm**



***d* = 25 mm**

- For P_h/d = 0.47, the heat transfer of the upper sphere is higher than the lower sphere
  - This is due to side flow effect.
  - Up to P_v/d = 2 (6 mm), up to P_v/d = 3 (15.8 mm), up to P_v/d = 5 (25 mm).

Results : Plating patterns appearing on lower sphere

$Ra_d = 1.33 \times 10^9$

Lower sphere

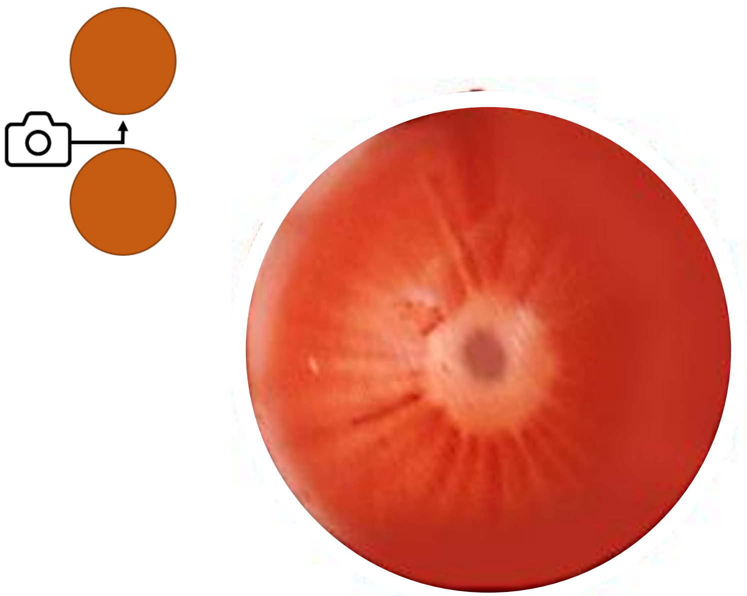
$Ra_d = 1.35 \times 10^9$

Single sphere
[Lee et al., 2017]

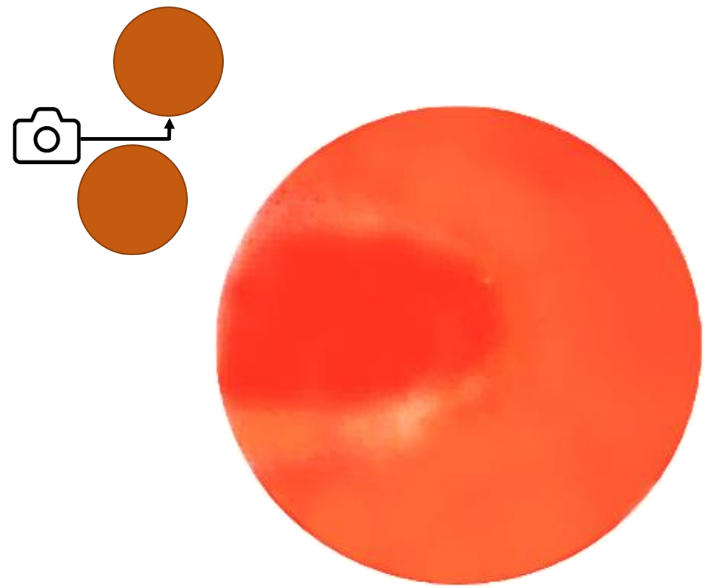
- The plating patterns of the lower sphere was the same as that of a single sphere.

Results : Plating patterns appearing on upper sphere

P_v/d = 1.06, upper sphere ($Ra_d = 1.33\times10^9$)



$P_h/d = 0$



$P_h/d = 0.47$

- At $P_h/d = 0$, the upper sphere was influenced by stagnant flow.
- At $P_h/d = 0.47$, the upper sphere was affected by side flow.

Conclusions and further studies

Conclusion

- **Natural convection heat transfer of two spheres with various pitch-to-diameter was performed using mass transfer experiment.**
  - **Two inline spheres**
    - ✓ When P_v/d is small, the heat transfer of the upper sphere was declined due to preheating effect and stagnant flow effect.
  - **Two staggered spheres**
    - ✓ As P_h/d increases, side flow effect occurred and heat transfer of the upper sphere increased.

Further studies

- **Experiments for extended test matrix**
  - Sphere diameter corresponding to turbulent flow regime ($Ra_d > 1.83\times10^9$)
- **Analysis of the geometrical effect for the influence of pitch-to-diameter on natural convection heat transfer**
  - 2D (Two cylinders) vs. 3D (Two spheres)

Thank you for attention.