# Realization of thermocline for thermal energy storage system study using a copper-sulfate electroplating system

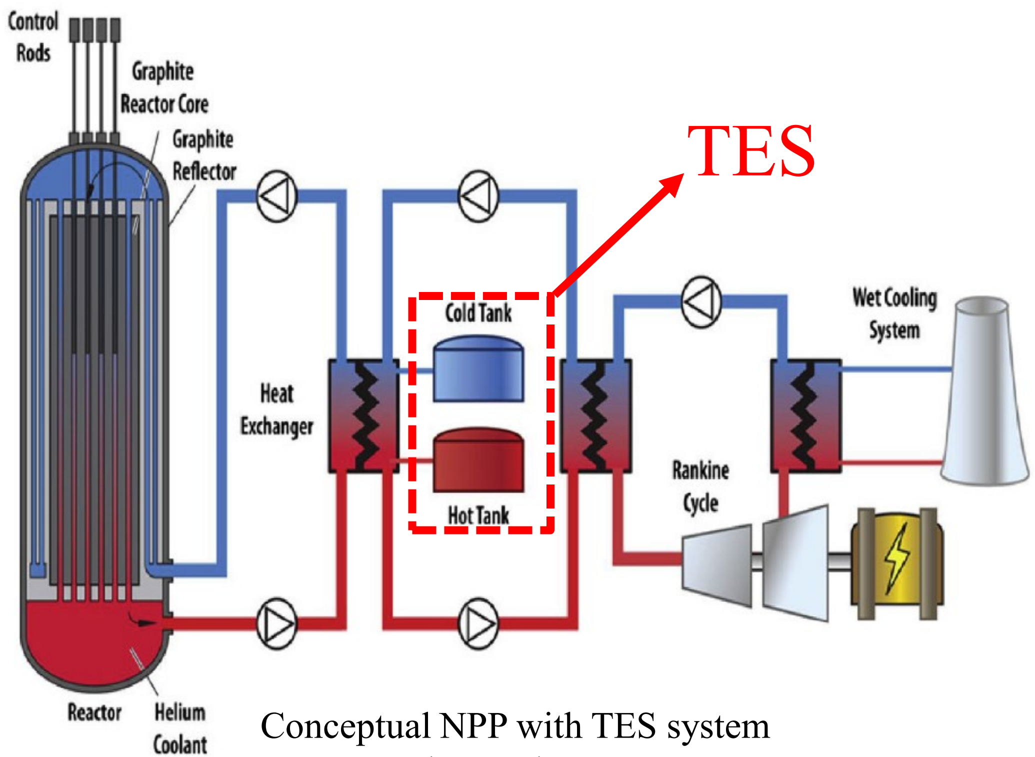
2022.10.20

**Min-Ju Kim**, Jeong-won Han and Bum-Jin Chung*

Kyung Hee University

# Introduction

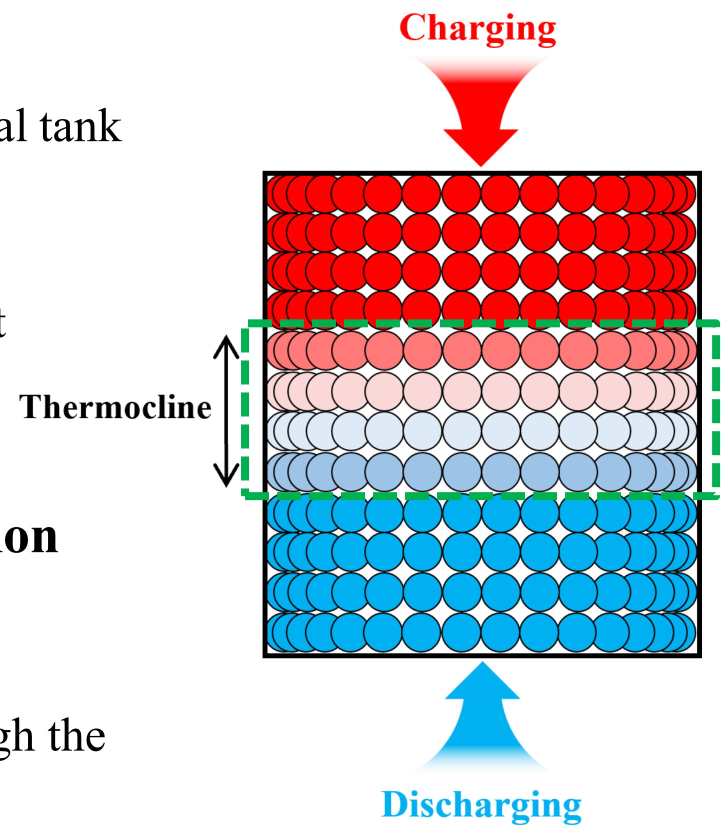
- Renewable energy generation rate ↑, intermittency issue arises
- Thermal energy storage (TES) can be a key solution for grid stability problem
- TES is considered for flexible operation of NPPs




Conceptual NPP with TES system
[Alva et al., 2018]

# TES system using packed bed

- **Packed bed thermal energy storage**
  - Randomly packed solid filler in cylindrical tank
  - Charging: hot fluid in → cold fluid out
  - Discharging: cold fluid in → hot fluid out
- **Different charging/discharging direction**
  - Thermocline formation
  - Keep constant hot temperature even though the tank is not completely charged




Principle scheme of packed bed TES

# Object of present study

- **Difficulties of TES experiments**
  - Expensive and time-consuming
  - Relying primarily on numerical investigations

- **Development of alternative experimental method**
  - Substituting of thermocline packed bed TES experiments
  - Utilizing the mass transfer experimental technique
  - Simulation of temperature gradient region (thermocline)

# Experimental setup

# Experimental methodology

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

Heat Transfer Problem → Mass Transfer Problem

↓

*Analogy concept*

Heat Transfer Solution ← Mass Transfer Solution

**[ Governing equations ]**

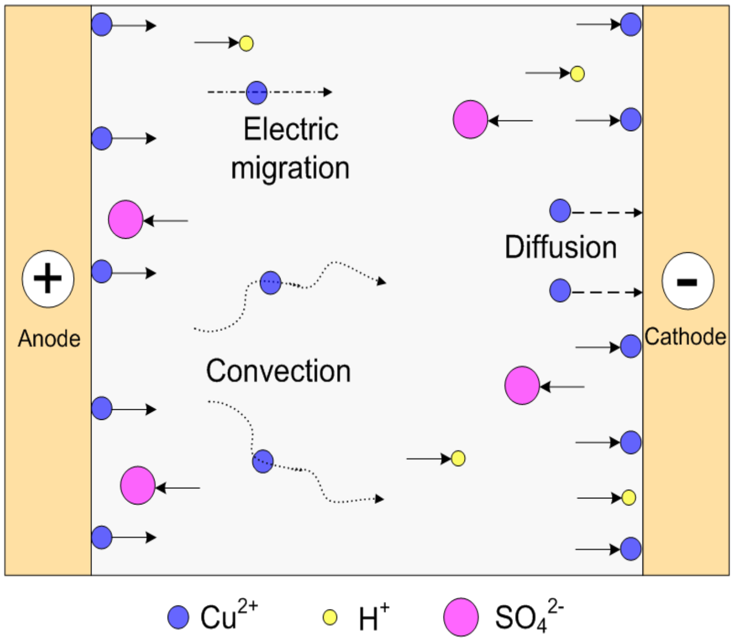
<table>
<tr><th>Heat transfer</th><th>Mass transfer</th></tr>
<tr><td colspan="2">$\frac{\partial u}{\partial x}+\frac{\partial u}{\partial y}=0$</td></tr>
<tr><td colspan="2">$\rho\frac{Du}{Dt}=-\frac{\partial P}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)+X$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

<table>
<tr><th colspan="2">Heat transfer</th><th colspan="2">Mass transfer</th></tr>
<tr><td>$Nu$</td><td>$\frac{hd}{k}$</td><td>$Sh$</td><td>$\frac{h_m d}{D_m}$</td></tr>
<tr><td>$Pr$</td><td>$\frac{\nu}{\alpha}$</td><td>$Sc$</td><td>$\frac{\nu}{D_m}$</td></tr>
<tr><td>$Ra$</td><td>$\frac{g\beta\Delta T d^3}{\alpha\nu}$</td><td>$Ra$</td><td>$\frac{gd^3}{D_m\nu}\frac{\Delta\rho}{\rho}$</td></tr>
</table>

# Copper electroplating system

**$CuSO_4$-$H_2SO_4$ solution**




**Anode** : $Cu \rightarrow Cu^{2+} + 2e^{-}$

**Cathode** : $Cu^{2+} + 2e^{-} \rightarrow Cu$

- **Mass transfer phenomena**

  = Diffusion + Convection + Electric migration

  Not exists in heat transfer, suppressed by $H_2SO_4$

- **Advantage of mass transfer experiment**
  - Simple experimental setup
  - No heat leakage
  - No radiation heat transfer

# Experimental methodology

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

Heat Transfer Problem → Mass Transfer Problem

↓

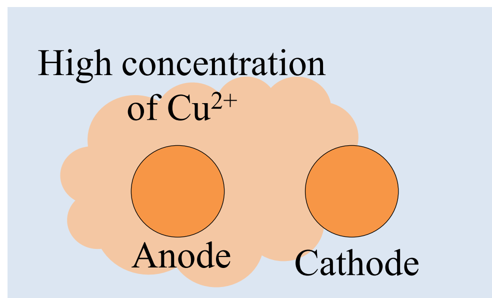
*Analogy concept*

Heat Transfer Solution ← Mass Transfer Solution

| Heat transfer | | Mass transfer |
|---|---|---|
| Hot wall | ⟷ | Cathode |
| Heat flux | | Electric current |
| Temperature | | Solution concentration |

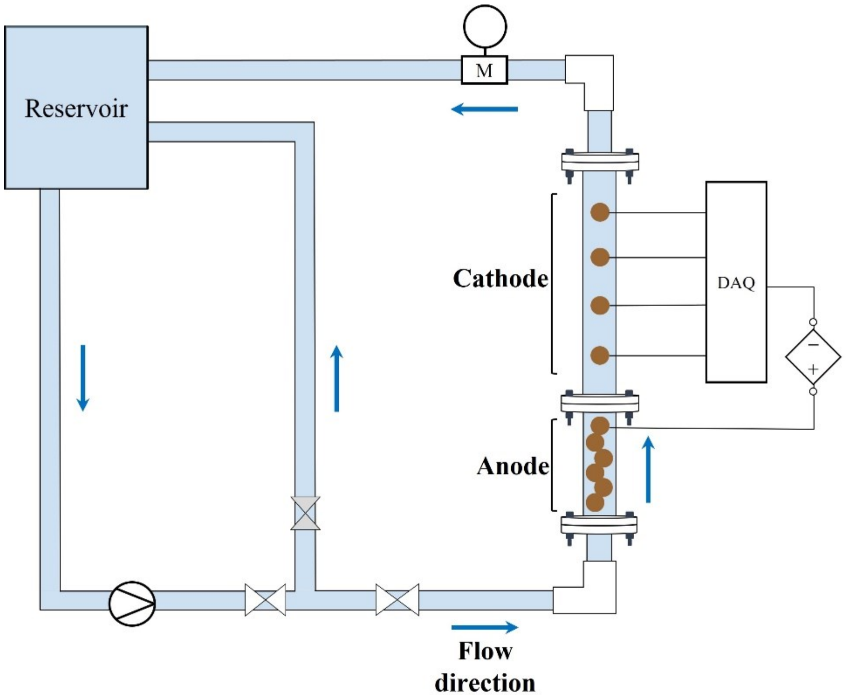
# Anode influence in mass transfer system

- **Position and distance of anode affects the measurement**
  - High concentration gradient of cupric ions is induced near the anode
  - In conventional mass transfer experiment, anode is located away from the cathode to preserve stable concentration gradient




- **However, to simulate temperature gradient in thermocline TES**
  - Should induces and maintains concentration gradient by maximizing anode influence.

# Apparatus and test matrix




| *D* (m) | *d* (m) | *H* (m) | ***Fluid velocity*** **(mm/s)** |
|---|---|---|---|
| 0.03 | 0.025 | 0.25 | 2.5, 10 |

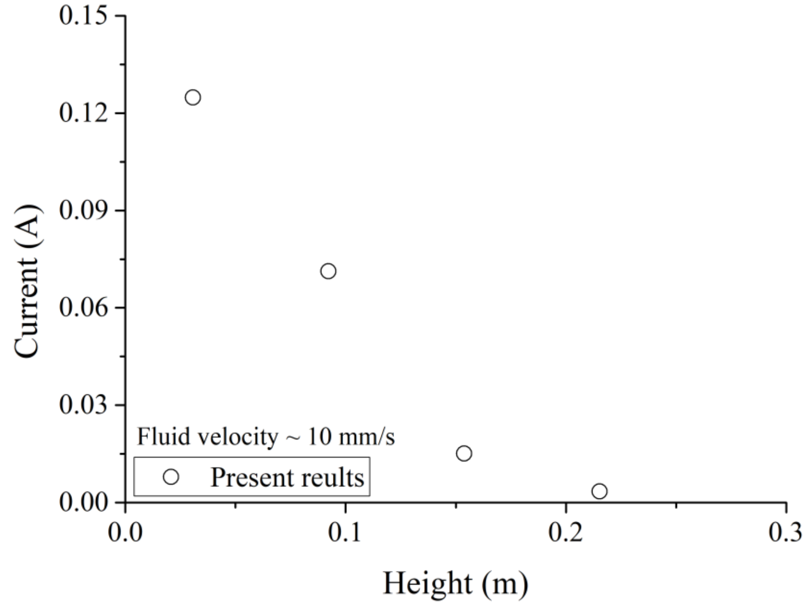
- 0.05M and 1.5M of $CuSO_4$-$H_2SO_4$ solution
- Fluid is pushed from the bottom to the top (discharging mode in TES)
- Voltage control (constant temperature cathode condition)

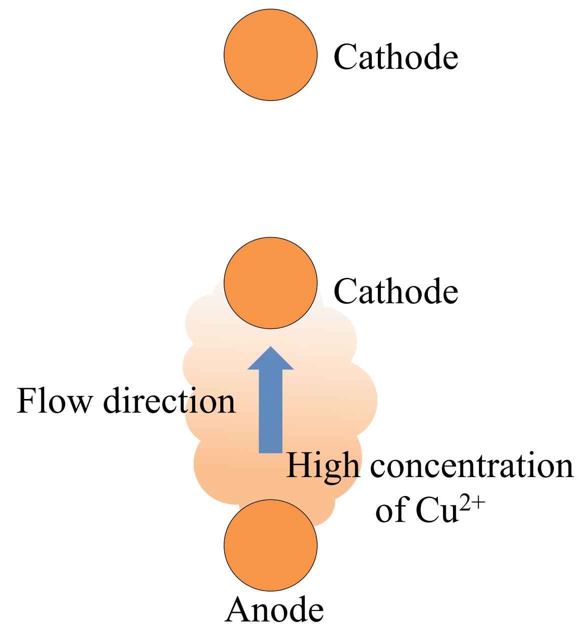
- **Anode is located just below cathodes**
  - To supply high concentration of cupric ion.
  - High density of cupric ions simulates the cold fluid in the TES system

# Results and discussion

# Results and discussion

- **Variation of measured current according to the height**

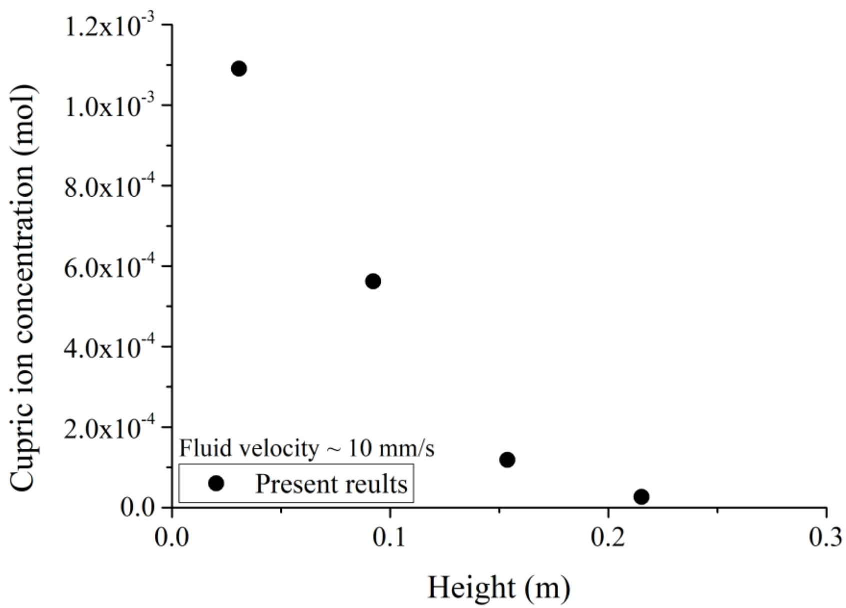



- Height ↑, electric current ↓
  - Front cathode meets the most abundant cupric ions
  - Concentration of the cupric ions gradually decrease.

# Results and discussion

- **Variation of local bulk concentration of cupric ion**



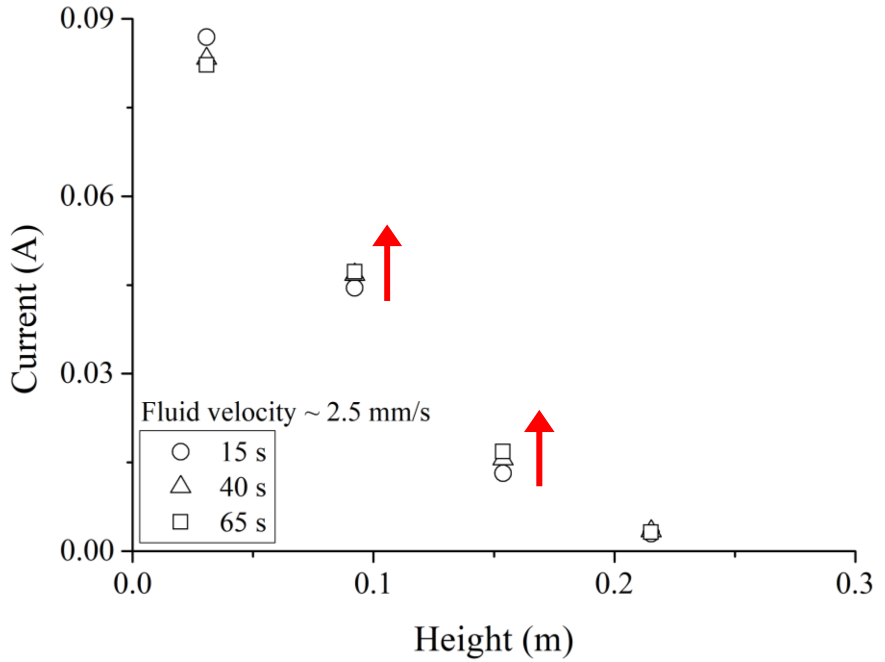

$$Local\ bulk\ concentration = \frac{\int I\ dt}{F \times n \times Local\ volume},$$

- $I$ : the measured current ($C/s$)
- $F$ : faraday constant (96,485 $C/mol$)
- $n$ : the number of electrons in charge transfer reaction

- Height ↑, local bulk concentration ↓
- Similar to the temperature gradient in the thermocline TES system.

# Results and discussion

- **Variation of current with time**




- Time goes by, electric current at high positioned cathodes increases.
- Concentration gradient moves by flow

# Conclusions

- **Temperature gradient zone was simulated by using mass transfer experiment**
  - Concentration gradient zone was formed by anode influence
  - Concentration gradient was moved by flow

- **Basic step for development of alternative experimental method for TES**
  - Not perfect to simulate temperature gradient
  - Further study needs to be performed under more sophisticated experimental conditions
    - Realistic packed bed configuration
    - Reducing uncertainty of calculated concentration

Thank you for your attention

# References

[1] A. Bruch, S. Molina, T. Esence, J. F. Fourmigue, R. Couturier, Experimental investigation of cycling behaviour of pilot-scale thermal oil packed-bed thermal storage system, Renewable Energy, Vol. 103, pp. 277–285, 2017.
[2] J. Y. Heo, J. H. Park, Y. J. Chae, S. H. Oh, S. Y. Lee, J. Y. Lee, N. Gnanapragasam, J. I. Lee, Evaluation of various large-scale energy storage technologies for flexible operation of existing pressurized water reactors, Nuclear Engineering and Technology, Vol. 53, pp. 2427–2444, 2021.
[3] C. Xu, Z. Wang, Y. He, X. Li, F. Bai, Sensitivity analysis of the numerical study on the thermal performance of a packed-bed molten salt thermocline thermal storage system, Applied Energy, Vol. 92, pp. 65–75, 2012.
[4] G. Li, Sensible heat thermal storage energy and exergy performance evaluations, Renewable and Sustainable Energy Review, Vol. 53, pp. 897–923, 2016.
[5] A. Bejan, Convection Heat Transfer, fourth ed. Wiley & Sons, New Jersey, 2003.
[6] C.W. Tobias and R.G. Hickman, Ionic mass transport by combined free and forced convection, International Journal of Research in Physical Chemistry Chemical Physics, Vol. 229, pp. 145–166, 1965.
[7] S.H. Ko et al., Applications of electroplating method for heat transfer studies using analogy concept, Nuclear Engineering and Technology, Vol. 38, pp. 251–258, 2006.
[8] H.K. Park and B.J. Chung, Mass Transfer Experiments for the Heat Load during In-Vessel Retention of Core Melt, Nuclear Engineering and Technology, Vol. 48, pp. 906–914, 2016.
[9] H.H. Ahn, J.Y. Moon, B.J. Chung, Anode influence on the electrochemical realization of packed bed heat transfer, Heat and Mass Transfer, Vol. 57, pp. 1685–1695, 2021.