Numerical Investigation on Mixed Convection Heat Transfer in a Packed Bed

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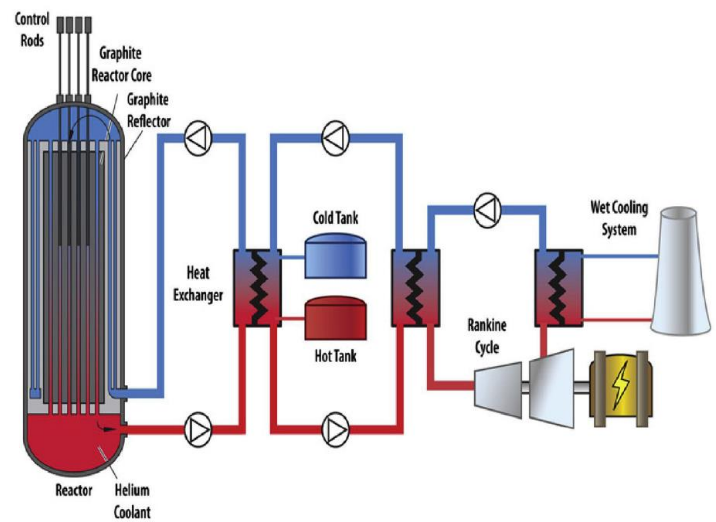
Introduction (1/2)

- **Challenges of renewable energy penetration**
  - Intermittent nature of energy source
  - Electric grid stability problem
- **Nuclear-Renewable Hybrid Energy Systems (N-R HES)**
  - Conceptual system integrating nuclear, renewables through energy storage
  - Conventional baseload operation → Flexible operation to compensate intermittency of renewables
- **Thermal Energy Storage (TES)**
  - Store energy in the form of heat
  - Widely used in concentrating solar power (CSP) plant
  - Being considered for use in NPPs



[Conceptual NPP with TES system]

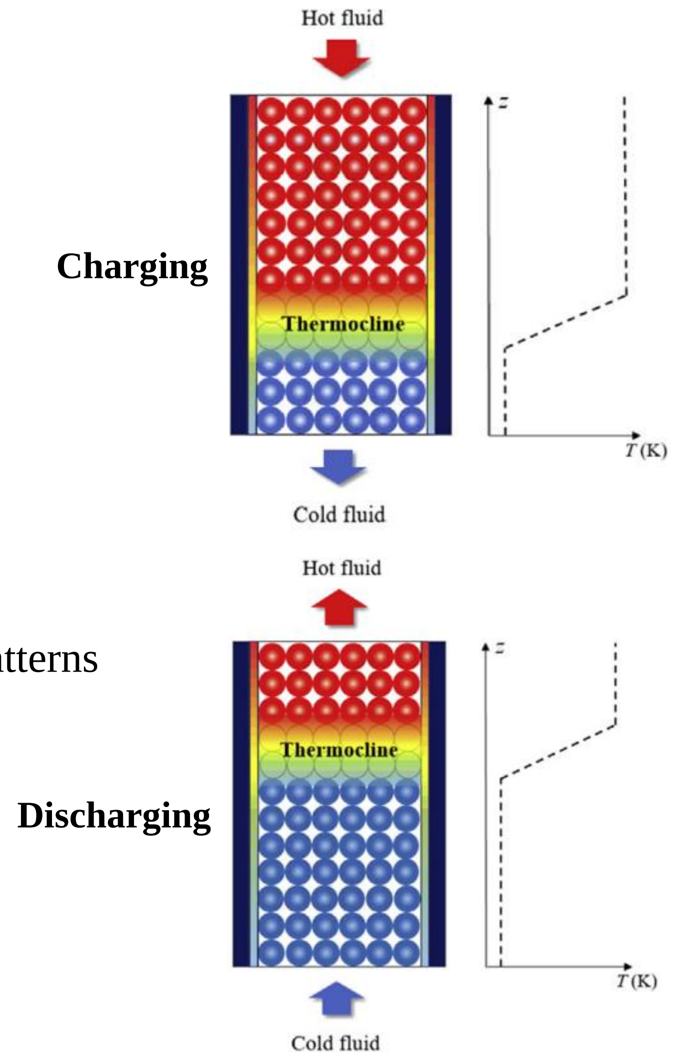
Introduction (2/2)

- **Packed bed Thermal Energy Storage (TES)**
  - Randomly packed solid filler in cylindrical tank
  - Charging : top-to-bottom flow
  - Discharging: bottom-to-top flow

- **Mixed convection heat transfer in packed bed TES**
  - Injection of low-speed heat transfer fluid
  - Changes in flow direction
  - Packed bed : Non-uniform temperature distribution and complex flow patterns

  Mixed convection + Structural characteristics

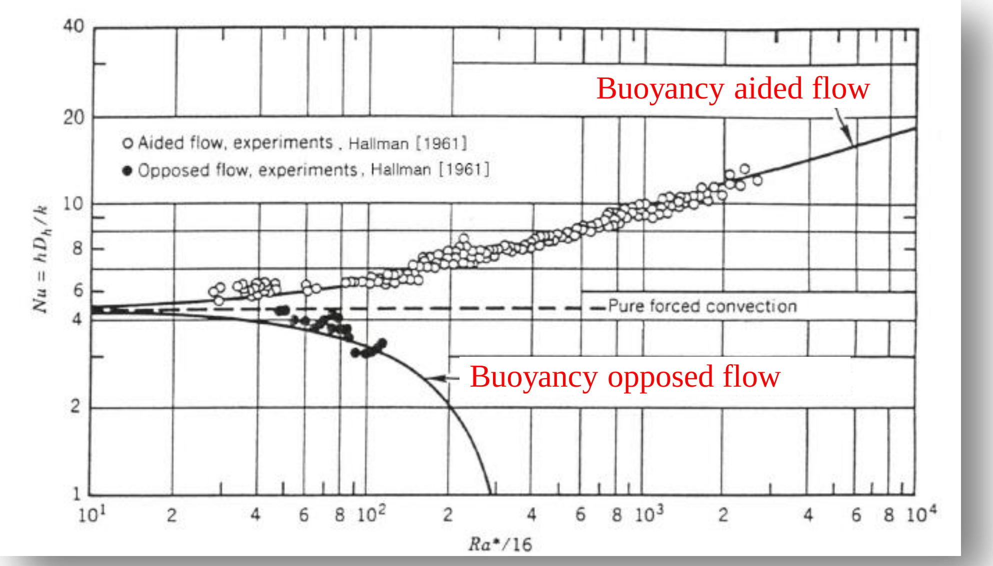
- **In this study, the phenomena of mixed convection heat transfer in packed bed was analyzed**



[Packed bed TES system (Xie *et al.*, 2022]

Laminar mixed convection in pipe

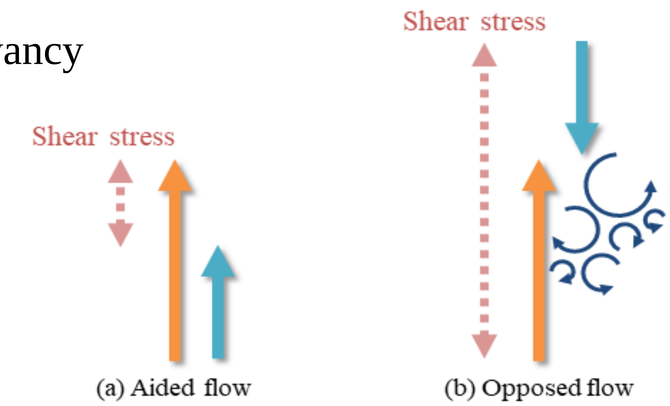
- **Buoyancy aided flow**
  - Heat transfer ↑
  - **Increase in flow velocity** due to the forced convection in the **same direction** as buoyancy
- **Buoyancy opposed flow**
  - Heat transfer ↓
  - **Decrease in flow velocity** due to the forced convection in the **opposite direction** to buoyancy

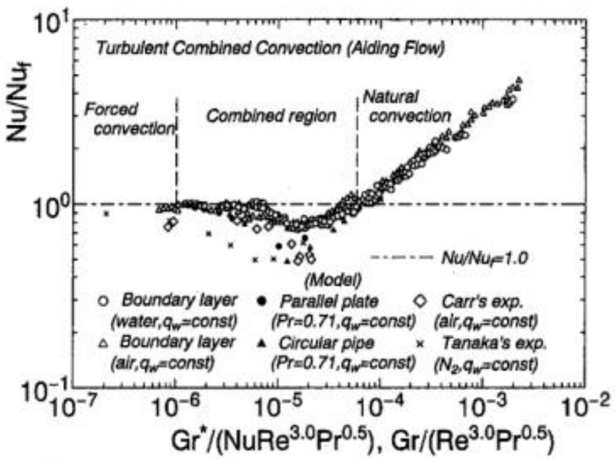


[Laminar mixed convection in vertical tube (Aung *et al*., 1987)]

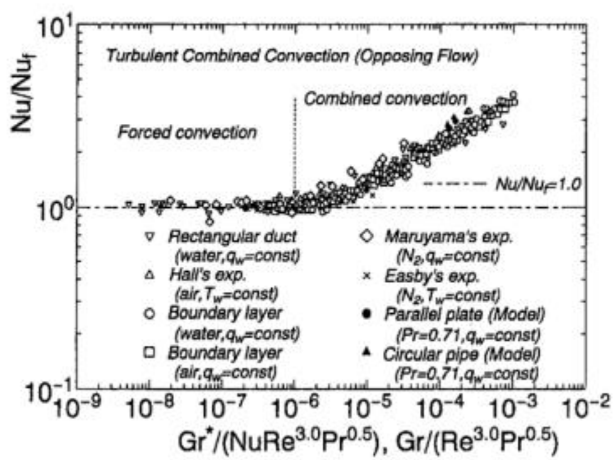
Turbulent mixed convection in pipe

- **Buoyancy aided flow**
  - Heat transfer decreases due to the increase in buoyancy coefficient, but then increases as the flow velocity increases further
  - Reduction of shear stress due to the flow in the same direction as buoyancy
  - Turbulent production ↓
- **Buoyancy opposed flow**
  - Heat transfer increases due to the increase in buoyancy coefficient.
  - Increasing shear stress in the opposite direction to buoyancy
  - Turbulent production ↑





(Buoyancy aided flow)



(Buoyancy opposed flow)

[Turbulent mixed convection in a vertical tube (Inagaki *et al*., 1996)]

Motivation and Objective

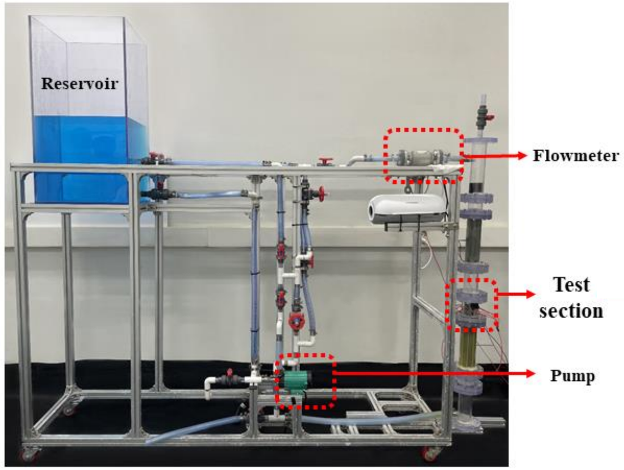
- **Phenomena difference**

	Pipe	Packed bed	
Heat transfer	Flow (shear)	Flow (shear)	Structural characteristics
Phenomenon	Turbulent production	Turbulent production	Vortex production
	Occurrence of turbulent motion through the interaction of buoyancy and flow		Occurrence of vortex motion through the collision between internal structure and flow

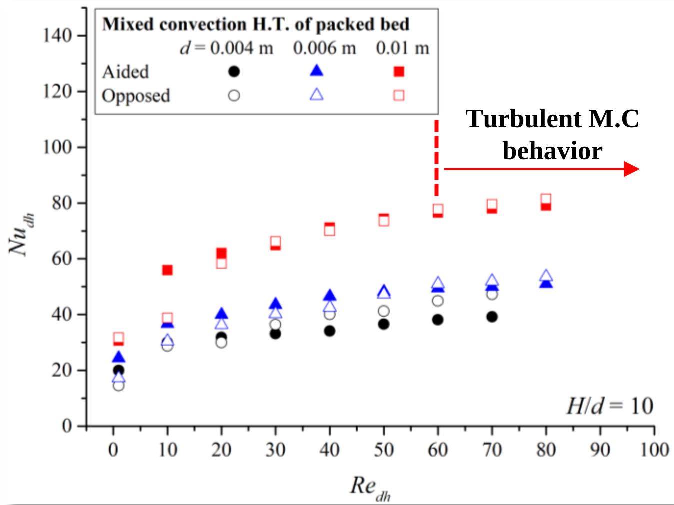
- **Objective of this study**
  - Numerical analysis on mixed convection heat transfer by varying parameters of packed bed
    - Tank height (*H*)
  - Analysis of local heat transfer for mixed convection behavior in packed bed

Existing study on mixed convection in packed bed

- **Existing study**



[Mass transfer experiment]



[Nu_{dh} according to Re_{dh}]

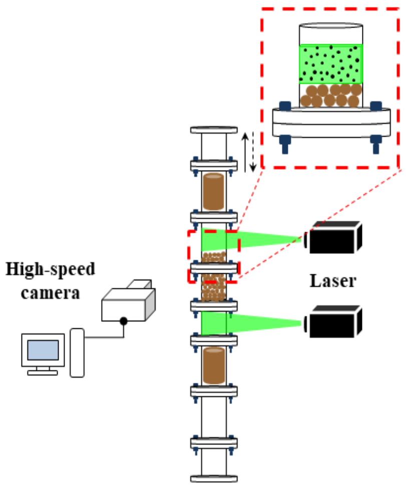
Heat transfer

Small Re_{dh}

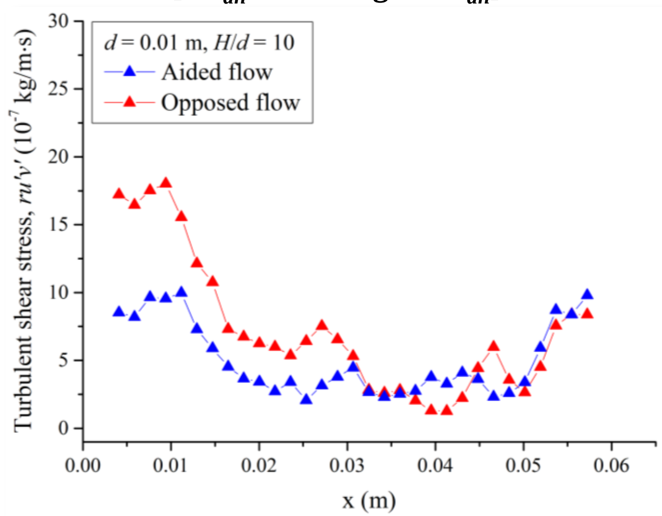
- Aided flow > Opposed flow
- Acceleration by buoyancy

Large Re_{dh}

- Aided flow < Opposed flow
- Vortex production
- Turbulent M.C behavior



[PIV experiment]



[Shear stress according to Re_{dh}]

Shear stress

Increased with Re_{dh}

- Aided flow < Opposed flow
- High shear stress for small d and large H

Numerical analysis

- Numerical study was conducted to clearly observe the turbulent mixed convection behavior in packed bed

Packed bed modeling
- Location coordinate (Python code)
- Ansys modeling

↓

Meshing
- Element dependency test

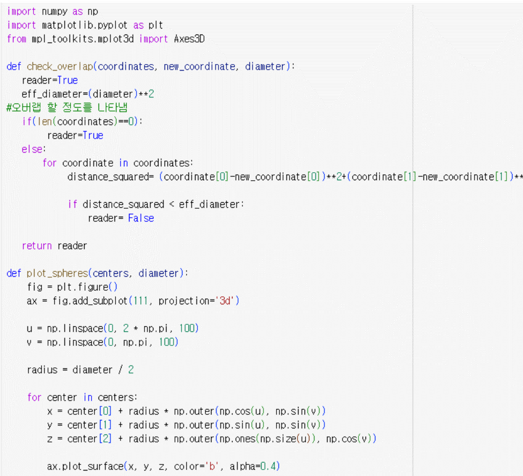
↓

Numerical analysis
- Flow velocity
- Heat transfer
- Turbulent intensity

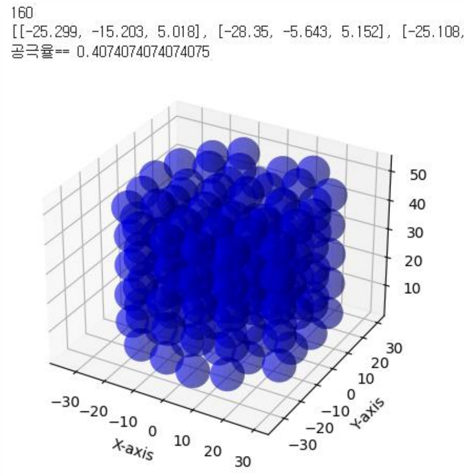
[Numerical analysis process]

CFD setup (packed bed modeling)

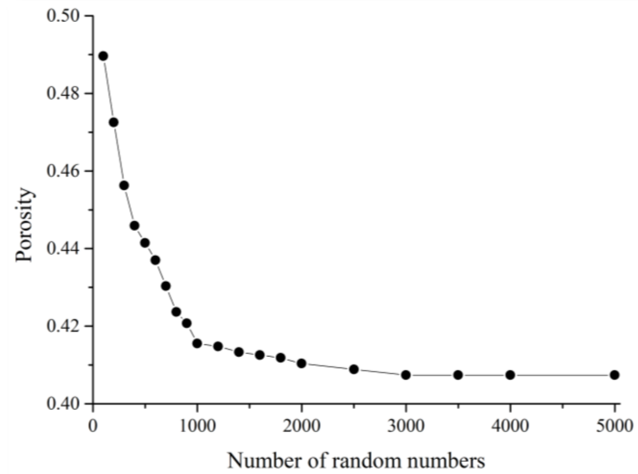
- **Location coordinate of packed bed**



```python
import numpy as np
import matplotlib.pyplot as plt
from mpl_toolkits.mplot3d import Axes3D

def check_overlap(coordinates, new_coordinate, diameter):
   reader=True
   eff_diameter=(diameter)**2
#오버랩 할 정도를 나타냄
   if(len(coordinates)==0):
        reader=True
   else:
       for coordinate in coordinates:
           distance_squared= (coordinate[0]-new_coordinate[0])**2+(coordinate[1]-new_coordinate[1])**

           if distance_squared < eff_diameter:
               reader= False

   return reader

def plot_spheres(centers, diameter):
    fig = plt.figure()
    ax = fig.add_subplot(111, projection='3d')

    u = np.linspace(0, 2 * np.pi, 100)
    v = np.linspace(0, np.pi, 100)

    radius = diameter / 2

    for center in centers:
        x = center[0] + radius * np.outer(np.cos(u), np.sin(v))
        y = center[1] + radius * np.outer(np.sin(u), np.sin(v))
        z = center[2] + radius * np.outer(np.ones(np.size(u)), np.cos(v))

        ax.plot_surface(x, y, z, color='b', alpha=0.4)
```

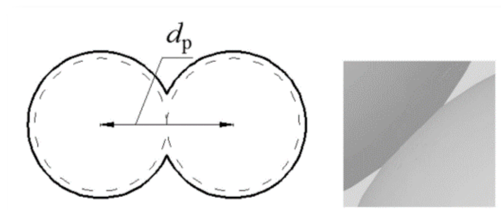


[Creating coordinates of packed bed in Python]



[Dependency test for random numbers]

- The location coordinates of packed bed were generated using random number generation in **Python code**
- Contact point model = **Overlaps** (less than 3 % of the sphere area)

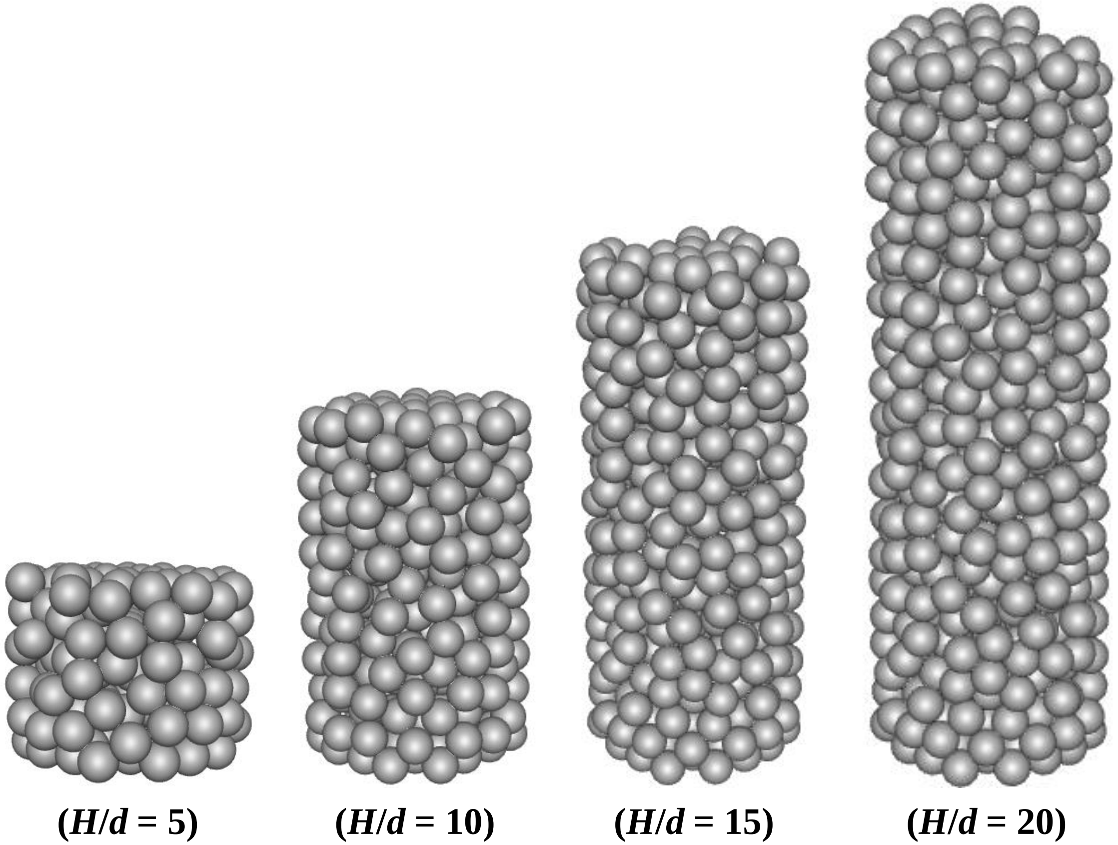


[Overlaps model (Bu *et al.*, 2004]

- As a result of dependency test of porosity according to random numbers, the porosity was constant at **0.41** after about 3,000 random numbers. (Porosity of packed bed = 0.39-0.43)

CFD setup (packed bed modeling)

- **Packed bed modeling**
  - Packed bed was simulated in ANSYS using location coordinates



[Packed bed modeling in ANSYS]

H/d	**Bed height (*H*)**	**Sphere diameter (*d*)**
5	0.05 m	0.01 m
10	0.10 m	
15	0.15 m	
20	0.20 m	

[*H* and *d* according to *H/d*]

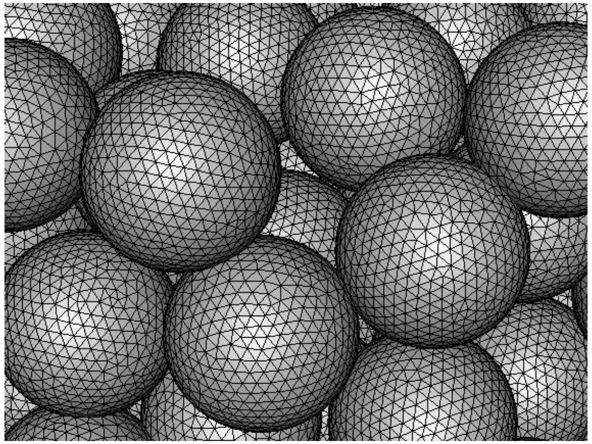
H/d	**Number of spheres**	**Porosity**
5	160	0.407
10	315	0.417
15	468	0.423
20	622	0.424

❖ **Porosity of packed bed = 0.41-0.43**

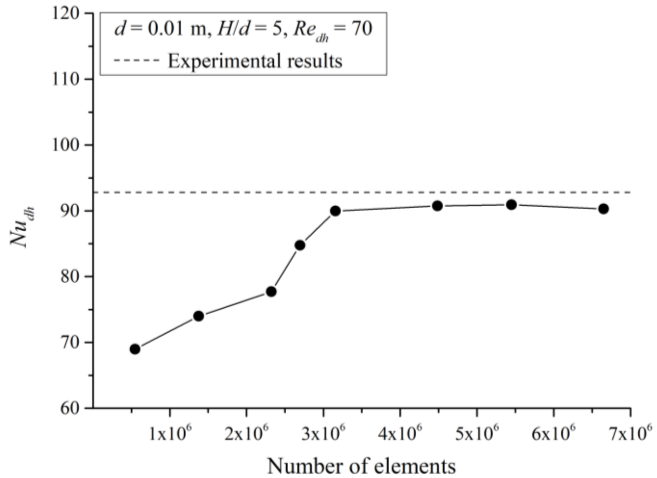
[Porosity of packed bed according to *H/d*]

CFD setup

- **Meshing**



[Mesh of packed bed in ANSYS meshing]

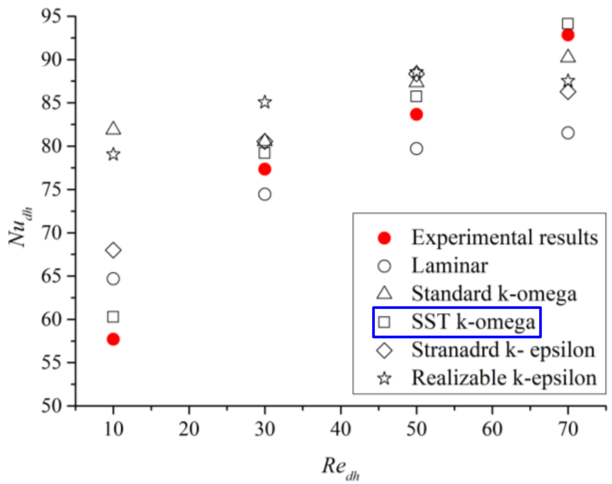


[Dependency test for number of elements]

Element size [mm]	Elements	Error rate [%]
1.0	1,378,047	-11.97
0.80	2,322,002	-8.69
0.75	2,696,680	-3.04
0.70	3,155,392	2.23
0.60	4,486,275	2.02
0.55	5,451,036	2.83
0.50	6,649,692	2.74

[Number of elements according to element size]

- **Turbulence model**

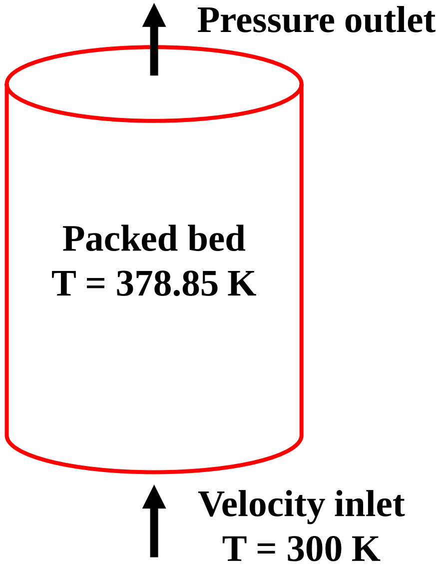


- **Turbulence model test**
  - RANS models except SST k-omega showed a large difference from experimental results in small Re_{dh}
  - Therefore, SST k-omega model was adopted as turbulence model in this work (Maximum relative error → 4.9 %)

CFD setup

- Simulation was performed by adopting the CFD code based on **ANSYS Fluent**

- Assumptions
  I. Uniform flow of constant velocity is injected into the tank
  II. Walls of bed are insulated (adiabatic condition)
  III. The properties of heat transfer fluid and solid spheres are independent of temperature



[Simulation method]

Scheme	Coupled
Turbulence model	SST k-omega
Spatial discretization	Second order
Residual	10^{-6}
Boundary condition	Inlet – velocity inlet Outlet – pressure outlet Wall – adiabatic

Test matrix

- **The range of test matrix for existing experimental studies has been extended**
  - H/d = 15, 20
  - Re_{dh} = 5-300

[Test matrix]

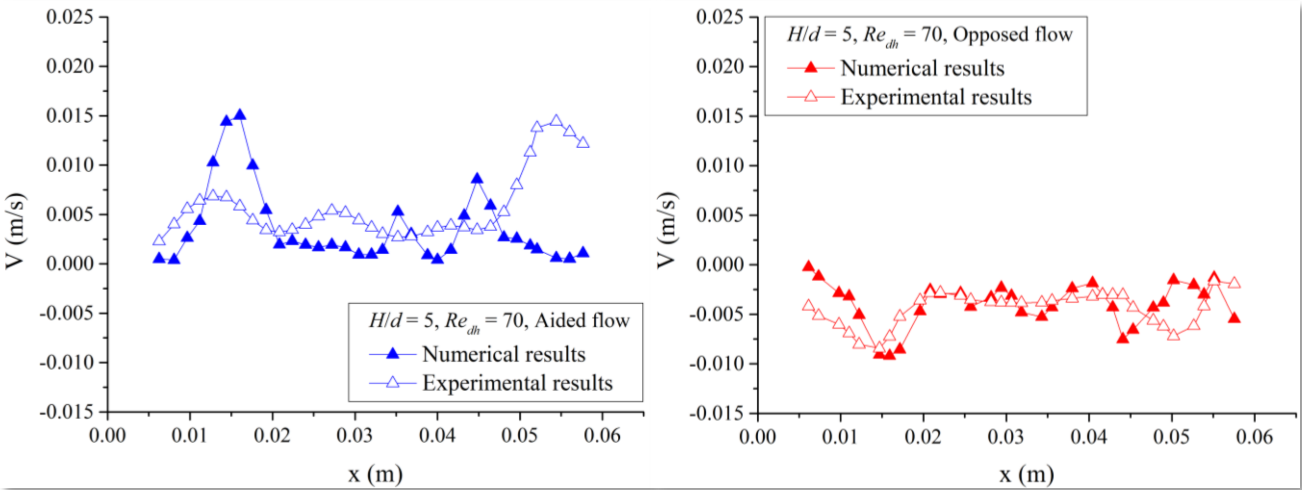
Pr	D [m]	d [m]	Ra_d	H/d	Re_{dh}	Temperature [K]		Flow direction
						Fluid	Spheres	
2,014	0.06	0.01	8.48×10^{-7}	5, 10, **15, 20**	5-**300**	300	378.85	Buoyancy aided, Opposed flow

[Properties of $CuSO_4$-H_2SO_4]

Density [kg/m³]	Viscosity [kg/(m·s)]	Specific heat [J/(kg· K)]	Thermal conductivity [W/(m·K)]	Thermal Diffusivity [m²/s]	Thermal expansion [1/K]
1097	1.25×10^{-3}	999.66	6.23×10^{-4}	5.68×10^{-10}	5.61×10^{-5}

Validation

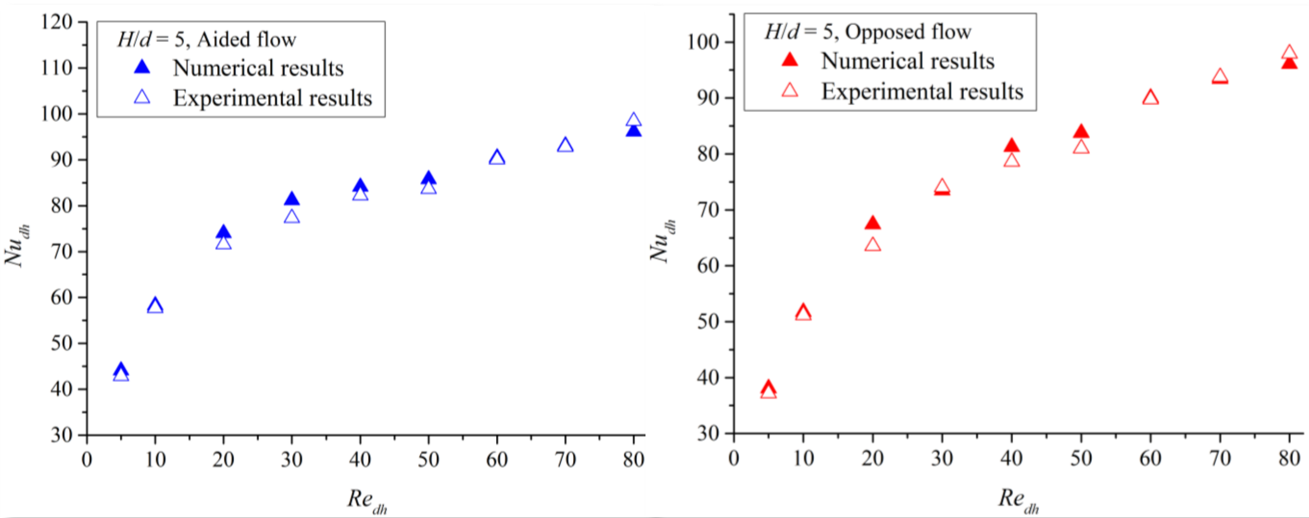
- **Flow velocity**



Flow velocity

- It showed non-uniform velocity distribution
- Peak values of velocity was similar to the existing experimental results

- **Heat transfer**



Heat transfer

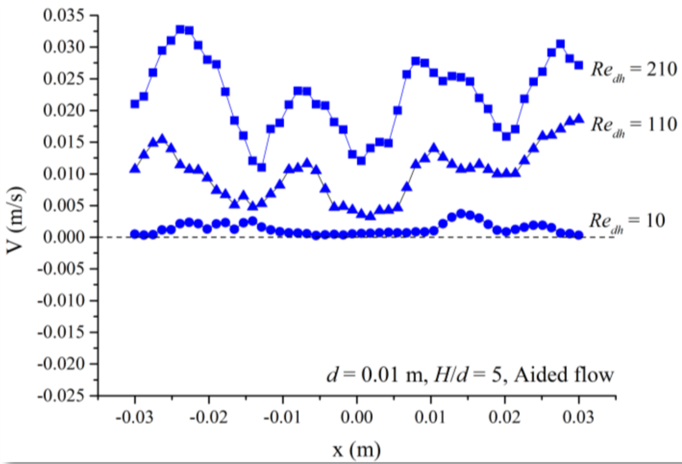
- Nu_{dh} for this work showed same trend as the results of experimental results

Maximum relative error

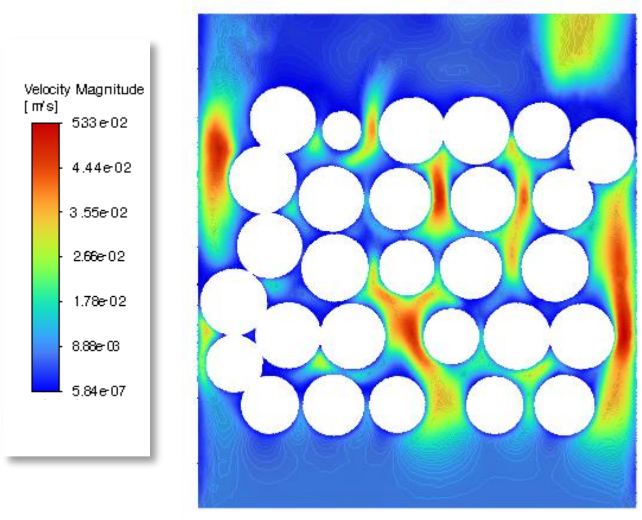
- $H/d = 5$ → 4.9 %
- $H/d = 10$ → 5.8 %

Results and discussion (CFD)

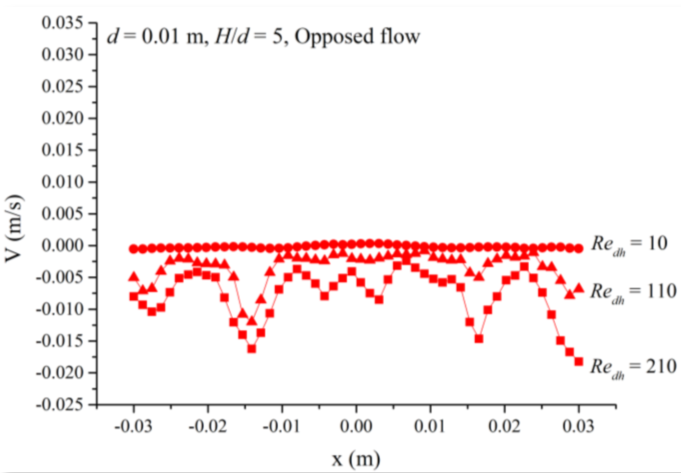
- **Flow velocity**



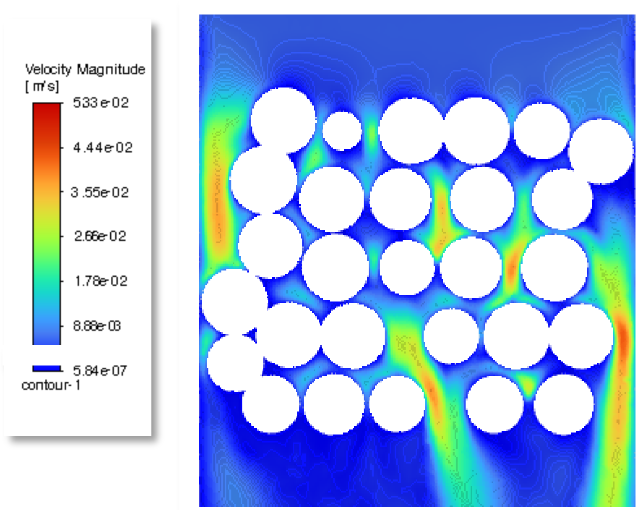
[Aided flow (*H*/*d*=5)]



[Contour of velocity (Aided)]



[Opposed flow (*H*/*d*=5)]



[Contour of velocity (Opposed)]

Flow velocity

Non-uniform behavior → Random packing

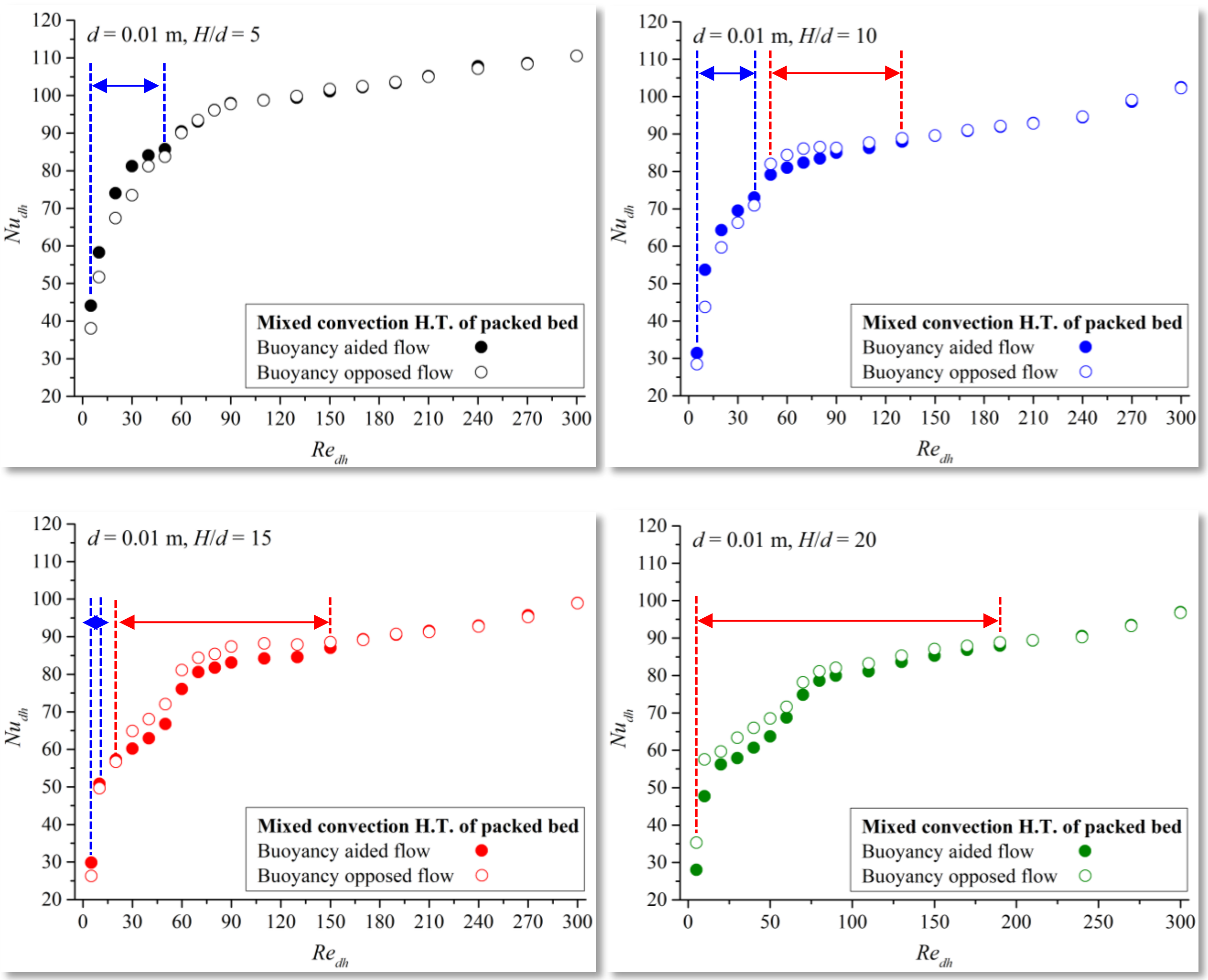
Wall region → Peak of velocity value

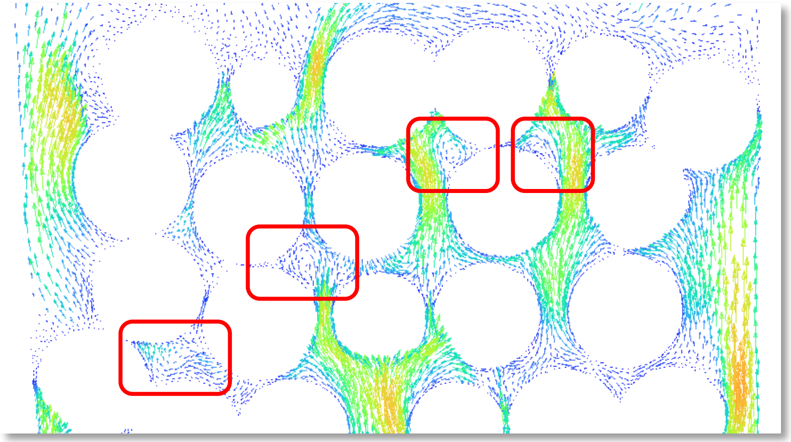
Increased with Re_{dh}

- Aided flow > Opposed flow
- Acceleration by buoyancy

Results and discussion (CFD)

- **Heat transfer**





[Velocity vector and vortex production]

Heat transfer

Small Re_{dh}

- Aided flow > Opposed flow
- Acceleration by buoyancy → Laminar M.C behavior

Large Re_{dh}

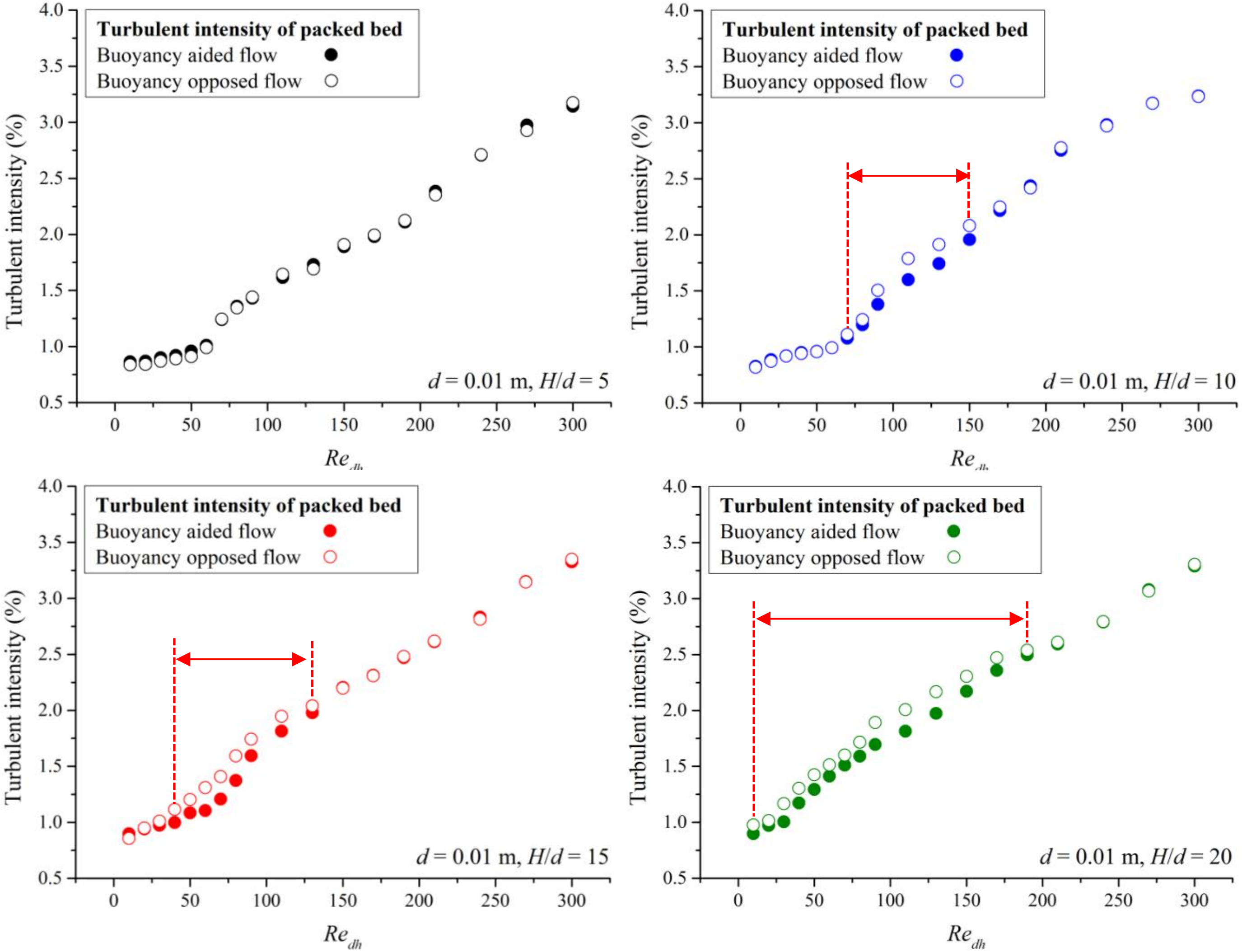
- Aided flow < Opposed flow
- Vortex production → Turbulent M.C behavior

Increased with H/d

- More impact on vortex production

Results and discussion (CFD)

- **Turbulent intensity**



Turbulent intensity

Turbulent M.C behavior region

- Aided flow < Opposed flow

Increased with *H*/*d*

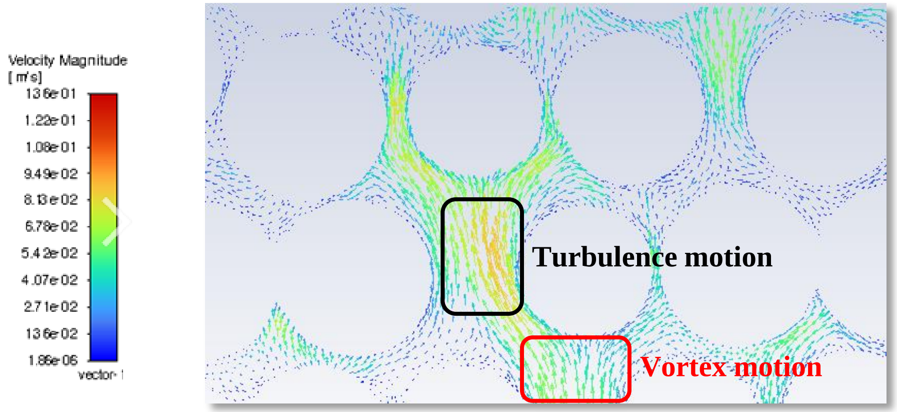
- More impact on turbulent intensity

$$I \equiv \frac{u'}{U}$$

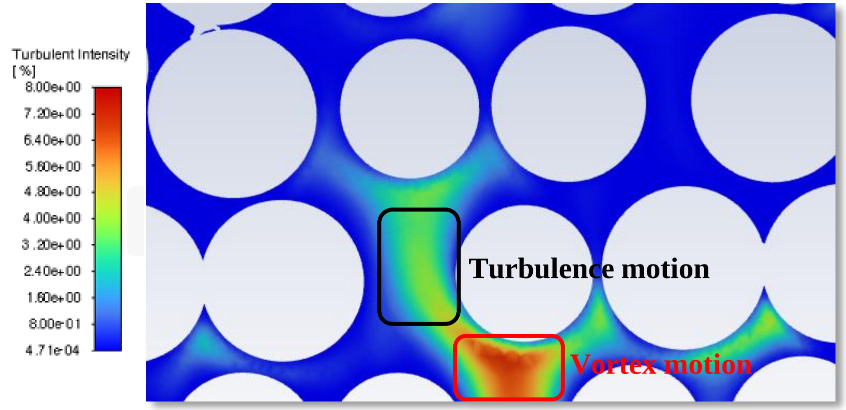
$$u' = \sqrt{\frac{1}{3}(u_x'^2 + u_y'^2 + u_z'^2)}$$

Results and discussion (CFD)

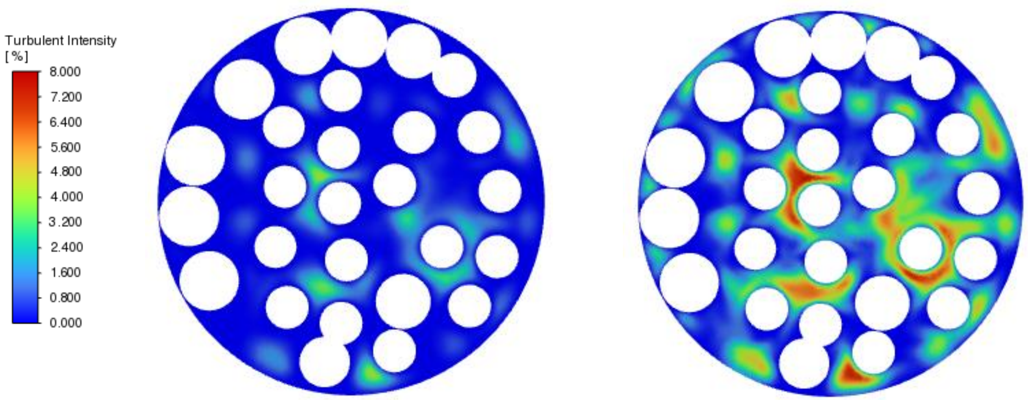
- **Turbulent intensity**



[Velocity vector]



[Contour of turbulent intensity]



(a) Re_{dh} = 10 **(b) Re_{dh} = 300**

[Contour of turbulent intensity according to Re_{dh}]

Turbulent intensity

Cause of increased turbulent intensity
- Turbulent production from flow
- Vortex production from packed bed

Mixed convection in packed bed
- Turbulence production < Vortex production

Conclusion

- **Numerical analysis on mixed convection heat transfer phenomena in packed bed was performed**

  - Varying the bed height

- **Packed beds were modeled using the location coordinates obtained through the in-house code**

  - The results of this study were consistent with those of existing experiments

- **Mixed convection heat transfer in packed bed**

  - Increased in flow velocity

    - Turbulent mixed convection behavior was observed due to the vortex production

  - Increased in bed height

    - Influence of vortex production increased

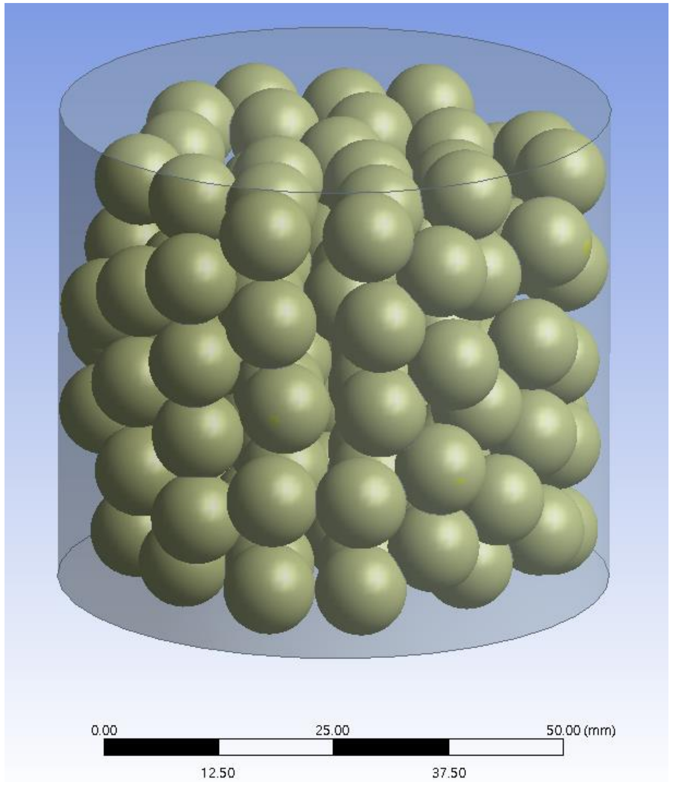
- **Mixed convection heat transfer in packed bed**

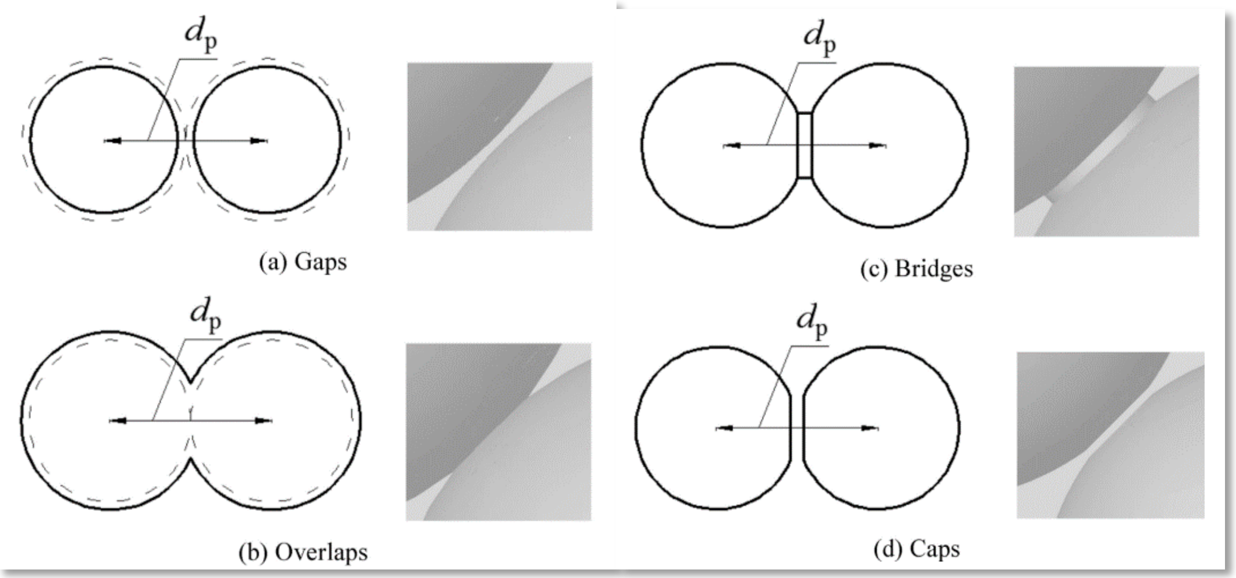
  - The behaviors of local mixed convection in packed were visualized to support the analysis results

Thank you for your attention

Appendix

Packed bed modeling





Methodology

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

Heat Transfer Problem → Mass Transfer Problem

Analogy concept

Mass Transfer Problem ↓ Mass Transfer Solution

Heat Transfer Solution ← Mass Transfer Solution

[Governing equations]

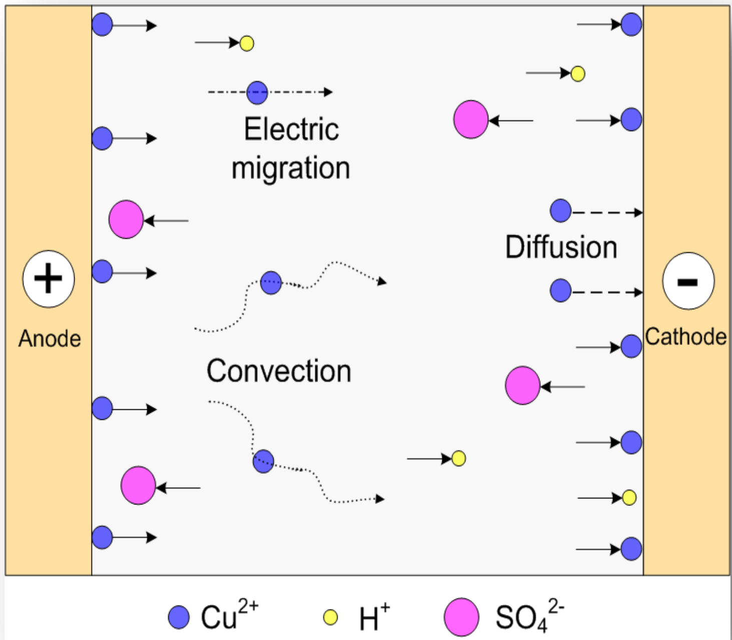
Heat transfer	Mass transfer
$\frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} = 0$	
$\rho \frac{Du}{Dt} = -\frac{\partial P}{\partial x} + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) + X$	
$\frac{DT}{Dt} = \alpha \nabla^2 T$	$\frac{DC}{Dt} = D_m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

[Dimensionless numbers]

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

Copper electroplating system

$CuSO_4$-H_2SO_4 solution



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

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

- **Total mass transfer rate (N_t)**

  = Diffusion (N_d) + Convection (N_c) + Electric migration (N_m)

  Not exist in heat transfer, thus suppress it using H_2SO_4

- **Mass transfer coefficient**

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

  $(1-t_n)I_{lim}/nF$ → **Mass flux**

  C_s → **$C_s \approx 0$**

$$h = \frac{q''}{(T_h - T_c)}$$

- **Advantage of mass transfer**
  - To achieve high Rayleigh number for small facility
  - No heat leakage
  - No radiation heat transfer

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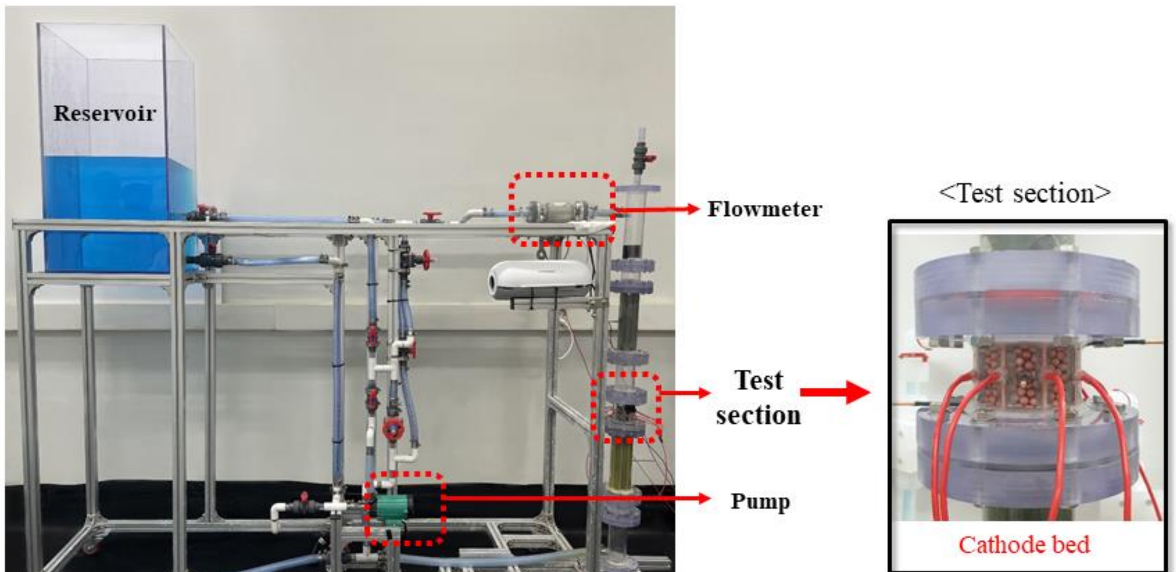
Experimental setup (Mass transfer)

- **The experiments of mixed convection heat transfer on all heating spheres in packed bed**



$d = 0.006$ m, $H/d = 10$

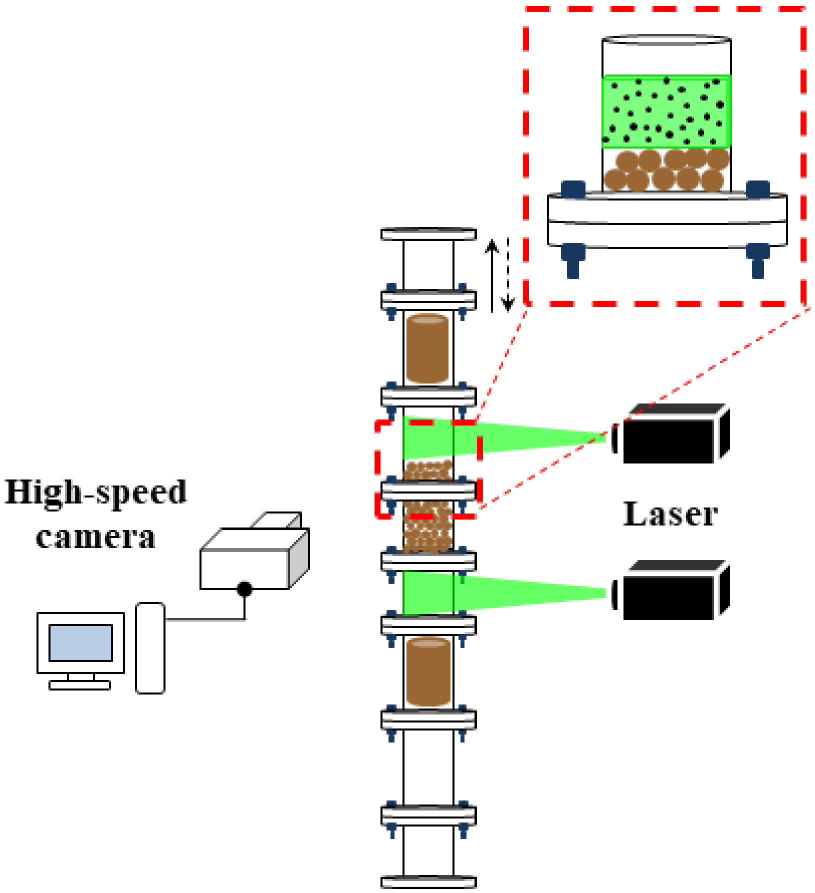
[Test matrix]

Sc	*D* [m]	*d* [m]	*H/d*	Re_{dh}	Flow direction
2,014	0.06	0.004	5, 10	1–70	Buoyancy aided, Opposed flow
		0.006		1–80	
		0.010		1-150	

- Each D/d → 6, 10 and 15
- Each H/d → 5, 10
- Volume flow rate = 0–2 L/min
- Porosity (ε) = 0.408–0.442
- The bed of glass spheres at upper and lower sections prevents the entrance and exit effects.
- All of the cases are under laminar condition.

Experimental setup (PIV)

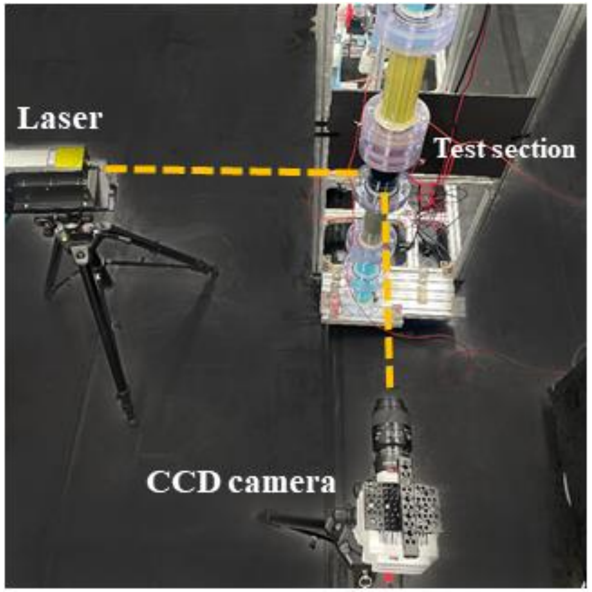
- **The experiments of PIV**



[Test matrix]

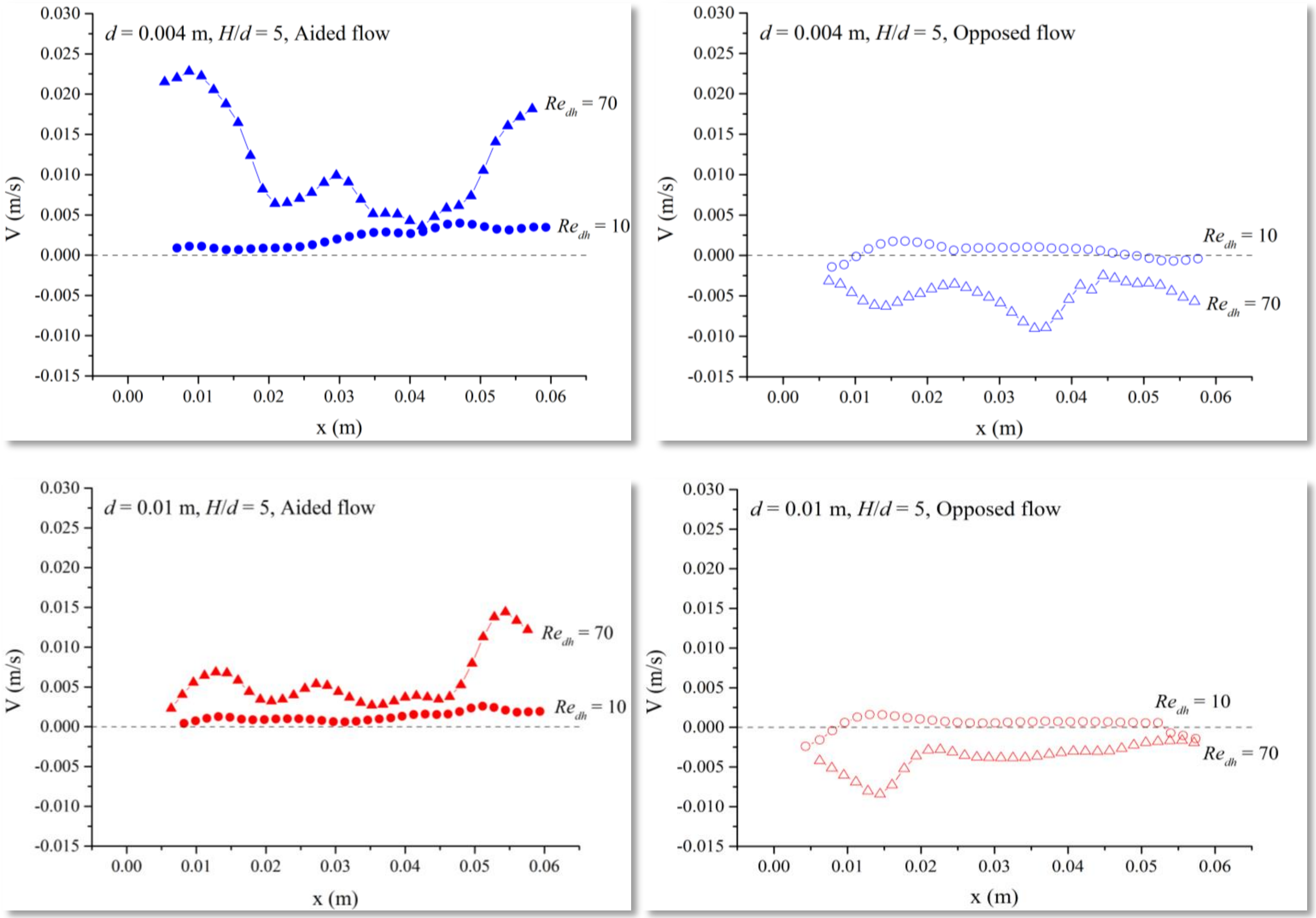
Sc	*D* [m]	*d* [m]	*H*/*d*	Re_{dh}
2,014	0.06	0.004	5, 10	10, 70
		0.010		10, 70, 170

- Filming the downstream
- Filming 1 cm away from the end of the bed
- Filming area is 3 cm × 3 cm



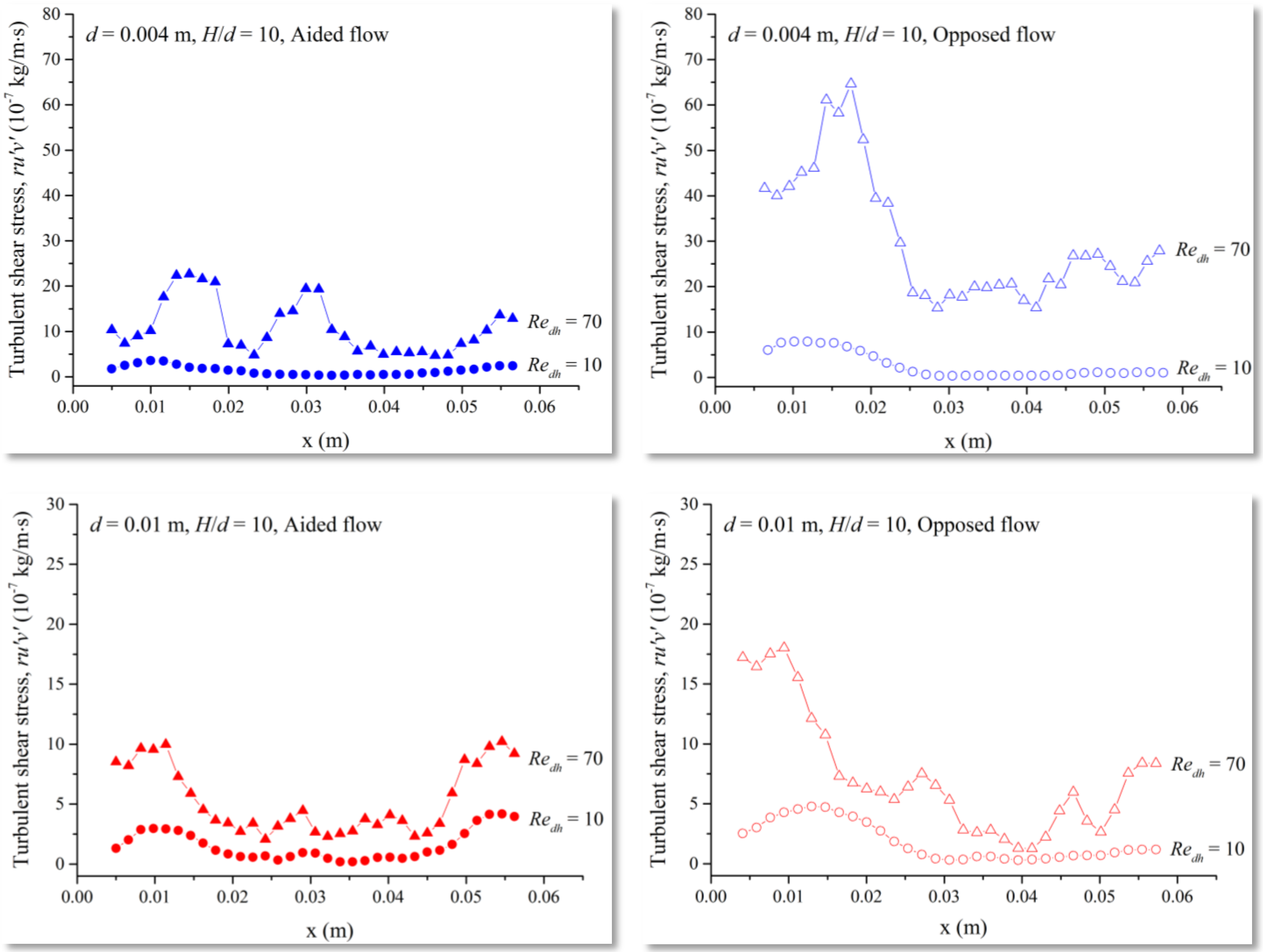
Results and discussion (PIV)

- **Flow velocity (*H*/*d* = 5)**



Results and discussion (PIV)

- **Turbulent shear stress (*H*/*d* = 10)**



Results and discussion (Heat transfer)

- **Heat transfer**