Influences of bed height on mixed convection heat transfer in a packed bed

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1. Introduction

Recently, the issues of variability and intermittency in renewable energy have been further emphasized as the rate of renewable energy generation increases in the electric grid system [1,2]. In response to these issues, numerous researchers have focused their efforts on studying thermal energy storage (TES) systems to facilitate the power control in various energy sources [3]. Packed bed TES is one of the energy storage types, which provides a flexible and efficient storage solution using the thermal stratification between the hot and cold fluids [4].

Packed bed TES involves a low-velocity charging and discharging process that minimizes mixing of fluids to keep the thermal stratification stable, enabling the coexistence of hot and cold fluids. The temperature gradient region between two fluids is called a thermocline [5]. Furthermore, this system employs a fluid with high buoyancy effect and operates at a very low velocity during the charging and discharging processes, resulting in mixed convection phenomena in the packed bed TES. The analysis of these mixed convection phenomena is challenging due to the influence of the packed bed geometry.

In this study, a computational study on mixed convection heat transfer in the packed bed geometry was conducted. The packed bed was modeled by utilizing in-house code to generate random numbers, and heat transfer analysis was conducted using Ansys Fluent a CFD commercial code. The bed height and Reynolds number were varied 5–10 and 5–300, respectively.

2. Background

2.1 Heat transfer on laminar mixed convection

Mixed convection is driven by the combined effect of natural and forced convections. Therefore, these phenomena can be categorized based on the flow direction of natural and forced convections. In general, when the direction of forced convection in the vertical tube aligns with the direction of buoyancy, it is termed buoyancy aided flow, while when they oppose each other, it is called buoyancy opposed flow.

In case of laminar mixed convection in the vertical tube, the direction of forced convection significantly affects the mixed convection heat transfer. Several researchers have reported that the heat transfer of the buoyancy aided flow is superior to that of the buoyancy opposed flow [6–8]. This is because the direction of aided flow aligns with buoyancy, resulting in an accelerated flow [6,7]. Conversely, in buoyancy opposed flow, the flow velocity is diminished due to the opposing direction of buoyancy, which leads to weakened heat transfer [8].

2.2 Heat transfer on turbulent mixed convection

The heat transfer of turbulent mixed convection in vertical tube is accompanied by the turbulence mechanism. Existing studies have shown that turbulent mixed convection has a different effect than in laminar region. They reported that in the case of heat transfer of buoyancy aided flow, it weakens as the buoyancy coefficient increases due to the buoyancy effect [9–10]. This is due to the reduced turbulent production at the edge of the viscous sublayer by the redistribution of shear stress near the heated walls and core regions [10].

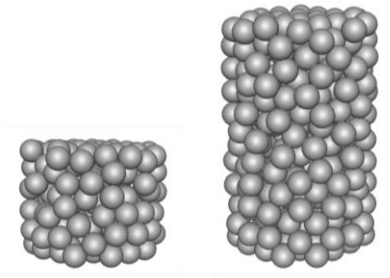
The heat transfer of buoyancy opposed flow is enhanced than that of the buoyancy aided flow [10–12]. In buoyancy opposed flow, forced convection operates in the opposite direction to the buoyancy, leading to increased shear stress by the friction with the buoyancy [11,12]. Thus, turbulence production in the flow is increased, thereby enhancing heat transfer.

3. Model description

3.1 Packed bed modeling

The packed bed was modeled using location coordinates obtained through a random number generator in Python code. To calculate the location coordinates of paced bed, input data such as the number of random numbers, sphere diameter, and the bed height were utilized. In addition, the packed bed was simulated using the design modeler in Ansys. Fig. 1 represents the packed bed for H/d of 5.

Figure 2 shows the results of the sensitivity analysis for the porosity based on the random number. According to the analysis results, the porosity converged to 0.41 after 2,000 cases, which is similar to the porosity of a randomly packed structure in the packed bed. Therefore, the number of random numbers was set to 2,000, and the location coordinates were calculated based on the height of the packed bed.



(a) H/d = 5 (b) H/d = 10

Fig. 1. Packed bed modeling in Ansys design modeler.

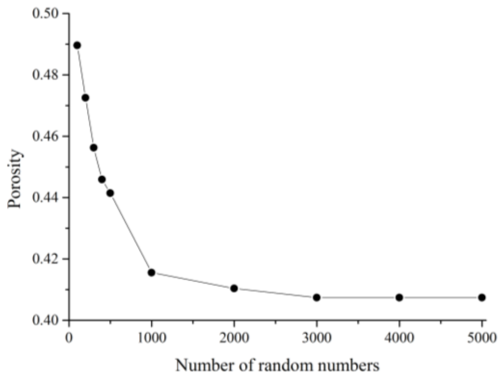


Fig. 2. Sensitivity analysis for random number for H/d = 5.

3.2 CFD model

In this work, the grid for each case was established in accordance with the height of the packed bed. The size of surface element was determined to be 0.7 mm through the dependency test, with approximately 3.1 million corresponding elements. For the analysis of temperature gradient on the sphere surface, a prism layer was utilized as the element condition, and the dimensionless wall distance(y^+) was maintained from 0 to 1.

In addition, the analysis was performed using Ansys Fluent, a CFD commercial code. The assumptions for this model are as below:

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

Coupled condition was adopted as the analysis solver, and SST k-omega was used as the turbulence model. This model requires a low y^+ and is recognized for its advantages in predicting heat transfer under low flow velocity conditions. The boundary conditions for the inlet and outlet are set as velocity inlet and pressure outlet, respectively, and the residual is 10^{-6}.

3.3 Test matrix

Table 1 shows the test matrix for mixed convection in packed bed. The diameter of bed(D) and spheres(d) was 0.01 m, which corresponds to Ra_{dh} of 8.48×10^{-7}. The bed height to sphere diameter ratios were 5 and 10. In addition, the temperature difference between the heat transfer fluid and sphere was about 78.85 K. The Re_{dh} varied from 5 to 300.

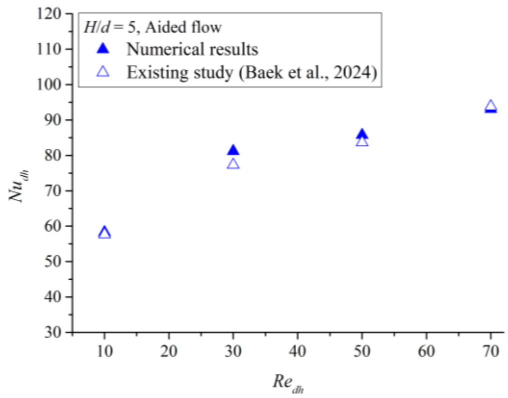
Table I: Test matrix for mixed convection in packed bed

Pr	D (m)	d (m)	Ra_{dh}	H/d	Re_{dh}
2,014	0.06	0.01	8.48×10^{-7}	5, 10	5–300

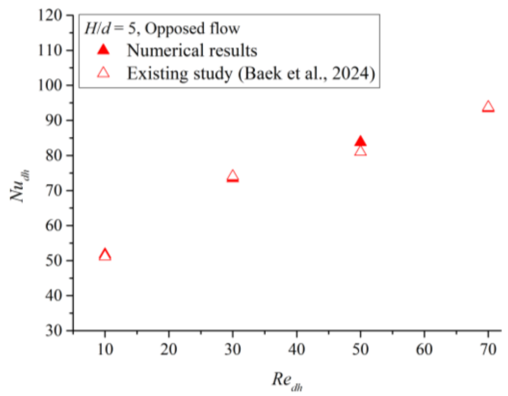
4. Results and discussion

4.1 Validation

We performed the validation test on the model in this analysis. Fig. 3 depicts a graph comparing the experimental results of mixed convection in the packed bed conducted by Baek et al. with the analysis results of this model [13]. The Nu_{dh} values corresponding to the flow velocity of buoyancy aided and opposed flow are presented. In all cases, the results of this work were similar to those of existing experiments, with a maximum relative error of 4.9 %.



(a) Aided flow



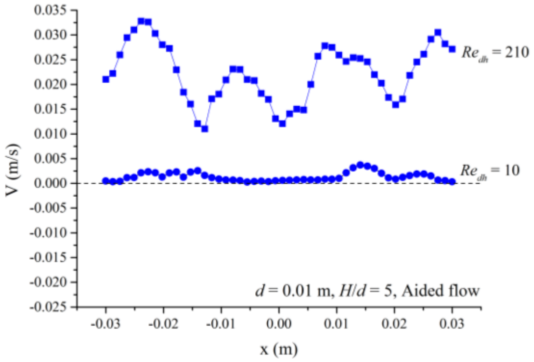
(b) Opposed flow

Fig. 3. Dependency test for element number for H/d = 5 and Re_{dh} =70.

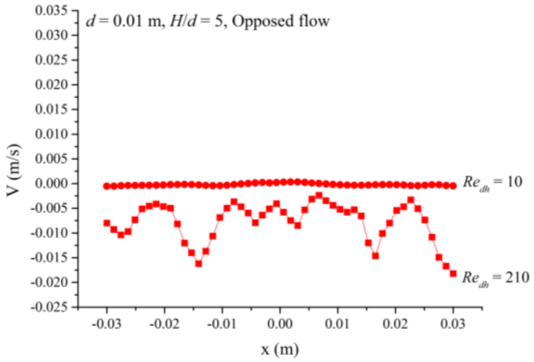
4.2 Flow characteristics of mixed convection in packed bed

Figure 4 shows the velocity profiles in packed bed according to the flow direction. The velocity profiles of both the buoyancy aided and opposed flow were non-uniform. This is due to the structural characteristics of the packed bed, which are influenced by the randomly accumulated spheres. At low flow velocity (Re_{dh}=10), the velocity distribution was flat along the x-direction because the effect of buoyancy was insignificant in all cases.

At high flow velocity, the velocity of the buoyancy aided flow increased significantly. This is because the forced convection and buoyancy directions align, resulting in flow acceleration. The velocity was peaked at the wall of the packed bed. As the flow velocity increased, the mixed convection flow moved toward the wall region with the highest local porosity. For the buoyancy opposed flow, as the flow velocity increased, forced convection became dominant over buoyancy, resulting in negative velocity measurements.



(a) Aided flow



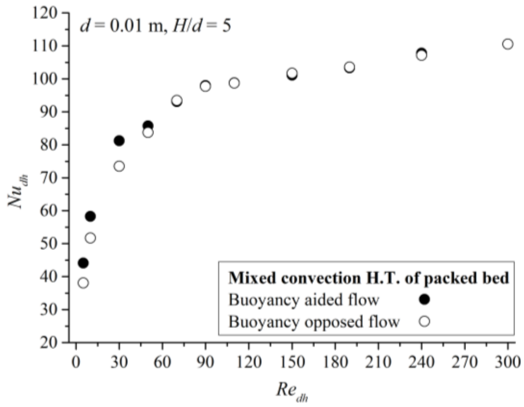
(b) Opposed flow

Fig. 4. Velocity distribution with Re_{dh} in packed bed for different flow directions.

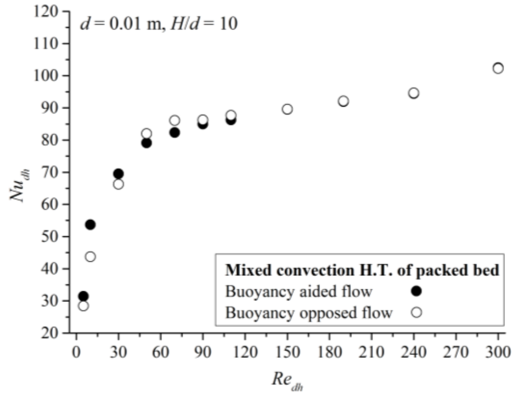
4.3 Heat transfer of mixed convection in packed bed

Figure 5 shows the Nu_{dh} values of packed bed velocity according to the flow direction. For H/d = 5, the heat transfer rate was higher than that of the opposed flow due to the acceleration of the flow at low Re_{dh} (Re_{dh} = 10–70). These observations were similar to the existing phenomena of laminar mixed convection observed in the vertical tube. When Re_{dh} was greater than 70, the effects of buoyancy in both flow direction cases weakened, and Nu_{dh} became almost the same.

For H/d = 10, the heat transfer of the aided flow was also improved compared to that of the opposed flow at low Re_{dh}, similar to the case of H/d = 5. However, as Re_{dh} increased, the heat transfer of the opposed flow was enhanced than that of the aided flow (Re_{dh} = 50–120). This corresponds to the turbulent mixed convection heat transfer behavior. This is due to the friction of the mixed convective flow resulting from the opposite directions of buoyancy and forced convection. With increasing flow velocity, the shear stress intensified, leading to the increase in the vortex generation. In addition, this turbulent mixed convection behavior becomes evident as the flow path becomes complex for high H/d ratios.



(a) H/d = 5



(b) H/d = 10

Fig. 5. Nu_{dh} variation with Re_{dh} in packed bed for different flow directions.

5. Conclusions

A computational analysis of mixed convection flow and heat transfer in the packed bed was performed. The packed bed was implemented by calculating the location coordinates through the random number in the in-house code. In addition, the model in this work was verified through comparison with the results of existing experimental studies.

For low *H*/*d*, the buoyancy aided flow showed enhancer heat transfer than the opposed flow due to acceleration of flow showing the laminar mixed convection behavior. However, for high *H*/*d*, the buoyancy opposed flow showed higher heat transfer rate because of vortices. This is attributed to the enhanced vortex production caused by the increase in shear stress of flow. Thus, the turbulent mixed convection heat transfer behavior became more evident for large *H*/*d*.

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