Experimental Study on Flow and Heat Transfer in Grid-Particle Composite Packed Beds: Postprint

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Abstract

Ordered particle packed beds offer the advantage of lower pressure drop compared to random particle packed beds; however, their practical implementation poses certain challenges. This study proposes a novel structure capable of rapidly achieving ordered packing, namely a composite particle packing structure with integrated grilles. The particle-fluid convective heat transfer coefficient within the grille-particle composite packing structure was investigated using the naphthalene sublimation heat-mass transfer analogy method. The results indicate that, compared with the simple cubic packing structure, the grille composite packing structure exhibits a marginally higher pressure drop but a substantial enhancement in heat transfer coefficient; conversely, when compared with random structures, it achieves a significant reduction in pressure drop with only a modest decrease in heat transfer coefficient. The grille-particle composite packing structure demonstrates the highest overall heat transfer coefficient, offering a new design paradigm for packed beds.

Full Text

Experimental Study on Fluid Flow and Heat Transfer in Grille-Sphere Composite Packed Bed

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Abstract

Structured packed beds offer lower pressure drop compared to randomly packed beds, but their practical implementation presents significant challenges. This paper introduces a novel configuration that enables rapid realization of ordered packing: the grille-sphere composite packed structure. The naphthalene sublimation technique combined with heat-mass transfer analogy was employed to investigate the particle-to-fluid convective heat transfer coefficient in this composite structure. Results demonstrate that compared to simple cubic packing, the grille-sphere composite packed bed exhibits slightly higher pressure drop but substantially enhanced heat transfer coefficient. Conversely, when compared to random packing, the composite structure achieves dramatically reduced pressure drop with only modest degradation in heat transfer performance. The grille-sphere composite packed bed achieves the highest overall heat transfer coefficient, offering a new design paradigm for packed bed systems.

Keywords: grille-sphere composite packed bed; structured packing; heat-mass transfer analogy; naphthalene sublimation; convective heat transfer

0 Introduction

Spherical packed beds are widely utilized as chemical reactors and pebble-bed nuclear reactors. Previous investigations by Ergun [?], Wakao et al. [?], Gunjal et al. [?], and Yang et al. [?, ?] have systematically studied flow and heat transfer characteristics in particle-packed beds.

The structural configuration of packed beds significantly influences their hydrodynamic and thermal performance. In randomly packed beds, the stochastic arrangement of particles creates complex and tortuous flow channels, resulting in substantial pressure drop. As flow rate increases, the enhancement in particle-to-fluid convective heat transfer coefficient comes at the cost of disproportionately large pressure drop increases, making random packing suboptimal for many applications [?]. In contrast, structured packed beds can substantially reduce pressure drop under appropriate configurations, such as simple cubic packing (SC) [?, ?]. However, random packed beds remain widely used in practice due to their low cost and ease of implementation.

To combine the advantages of both random and simple cubic packing while mitigating their respective drawbacks, this study proposes a grille-sphere composite packed structure that enables rapid achievement of ordered packing. In this configuration, the flow channel is first partitioned by a grille, and particles are then packed within each grille sub-channel. Since wall constraints promote relatively ordered particle arrangement near solid boundaries [?], the composite structure significantly improves packing order compared to random configurations, thereby substantially reducing pressure drop.

The present investigation focuses on a grille configuration with a channel-to-particle diameter ratio of unity, where each sub-channel accommodates exactly one column of spheres, effectively forming an SC arrangement. The entire structure can thus be viewed as multiple SC configurations in parallel. When air flows through the system, convective heat transfer occurs between the air and spheres. The naphthalene sublimation heat-mass analogy method was employed to determine the particle-to-fluid convective heat transfer coefficient and pressure drop characteristics, with results compared against both random packing and SC structures.

1 Experimental System

The naphthalene sublimation technique determines convective heat transfer coefficients by measuring mass transfer rates during sublimation. In this study, air served as the working fluid, supplied by a compressor and regulated by a control valve before exhausting to the atmosphere after passing through the test section. The experimental system is illustrated in [Figure 1: see original paper]. Air flow rate and temperature were measured using a vortex flowmeter and mercury thermometer, respectively. Pressure drop across the test section was recorded by a pressure scanning valve. Mass changes of the test specimens were measured with an analytical balance, and experimental duration was timed with a stopwatch.

The test section, fabricated from acrylic, had a length of 192 mm and a square cross-section of 96 × 96 mm. The stainless steel grille divided the flow channel into 7 × 7 sub-channels, each packed with 12 mm diameter glass spheres. In the naphthalene sublimation experiments, naphthalene spheres (cast in molds) replaced some glass spheres. When air flowed through the test section, naphthalene sublimation caused measurable mass loss. By weighing the naphthalene spheres before and after each test, the mass transfer rate between naphthalene and air was determined for specific configurations and operating conditions, enabling calculation of the corresponding heat transfer rate via heat-mass analogy theory. To eliminate entrance and exit effects, naphthalene spheres were positioned in the middle section of the test apparatus [?].

2 Data Processing Methods

The fundamental formulas employed for data reduction are presented below.

(1) Porosity

$$\varepsilon = \frac{V_{\text{gas}}}{V_{\text{tube}}} = \frac{V_{\text{tube}} - V_s}{V_{\text{tube}}}$$

where V_{gas} is the air flow volume (m^3), V_{tube} is the total channel volume (m^3), and V_s is the volume occupied by the packing material (m^3).

(2) Reynolds Number Re$_p$

$$\mathrm{Re}_p = \frac{q_V d_p}{A_C \nu}$$

where ν is the kinematic viscosity of air (m^2/s), calculated as for pure air; q_V is the volumetric flow rate (m^3/s); d_p is the particle diameter (m); and A_C is the cross-sectional area of the channel (m^2).

(3) Sherwood Number Sh

$$\mathrm{Sh} = \frac{h_m d_p}{D_f}$$

where h_m is the convective mass transfer coefficient (m/s), d_p is the particle diameter (m), and D_f is the diffusion coefficient of naphthalene in air (m^2/s). The Schmidt number Sc is taken as 2.5. The convective mass transfer coefficient is calculated as:

$$h_m = \frac{\Delta m}{\tau A(\rho_s - \rho_{s,\mathrm{bulk}})}$$

where Δm is the mass change of naphthalene (kg), τ is the experimental duration (s), A is the sublimation area (m^2), taken as the total surface area of all naphthalene spheres in the test section, ρ_s is the saturated vapor concentration of naphthalene at the sphere surface (kg/m^3), and $\rho_{s,\mathrm{bulk}}$ is the bulk naphthalene vapor concentration in the air stream (zero in these experiments). The saturated vapor concentration at the naphthalene surface is calculated from the following correlation [**?**]:

$$\rho_s = f(T_w)$$

where T_w is the naphthalene sphere surface temperature (K), taken as the average of the inlet temperatures measured before and after each experiment.

(4) Heat-Mass Transfer Analogy [?]

$$\mathrm{Nu} = \mathrm{Sh}\left(\frac{\mathrm{Pr}}{\mathrm{Sc}}\right)^n$$

where Nu is the Nusselt number, Sh is the Sherwood number, Pr is the Prandtl number of air, Sc is the Schmidt number, and n is the analogy exponent, taken as $n = 1/3$.

The particle-to-fluid convective heat transfer coefficient was measured at five volumetric flow rates under fully developed conditions. The data were correlated in terms of dimensionless Nusselt number as a function of Reynolds number, as shown in [Figure 3: see original paper]. The experimental results are compared with predictions for random packing (Wakao correlation [?]) and SC packing [?] for the same particle diameter.

Pressure drop across the grille-sphere composite packed bed was measured at various air flow rates. The relationship between pressure drop per unit length and Reynolds number is presented in [Figure 2: see original paper]. On the log-log coordinates, the data exhibit an essentially linear relationship, indicating that pressure drop increases progressively with flow rate. [Figure 2: see original paper] also includes pressure drop data for SC packing and random packing structures composed of 12 mm spheres. The solid line represents the pressure drop for random packing (Ergun correlation [?]), while the dashed line denotes SC packing pressure drop [?].

The results indicate that at a given Re_p, the pressure drop in the grille-sphere composite packed bed is slightly higher than that of SC packing but substantially lower than random packing. Specifically, the pressure drop is 1.34 times that of SC packing while only 30% of that in random packing. The increased pressure drop relative to SC packing arises from the additional flow resistance and reduced flow area caused by the grille. However, the pressure drop remains significantly lower than in random packing because the composite structure maintains ordered flow paths within each sub-channel, avoiding the complex tortuous passages characteristic of random packing. From a pressure drop perspective, simple ordered structures like SC packing effectively reduce flow resistance.

As shown in [Figure 3: see original paper], at identical Re_p, the Nusselt number for the grille-sphere composite packed structure is lower than that of random packing but higher than SC packing. The composite structure achieves a Nu approximately 1.94 times that of SC packing, reaching 76% of the value for random packing. In contrast, SC packing exhibits weak heat transfer performance, with Nu only 39% of that in random packing, despite its low pressure drop. The enhanced Nu in the composite structure relative to SC packing results from flow field modifications induced by the grille, which increases both maximum and average flow velocities in the sub-channels. However, because flow is confined within individual sub-channels, radial mixing is less intense than in random packing, resulting in inferior heat transfer performance.

From a heat transfer perspective, random packing provides the best thermal performance among the three configurations, primarily due to its lower porosity compared to SC and composite structures. Lower porosity means more spheres can be packed in a given volume, and the chaotic arrangement creates strong flow disturbances that enhance particle-fluid heat transfer.

3.3 Overall Heat Transfer Coefficient

The preceding results reveal that SC packing offers optimal pressure drop performance but suffers from significantly reduced heat transfer, while random packing provides the best heat transfer but at the expense of high pressure drop. The new grille-sphere composite structure substantially reduces pressure drop compared to random packing while maintaining relatively high heat transfer performance, and significantly enhances heat transfer relative to SC packing with only modest pressure drop increase. This superior matching of pressure drop and heat transfer characteristics is practically desirable. To quantitatively evaluate this balance, we define an overall heat transfer coefficient as the heat transfer coefficient per unit pressure drop:

$$\gamma = \frac{h}{\Delta p/\Delta x}$$

[Figure 4: see original paper] compares the overall heat transfer coefficients of random, SC, and grille-sphere composite packed beds. The results demonstrate that the grille-sphere composite packed bed achieves the highest overall heat transfer coefficient across all Re_p values, confirming its excellent combined flow and heat transfer characteristics.

These findings provide a new approach for enhancing packed bed performance. By introducing a grille structure that leverages wall constraints to improve packing order, pressure drop can be substantially reduced. Simultaneously, the grille divides the flow channel into multiple sub-channels, increasing local flow velocities and thereby enhancing heat transfer coefficients compared to unstructured arrangements.

4 Conclusions

1. The proposed grille-sphere composite packed structure improves the orderliness of random packing, enabling rapid achievement of relatively ordered packing configurations.
2. Compared to SC packing, the grille-sphere composite packed bed exhibits moderately higher pressure drop (1.34 times) while achieving substantially enhanced Nusselt number (1.94 times).
3. Compared to random packing, the composite structure dramatically reduces pressure drop (to 30% of random packing) with only modest reduction in Nusselt number (to 76% of random packing).
4. The grille-sphere composite packed bed achieves the highest overall heat transfer coefficient among the three configurations, demonstrating its superior combined performance.

References

[?] Ergun S. Fluid Flow through Packed Columns [J]. Chemical Engineering Progress, 1952, 48(2): 89-94

[?] Wakao N, Kaguei S, Funazkri T. Effect of Fluid Dispersion Coefficients on Particle-to-Fluid Heat Transfer Coefficients in Packed Beds [J]. Chemical Engineering Science, 1979, 34(3): 325-336

[?] Gunjal P R, Ranade V V, Chaudhari R V. Computational Study of a Single-Phase Flow in Packed Beds of Spheres [J]. AIChE Journal, 2005, 51: 365-378

[?] Yang J, Wang Q W, Zeng M, et al. Computational Study of Forced Convective Heat Transfer in Structured Packed Beds with Spherical or Ellipsoidal Particles [J]. Chemical Engineering Science, 2010, 65(2): 726-738

[?] Yang J, Wang J, Bu S S, et al. Experimental Analysis of Forced Convective Heat Transfer in Novel Structured Packed Beds of Particles [J]. Chemical Engineering Science, 2012, 71(6): 126-137

[?] Romkes S, Dautzenberg F, Van den Bleek C, et al. CFD Modelling and Experimental Validation of Particle-to-Fluid Mass and Heat Transfer in a Packed Bed at Very Low Channel to Particle Diameter Ratio [J]. Chemical Engineering Journal, 2003, 96(1): 3-13

[?] Calis H, Nijenhuis J, Paikert B, et al. CFD Modelling and Experimental Validation of Pressure Drop and Flow Profile in a Novel Structured Catalytic Reactor Packing [J]. Chemical Engineering Science, 2001, 56(4): 1713-1720

[?] WANG Jingyu, LIU Yan, YANG Jian, et al. Study on Particle-to-fluid Convective Heat Transfer Characteristics in Randomly Packed Bed [J]. Journal of Engineering Thermophysics, 2016, 37(10): 2202-2205

[?] Sogin H H. Sublimation from Disks to Air Streams Flowing Normal to Their Surfaces [J]. Trans ASME 1958, 80(1): 61-69

[?] Goldstein R J, Cho H H. A Review of Mass Transfer Measurement Using Naphthalene Sublimation [J]. Experimental Thermal and Fluid Science, 1995, 10(4): 368-397

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