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Coupled Effects of Packing Structure and Flow Regime on Radial Heat Transfer in 2D Packed Beds

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ABSTRACT

This study focuses on analyzing radial heat transfer behavior in packed bed systems using numerical modeling. Improving radial heat transfer under laminar flow conditions continues to be an important challenge across mechanical, aerospace, and chemical engineering applications. Emphasis is placed on conjugate heat transfer effects arising from coupled thermal interactions between the fluid and solid phases. This computational study examines the influence of porosity, diameter ratio, thermal conductivity, and packing arrangement on radial heat transfer performance as a function of the Reynolds number. A simplified annular tube geometry packed with circular particles (2D) is employed. Radial heat transfer performance is evaluated using effective thermal conductivity (ETC) as an integrated measure of heat transport within the packed bed, which represents the overall effectiveness of radial heat transfer. The simulations are limited to laminar flow conditions, reflecting operating regimes where low velocities are preferred to reduce pressure drop. A two-dimensional rectangular packed bed is filled with circular particles having varying diameter ratios (defined as the tube-to-particle diameter ratio, $1 < \wedge < 10$) and different porosities to investigate their effects on radial heat transfer. Two packing configurations regular and staggered are considered to evaluate the influence of packing structure on the effective thermal conductivity (ETC). The results indicate that radial thermal conductivity in two-dimensional packed beds is strongly dependent on particle size and packing arrangement. For aluminum particles, staggered packing with a diameter ratio ($\wedge$) of 3.39 yields the highest radial thermal conductivity, whereas in regular packing the maximum conductivity is observed at a diameter ratio of 3.21. Additionally, staggered packing of wood particles with a diameter ratio of 3.39 exhibits radial thermal conductivity comparable to that of regularly packed aluminum particles with a diameter ratio of 1.07.

1. Introduction

Packed bed reactors are commonly employed in industrial processes such as chemical conversion, material processing, and separation operations. These systems are also utilized in thermal applications including drying technologies, heat exchange devices, and solar energy storage. In its simplest configuration, a packed bed comprises a confining channel filled with solid packing elements. Common packing materials include steel, aluminum, and glass, and are commonly shaped as spheres, cylinders, hollow cylinders, irregular particles, or Raschig rings. Owing to their broad applicability in heat and mass transfer processes, the design of packed beds involves consideration of numerous parameters.

The heat transfer performance of a packed bed is quantified using effective thermal conductivity (ETC), which represents the overall effectiveness of radial heat transfer. The ETC is determined as a function of the wall heat transfer coefficient, wall temperature, extrapolated wall temperature, and radial temperature distribution. These parameters are obtained from COMSOL simulations and are subsequently used to calculate the ETC of the packed bed.

Gianpkoplis, Warren, and et.al [1,2] emphasize that there is a wide range of energy storage techniques available for diverse types of electrical applications. Packed bed reactors are not subject to significant geographical constraints or limitations. This form of thermal energy storage is relatively low in cost, contributes to mitigating the depletion of fossil fuels, and is environmentally friendly compared to many other renewable energy storage technologies. Packed bed thermal energy storage systems are employed in a variety of heating applications, including solar power storage, advanced adiabatic compressed air energy storage, pumped thermal energy storage, and liquid air energy storage.

The performance of thermal energy storage systems depends on several factors, such as heat transfer between the solid and fluid phases, thermal conduction within the packed bed, and heat losses through the reactor walls. Furthermore, the effectiveness of thermal storage is influenced by fluid flow configuration, particularly the axial and radial flow characteristics.

This study highlights the impact of packing size (tube-to-particle ratio) on the flow paths and heat transfer surface area. Larger packing elements create larger voids, reducing heat transfer efficiency, whereas smaller particles increase the surface area but can lead to higher pressure drops. The thermal conductivity of the packing material (metal, ceramic, composite) was also evaluated for its effect on heat transfer performance, with the goal of identifying optimal materials for specific applications. Additionally, the Reynolds number, a dimensionless quantity representing the flow regime, was used to assess the impact of the flow conditions on heat transfer. Laminar flow (low Reynolds number) was found to be desirable for minimizing pressure drops and enhancing thermal stability.

This paper integrates these factors through computational modeling and applies appropriate boundary conditions to optimize packed bed designs for enhanced thermal management, particularly for the Fischer-Tropsch applications.

Disclosure:

Portions of the modeling framework and baseline analysis in this study build upon the author's prior doctoral research and related publications. The present work extends those studies through revised interpretation, restructured analysis, and focused examination of packing arrangement and porosity effects under two-dimensional laminar flow conditions.

2. Literature Review

Radial heat transfer in packed beds is governed by parameters such as diameter ratio (bed-to-particle diameter ratio), particle material, shape, and packing arrangement. Demirel et al. [3] and Dixon [4] demonstrated that the effective radial thermal conductivity (ETC) increases with Reynolds number for various materials and geometries, with Dixon [4] reporting the highest ETC values for ceramic hollow cylinders at a diameter ratio of 5.1. Studies by Demirel et al. [3], Dixon [4], and Freiwald and Paterson [5] showed that Raschig rings and spherical particles with diameter ratios between approximately 5.6 and 7.9 yield ETC values in the range of 20–120 for Reynolds numbers between 300 and 1400, while Smirnov et al. [6] reported lower and non-linear ETC increases for expanded polystyrene spheres.

Pressure drop and packing structure were highlighted as critical design factors by Zehua et al. [7], who demonstrated that hollow-structured packed beds significantly reduce pressure drop while improving heat transfer efficiency, with an optimal diameter ratio of 2.88. Smirnov et al. [6] further showed that shaped particles enhance radial heat transfer and reduce pressure drop, with radial conductivity increasing with channel cross-sectional area. The importance of diameter ratio and wall effects was emphasized by Dixon [4] and Peng et al. [8], who reported enhanced ETC and Nusselt numbers for small diameter ratios, as well as periodic oscillations of the fluid-to-wall heat transfer coefficient.

Comparative studies by Ying et al. [10] and Borkink and Westerterp [9] indicated that ring-type packings and spherical particles with small diameter ratios can produce comparable wall-to-fluid heat transfer coefficients, with particle arrangement playing a crucial role in radial heat transfer performance. Mariana et al. [11] identified higher ETC values for spherical particles with diameter ratios between 5 and 15, while Borkink and Dong-Young et al. [9,12] reported a decrease in Nusselt number with increasing packed bed height. Yusuke et al. [13] highlighted the roles of void fraction, particle contact, and combined heat transfer mechanisms, and Mandal et al. [14] demonstrated that ETC increases with superficial velocity, particle size, and the use of helium as a working fluid.

3. Methodology

3.1 Conservation of mass

$$\rho\nabla \cdot (u) = 0 \quad (1)$$

3.2 Conservation of momentum

$$\rho\, (u \cdot \nabla)\, (u) = \nabla \cdot [-P[I] + [A]] + F + \rho g \quad (2)$$

$$A = \mu(\nabla u + (\nabla u)^T)$$

3.3 Conservation of energy

$$(\rho\, c_p)\, u \cdot \nabla T + \nabla \cdot q = Q + q_0 + Q_{vd} \quad (3)$$

$$q = -K \cdot \nabla T$$

3.4 Effective Thermal Conductivity of a packed bed

The ETC of a rectangular packed bed is calculated using equation (5). [15, 16, 17,18]

$$Q = \frac{K_e\ \Delta T_{Avg}}{L} \quad (4)$$

$$K_e = \frac{Q\, L}{\Delta T_{Avg}} \quad (5)$$

4. Design and Analysis

The design and analysis of packed bed was performed using COMSOL Multiphysics software to capture the results effectively.

4.1 Design

In the present study, a two-dimensional rectangular packed bed with a length of 60 mm and a width of 20 mm is considered. The bed is filled with solid circular particles, as illustrated in Figure 1, and analyzed for a range of diameter ratios ($1 < \wedge < 10$). The solid particles are assumed to be composed of aluminum, brick, and other selected materials to evaluate the effect of particle thermal conductivity on radial heat transfer. Figure 1 presents the geometries corresponding to different diameter ratios while maintaining constant porosity. Adequate spacing between the particles is provided to allow fluid flow through the packed bed [17].

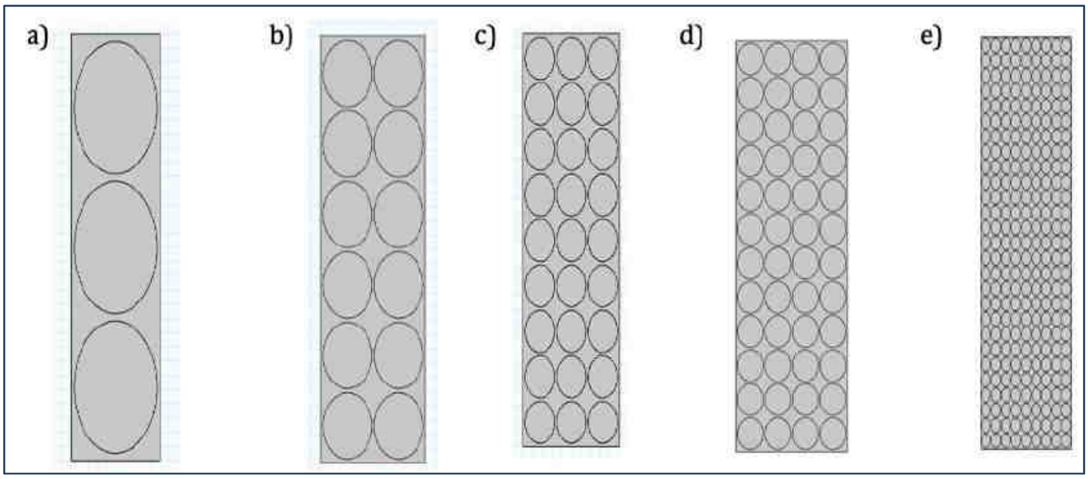

Figure 1: Packed bed with circles with different diameter ratio of a circle a) $\wedge = 1.07$, b) $\wedge = 2.14$, c) $\wedge = 3.21$, d) $\wedge = 4.28$, and e) $\wedge = 9.66$ [17]

Similarly, a staggered packing arrangement of circular particles with three diameter ratios and a porosity of 0.316 is considered, as shown in Figure 3, for comparison with the regular packing configuration presented in Figure 2. This setup is used to investigate the effect of packing patterns on radial heat transfer. In the staggered arrangement, the spacing between particles is non-uniform [17].

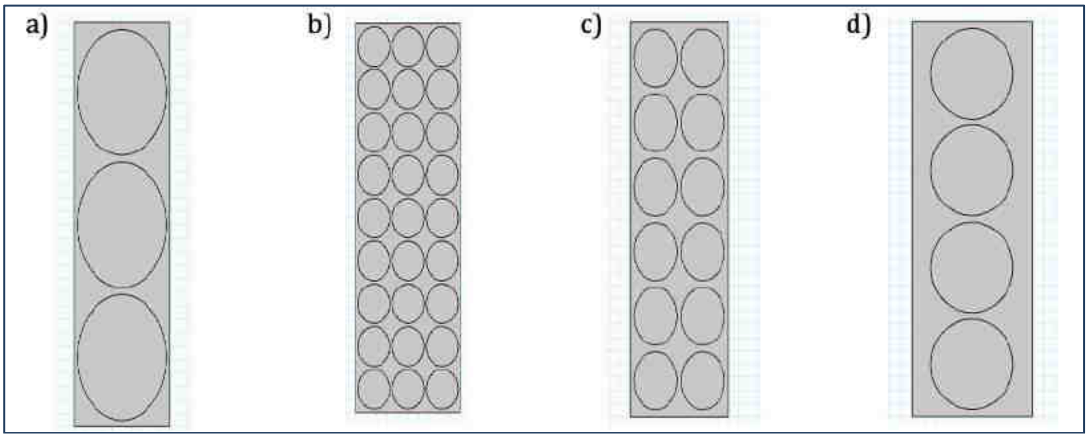

Figure 2: Packed bed with regular packing with different porosity $a)\ \varepsilon = 0.316$, $b)\ \varepsilon = 0.34$, $c)\ \varepsilon = 0.387$, and $d)\ \varepsilon = 0.505$ [17]

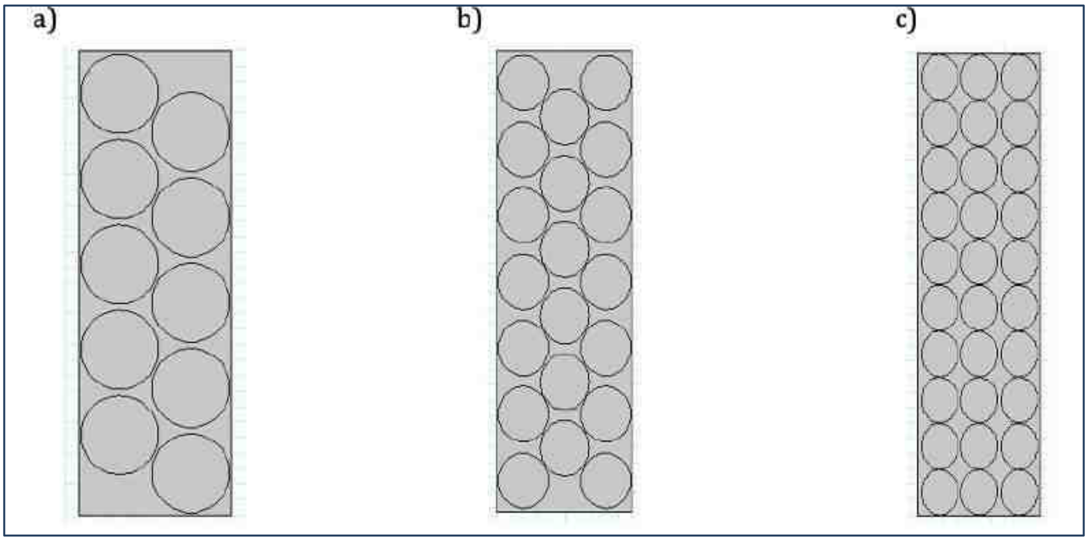

Figure 3: Packed bed with staggered packing with porosity of 0.316 with different diameter ratio $a)\ \wedge = 1.94$ $b)\ \wedge = 2.77$ $c)\ \wedge = 3.39$ [17]

4.2 Meshing

The mesh size varies with the diameter ratio because the gaps between the packed particles differ for each configuration. For all two-dimensional geometries, a triangular mesh with physics-controlled settings is employed. Here are the different meshes for a packed bed [17].

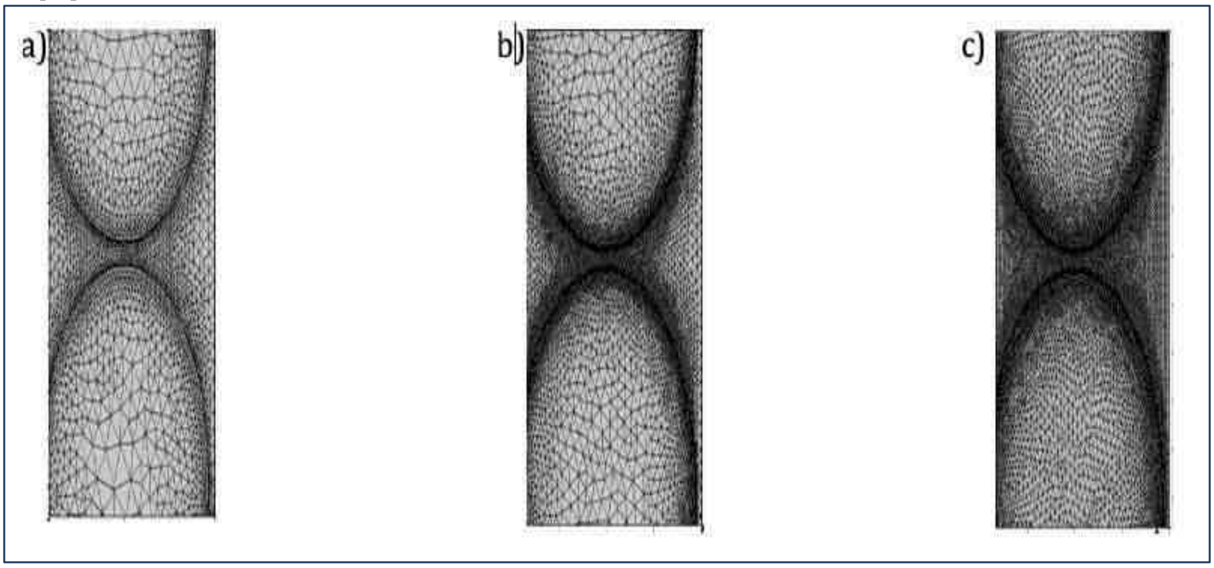

Figure 4: Packed bed mesh a) Fine mesh b) Extra fine mesh c) Extremely fine mesh [17]

Grid independence study was conducted on all three meshes which are shown in Table 1.

Table 1: Grid independence study [17]

Mesh type	Reynolds number	Temperature (K)
Fine	10	328.30
Extra fine	10	328.32
Extremely fine	10	328.32

Table 1 shows that extra fine mesh and extremely fine mesh provided the same average temperature. So, extra mesh was chosen for all cases in this study to reduce computational time and obtain accurate results.

4.3 Results

Periodic boundary conditions were employed at inlet and outlet of the bed to reduce computational effort, and the upper bed wall exposing to natural convection at ambient temperature and lower wall expose to temperatures at 400 K, 500 K, and 600 K. As laminar flow is considered, all simulations were performed with Reynolds numbers less than 10 for a packed bed.

4.3.1 Effect of Reynolds Number on Radial Heat Transfer in a Packed bed (Regular Packing)

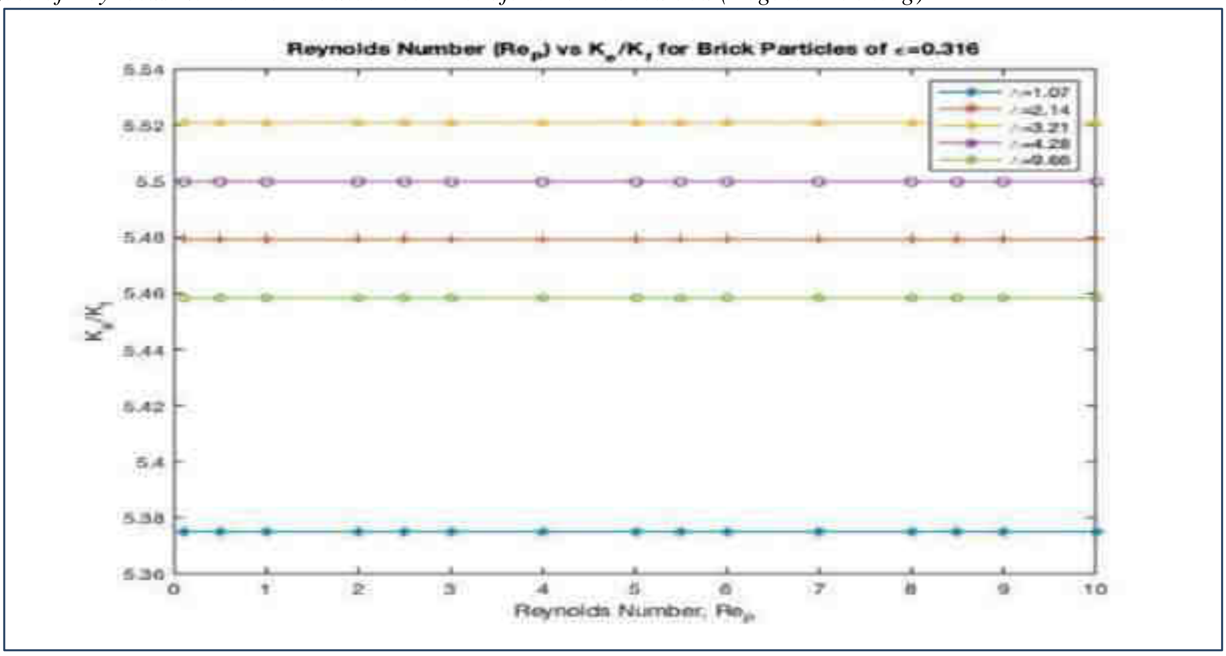

Figure 5: Effect of Reynolds number on radial heat transfer for different diameter ratios with brick packing [17]

Figure 5 shows the ratio of Ke/Kf characterizes the radial heat transfer behavior in packed beds and is a dimensionless parameter. A diameter ratio of 3.21 yields a relatively high Ke/Kf both brick and aluminum particles. In contrast, and diameter ratio of 1.07 results in lower Ke/Kf values for both materials. The diameter ratio of 4.28 produces Ke/Kf values comparable to those obtained at a diameter ratio of 3.21 for both particle types, as illustrated in Figures 5 and 6. This behavior can be attributed to variations in the conduction pathways between the particles and the wall, the interstitial gaps, and the particle size.

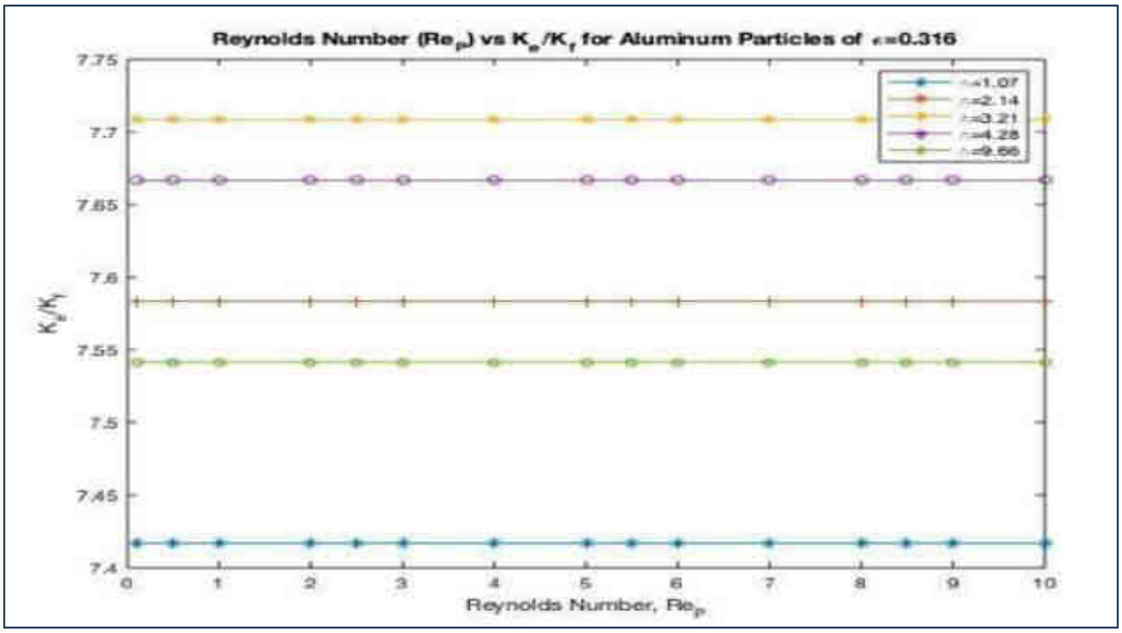

Figure 6: Effect of Reynolds number on radial heat transfer for different diameter ratios with aluminum packing [17]

The thermal conductivity of the packing material has a significant influence on the ratio Ke/Kf. As shown in Figure 5, brick particles yield a maximum Ke/Kf value of 5.52, whereas Figure 6 indicates that aluminum particles produce a higher Ke/Kf value of approximately 7.71.

Within the narrow laminar regime considered, variations in Reynolds number introduce only second-order changes to radial heat transfer, indicating that geometric and material effects dominate system behavior.

4.3.2 Effect of Porosity on Radial Heat Transfer in a Packed bed (Regular Packing)

The ratio of Ke/Kf increases with decreasing porosity. At a porosity of 0.316, the highest Ke/Kf value of approximately 7.5 is observed, whereas porosities of 0.387 and 0.505 yield lower Ke/Kf values of around 5.5. A pronounced difference in Ke/Kf is evident between porosities of ε = 0.34 and 0.387 when compared to the variation between ε=0.316 and 0.34, as illustrated in Figure 7. For each porosity considered, Ke/Kf remains nearly constant with increasing Reynolds number within the laminar flow regime. This trend is associated with suppressed secondary motion and limited fluid circulation at low Reynolds numbers [17].

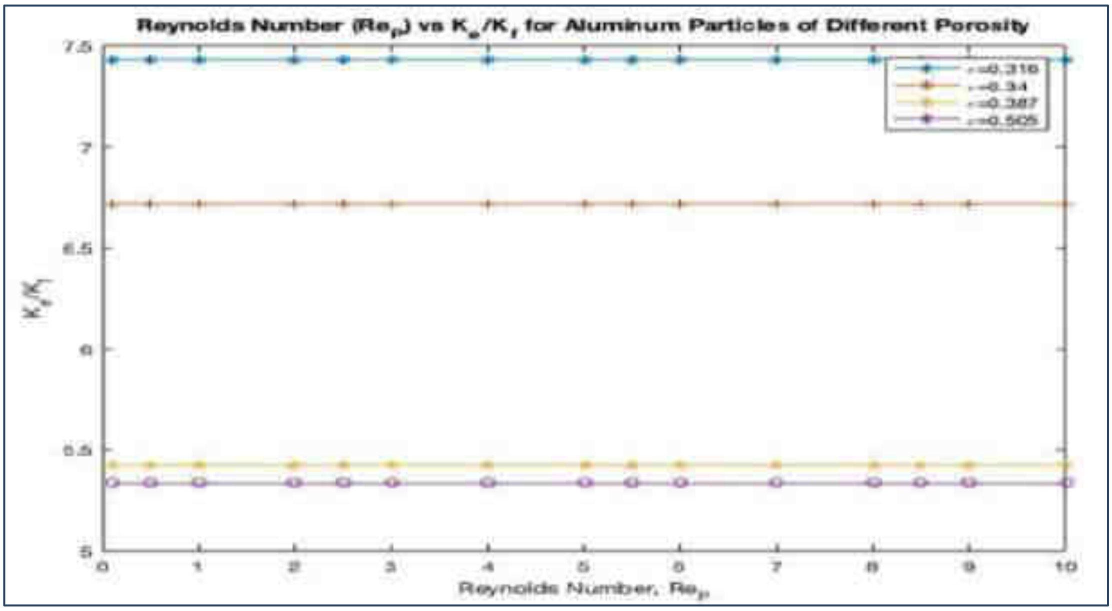

Figure 7: Packed bed with aluminum packing for 4 different porosity designs at 300 K [17]

Table 2: Variation of ETC (Ke/Kf) packed bed with different materials and various porosity [17]

Packing material	ε = 0.316	ε = 0.34	ε = 0.387	ε = 0.505
Brick	5.413	5.055	4.385	4.109
Glass	6.546	6.005	5.000	4.809
Steel	7.282	6.699	5.434	5.321
Iron	7.420	6.710	5.434	5.327
Aluminum	7.433	6.720	5.434	5.335

The effective radial thermal conductivity ratio (Ke/Kf) in packed beds is strongly influenced by bed geometry, porosity, and packing material thermal conductivity. Variations in diameter ratio affect particle–wall and inter-particle gaps, which in turn modify conduction pathways and mesh requirements in numerical simulations. Intermediate diameter ratios (e.g., 3.21 and 4.28) yield higher and comparable Ke/Kf values, whereas lower diameter ratios (e.g., 1.07) result in reduced heat transfer performance.
Materials with higher thermal conductivity, such as aluminum, produce significantly larger Ke/Kf values than low-conductivity materials such as brick. In all cases, Ke/Kf remains nearly constant with increasing Reynolds number within the laminar flow regime due to the absence of secondary flow and circulation effects.
Reducing void fraction alters particle contact networks and wall proximity, which collectively increases conductive heat transfer contributions within the packed bed. Among the configurations analyzed, the minimum porosity (ε = 0.316) yields the highest Ke/Kf, indicating superior radial heat transfer performance. Overall, packing material thermal conductivity and porosity are the dominant parameters governing radial heat transfer and effective thermal conductivity in packed beds.

4.3.3 Effect of Packing Arrangement on Radial Heat Transfer in a Packed bed

Table 3: Variation of ETC (Ke/Kf) packed bed with different materials and different diameter ratios [17]

Packing material	1.95	2.77	3.39
Brick	5.112	5.183	7.174
Glass	6.037	6.291	10.625
Steel	6.704	7.179	14.212
Iron	6.716	7.195	14.287
Aluminum	6.725	7.208	14.341

Table 3 demonstrates that packing structure, diameter ratio, and the thermal conductivity of the packing material are critical parameters influencing effective thermal conductivity (ETC). For staggered packing at a diameter ratio of 1.95, the difference in Ke/Kf between brick and aluminum particles is approximately 1.5. In contrast, at a diameter ratio of 3.39, the corresponding difference increases to about 7, which is nearly five times greater than that observed at a diameter ratio of 1.95. Furthermore, the Ke/Kf value for brick packing at a diameter ratio of 3.39 exceeds that of aluminum packing at a diameter ratio of 1.95 and is nearly equal to that of aluminum packing at a diameter ratio of 2.77.

4.3.4 Comparison between Regular and Staggered Packing of a Packed bed

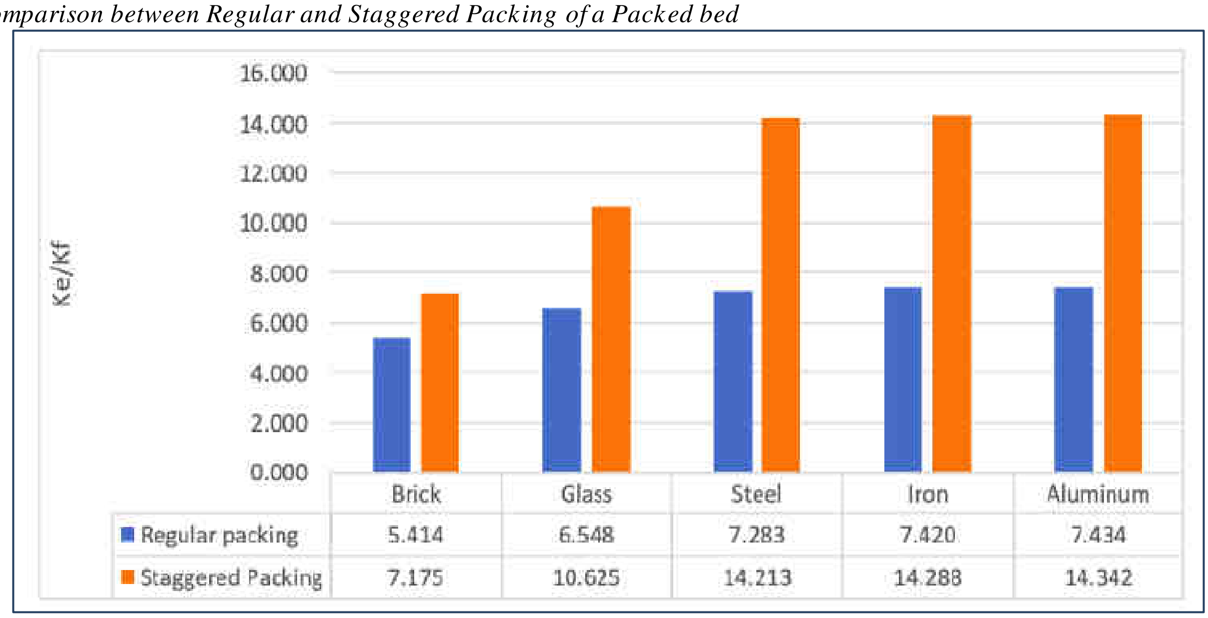

Figure 8: Maximum Ke/Kf for regular and staggered packing [17]

Analysis of the numerical results reveals that heat transfer enhancement does not arise from a single controlling variable, but rather from interactions between packing geometry and material conduction. Changes in particle size modify wall proximity and contact density, while reduced porosity increases conductive connectivity across the bed. These geometric effects outweigh the influence of flow rate within the laminar regime, resulting in comparable Ke/Kf values across the Reynolds numbers examined.

5. Conclusions

This paper presents a computational investigation of radial heat transfer in packed beds using two-dimensional simulations in COMSOL Multiphysics. The study examines the effects of porosity, diameter ratio, packing material thermal conductivity, packing arrangement, and Reynolds number on effective thermal conductivity (ETC). Results show that lower porosity significantly enhances radial heat transfer, with aluminum particles at a porosity of 0.316 achieving the highest Ke/Kf value of 7.71, while brick particles at a porosity of 0.505 yield the lowest value of 4.109. Packing structure and diameter ratio also play a critical role: regular aluminum packing with a diameter ratio of 3.32 produces an ETC of 7.71, whereas staggered aluminum packing with a diameter ratio of 3.39 achieves a substantially higher ETC of 14.34. Within the laminar regime investigated, variations in Reynolds number do not produce a noticeable impact on radial heat transfer. The present simulations demonstrate that, for two-dimensional packed beds under laminar flow, heat transfer behavior emerges from the combined influence of void structure, particle geometry, and solid conduction properties. All conclusions are specific to two-dimensional packed beds operating under steady laminar flow and should not be generalized to turbulent or three-dimensional system.

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