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Characterization Study of the Impact of Non-Dimensional Parameters on Radial Heat Transfer in Packed Beds

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Abstract

The simulation of packed beds packed with long tubes through choice of suitable packing materials and the size of particles to be used to achieve maximum heating efficiencies is one major problem in most industrial applications. This work proposes the development of a computer simulation model to analyze the impact of the most important nondimensional parameters on the radial heat transfer efficiency in a packed bed. Experiments are conducted considering the impact of the particle diameter, properties, as well as bed arrangement on the radial heat transfer in a packed bed as a function of the Reynolds number. The experimental work is performed on a plain annulus filled with circular two-dimensional objects in the two-dimensional simulation model. This is followed by spherical objects in the three-dimensional simulation model. Effective Thermal Conductivity is taken as the criterion in the analysis.

The study focuses on steady-state, laminar flow ($Re_P < 10$) which is common in the case of Fischer-Tropsch to reduce pressure drop by slow moving fluid. For better insight into the impact of the effects of porosity and the aspects ratios of the particulates (tube diameter-to-particulates of 1.2 to 10), preliminary two-dimensional simulations were performed using two packing styles: organized and staggered. The 2D analysis provided an insight into the design of 3D simulations, which are 15-20 times more computationally intensive.

Cylindrical packed beds comprising of a ball that has different aspect ratios and constant porosity (ranging from 2 to 10) were tested at radial packing and hollow packing configuration in 3D analyses. It shows that the radial packing is the best in terms of getting the optimal ETC compared to the other configurations whereas the brick particle always gives lower ETCs with no affectedness on the packing arrangement or the aspect ratio. Remarkably, changes in Reynolds numbers did not play a significant role in ETC with air as a fluid, showing that packing geometry and material properties play a predominant role in the case of laminar flows.

Keywords: *Conjugate Heat Transfer, Non-Isothermal Flow, Packed Bed, Radial Heat Transfer, Effective Thermal Conductivity, Laminar Flow; Packing Arrangement, Packing Material, Pressure Drop, Periodic Boundaries, Fischer-Tropsch.*

I. INTRODUCTION

Packed beds have proven to be very efficient in chemical, energy and process engineering processes because of their large surface area of heat and mass transfer, easy design and ability to handle both fluids and solid materials [1][2][4]. They are typically used in reactors, thermal energy storage, drying, and catalytic processes [3][5][6][7]. For the optimization of the thermal performance of packed beds and ensuring the efficiency of the beds, there is a need to understand the heat transfer characteristics in the packed beds. This is especially true in the case of radial heat transfer in the case of cylindrical or tube packed bed systems where the effects of the temperature distribution could play an important role in determining the efficiency of the system [8][10].

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- *Nomenclature*

Δ	Change
ε	Void fraction
Λ	Aspect ratio or tube to particle diameter ratio
μ	Dynamic viscosity of air, kg m^{-1} s^{-1}
Φ_S	Shape factor or sphericity factor
ρ	Density of air, kg m^{-3}
ρc_p	Volumetric heat flux, KJ m^{-3} k^{-1}
θ	Non dimensional temperature
c_p	Specific heat of air, KJ kg^{-1} k^{-1}
D	Diameter, m
F	Force vector, N s^{-1}
g	Gravitational constant
h	Heat transfer coefficient, w m^{-2} k^{-1}
I	Lagrange multiplier
K_e	Effective thermal conductivity, w m^{-1} k^{-1}
K_f	Thermal conductivity of a fluid (air), w m^{-1} k^{-1}
L	Length of a bed. m
P	Pressure, pa
Q	Heat source, w m^{-2}
q_o	Heat flux vector, w m^{-2}
R	Radius, m
r	Radial direction
Re_p	Reynolds number of a packed bed
s	Surface area, m^2
T	Temperature, k
u	Velocity vector, m s^{-1}
v	Volume, m^3
V_0	Superficial velocity, m s^{-1}

The fluid flow, the geometry of particles, and the thermal characteristics of materials are some combinations that affect the heat transfer in packed beds [11][12]. The most common non-dimensional numbers are the Reynolds number, Nusselt number, and shape factors which are commonly used to describe the flow and thermal behavior of the bed [13][14]. These parameters are used to characterize the complicated processes between the solid particles and the fluid passing through the interstitial spaces. This has been experimentally and numerically demonstrated to be highly contingent on the arrangement of the particles, the packing density, and the fluid properties of the packed beds, which form the effective thermal conductivity (ETC) [15][16][17][18].

In recent research, sophisticated models, such as the computational fluid dynamics (CFD), discrete element modeling (DEM), and hybrid CFD-DEM, have been used to predict flow and heat transfer attributes more rigorously [1][2][4]. Semi-analytical methods like the Complex Variable Semi-Analytical Method (CVSAM) have also been used to compute the ETC and its sensitivity to flow and thermal conditions, and this gives good information regarding the reliability and optimization of the system [5][8][10]. Moreover, machine learning technologies also have been investigated to anticipate the temperature fields and optimize the design variables of packed beds during various operating conditions [6][7].

Although a lot of research has been done on packed bed heat transfer, it is still necessary to conduct systematic studies that quantify effects of non-dimensional parameters on radial heat transfer. These investigations would be of paramount importance in enhancing the accuracy of design, minimizing energy loss and in increasing the performance of thermal systems packed bed based. This paper intends to fill the gap in literature by undertaking an in-depth characterization of the radial heat transfer in packed beds, focusing on the effects of the most significant non-dimensional parameters, that is the Reynolds number, shape factor of the particle, and the thermal conductivity of the packed bed material. The expected outcomes of the proposed investigation aim at the optimization of the packed bed thermal system business in the energy and process industry sector.

II. LITERATURE REVIEW

Packed bed heat transfer is a topic that has received considerable research because of its importance in both chemical, thermal and energy processes. The latest studies have been aimed at determining the implications of particle arrangement, fluid flow and non-dimensional parameters on heat transfer efficiency.

Sambo et al. [19] performed a numerical and experimental research on the air preheating of manganese ore in packed beds up to 600 o C. Their research observed that the size of the particles and the density of the packing influence the temperature of the material and the rate of heat transfer, with non -uniform heating potentially having a serious effect on the efficiency of the process.

Diaz Ulloa et al. [20] designed Nusselt number correlations in convective heat transfer in dual core-ring packed beds. Their experimental data revealed that geometry and flow characteristics of the bed significantly influence the values of the convective heat transfer coefficients, which confirms that exact relations are needed to determine thermal performance in complex packed bed systems.

Gorla [21] was studying the influence of thermal conductivity, Reynolds number, aspect ratio, and packing arrangement on heat transfer in a packed bed, in a radial manner. However, results revealed that the aspect ratio of the bed, together with the flow regime, are factors to consider in the selection of the effective thermal conductivity, in addition to the sensitivity of the radial heat transfer process to the particle packing configuration.

Zou et al. [22] discussed modeling at the particle-pore-scale on the topic of how porosity and the pore structure of a packed bed affect heat transfer. These authors were able to attain results which showed that "porosity and distribution of interstitial voids play a relevant role in local and global heat transfer rates and that microstructural bed properties become vital in thermal models".

Walayat et al. [23] conducted experimental and numerical research of the effective thermal conductivity in packed beds made of thermochemical energy storage substances. Their study showed that the packing arrangement and networks of particle contacts were very important in ETC and that proper estimation of ETC is important in the design of the energy storage systems at high temperatures.

Pichler et al. [24] examined the effect of contact point treatment of particles in CFD simulation of heat transfer in packed beds. The study found that a model of small differences in the models of particle contacts can cause a great deviation in the calculation of heat transfer, and it is important to ensure the accurate models of particle interaction in computerized models.

Beaulieu et al. [25] examined the effect of surface roughness on heat transfer in packed beds of a particle that is a sphere. Their findings showed that surface roughness has a potential of enhancing convective heat transfer through increasing turbulence and inter-particle contact effects, which showed that microscale surface features are essential in the thermal design of packed beds.

Taken together, these studies emphasize the need for the concept that the radial transfer of heat in a bed of particles is influenced by several parameters including the size, shape, surface roughness, arrangement, bed porosity, and flow type. Despite the improvement in the numerical and experimental approaches used in the research of the processes involved in the process of heat transfer, studies are needed that consider different parameters in order to optimize the effectiveness of the bed in the operating process. The research expands these observations by considering in detail how non-dimensional parameters influence the radial heat transfer in packed beds with the aim of coming up with an all-encompassing characterization of thermal system optimization.

III. SOLUTION APPROACH AND METHODOLOGY

- *Governing Equations of a Packed Bed*

The equations that are applicable to packed beds are utilized as models that predict the balances of mass, momentum, and energy in a packed bed. Simplifications that are assumed to make the actual process calculable include steady heat transfer, incompressible fluid, unvarying porosity with respect to time and space, interconnecting pore spaces, fluid particles in the pore spaces, and fixed bed particles with the fluid.

Various models exist in math to describe the fluid flow phenomenon; however, the use of partial differential equations is common to get the exact information. As is known, the density is negligible in the incompressible flow since there is no considerable variation in the density of liquids and gases under normal pressure and temperature.

- *Conservation of Mass*

$$\rho \nabla \cdot (u) = 0 \tag{1}$$

The equation (1) expresses the conservation of mass within a packed bed with porous media, or the continuity equation. This equation says that the rate of change of fluid mass within a packed bed is equal to mass flux into a control volume. [30].

- *Conservation of Momentum*

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

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

The momentum Eq. 2 clarifies the physical meaning of viscous forces A included in that equation. On the other hand, the turbulent viscous dissipation term is neglected, and viscous forces are considered to be zero A=0.

The other important parameters give the momentum of pressure loss due to flow across the bed between inlet and outlet, as well as the body force and gravitational force vectors, respectively [30]. Darcy's law is applicable for fluid flow through a porous medium and is only valid for a packed bed with Reynolds numbers below 10. For Reynolds numbers greater than 10, other effects such as turbulence resistance need to be taken into consideration.

- *Conservation of Energy*

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

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

$$Q_{vd} = \tau : \nabla u + Q_{turb}$$

The Navier-Stokes equations give the solution for the pressure and velocity fields. In the case where the temperature information is required, the energy equation must be considered as well [30]. In the present research work, the packed bed involved the study of heat transfer in fluids and in solids.

The equations of heat transfer are the same for both types of flow, which implies that the laws governing the heat transfer are the same in both cases. Since the viscous dissipation term in turbulent flow has been ignored in the case of laminar flow, the term does not contribute to the flow of heat.

➢ *Shape Factor*

The shape factor is determined based on the particle shape in a packed bed using equation (4) [31]

$$\frac{s_p}{v_p} = \frac{6}{\Phi_s D_p} \tag{4}$$

The shape factor for spherical particles is one.

➢ *Reynolds Number for a Packed Bed*

The Reynolds number for a packed bed is determined by the packing particle diameter [31]:

$$Re_p = \frac{2}{3}\frac{\rho V_0\, D_p}{\mu(1-\epsilon)}\Phi_s \tag{5}$$

The Reynolds number for spherical particles is

$$Re_p = \frac{\rho V_0\, D_p}{\mu(1-\epsilon)} \tag{6}$$

➢ *Effective Thermal Conductivity (ETC) for a Packed Bed*

- *ETC for a 2D Packed Bed*

The ETC for a 2D rectangular packed bed is calculated using equation (7). [21, 22]

$$Q = \frac{K_e\, \Delta T_{Avg}}{L} \tag{7}$$

- *ETC for a 3D Packed Bed*

The ETC for a 3D cylindrical packed bed is calculated using equation (8).

$$K_e \frac{\partial T}{\partial r} = h_w(T_w - T_b) \tag{8}$$

The temperature distribution is defined by polynomial approximation.

$$T = a_0 + a_1 r + a_2 r^2 + a_3 r^3 \tag{9}$$

Boundary conditions for a cylindrical packed bed of spheres is:

$$r = 0, T = T_H$$

$$r = R, T = T_w$$

$$r = 0, \frac{\partial T}{\partial r} = 0$$

The final ETC equation for a 3D packed is

$$K_e = \frac{h_w(T_w - T_b)}{T_w - T_H} R \tag{10}$$

The non-dimensional ETC is as follows

$$\frac{K_e}{K_f} = \frac{h_w(T_w - T_b)}{K_f(T_w - T_H)} R \tag{11}$$

The Effective Thermal Conductivity and Sensitivity have been developed by previous researchers using the Complex Variable Semi-Analytical Method (CVSAM). The sensitivity result is important to establish reliability in systems, including ball-grid array packages. In addition to this aspect, Neural Networks can be applied to predict temperatures in heat-generating bodies. A finite volume program has been designed to solve heat transfer processes associated with heat-generating bodies. CVSAM has been beneficial in addressing sensitivity analysis for different fluid flow conditions. Inverse numerical analysis has been applied to model properties of heat-generating materials by making temperature measures at the outer boundary. The accuracy and effectiveness of this process are improved by applying sensitivity information with high accuracy available from CVSAM. This sensitivity data is important in evaluating reliability in systems, including ball grid array packages, while machine learning approaches can improve temperatures in heat-generating bodies [25,26,27,28,29].

IV. DESIGN AND ANALYSIS

The computational model of the packed bed has been developed and solved by making use of COMSOL Multiphysics due to the ease it offers for working under periodic boundary conditions. The steps for developing a computational model involve designing geometry, selecting material, selecting the heat transfer and fluid flow physics phenomena, and finally obtaining the results. The results obtained make it easier for analysis by providing values for the mass-weighted average wall temperature and velocity magnitude, as well as the bulk temperature of the packed bed. The non-isothermal temperature and velocity contours have been obtained to better understand the results.

➢ *Packed Bed Design*

The diameter of a packed bed to the diameter of a particle (aspect ratio) in packed beds typically ranges from 2 to 15, as indicated in Table 1. However, this range may vary depending on the application. In most cases, it is essential to position packed bed reactors vertically to ensure proper channeling to minimize void age.

In terms of simplifying the geometry, a 3D cylindrical packed bed, which consists of spherical particles arranged in a radial or hollow packing configuration, can be modeled as a 2D rectangular bed. This simplification involves flattening the geometry along one axis (e.g., the radial direction in a cylinder), resulting in a 2D model that still represents the arrangement and interactions of the particles. The bed's symmetry and key features are retained in this 2D representation.

For the proposed study, the bed geometry considered was a 2D rectangular bed with a length of 60mm and a width of 20mm. The bed was packed with solid circular particles with an aspect ratio of $1.2 < \Lambda < 10$. The materials that composed these particles included aluminum, brick, and other materials to investigate the influence of thermal conductivity. Different geometries with varying aspect ratios were designed while maintaining constant porosity to ensure there is adequate space between particles for flow passage.

Additionally, geometries of packed beds with four different porosities, each having varying aspect ratios, were designed, to better understand the effect of the porosity on the radial effective thermal conductivity. Furthermore, a staggered packed bed design was developed, having three aspect ratios, while the porosity was fixed at 0.32, to compare the heat transfer capability of the staggered design with the normal design. In the staggered design, the spacing between the particles varies.

A 3D cylindrical packed bed with a diameter of 40mm, with an approximate porosity of 0.3 (judging from the 2D results), has also been examined. A cylindrical packed bed is adopted to facilitate an equal distribution of particles inside the bed. The length of the bed depends on the value of the diameter of the particles. The bed is constructed of aluminum with a cylindrical copper heating element at its center. Surrounding the heating element are solid spherical particles. In the 3D model, the packed bed models have been created with three different values of the aspect ratio ranging from 2 to 9 while keeping a fixed bed diameter. The solid spherical particles are made of brick, iron, steel, and aluminum. Aluminum, steel, and iron were chosen for their high thermal conductivity, mechanical strength, corrosion resistance, and ability to be molded into shapes that enhance heat transfer. The material selection is based on the specific requirements of the application; aluminum is favored for its light weight and high conductivity, steel for its durability and versatility, and iron for its cost-effectiveness and strength in such applications.

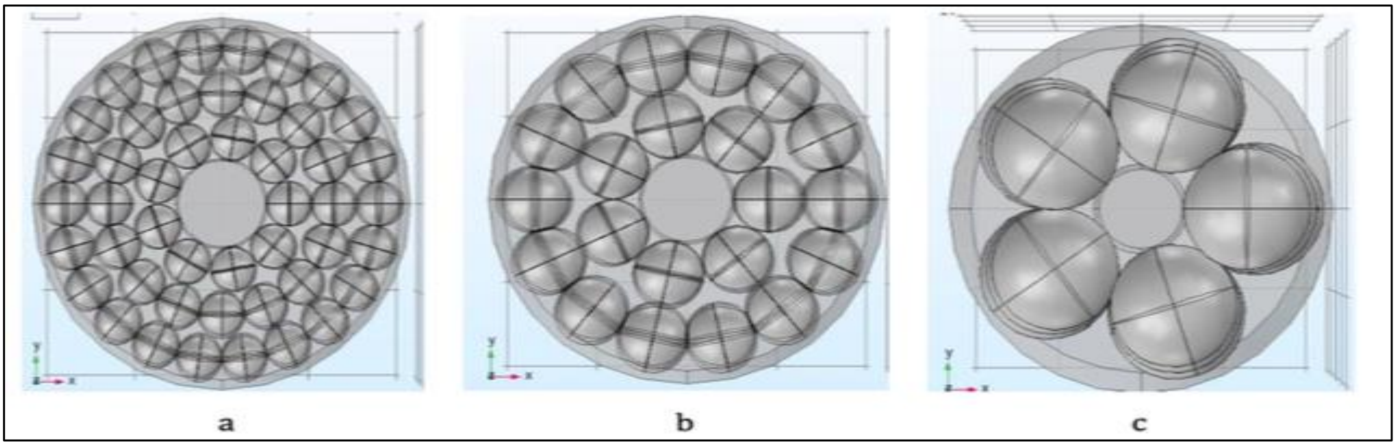


Fig 1 Geometries of Radial Packing Spheres in a 3D Packed Bed, d=40mm, a) Λ= 8.2 b) Λ= 5.46 c) Λ= 2.73

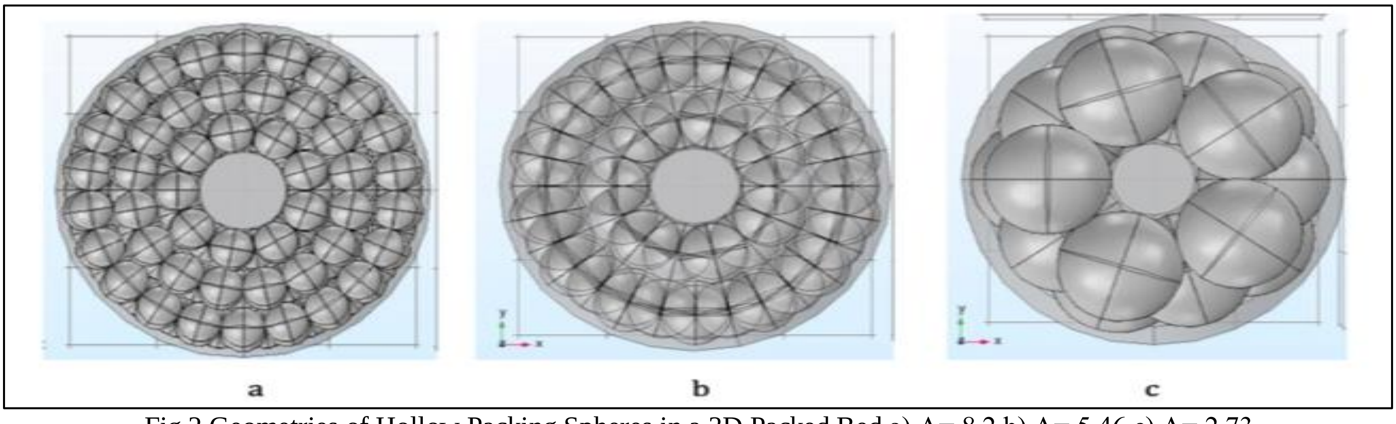


Fig 2 Geometries of Hollow Packing Spheres in a 3D Packed Bed a) Λ= 8.2 b) Λ= 5.46 c) Λ= 2.73

As mentioned in section 1, there are various types of structured packing designs. Due to the design constraints imposed on the bed involving the heater (with a diameter of 10mm) at the center, only two types of packing designs were selected: the radial packing design and the hollow packing design shown in figures 1 and 2. This is in order to avoid errors during meshing. A 0.5mm gap was therefore used between the packing particles and the walls.

- *Initial and Boundary Conditions*

The initial temperature of the subject has been taken as ambient. In the case of a 2D rectangular packed bed, the upper wall of the bed is exposed to an ambient temperature of 300 K and natural convection to simulate a realistic heat transfer process between the bed and the surrounding fluid. The lower wall of the bed is taken as a heat source of 400 K. This boundary condition is essential for driving the thermal convection and conduction processes through the bed material.

In the 3D cylindrical packed bed reactor simulation, the cylinder heater is at 400 K, but the walls in the packed bed experience natural convection and ambient conditions. The packing material for particles is brick, iron, steel, and aluminum.

The simulation was done at the state of steady state laminar flow and Reynolds numbers of 0.5, 1, 2, 5, and 10. The fluid used was air. In light of the real application of the problem. In other words, a diameter of the packed bed ranging from 5 to 10 m and a length of about 20 to 25 meters. The bed was set to have periodic boundaries on both the inflow and the outflow of the air. The new solution cuts down on computing and leads to a net heat flux in a radial direction.

Validation cases were performed using periodic boundary conditions with velocity-pressure boundary conditions to verify whether the system was fully developed thermally and hydraulically. The validation results demonstrated that periodic boundary conditions are suitable for long tubes, providing better results and significantly reducing computational time (approximately 10 times faster).

Conjugate heat transfer physics and non-isothermal Multiphysics were used to combine heat transfer and fluid flow to solve continuity equations [21, 22].

- *Grid Independence Study*

Table 1 3D Mesh Independent Study for Radial Packing of Aluminum Spheres with Λ =5.33 at T_H=400 K at Re_p 10.

Mesh size (cells)	**T_{Avg} at wall**
0.7 M	363.62 K
1.2 M	363.84 K
2.7 M	363.89 K
3.8 M	363.89 K

The impact of mesh sizes including 2.7M and 3.1M cells on average wall temperature. Results show that the average temperature values for both mesh sizes are nearly identical, indicating that increasing the mesh size from 2.7M to 3.1M does not significantly affect the result. This suggests that the 2.7M cell mesh is sufficiently refined to accurately capture the essential thermal and flow characteristics.

Using the 2.7M mesh instead of the 3.1M mesh offers a computational efficiency advantage without compromising the result accuracy because it reduces memory and processing time. The mesh size of 2.7M cells provides an optimal balance between computational cost and accuracy, making it ideal for simulations requiring reduced computational resources or for time-sensitive analyses.

Furthermore, this study confirms that the mesh quality is adequate to resolve critical temperature and flow gradients near the wall, which are important for accurate thermal simulations. Consistent results across both mesh sizes support the conclusion that the 2.7M mesh is both grid-independent and sufficiently refined for high-quality, efficient simulations.

V. RESULTS

The outcomes of the 2D simulation of the packed bed gave valuable information regarding the topic, underlining the role of porosity and other variables in the ETC of the packed bed. However, for the 2D simulation, the mesh variables and the boundary conditions vary by a very small margin. Additionally, the forces and the momentum in the third dimension are negligible. Even though 3D simulations are cumbersome and time-taking computations, they give a far more detailed and precise picture of the scenario.

- *Effect of Packing Material and Aspect Ratio in a 3D Packed Bed with Radial Packing Arrangement*

Thus, as can be seen from Table 2, the brick particles have their ETC maximum at an aspect ratio of 2.733 and minimum at an aspect ratio of 5.466, while for the packing particles of steel and iron, the highest value of ETC appears at an aspect ratio of 5.466 and the lowest at an aspect ratio of 8.2. For aluminum packing particles, the maximum ETC appeared at an aspect ratio of 5.466, and the minimum value of ETC occurred at an aspect ratio of 2.733.

Table 2 Variation of Highest ETC in 3D Packed bed with Radial Packing spheres of 3 Different Aspect Ratios and for 4 Different Materials

Packing material	Λ = 2.733	Λ = 5.466	Λ = 8.2
Brick	3.6	3.3	3.425
Steel	6.2	6.93	5.25
Iron	6.35	7.23	5.65
Aluminum	6.43	7.52	6.7

As represented in the formula of Ergun's equation [31], the pressure drops increased as the particle diameter decreased. In the radial packing setup, the configuration represented by Λ = 8.2 generates the lowest ETC, whereas the smaller particle size and increased pressure drop suppress the contribution of the flow in the radial direction. For the Λ = 2.733 setup, the ETC improved over the Λ = 8.2 setup, but the increased gap between the spheres in the wall region lowered the contributions of the radial conduction. The aspect ratio of 5.46 enables the enhancement of the radial transport in the packed bed, where the aspect ratio provides equal contributions of the pressure drop, particle distance, and wall conduction in the most effective manner. The aspect ratio plays a major role in the packed bed design to serve respective applications.

Additionally, the ETC was approximately twice that of brick particles when the packing material was composed of aluminum spheres across all configurations. The performances of steel and iron spheres are comparable to that of aluminum. In packed beds operated at steady state within a laminar flow regime, the conduction within the solid spheres plays a dominant role. These results underscore the importance of high thermal conductivity materials in improving radial heat transfer. It should be noted that the Reynolds number had no effect on radial heat transfer at steady-state laminar flow.

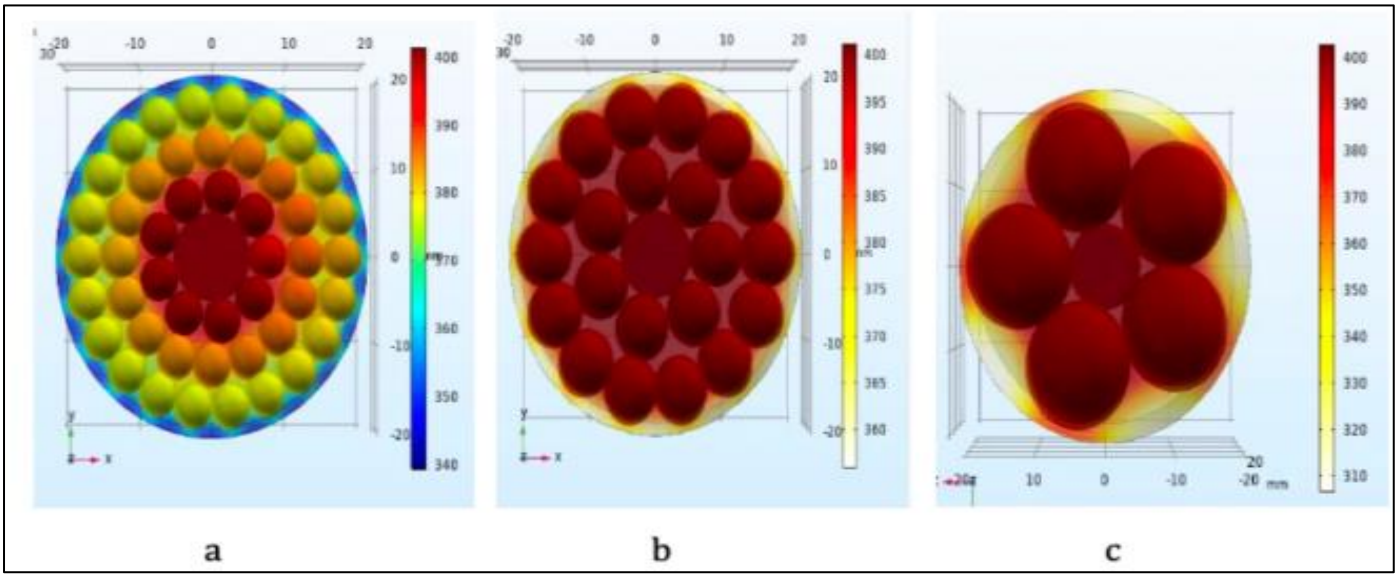


Fig 3 Radially Packed Aluminum Spheres Temperature Contours in a Packed Bed at Re_P 10 a) Λ =8.2 b) Λ=5.46 c) Λ =2.733

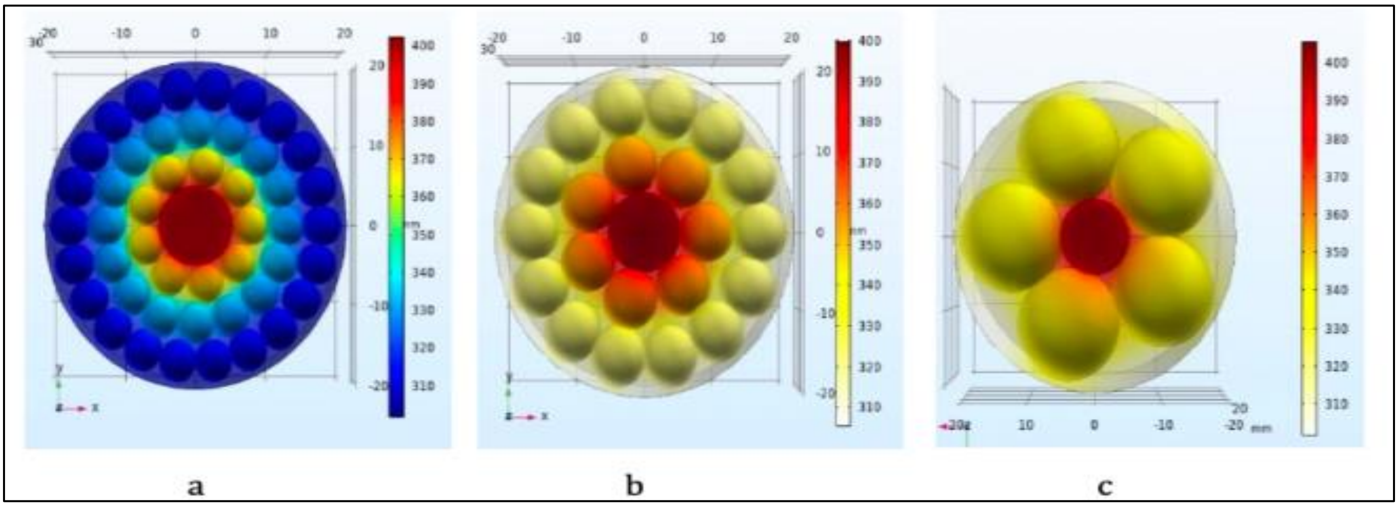


Fig 4 Radially Packed Brick Spheres Temperature Contours in a Packed Bed at Re_P 10 a) Λ =8.2 b) Λ=5.46 c) Λ =2.733

In Figure 3(b), there is a high temperature distribution in the radial direction, whereas in Figure 5.1(c), the temperature distribution in the radial direction is low owing to the larger voids between the spheres. Also, in Figure 5.2(c), there is a high temperature distribution in the radial direction, whereas in Figure 4(b), the temperature distribution in the radial direction is low. This can be related to the properties of the packing material.

➢ *Effect of Packing Material and Aspect Ratio in a 3D Packed Bed with Hollow Packing Arrangement*

As compared with the radial packing configuration, for an aspect ratio of 2.733, the maximum ETC is obtained. The aspect ratio of 8.2 gives the lowest ETC for steel, iron, and aluminum materials, while an aspect ratio of 5.466 gives the lowest ETC for brick particles (Table 3). Hence, an aspect ratio of 2.733 is considered most appropriate for a hollow packing configuration of spheres in a packed bed for efficient radial heat transfer.

Table 3 Variation of Highest ETC in 3D Packed Bed with Hollow Packing Spheres of Three Different Aspect Ratios and for 4 Different Materials

Packing material	**Λ = 2.733**	**Λ = 5.466**	**Λ = 8.2**
Brick	3.6	3.33	3.57
Steel	6.2	5.6	5.0
Iron	6.3	5.7	5.2
Aluminum	6.45	5.9	5.9

As mentioned in section 5.1, the lower the pressure drop is obtained by the greater the particle diameter. In the hollow packing arrangement, the pressure drop is smaller compared to the other packings because of the arrangement and the gaps between the particles. Thus, in the hollow arrangement, the cases having Λ = 8.2 & Λ = 5.466 will have lower values of Effective Thermal Conductivity (ETC) than the values considering Λ = 2.733. It could be attributed to the fact that the bigger spheres take up more space in the wall region; hence, the amount of conduction is increased, and hence enhanced radial heat transfer is achieved.

In all cases, the packing material made of aluminum spheres generated over 150% of the ETC observed with brick particles. The trends for the steel and iron spheres are identical to those of the aluminum spheres. In packed beds under a laminar flow regime, heat transfer is dominated by the conduction within the solid spheres. These results clearly illustrate the important effect of high thermal conductivity materials on enhancing radial heat transfer in packed beds.

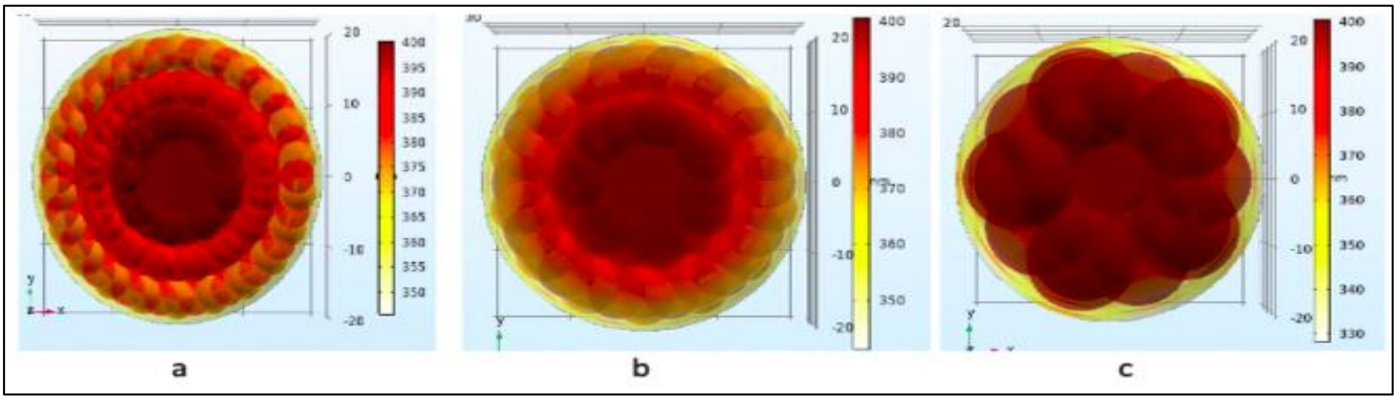


Fig 5 Hollow Packed Aluminum Spheres Temperature Contours in a Packed Bed at Re_P 10 a) Λ =8.2 b) Λ=5.46 c) Λ =2.733

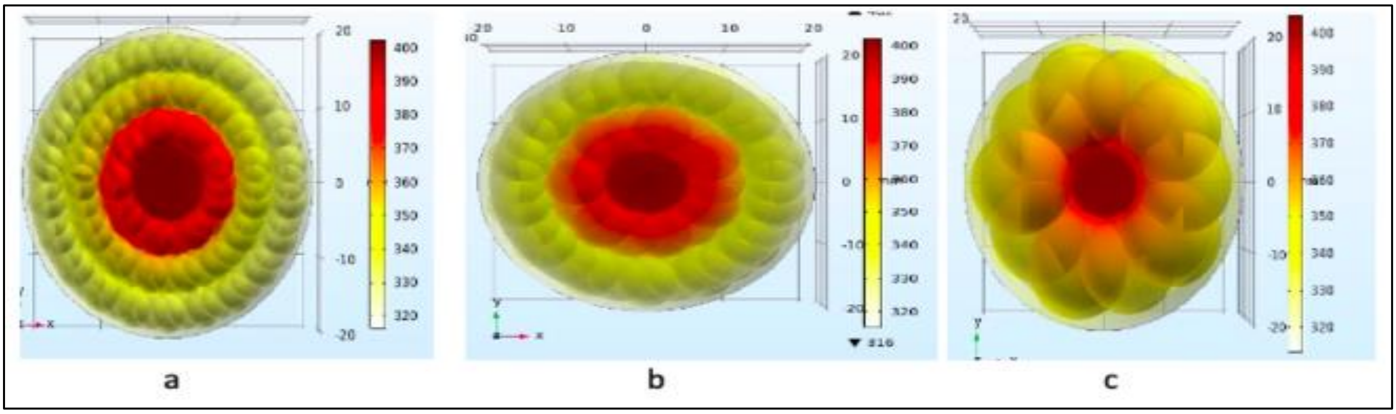
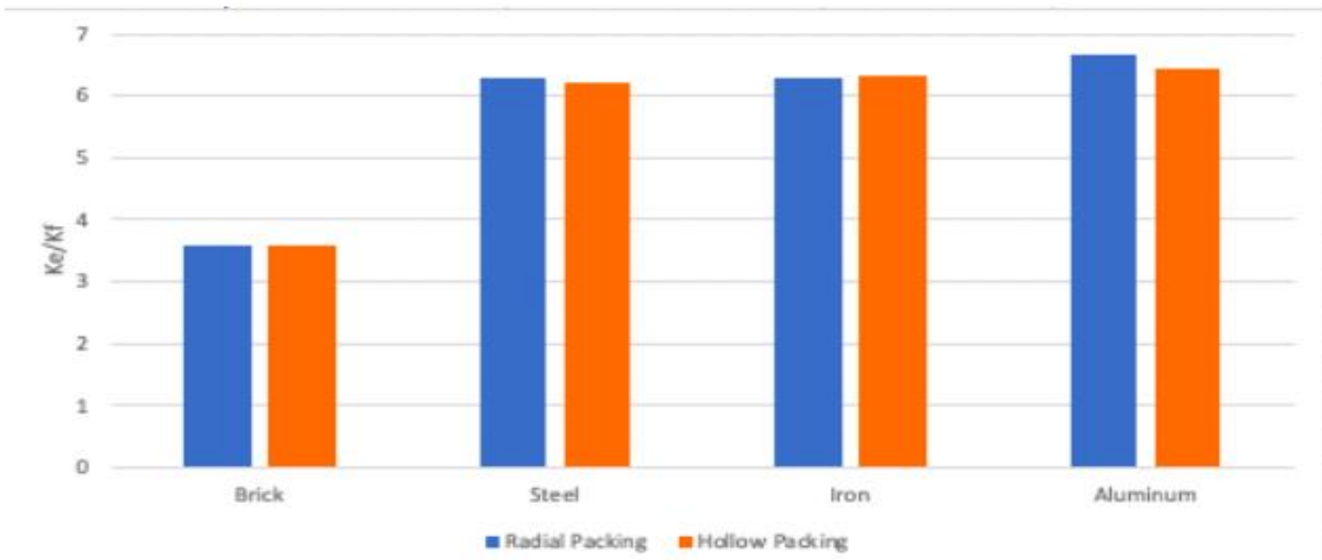


Fig 6 Hollow Packed Brick Spheres Temperature Contours in a Packed Bed at Re_P 10 a) Λ =8.2 b) Λ=5.46 c) Λ =2.733

In Figure 5 (c), the high temperature distribution is depicted, which is the result of the higher particle distribution in the hollow setup, while in Figures 5 (a) and (b), the temperature distributions are low in relation to the radial temperature distribution. A similar trend is noted in Figure 6 (c), where the temperature distribution is higher, followed by the low temperature distributions in Figures 6 (a) and (b), and this can be related to the lower particle distribution. Finally, the effect of the Reynolds number is small in the laminar region, as the latter does not contribute much to the flow separation and secondary currents, hence the temperature distribution.

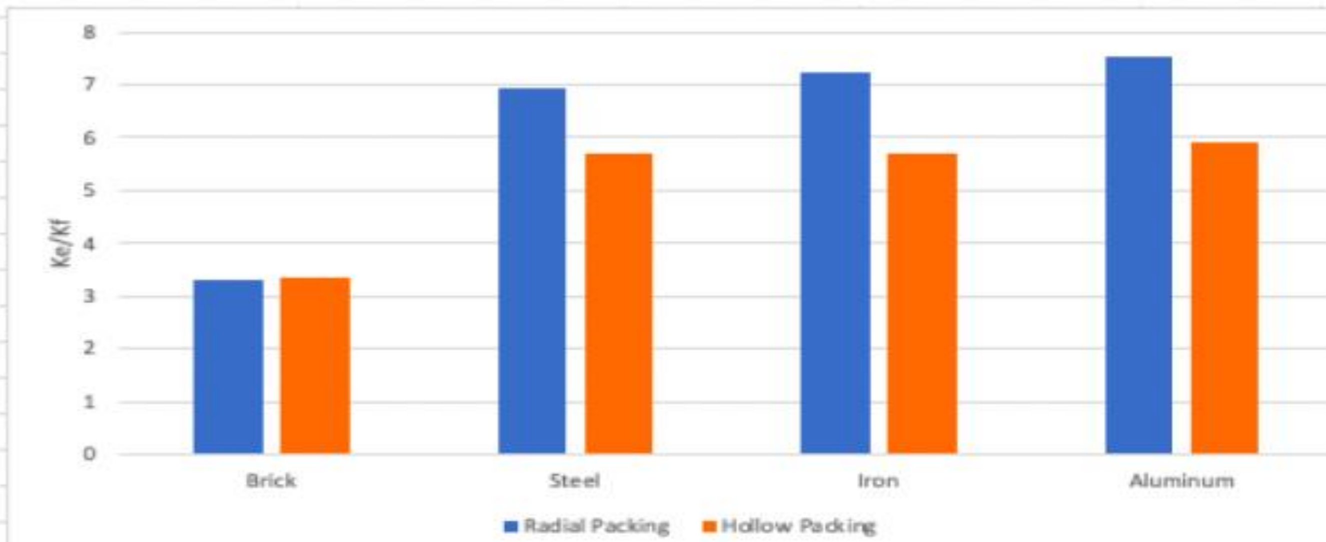
- *Comparison Between Radial Packing and Hollow Packing in a 3D Packed Bed*

The value of 2.733 resulted in the same values of the thermal conductivity of all materials irrespective of the arrangement as seen in Fig. 7. Steel, Iron, and Aluminum Spheres had the same values of the thermal conductivity in both arrangements. However, in the radial arrangement of 5.466 and 8.2, the values of thermal conductivity of all materials were higher compared to that of the hollow arrangement.



	Brick	Steel	Iron	Aluminum
Radial Packing	3.6	6.3	6.3	6.65
Hollow Packing	3.6	6.205	6.325	6.43

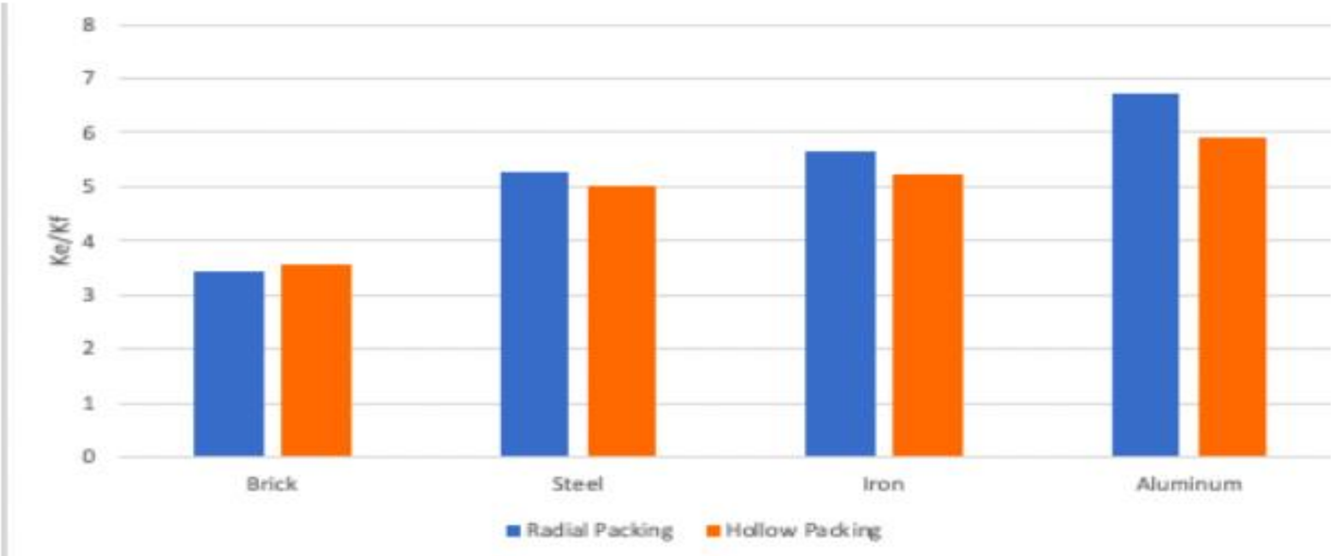
Fig 7 Comparison of Highest ETC for the Radial and Hollow Packing with Aspect Ratio of 2.733



	Brick	Steel	Iron	Aluminum
Radial Packing	3.31	6.93	7.23	7.52
Hollow Packing	3.34	5.7	5.7	5.895

Fig 8 Comparison of Highest ETC for Radial and Hollow Packing with Aspect Ratio of 5.46

The aspect ratio of 5.466 corresponding to a radial packing arrangement of aluminum spheres in a packed bed gives the maximum ETC of 7.52, as seen in Figure 8, since there are a promising pressure drop and an increase in the conductive aspect near the wall. Likewise, for the aspect ratio of 2.733 corresponding to a hollow packing arrangement of aluminum spheres in a packed bed, the maximum ETC of 6.45 is attained, as seen in Figure 9, since there is an increase in the number of spheres occupying the region around the wall of the packed bed. The steel, iron, and aluminum spheres have almost similar ETC values for both radial and hollow packing arrangements with an aspect ratio of 2.733 and 5.466. Consequently, steel or iron spheres, being less expensive than aluminum spheres, can substitute for the other without a substantial decrease in their performance. But when considering steel and iron for radial packing with an aspect ratio of 8.2, aluminum spheres have a higher ETC compared to the other two materials. This fact is attributed to the increase in the conductive effect corresponding to the packed bed using small spheres.



	Brick	Steel	Iron	Aluminum
Radial Packing	3.433	5.25	5.65	6.7
Hollow Packing	3.58	5.02	5.225	5.9

Fig 9 Comparison of Highest ETC for Radial and Hollow Packing with Aspect Ratio of 8.2

Arrangements in the packing are essential in determining the heat transfer rate in the radial aspect. While the hollow packing arrangement provides a lower pressure drop than that in the radial packing arrangement, the radial packing arrangement is much more efficient than the hollow packing in the radial heat transfer process.

Effective thermal conductivity (ETC) depends on the aspect ratio for different packing configurations. In the radial packing configuration, the ETC rises by approximately 13% to an aspect ratio of 2.733 to 5.466, then reduces by approximately 13% at an aspect ratio of 5.466 to 8.2. Based on these data, an optimal aspect ratio of 5.466 was obtained for radial packing configurations for better heat transfer. In the hollow packing configuration, the ETC reduced with an increase in the aspect ratios. In the hollow packing configuration, the ETC reduces by approximately 8% at an aspect ratio of 2.733 to 5.466, then tends to be constant at an aspect ratio of 5.466 to 8.2. Thus, an optimal aspect ratio of 2.733 for hollow packing configurations was obtained for better heat transfer performance.

- *Effect of Reynolds Number on Effective Thermal Conductivity*

Investigation regarding the impact of the value of the Reynolds number on the Effective Thermal Conductivity (ETC) of the 3D packed bed has been done by changing the value of the Reynolds number from 0.5 to 10. However, from Fig. 10, it has been completely justified that with an increase in the value of the Reynolds number, there will be little impact on the value of ETC for radial as well as hollow packing patterns. Even the slightest variations in the value of ETC were not observed. It has clearly proved that it is true that there will be little impact due to the flow rate of fluid (which can be measured by arriving at the value of the Reynolds number for the situation). Thus, it can be said that there will be little effect due to the value of the Reynolds number for increasing radial heat transfer in the laminar region.

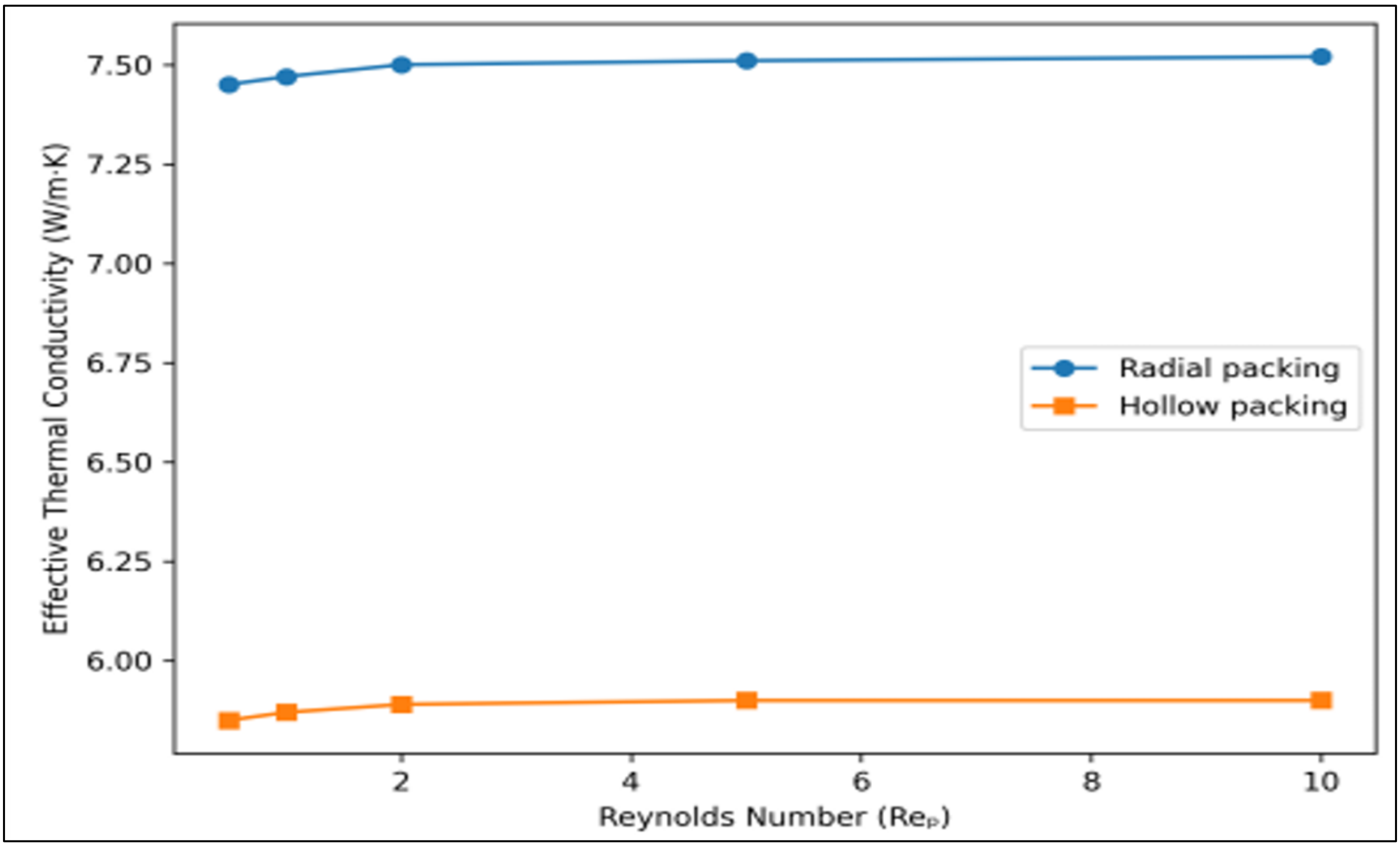


Fig 10 ETC vs Reynolds Number for Radial and Hollow Packing Arrangements

➢ *Effect of Packing Material on Effective Thermal Conductivity*

The effect of the packing material on the Effective Thermal Conductivity (ETC) has been studied by taking brick, steel, iron, and aluminum particles encountered in radial and hollow packing. From fig. 11, it can be realized that as the thermal conductivity of the packing material increases, there is a rise in the value of ETC; however, the maximum values of ETC are produced by aluminum particles and the least by the brick particles. The difference in the values of ETC for different materials is not large; therefore, if better thermal conductivity is produced, there will be little further improvement. The values of ETC in the case of radial packing are higher than the values of ETC of hollow packing because of the mode of interaction of particles.

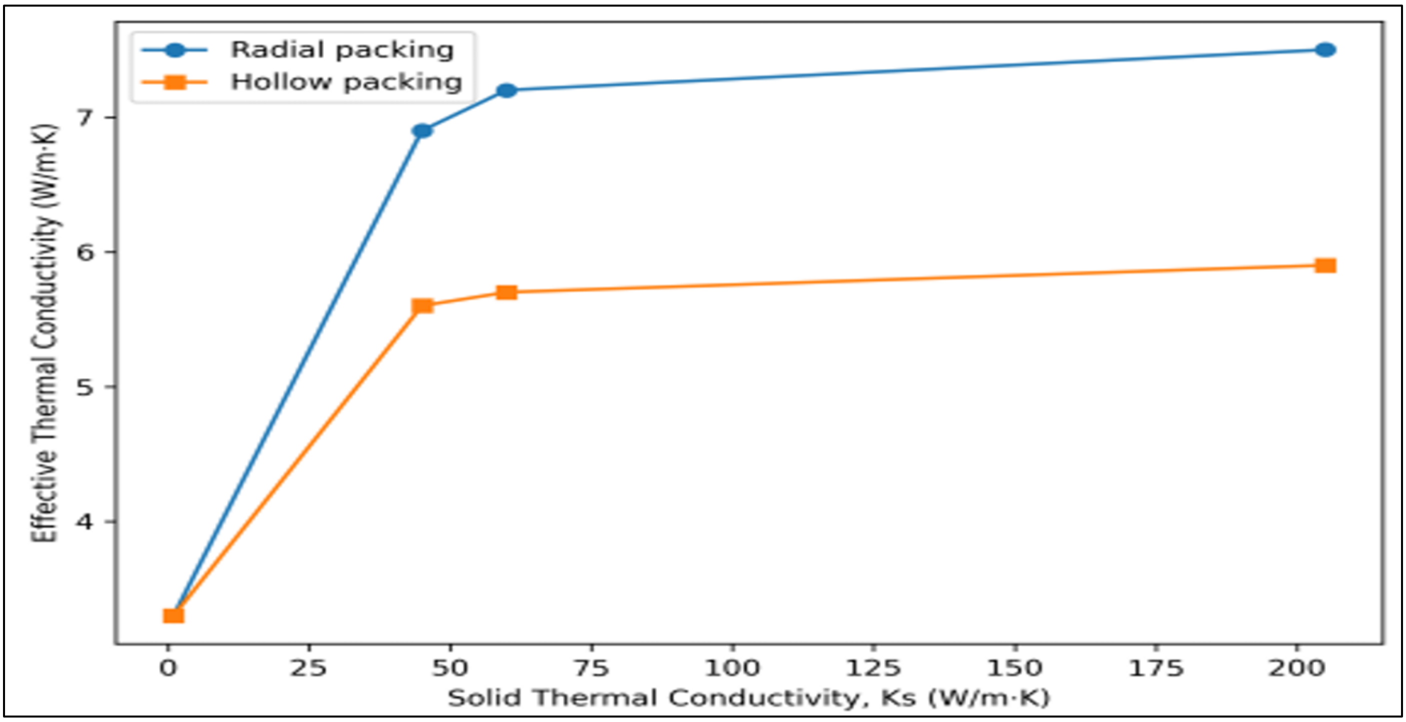


Fig 11 Normalized ETC vs Solid-to-Fluid Thermal Conductivity Ratio

- *Effect of Aspect Ratio on Effective Thermal Conductivity*

The influence of the aspect ratio (Λ) on the Effective Thermal Conductivity (ETC) of the 3D packed bed was studied for both radial and hollow packing patterns using aluminum spheres. As seen in fig. 12, from the results, the effect of the aspect ratio is very significant in deciding the value of the thermal conductivity of the packed bed for both the arrangements. In the radial arrangement of the packed bed, the value of the thermal conductivity rises with the aspect ratio from 2.733 to 5.466 and then falls for Λ = 8.2; this implies that an optimum aspect ratio is required in the packed bed arrangement. However, in the hollow arrangement of the packed bed, the thermal conductivity continuously falls with the rise in the aspect ratio; the maximum thermal conductivity is found at an aspect ratio of 2.733.

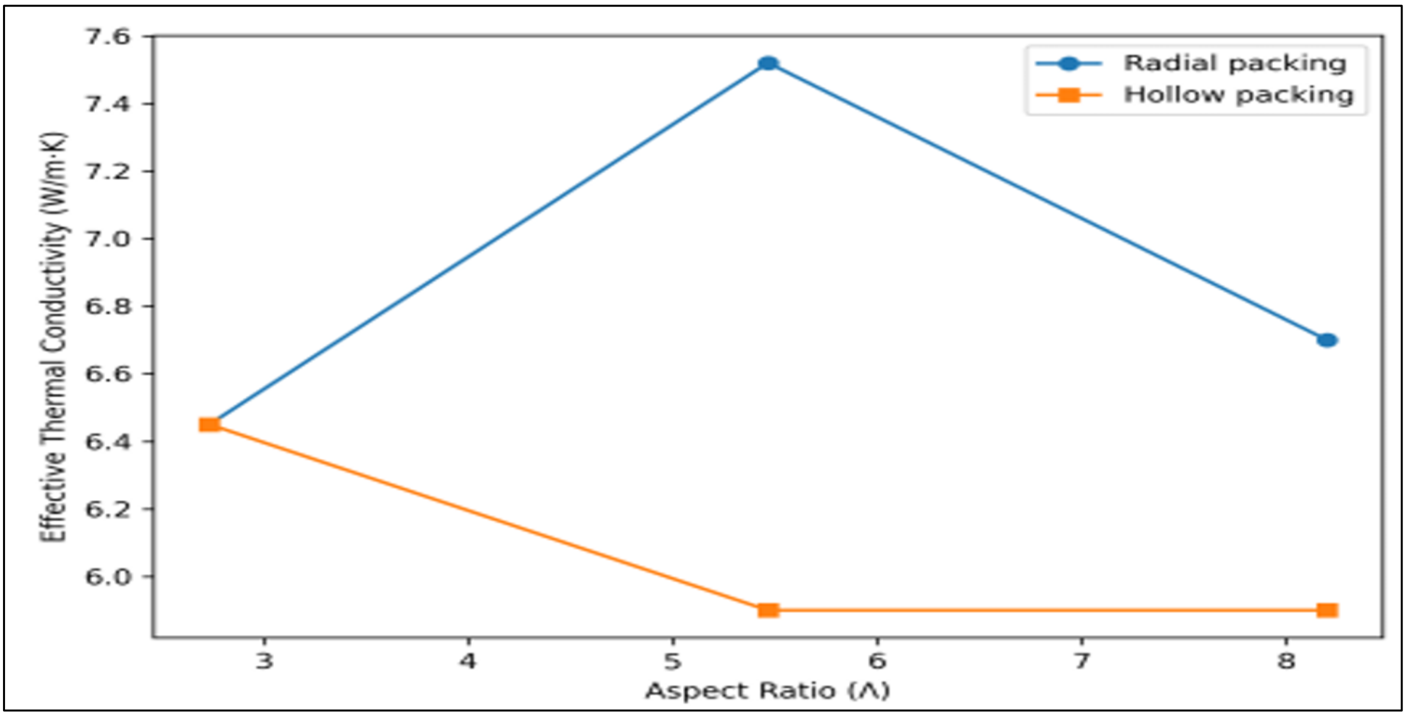


Fig 12 Normalized ETC vs Solid-to-Fluid Thermal Conductivity Ratio

VI. CONCLUSION

This work utilizes computational models in COMSOL Multiphysics to study the radial heat transfer performance in packed beds. This paper concludes that the optimization of thermal conductivity (ETC) in 3D packed beds is based on packing and the properties of the material. It highlights the radial packing with an aspect ratio of 5.466 that offers the highest ETC, specifically for high-conductivity materials like aluminum, because this arrangement strikes a balance in pressure drop, particle spacing, and wall conduction to give good heat transfer. Hollow packing has a lower aspect ratio of 2.733 and delivers better performance under certain conditions but generally exhibits poor heat transfer performance compared to radial packing. Material choice is also crucial, with aluminum significantly outperforming low-conductivity materials like brick. For efficient heat transfer, radial packing with an aspect ratio of 5.466 is recommended, whereas hollow packing may be suitable for less demanding heat transfer applications. These findings highlight the importance of the packing arrangement, porosity, and aspect ratio in influencing heat transfer.

In summary, applying the study's conclusion to Fischer- Tropsch reactors would involve selecting packing arrangements (preferably radial packing with an aspect ratio of 5.466) and high-conductivity materials (such as steel or aluminum) to improve heat transfer. In applications where cost is a concern, hollow packing with a smaller aspect ratio can be a viable alternative, but only for less demanding heat transfer scenarios.

FUTURE WORK

This calculation can be carried out at different temperatures of the heaters, packing configurations, or in the transition region (10 < Rep < 1000) to test how the non-dimensional parameters, such as the Reynolds number, can affect the ETC of a packed bed.

An experimental study may also be conducted to determine how accurately computational results are obtained using benchmark results regardless of assumptions made.

REFERENCES

[1]. Zahir, A., Kumar, P., Saptoro, A., Shah, M., Tiong, A. N. T., & Hameed, S. (2023). Parametric study of experimental and CFD simulation based hydrodynamics and mass transfer of rotating packed bed: a review. *Archives of Computational Methods in Engineering*, *30*(6), 4001-4031.

[2]. Zhang, Q., Xia, Y., Cheng, Z., & Quan, X. (2024). DEM-CFD Simulation Analysis of Heat Transfer Characteristics for Hydrogen Flow in Randomly Packed Beds. *Energies, 17*(9), 2226.

[3]. van Schagen, Tim, and Derk WF Brilman. "1D Modeling Approach for Heat Transfer in Packed Beds with Embedded Heat Sources." *Industrial & Engineering Chemistry Research* 62, no. 39 (2023): 16139-16153.

[4]. Patil, S., Gorges, C., Bonilla, J. L., Stelter, M., Beyrau, F., & van Wachem, B. (2024). Experimental and numerical investigation to elucidate the fluid flow through packed beds with structured particle packings. *Particuology*, *89*, 218-237.

[5]. Baek, S. I., Moon, J. Y., & Chung, B. J. (2022). Natural convective heat transfer influence between two spheres in a packed bed. *International Communications in Heat and Mass Transfer*, *139*, 106430.

[6]. Niu, Z., Lu, X., & Li, Z. (2024). Investigation of Heat and Moisture Transfer during the Drying of Packed-Bed Porous Media in Soybeans. *Applied Sciences*, *14*(5), 1935.

[7]. Schwarzmayr, P., Birkelbach, F., Walter, H., Javernik, F., Schwaiger, M., & Hofmann, R. (2023). Packed bed thermal energy storage for waste heat recovery in the iron and steel industry: An experimental study on powder hold-up and pressure drop. *arXiv preprint arXiv:2307.01585*.

[8]. Birhanu, B., Mozafari, R., Coventry, J., Rosengarten, G., & Mojiri, A. (2025). Impact of heat transfer fluid on thermal characteristics of packed bed thermal energy storage. *Applied Thermal Engineering*, 127239.

[9]. Trevisan, S., Wang, W., Guedez, R., & Laumert, B. (2022). Experimental evaluation of a high-temperature radial-flow packed bed thermal energy storage under dynamic mass flow rate. *Journal of Energy Storage*, *54*, 105236.

[10]. Ahmed, Z., Constantin, A., & Bindra, H. (2022). The thermal response of a packed bed thermal energy storage system upon saturated steam injection using distributed temperature sensing. *Energies*, *15*(10), 3704.

[11]. Li, X., Yang, K., Wang, Y., & Du, X. (2024). Simulation of fluid flow and heat-moisture transfer mechanism in packed bed based on double-diffusion model. *Chemical Engineering Communications*, *211*(5), 647-663.

[12]. Schroeder, N., McLaughlin, L., & Ho, C. (2022). *Testing and Model Validation of a 100 kWh Radial Packed-Bed Thermal Energy Storage System* (No. SAND2022-13917C). Sandia National Lab.(SNL-NM), Albuquerque, NM (United States); Sandia National Laboratories,, Temporary Assignment.

[13]. Liu, S., Ahmadi-Senichault, A., Pozzobon, V., & Lachaud, J. (2024). Multi-scale investigation of heat and momentum transfer in packed-bed TES systems up to 800 K. *Applied Energy*, *366*, 123285.

[14]. Ma, X., Fan, C., Shao, W., Cao, Q., & Cui, Z. (2023). Numerical and experimental studies of packed bed thermal energy storage system based on a novel transient energy model. *Energy Science & Engineering*, *11*(2), 727-744.

[15]. Sun, Y. S., Han, Y., Li, G. D., Shen, H. Y., Chi, X. M., & Zhang, C. Y. (2022). Numerical study of high-temperature cascaded packed bed thermal energy storage system. *Case Studies in Thermal Engineering*, *37*, 102258.

[16]. van Schagen, T., & Brilman, D. W. (2023). 1D Modeling Approach for Heat Transfer in Packed Beds with Embedded Heat Sources. *Industrial & Engineering Chemistry Research*, *62*(39), 16139-16153.

[17]. Hassan, E. B. E. (2023). *Flow and heat transfer in packed beds of rock* (Doctoral dissertation, Stellenbosch: Stellenbosch University).

[18]. Sassanis, V., Gamet, L., Rolland, M., Ma, R., & Pozzobon, V. (2021). Numerical determination of the volumetric heat transfer coefficient in fixed beds of wood chips. *Chemical Engineering Journal*, *417*, 128009.

[19]. Sambo, S. N., Hockaday, L., Seodigeng, T., & Reynolds, Q. G. (2025). Numerical and Experimental Study of Packed Bed Heat Transfer on the Preheating of Manganese Ore with Air up to 600° C. *Metals*, *15*(3), 269.

[20]. Díaz-Ulloa, P., Garrido-Figueroa, B., Guerrero, S., & Cornejo, I. (2025). Nusselt Number Correlation for Convective Heat Transfer in Dual Core-Ring Packed Beds. *Chemical Engineering Science*, 123067.

[21]. Gorla, N. K. R. (2021). *Effect of Thermal Conductivity, Reynolds Number, Aspect Ratio and Packing Arrangement on Radial Heat Transfer in Packed Beds* (Doctoral dissertation, The University of Texas at Arlington).

[22]. Zou, Y., Kuang, S., Wu, Y., & Yu, A. (2025). Particle-pore-scale modelling and analysis of heat transfer in packed beds: effects of bed porosity and pore structure. *Applied Thermal Engineering*, 127601.

[23]. Walayat, K., Duesmann, J., Derks, T., Houshang Mahmoudi, A., Cuypers, R., & Shahi, M. (2021). Experimental and numerical investigations for effective thermal conductivity in packed beds of thermochemical energy storage materials. *Applied thermal engineering*, *193*, 117006.

[24]. Pichler, M., Haddadi, B., Jordan, C., Norouzi, H., & Harasek, M. (2021). Effect of particle contact point treatment on the CFD simulation of the heat transfer in packed beds. *Chemical Engineering Research and Design*, *165*, 242-253.

[25]. Beaulieu, C., Vidal, D., Yari, B., Chaouki, J., & Bertrand, F. (2021). Impact of surface roughness on heat transfer through spherical particle packed beds. *Chemical Engineering Science*, *231*, 116256.