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CFD-DEM predictions of heat transfer in packed beds using commercial and open source codes

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Abstract

Gas-particle heat transfer rates are investigated using particle-resolved direct numerical simulation (PR-DNS). We utilize a discrete element method (DEM) approach to first obtain a realistic packing of the particles, and then build a computational mesh based on these particle positions for running PR-DNS. A common challenge in such investigations is the region of close proximity or overlap between adjacent particles, which can result in highly skewed cells while meshing. The simplest method for addressing this challenge was investigated in this paper: particle shrinkage. We investigated the hypothesis that the void fraction variations caused by particle shrinkage could be tolerated when using a correlation with void fraction dependence. However, this hypothesis was proved false because the particle assembly created by shrinking all particles was evenly spaced and not random, resulting in an over prediction of heat transfer relative to existing correlations. When a random particle arrangement was simulated, however, results matched well with correlations. In addition, we find that DNS results using the commercial CFD code ANSYS FLUENT and the open-source code OpenFOAM® return very similar results. The computational performance was similar, with (i) OpenFOAM being faster for a fixed number of iterations, and (ii) ANSYS FLUENT requiring a smaller number of iterations to find convergence.

Keywords: Computational Fluid Dynamics (CFD), DEM (Discrete element Method), packed bed reactors, heat transfer, commercials vs open source code

I. INTRODUCTION

Gas-particle heat transfer is one of the most studied topics in the literature for packed bed reactors. Numerous methods and correlations have therefore been suggested in the literature for modelling of gas-particle heat transfer. Still, the majority of the proposed heat transfer correlations are derived from experimental data, and only recently, there have been a number of studies utilizing direct numerical simulations (DNS) for the prediction of heat transfer rates. Given the experimental uncertainties involved in existing correlations, these PR-DNS (particle-resolved DNS) methods are proposed as a more accurate framework for deriving gas-particle heat transfer models.

PR-DNS for the derivation of accurate heat transfer correlations in realistically packed particle assemblies is therefore an important research question and has been published yet in our knowledge. A single complete empirical correlation for heat and mass transfer in packed beds, fluidised beds and single particle, valid for both analytical and experimental conditions, was first introduced by Gunn.[1] The correlation was valid for a wide range of porosity ($0.35<\varepsilon<1$), Reynolds number and Prandtl number. However, a modelling study by Tavassoli et al.,[2] has recently suggested that the correlation is only accurate for rather dilute systems ($\varepsilon>0.7$). This hints to a possible shortcoming of the parameters in the Gunn correlation to predict heat (and mass) transfer rates in dense systems.

Deen et al.,[3] used DNS to refit the model from Gunn,[1] to improve the accuracy for porosities ranging from 0.5 to 1, and a variety of Reynolds numbers for monodisperse particles. Most important, the simulations of Deen et al. were performed in laterally-periodic, but rather thing slaps of particles. Similar work using PR-DNS was done by Sun et al.,[4] however, in fully periodic domains. Both studies suggested an improved empirical correlation for heat and mass transfer in packed beds, utilizing the concept of a cup-mixing (bulk) temperature for the fluid. This cup-mixing temperature was calculated using the planes in the direction perpendicular to the flow direction. We note in passing, that this cup-mixing temperature is not available in simulations on a coarser length scale (e.g., two-fluid model simulations, TFM). Hence, a correction needs to be applied when using the average fluid temperature in TFM-based simulations as noted by Sun et al.[4].

The major problem associated with developing a realistic packed bed particle arrangement through DEM is the particle-particle and particle-wall overlap. This overlap leads to highly skewed cells in the proximity regions of particle-particle and particle-wall contacts. Such highly skewed cells should be avoided because they can decrease the convergence and accuracy of the solution.

There are many solutions to this overlapping problem suggested in the literature. Ookawara et al. [5] introduced a method to join the particles by a cylinder if the distance between the particles decreases a predefined value. This method accounts for the pressure drop correctly but the overall porosity of the bed gets highly affected. Eppinger et al. [6] described a method to flatten the particle surfaces locally in order to avoid the overlap. The above methods are classified as local modification methods.

Guardo et al. [7] suggested to increase the particle size by a certain value, in this way the contact points become contact areas and consequently decreases the skewed cells in the geometry. The most common method available to deal with the overlapping problem is to shrink the particles in the packed bed by certain values, and hence to avoid the overlap. Such a methods is classified under the category of and overall modification, because it affects the overall structure of the packed bed. Many publications using different shrinkage factors have used this method to deal with the particle-particle and particle-wall contacts. This is an easy method to implement but it strongly affects the porosity of the bed. Bai et al.,[8] used the particle bed with 1% shrinking, Atmakidis,[9] preferred to shrink the particles by 2%, Lopes,[10] used a shrinking of 3% for the bed, while Dixon,[11] firstly presented the work with shrinking by a factor of 1% and then in Dixon et al., [12] reduced the particles by 0.5% to avoid contact. Calis et al.,[13] used 1% shrinkage factor after generating the bed, both 2% and 1% shrinkage was checked for the change in friction factors from the pressure drop simulations to check the validity of 1% shrinkage. Similar trend was followed by Reddy and Joshi,[14] by a shrinkage of bed by 1% to avoid overlap. The influence of the shrinking factors on the heat transfer and fluid velocity was investigated by Romkes et al.,[15], different shrinking factors 1%, 2% and 5% were compared and it was decided that the 1% shrinkage is representative of the full contact of particles, given a 5% relative error corridor is acceptable.

A review of all the methods available to deal with the problem was given by Dixon et al.[16] They suggested two types of changes in the bed: a local modification, and an overall modification of the packed bed. The suggestion was leaned towards using local modification of the bed than the overall modification, with a better approximation for porosity and pressure drop using caps and bridge method.

Numerous methods for generating the particle bed have also been investigated in the literature. Soleymani et al. and Jafari et al., [17, 18] generated a packed bed with non-overlapping particles with an unknown random arrangement. Gunjal et al.,[19] utilized a periodic box setup with particles arranged at a distance of 1mm from each other. Lee et al.,[20] utilized a body centred cubical (BCC) and face centred cubical (FCC) arrangement with distance of 1mm between the particles for their heat transfer study with large eddy simulations (LES). Deen et al., [3, 21] used a Monte-Carlo method to generate the random packed bed, and to avoid the overlap for their DNS.

In this paper, the overall modification methods are dealt with in detail for the heat transfer problems. The main focus of this work is to test the validity of shrinking the particles in packed beds for heat transfer calculations and to highlight whether such packings can be considered realistic or random. The effect of shrinking is studied in detail by comparing the results of heat transfer with the heat transfer correlations valid for random packings (Sun et al. and Deen et al.). [3, 4] The effects caused by shrinking are reported and documented. In addition, this work compares heat transfer predictions in packed beds by using both commercial (ANSYS FLUENT) and open source (OpenFOAM) software.

II. METHODOLOGY

A. Particle Bed Generation (DEM)

DEM (Discrete Element Method) is used to generate the packed bed in this work. The particles are injected in a cylindrical geometry with gravity force and when the particles get settled the packed bed is obtained. More details about the particle arrangement and the DEM setup used to obtain the packing are given in Table 1 and Table 2.

The particle bed generated through DEM has particle and particle overlaps which will be removed by shrinking the particles as discussed in the last section (Introduction). Different shrinking factors are considered later in this work and their effects are then documented.

TABLE 1: THE REACTOR GEOMETRY WITH MESHING DETAILS

Parameters	Value
Number of particles	100
Diameter of the particles (d_p) (m)	5e-3
Diameter of the reactor (D) (m)	0.03
N value of the reactor	6
The cell size of surface mesh on the particles (m)	1e-4
Maximum face size for the mesh (m)	1e-3
Resolution of mesh on particles for DNS	$d_p/50$
Growth rate of mesh	1.2

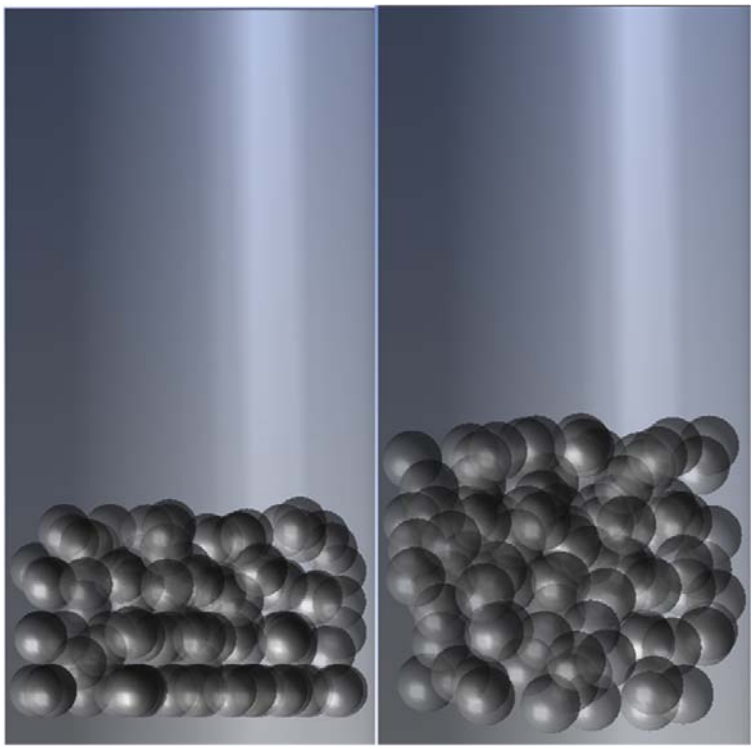

Figure 1: Final realistic packing inside the reactor (left) and random particle bed (right) generated in Workbench

TABLE 2: DEM PARAMETERS FOR THE NORMAL AND TANGENTIAL AND GRAVITY FORCES

Parameters	Law	Value
Particle normal force Spring Dashpot for DEM	Spring dashpot	*K* = 250 *Eta* = 0.9
Particle tangential force parameter for DEM	Friction-dshf	*mu-stick* = 0.5 *mu-slide* = 0.2 *mu-limit* = 0.1
Gravity force		-9.81 m/s^2

B. Random packing from DEM

To generate a random particle arrangement of higher porosities, particles are injected into the reactor geometry as explained in section (Particle Bed generation) without the gravity force. Initially, there is a significant degree of overlap between the injected particles, thus creating large repulsive forces which accelerate the particles in different directions. As a result, particles move around and collide in a random fashion. After 20 s of this random particle translation and collision, the simulation is stopped and the resulting random particle positions are exported as described before. The resulting geometry is shown in Fig. 1.

C. Mesh

The obtained geometry given in Fig. 1 is then meshed using ANSYS Meshing. There are different mesh types available for the complicated geometries of the packed beds. Tetrahedral cells form the most basic form of unstructured mesh, but large meshes are required to obtain the same level of accuracy as compared with Polyhedral and Cutcell and therefore tetrahedral is not used in this work. Polyhedral meshing is difficult to obtain directly in ANSYS Meshing and has to be converted using Fluent which makes it inconvenient for export to OpenFOAM for the comparison done in this work. The structured hexahedral mesh created using the cutcell method can limit the number of cells required and can also be conveniently exported to OpenFoam®. It is therefore selected for this study with the details shown in Table 1.

The reactor geometry shown in Fig. 2 is meshed with the refinement near the particle surfaces and in the proximity region between the two particles. The particles are to be resolved for the Direct Numerical Simulation (DNS); therefore the resolution of $d_p/50$ is used on the particle surfaces as shown in Fig. 2. This degree of resolution is sufficient to resolve the heat transfer around individual particles in the packed beds.

D. Computational Fluid Dynamics

The meshed geometry is solved under steady state conditions since transient effects in the packed bed region can be assumed to negligible at operating low Reynolds numbers. Transient effects are stronger in the regions above the packed bed but the focus of this work was working on heat transfer in the packed bed region to compute the Nusselt

number for the particle to fluid heat transfer. Therefore, the steady state simulations provide a computationally cheaper solution to the heat transfer problems.

E. Model equations

The conservation equations of continuity, momentum, and energy for the incompressible, steady state, Newtonian fluid solved for the DNS are given by

$$\nabla . \vec{u} = 0 \tag{1}$$

$$\nabla . (\rho \vec{u} \vec{u}) = -\nabla p + \mu \nabla^2 \vec{u} + \rho \vec{g} \tag{2}$$

$$\rho C_p \nabla . (T \vec{u}) = K_f \nabla^2 T \tag{3}$$

The particle equation of motion solved in the DEM simulations is given below.

$$m_p \frac{dv}{dt} = m_p g + \sum_{i=1}^{j} (F_{p,i,n} + F_{p,i,t}) \tag{4}$$

Rotational particle motion was not solved as this was not necessary to obtain a randomly dispersed particle array.

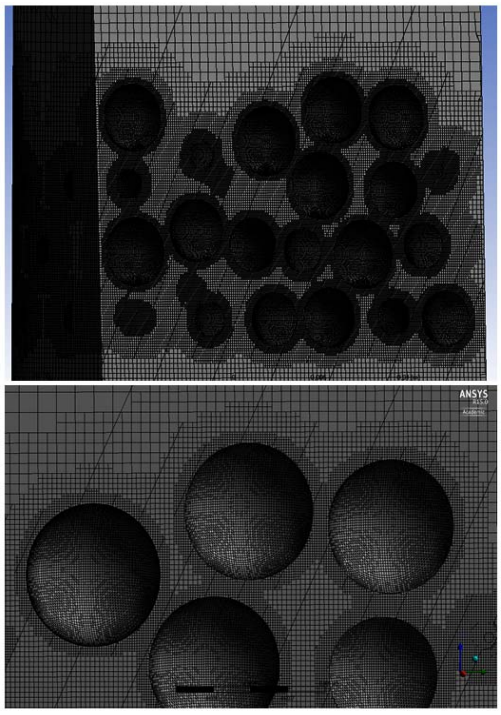

Figure 2: The reactor geometry at plane y=0 (above) and the particles resolved with dp/50 using a cutcell mesh

F. Boundary conditions

The particles maintained at a temperature of 573 K are cooled by a flowing fluid (air in this work) at 473 K. Table 3 shows the flow properties used in the simulations.

TABLE 3: FLOW PROPERTIES

Parameter	Value
Diameter of the particle (d_P) (m)	5e-3
Density (ρ) (kg/m^3)	1.225
Viscosity (μ) (kg/m s)	1.789e^{-5}
Thermal conductivity (k) (W/m K)	0.0242
Specific Heat capacity (C_p) (J/kg K)	1006
Prandtl number	0.744
Temperature of Inlet (K)	473
Temperature of particles surface (K)	573

The cylindrical reactor geometry contains a velocity inlet and a pressure outlet. The reactor wall is modelled with a no-slip boundary condition, and with zero heat flux. The heat transfer coefficient in the bed is calculated with the help of the heat flux through the particle surfaces from (5). The bulk fluid temperature is calculated using (6), i.e., the flux-averaged fluid temperature was computed. This is similar to the cup-mixing temperature used in literature. The values of the heat transfer coefficient are computed in the region of interest as described later in section (Case Setup).

$$\varphi_{P\to f} = h\,(T_P - T_{bulk}) \tag{5}$$

$$T_{bulk} = \frac{\int (u.\,e_z) T\, dV}{\int (u.\,e_z)\, dV} \tag{6}$$

G. Solver settings

ANSYS FLUENT is used to solve the heat and fluid flow around the particles in the bed. The phase-coupled SIMPLE algorithm with 2nd order spatial discretization schemes are used to obtain the solution.

III. VALIDATION FOR A SINGLE PARTICLE

This section of the paper validates the method outlined in section Methodology for a single particle before it is applied for more complex case simulations.

The heat transfer coefficient (Nusselt Number) and drag coefficient calculated from single particle surface immersed in fluid domain is computed for several particle Reynolds numbers varying between 20 and 400. The results for the convective heat transfer were compared to the experimental correlation from Ranz-Marshall,[22].

The comparison of heat transfer from the simulation and the experimental correlation is represented in Table 4 and Fig. 3. It is seen that the comparison of results is good, and the relative error exceeds 5% only at very low Reynolds numbers which are not of interest for packed bed operation.

TABLE 4: COMPARISON OF HEAT TRANSFER COEFFICIENT WITH RANZ_MARSHALL CORRELATION

Re	h_Ranz-Marshall (W/m²K)	simulation (W/m²K)	% (relative difference)
20	21.44	20.22	-6.099
40	26.32	25.35	-3.861
60	30.06	29.28	-2.695
80	33.22	32.50	-2.200
100	35.10	35.34	-1.871
200	46.90	46.83	-0.152
400	62.31	62.87	0.881

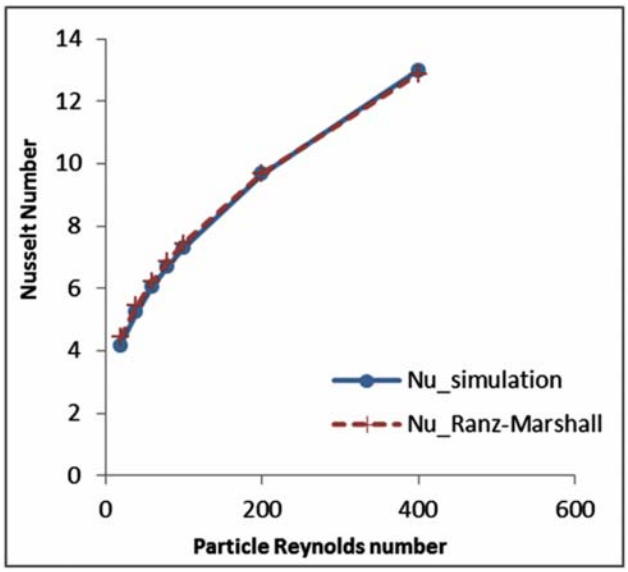

Figure 3: Prediction of heat transfer coefficient variation with particle Reynolds numbers

III. RESULTS AND DISCUSSIONS

This section compares the effect of different shrinking factors on the packed bed and checks whether the packed bed after shrinking can still be accounted under realistic packing or even random packings. The accuracy of the results from the different codes is validated, and the performance of commercial and open source codes is compared.

H. Case Setup

A reactor with an N value (ratio of reactor diameter to particle diameter) greater than 4 can be assumed to be less sensitive to the wall effects (Dixon).[23] Similar findings were presented by Smirnov et al., [24] for N > 3.5. The reactor in this work is with $N = 6$. To be sure that the wall effects, inlet effects and outlet effects do not affect the heat transfer calculations strongly, a region of interest is considered (Fig. 4) thus minimizing these effects. The data for the bed porosity and the convective heat transfer is calculated inside this region of interest.

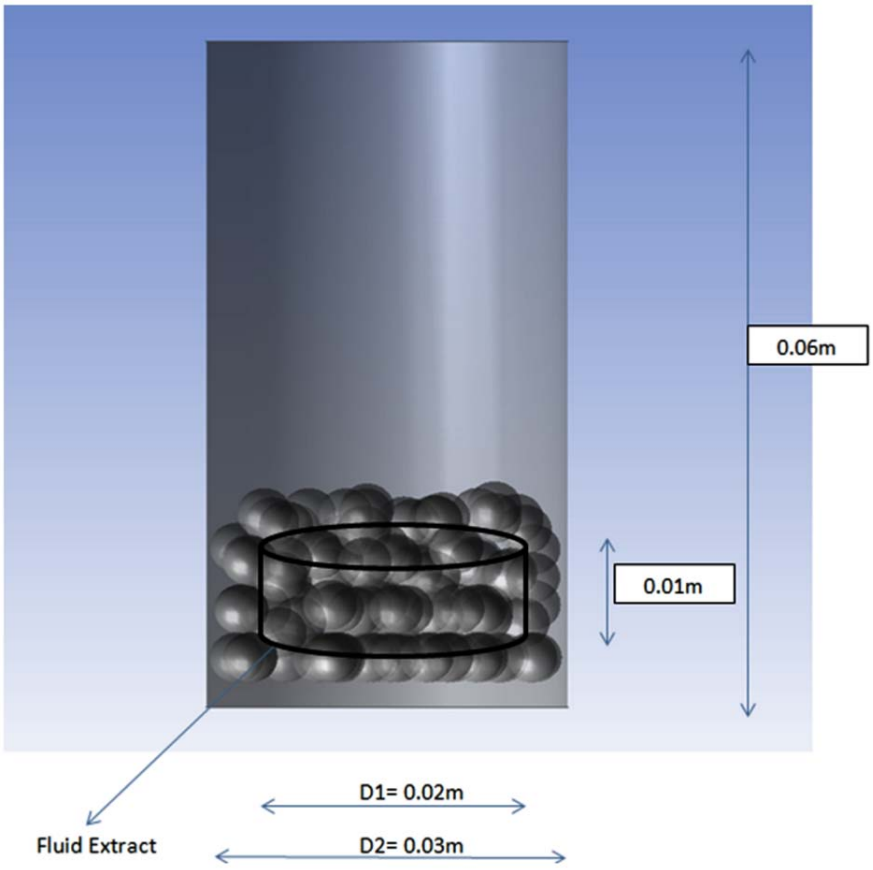

Figure 4: Representation of the region of interest in the packed bed region.

Various degrees of shrinkage were applied to the particle bed in order to avoid overlap and a change of the bed porosity. The five cases to be discussed in the next section are outlined in Table 5. Each of these five cases was simulated at four different particle Reynolds Numbers ranging between 36 and 144.

TABLE 5: SCHEMATIC REPRESENTATION OF DIFFERENT PACKED BED SETUPS ACHIEVED BY SHRINKING

Shrinkage (%)	Particle Diameter [mm]	Bed Porosity (Fluid Extract Region)
1.5 %	4.925	0.425
4 %	4.8	0.4755
10 %	4.5	0.5535
20 %	4.0	0.7256

I. Heat Transfer for Different Porosities

The comparison study for the spherical particle packed bed generated through shrinking is obtained by analysing the results of convective heat transfer coefficient from ANSYS FLUENT and then benchmarking the results against

the experimental correlation results by Gunn, [1] as well as two recent correlations derived from DNS results (Deen et al. and Sun et al.).[3, 4].

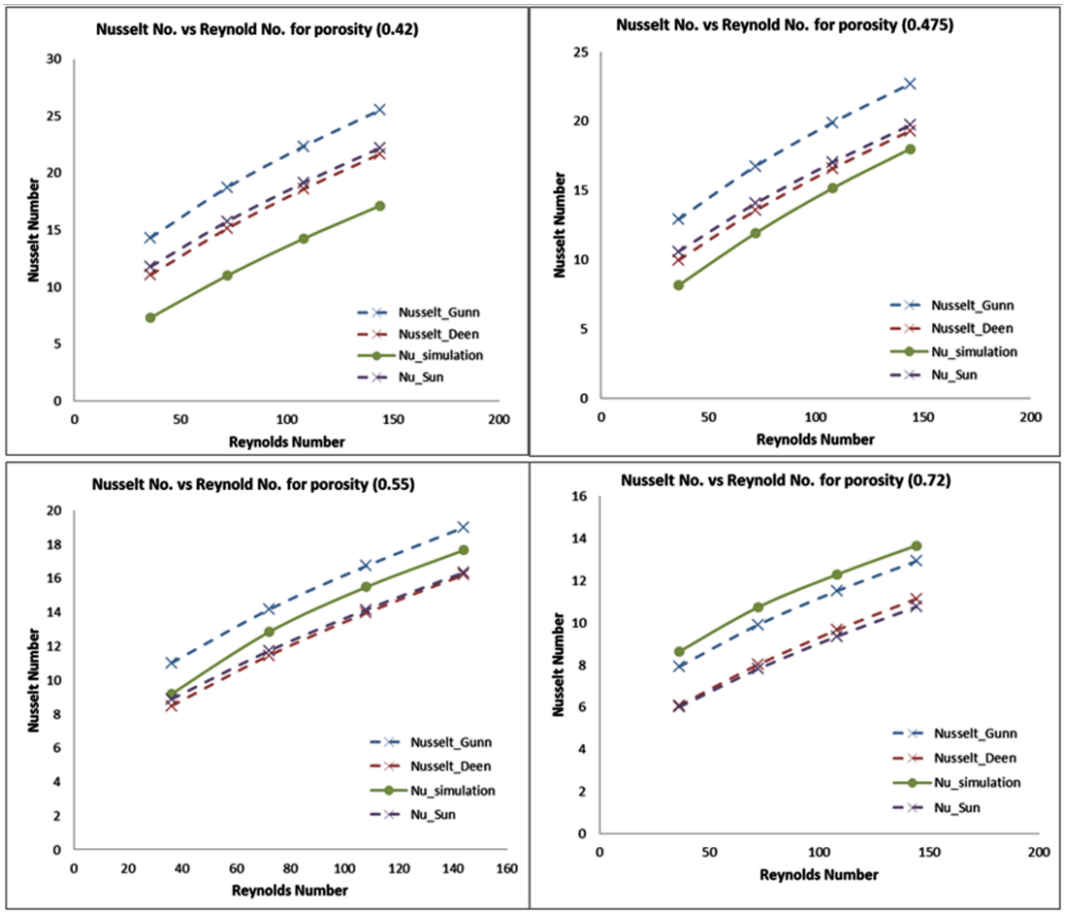

Figure 5: Comparison of heat transfer coefficient with the correlations over a range of Reynolds numbers and porosity values (obtained by shrinking factors)

The plots for the convective heat transfer from the particle surfaces in the region of interest for various porosities and different particle Reynolds numbers are shown in Fig. 5. It can be seen that for porosity ($\varepsilon = 0.42$), i.e., the closest to realistic packing, the heat transfer is under-predicting to the Gunn, Deen and Sun correlation results. This is not in good comparison and can be because of the validity of Sun et al.,[4] is for porosity ($0.5 < \varepsilon < 1$) i.e. random packings and not realistic packings. The comparison is similar for the correlation of Deen et al.,[3] which agrees closely with the results from Sun et al. [4] The validity of Gunn,[1] has already been discussed by Tavassoli et al.,[2] suggesting that is only valid for dilute systems with porosity ($\varepsilon > 0.7$).

For the higher porosity values ($\varepsilon = 0.47$, 0.55 and 0.72) which are achieved by shrinking the particles, the predicted heat transfer coefficients steadily increase when compared to the correlation values. Eventually, results from this study over predict all the experimental correlation values at porosity ($\varepsilon = 0.72$).

The reason for this trend is that a particle bed created by a large degree of particle shrinkage can be considered as neither a realistic nor a random packing. Particles in this kind of arrangement are equally spaced from each other,

thus maximizing the degree of gas-particle contact. In contrast, in a random packing (for which the various published correlations are valid), particles may shield each other. We speculate that this results in regions of relatively high voidage, where the gas slips past the particles, and hence heat transfer is limited. Our speculations are supported by a set of simulations in which a different packing was considered. Specifically, heat transfer in the random packing shown in Figure 1 with the same setup for geometry, meshing and solution as mentioned in Table 1 and Table 3, was analyzed. Therefore, this new random packing with a porosity of $\varepsilon = 0.62$ was generated, and compared to a bed with the same porosity but prepared by shrinking our old packing from section on Particle bed generation up by a factor of 13%.

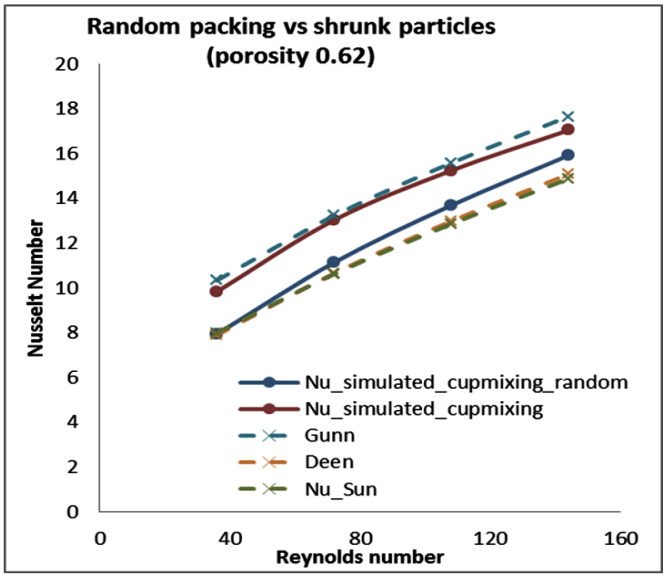

Figure 6: Comparison of heat transfer coefficient for shrunk and randomly generated particle bed

A variety of flow situations characterized by Reynolds numbers between 36 and 144 were analyzed for both packings. Fig. 6 illustrates that our results using a random packing are in close agreement with the DNS results from Deen et al. and Sun et al., [3, 4] within a 5% error corridor. This result serves as a validation of our simulation methodology against previous DNS results for random packings of higher void fractions. Most important, this result highlights the limitation in the method of varying the packing porosity by shrinking the particles.

Furthermore, this result serves as a validation of this method against previous DNS results for random packings of higher void fractions. This reemphasizes the result for the lowest porosity case shown in Fig. 5 where the DNS results from this study returned substantially lower heat transfer than all the correlations. This apparent inaccuracy of existing correlations in realistic packed bed packings is recommended for closer examination in future works.

IV. COMPARISON OF ANSYS FLUENT AND OPENFOAM

J. Heat transfer predictions

To verify the accuracy of the open source code OpenFOAM and the commercial code ANSYS FLUENT for the heat transfer calculations, a comparison from the results for the heat transfer coefficient over four (4) different cases is studied.

To validate the trend observed in the results obtained with FLUENT, 4 different cases as shown in Table 6 are simulated in OpenFOAM. To ensure a fair comparison, an identical setup is used for both codes when predicting the heat transfer rate as mentioned in previous sections (particle bed generation, random packing for DEM and case setup). The results obtained from OpenFoam and FLUENT match quite well within a 2% error corridor for $\varepsilon = 0.72$, and within 1% for $\varepsilon = 0.42$ (see Table 6 and Fig. 7).

TABLE 6: NUSSLT NUMBER COMPARISON BETWEEN OpenFOAM (OF) AND FLUENT

Porosity (ε)	Reynolds number	Code	Nusselt number	Difference (%)
0.42	36	FLUENT	7.327	0.398
		OF	7.357	
	144	FLUENT	17.141	-0.405
		OF	17.072	
0.72	36	FLUENT	8.634	1.640
		OF	8.776	
	144	FLUENT	13.662	1.630
		OF	13.885	

The typical velocity profile (Fig. 8) in realistic packing ($\varepsilon = 0.42$) shows similar detailed flow and temperature profiles being resolved by both codes, thus verifying the similar quantitative predictions given in Table 6.

K. Performance analysis

Two performance tests are studied using 20% shrinkage ($\varepsilon = 0.72$) and Reynolds number ($Re = 36$):

Sprint race: In this test the simulation for $\varepsilon = 0.72$ and $Re = 36$ is run using both codes for 20 iterations using eight cores of similar clock speed and with the same under relaxation factors for energy, pressure and momentum. The difference of the wall time at the end of iteration 21 and at the end iteration 1 is then computed. The time between the end of iteration 1 and end of iteration 21 is considered. This is because the time overhead due to matrix assembling is excluded in the computation time, which is negligibly small in a typical solution. The results from the sprint test are shown in Table 7, it is seen that for the same solver settings (Multigrid Solver) OpenFOAM takes a lesser time per iteration (15.25 s) when compared with the per iteration time (19.9 s) consumed by ANSYS FLUENT.

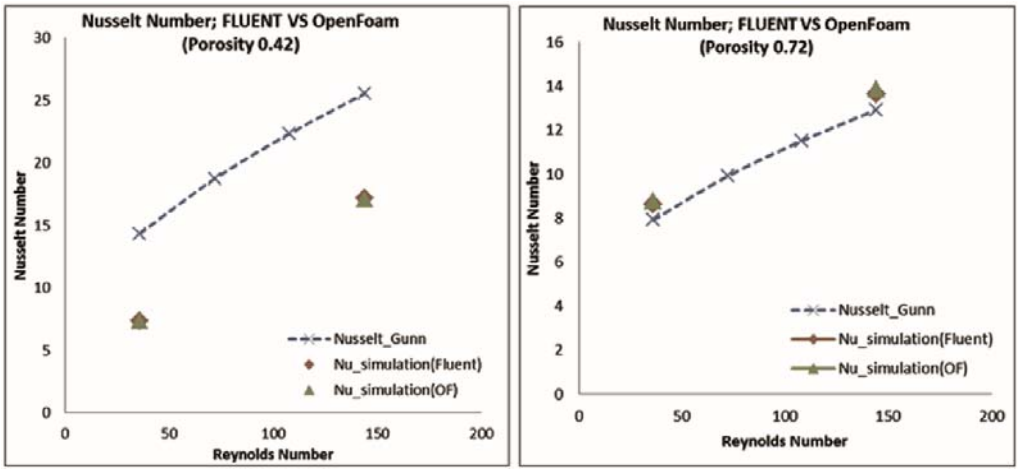

Figure 7: Comparison between FLUENT and OpenFOAM

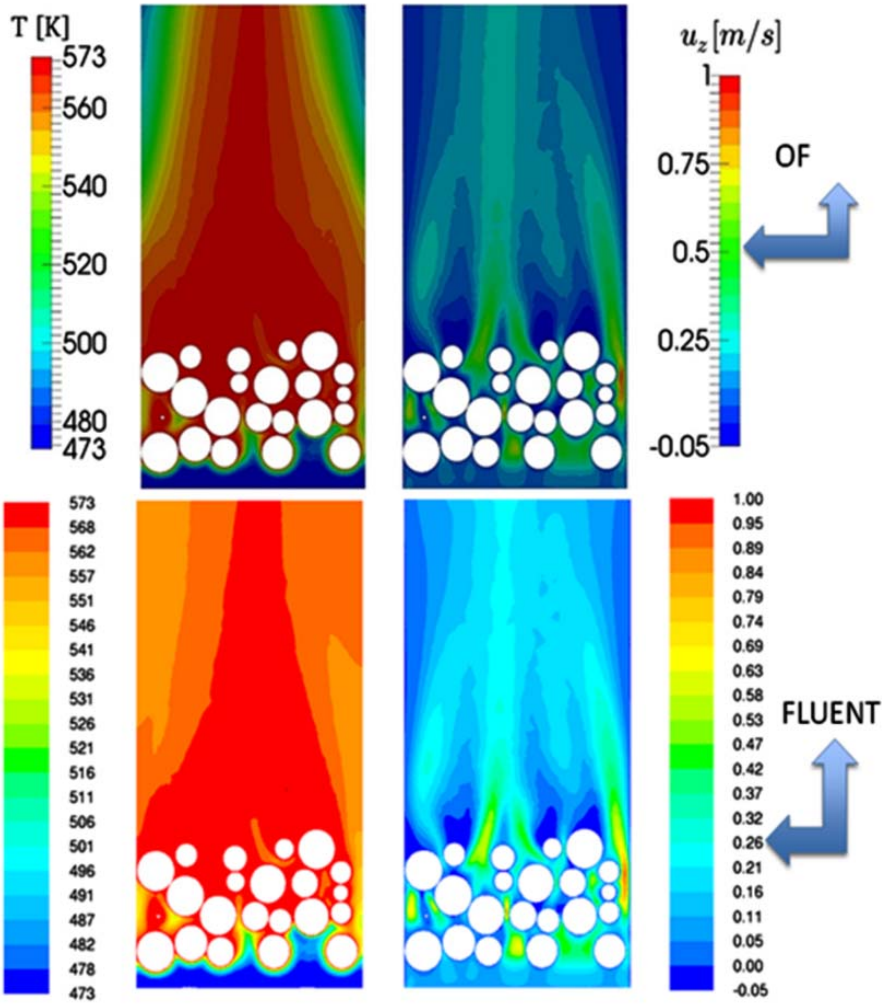

Figure 8: Representation of the velocity and temperature profile obtained from FLUENT and OpenFOAM (Plane y = 0; Re 36; $\varepsilon = 0.42$)

TABLE 7: PERFORMANCE TEST (SPRINT RACE) FOR 20 ITERATIONS

Code	Time (s)	Solver	Per iteration time (s)
FLUENT	398	AMG	19.9
OpenFOAM	305	GAMG	15.25

TABLE 8: PERFORMANCE TEST (MARATHON)

Code	No. of iterations	Solver
FLUENT	1083	AMG
OpenFOAM	2312	DILUPBiCG

Marathon: For the second performance test both the codes (software) running the same simulation are run until convergence. Convergence is monitored considering the residual parameters of the continuity, velocity and energy transport equation. An additional parameter described by the area weighted average of heat flux from the particle surfaces in the region of interest (Fig. 4) is also monitored. The parameters are monitored to reach the convergence of level 10^{-5} in both codes. It can be seen in Table 8 that the total number of iteration to convergence taken by FLUENT is only 46.8% of that consumed by OpenFOAM. The solver used by FLUENT simulations is AMG (Algebraic multigrid). When working with OpenFOAM the multigrid solver (GAMG) is only available for pressure, not temperature. Therefore to reach the degree of accuracy DILUPBiCG (Diagonal Incomplete LU preconditioned Biconjugate gradient) was used.

IV. Summary and Conclusions

The research problem targeted by this paper is the derivation of heat transfer correlations from PR-DNS for realistic packings of spherical particles. PR-DNS is commonly used for deriving heat transfer correlations at higher void fractions using random particle assemblies, but this flow situation is more suitable to fluidized beds than packed beds. Since particles in packed beds are about one order of magnitude larger than particles in fluidized beds, gas-particle heat transfer is a much more important limiting phenomenon in packed beds than fluidized beds.

For this reason, this work presents a method for conducting PR-DNS heat transfer studies in realistic packings of spherical particles. The most important challenge posed by this method is the regions of close proximity/overlap between particles, which result in highly skewed cells when the geometry is meshed. This study investigates the effect of overcoming this challenge by shrinking of particles in the bed. Comparison with heat transfer correlations available in the literature showed that particle shrinkage is not an attractive method to generate different porosity beds. The bed of particles (when shrunk) leads to a packing of equally spaced particles at a higher overall void fraction, which is neither a random nor a realistic packing. This packing over predicts the degree of gas-particle contact, and therefore also the degree of heat transfer relative to a random particle arrangement.

The correlations from Deen et al. and Sun et al., [3, 4] are valid for random packings ($0.5 < \varepsilon < 1$). Our results for a random packing with a porosity of $\varepsilon = 0.62$ are in close agreement with these correlations. However, our DNS

results for heat transfer in more dense (i.e., $\varepsilon = 0.42$) and wall-bounded packings differ significantly from Sun et al.'s and Deen et al.'s correlations for random packings. Thus, the question arises on the validity of these correlations for wall-bounded packings, and under denser particle concentrations.

The presented method with shrinking the particles improves on other works in that it can generate realistic packings. However, the accuracy of heat transfer predictions from this methodology is not sufficient for the derivation of reliable packed bed heat transfer correlations. Other more complex methods such as creating small gaps or bridges between adjacent particles will therefore be investigated in future works.

In addition an attempt is made to study the prediction of gas-particle heat transfer rates with the commercial code (FLUENT) and open source code (OpenFOAM) suggesting similar predictions. Computational performance of the two codes was also similar. On one hand the sprint race shows that OpenFOAM is clearly faster, when per iteration time is concerned. On the other hand the marathon test shows FLUENT gives the result in a smaller number of iterations. The origin of this difference is unclear, since a detailed documentation of FLUENT's algorithms is not available.

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NOMENCLATURE

Symbols

Re	Reynolds number
Nu	Nusselt number
Pr	Prandtl number
d_p	Diameter of the particle (m)
D	Diameter of the reactor (m)
j	Number of particles
K_f	Thermal Conductivity of fluid (W/ m K)
m_P	Mass of the particle (kg)
C_p	Specific Heat Capacity of fluid (J/Kg K)
h	Heat transfer coefficient (W/m^{2}K)
T_{bulk}	Bulk fluid temperature (K)
T_P	Particle surface temperature (K)
T	Temperature of the fluid (K)
e_z	Unit vector in z-direction
$\mathbf{u}$	Superficial velocity of the fluid (m/s)
v	Velocity of the particles for DEM (m/s)
u_z	Velocity of the fluid in Z-direction (m/s)
N	Ratio of diameter of reactor to diameter of the particle
dV	Volume in the region of interest
g	Gravity (m/s^2)

Greek

ε	Porosity (void fraction)
ρ	Density of fluid (kg/m^3)
μ	Viscosity of fluid (kg/ m s)
$\varphi_{f\to P}$	Heat flux from fluid to particles (W/m^2)

Vectors:

$\vec{u}$	Fluid velocity (m/s)
$\vec{g}$	Gravity (m/s^2)

Subscripts:

P	particle
f	fluid
n	normal
t	tangential

Operators:

∇	Gradient operator (m^{-1})
$\nabla \cdot$	Divergence operator (m^{-1})
∇^2	Laplace operator (m^{-2})
$\frac{d}{dt}$	time derivative (s^{-1})