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Numerical Study of Forced Convective Heat Transfer in Grille-Sphere Composite Packed Bed With Taguchi-CFD Method

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In the present paper, a grille is inserted into the packed bed to construct a grille-sphere composite packed bed with small grille-sphere packed channels inside, which would be helpful to improve the flow homogeneity and heat transfer performance inside. The tube to particle diameter ratio of the packed bed is relatively large, while the tube to particle diameter ratio of the grill-sphere packed channel is relatively small. Due to the effect of grille on the porosity, the pressure drop and heat transfer characteristics in the grille-sphere packed channels are significant. Furthermore, the Taguchi-CFD method is used to study the grille effects in detail, including grille thermal conductivity, grille thickness and tube to particle diameter ratio of the channel. It is found that, the effect of the tube to particle diameter ratio (N) would be the most significant, while the effects of grille thermal conductivity and grille thickness would be relatively small. Therefore, the tube to particle diameter ratio is considered as the main factor for an optimum design in grille-particle composite packed bed.

1. Introduction

Packed beds are widely used in chemical and nuclear energy industries, such as biofilm reactors and high temperature gas cooled nuclear reactors (Domingos et al., 2016). Traditional packed bed is usually arranged randomly, where the flow and heat transfer inside would be quite inhomogeneous. The temperature distribution is non-uniform and hot-spots are difficult to predict accurately. Besides, the pressure drop of randomly packed bed is higher than structured packed bed (Yang et al., 2010). In recent years, there has been considerable interest in structured packed beds, such as the simple cubic packing (SC), the body-centred cubic packing (BCC) and the face-centred cubic packing (FCC). Compared with the randomly packed bed, flow in structured packed bed is periodic and the temperature distribution is divinable. However, in reality, the high cost to achieve structured packing limits its application.

A novel type catalytic reactor containing a plurality unit cells with a very low tube to particle diameter ratio, called composite structured packing (CSP), is proposed by Strangio et al (2001). When the tube to particle diameter ratio equal to 1.0, the wall keep all particles packing structured and the whole packed bed is very similar with simple cubic packing. The porosity, fluid flow and heat transfer in single channel of CSP have also been investigated by Calis et al. (2001) and Romkes et al. (2003). The engineering correlations of pressure drop and heat transfer are obtained by fitting CFD results and agree well with their experimental results. In their research, the wall of each single channel is treated as thermal isolation. However, the convection between wall and fluid, the conduction in grille and the conduction between particle and grille have significant effects on the heat transfer in CSP. To investigate this problem, Wang et al. (2016) proposed a grille-sphere composite structured packed bed. The pressure drop and convective heat transfer in whole packed bed were experimentally studied in detail, including the particle-to-fluid heat transfer and grille-to-fluid heat transfer. However, in their research, the effect of tube to particle diameter ratio and property of grille were not studied. It is necessary to learn the effect of various design parameters of grille on the packed bed heat transfer performance and to find out an optimized parameter combination.

In the present study, the Taguchi method (Taguchi and Konishi, 1987) is adopted with computational fluid dynamics (CFD) studies. The effects of various design parameters are analysed on the heat transfer characteristics of grille-sphere composite packed beds.

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2. Models of grille-sphere composite packed bed

2.1 Physical Model

A graphite grille is inserted into a randomly packed bed, which is similar to HTR-10, this progress is illustrated in Figure 1. HTR-10 is a high temperature gas cooled reactor with reactor power of 10 MWt. The core of HTR-10 consists of 27,000 spherical pebble-bed fuels with diameter of 60 mm (Wu et al., 2002). Other parameters are shown in Table 1 (Ge et al., 2016). The graphite grille and fuel particles construct a novel grille-sphere composite packed bed, as is shown in Figure 1.

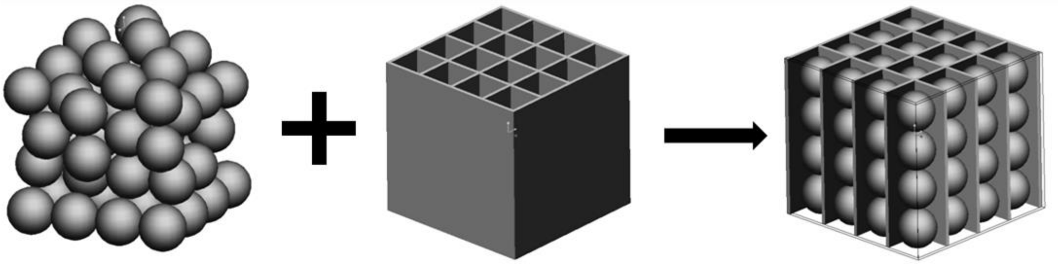

Figure 1: The progress of generating a grille-sphere composite packed bed

Table 1: The main characteristics of HTR-10

Parameter	Value
Primary helium pressure	3.0 MPa
Inlet / Outlet temperature of helium	523.15 K / 973.15 K
Average thermal power of fuel element	0.37 kW
Density of fuel element	1,840 kg/m^3
Capacity of fuel element	1,760 J/kg·K
Thermal conductivity of fuel element	31.2 W/m·K

The design parameters of grille are shown in Figure 2, which includes the diameter length (L), thickness (δ) and thermal conductivity (λ). Since the tube to particle diameter ratio (N) is more widely used than the diameter length in packed bed, the tube to particle diameter ratio (N) is chosen as a design parameter in this work. It can be defined as follow:

$$N = L / d_{\mathrm{p}} \tag{1}$$

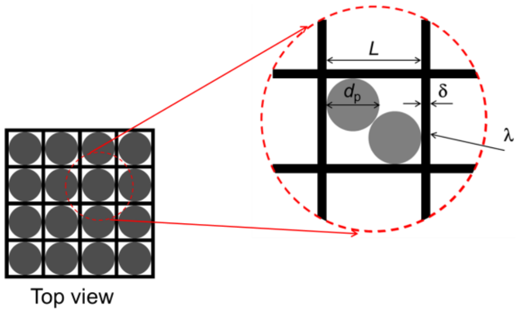

Figure 2: The design parameters of grille

The packing structures are generated by using the discrete element method proposed by Cundall (1971). With the same tube to particle diameter ratio, the packing structure would be different. Therefore, each packing with a fixed N are reconstructed with ten times and the porosities of these packings are shown in Figure 3. Five different N are selected for CFD simulations, including N=1.0, 1.5, 1.6, 1.8 and 2.0. The packings with N=1.0 and N=2.0 are chosen, because their packing structures are similar with simple cube packing (SC); N=1.5 and N=1.8 are the peaks of porosity curves; N=1.6 is the valley between N=1.5 and N=1.8.

2.2 Mathematical Model

The packing structure within each channel is assumed to be uniform, and one of the channels is used for the simulation with symmetry boundary condition. The gas force convection of fluid domain and the heat conduction of solid domain, including particle and grille, are taken into account. For different cases, the mass flow rate is kept the same. The RNG k-ε turbulence model and the scalable wall treatment are adopted in the present work.

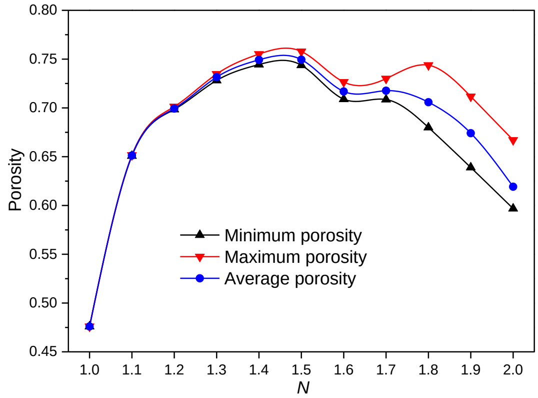

Figure 3: Porosity of packing structure with different N

2.3 Model Validation

In order to validate our computational model, the forced convective heat transfer in SC packing is chosen for comparison purposes. Figure 4 shows the comparisons between reference results and present results. For the drag coefficient and Nusselt number, the maximal deviations between experimental data and present simulation data are less than 5%. It indicates that, the present computational model is available to predict the fluid flow and heat transfer in packed beds.

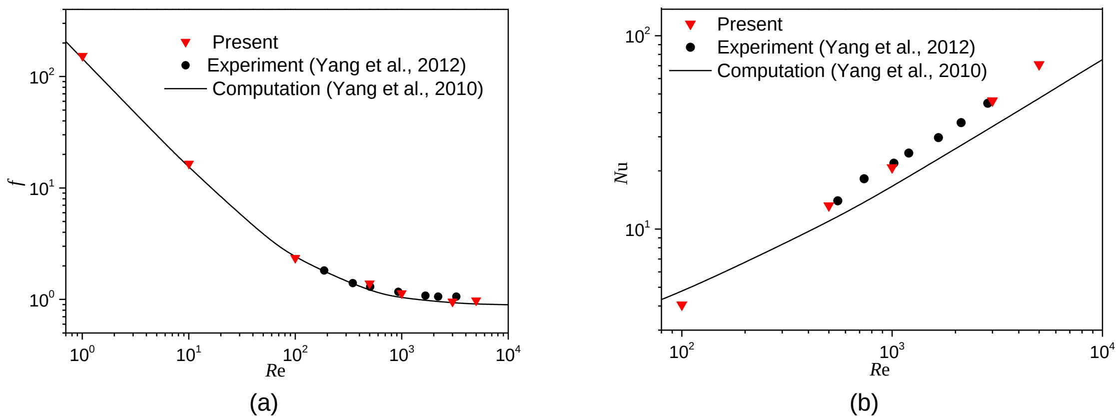

Figure 4: Model validation (a) Drag coefficient, (b) Nusselt number

3. Taguchi Method

The Taguchi method (Taguchi and Konishi, 1987) is adapted for the optimization of multi parameter effect. The values of three design parameters are divided into five levels, as show in Table 2. To investigate all possible parameter combinations, 3^5=125 cases need to be calculated. With Taguchi method, a suitable orthogonal array can not only reduce most of calculation, but also can clearly present the influence of each undetermined parameters on the target. Numerical simulations are performed to optimize the performance of the heat exchanger using the $L_{25}(5^6)$ orthogonal array table for the design points, as shown in Table 3.

Table 2: Design parameter values

Design parameters	Symbol	Level				
		1	2	3	4	5
Tube to particle diameter ratio (-)	N	1.0	1.5	1.6	1.8	2.0
Grille thickness (mm)	δ	4	6	8	10	12
Grille Thermal conductivity (W/m·K)	λ	7.5	15	30	60	120

For safe operation of high temperature gas cooled reactor, keeping the maximal fuel element temperature lower than the permitted limit for TRISSO fuel is the most important design principle. In this work, we apply Taguchi method to investigate the effect of the grille design parameters on the maximal fuel element temperature in HTR-10. The signal to noise (*SN*) is used to statistically analyse the heat transfer performance, which is calculated as follow:

$$SN = -10\log[T_{\max}^2] \tag{2}$$

Table 3: Orthogonal array table of $L_{25}(5^6)$

Case	Design parameters			Case	Design parameters		
	N	δ	λ		*N*	δ	λ
1	1	1	1	14	3	4	1
2	1	2	2	15	3	5	2
3	1	3	3	16	4	1	4
4	1	4	4	17	4	2	5
5	1	5	5	18	4	3	1
6	2	1	2	19	4	4	2
7	2	2	3	20	4	5	3
8	2	3	4	21	5	1	5
9	2	4	5	22	5	2	1
10	2	5	1	23	5	3	2
11	3	1	3	24	5	4	3
12	3	2	4	25	5	5	4
13	3	3	5				

4. Results and Discussion

The maximal temperature and corresponding signal-to-noise (*SN*) ratio of each simulation case are shown in Figure 4. Design parameter effect and contribution ratio (*CR*) for each level are presented in Table 5 and Figure 5, respectively. The *SN* ratio of each design parameter in Table 4 is derived from the sum of *SN* ratios corresponding to each level in Table 4. The performance statistic (*R*) is the difference of maximal and minimal of the *SN* ratio for each design parameter (*N*, δ, λ). The contribution ratio (*CR*) stands for the influence of each design parameter on the target, which is the maximal fuel element temperature in high temperature gas cooled reactor. It can be defined as follow:

$$CR_i = \frac{R_i}{R_{total}} \tag{3}$$

Where $i = N$, δ or λ.

Table 4: Design parameters and effect of all cases

Case	Design parameters			T_{max} (K)	*SN*
	N (-)	δ (mm)	λ (W/m·K)		
1	1.0	4	7.5	825.26	-58.33
2	1.0	6	15	818.65	-58.26
3	1.0	8	30	813.82	-58.21
4	1.0	10	60	805.92	-58.13
5	1.0	12	120	803.02	-58.09
6	1.5	4	15	1,005.72	-60.05
7	1.5	6	30	986.77	-59.88
8	1.5	8	60	967.63	-59.71
9	1.5	10	120	948.03	-59.54
10	1.5	12	7.5	994.10	-59.95
11	1.6	4	30	1,215.80	-61.70
12	1.6	6	60	1,159.64	-61.29
13	1.6	8	120	1,118.86	-60.98
14	1.6	10	7.5	1,243.86	-61.90
15	1.6	12	15	1,201.25	-61.59
16	1.8	4	60	930.66	-59.38

Case	Design parameters			T_{max} (K)	*SN*
	N (-)	δ (mm)	λ (W/m·K)		
17	1.8	6	120	917.97	-59.26
18	1.8	8	7.5	954.96	-59.60
19	1.8	10	15	943.09	-59.49
20	1.8	12	30	930.98	-59.38
21	2.0	4	120	989.03	-59.90
22	2.0	6	7.5	1,037.51	-60.32
23	2.0	8	15	1,018.58	-60.16
24	2.0	10	30	1,001.05	-60.01
25	2.0	12	60	987.41	-59.89

Table 5: Performance statistics and contribution ratios of parameters

	SN_1	SN_2	SN_3	SN_4	SN_5	*R*	*CR*
N	-291.02	-299.13	-307.45	-297.10	-300.28	16.42	84.44%
δ	-299.36	-299.01	-298.66	-299.06	-298.90	0.70	3.59%
λ	-300.10	-299.56	-299.18	-298.39	-297.77	2.33	11.97%

Through 25 cases, the contribution ratio of every design parameter can be evaluated as follows: 84.44% for tube to particle diameter ratio, 11.97% for thermal conductivity of grille, and 3.59% for the thickness of grille, as shown in Figure 5. It indicates that, the tube to particle diameter ratio has the most significant influence on the objective function. Therefore, more attention should be paid to this design parameter when designing the graphite grille in high temperature gas cooled reactor.

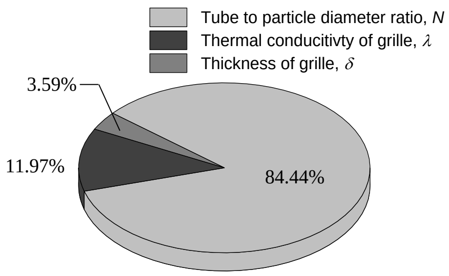

Figure 5: Contribution ratio of design parameters

Figure 6 shows the *SN* ratio of every design parameter varies with different levels, which is useful for optimizing design parameters. The *SN* ratio of design parameter δ and λ vary slightly with different levels, since these two design parameter have litter effects on the objectivity function. From Figure 6, we can also find out that, the *SN* ratio of *N* have an obvious change with different levels. This can be explained by the fact that, the tube to particle diameter ratio *N* has significant effect on the structure of packed bed and the heat transfer performance inside. The level 1 of *N*, the level 3 of δ and the level 5 of λ are the best levels, respectively. The results show that *N* (1), δ(3), λ(5) is the best design parameter combination. However, this kind of design parameter combination does not exist in Table 3. Therefore, this design parameter combination is built to a new case (26 case), then it is calculated and compared with other 25 cases in Table 3.

As shown in Figure 7, the maximal fuel element temperature in packed bed is compared, including 25 cases in Table 3 and the case 26. It can be seen that, the maximal temperature of case 5 is the smallest of the 25 cases with T_{max} of 803.02 K, while the maximal temperature of case 26 is smaller than case 5 with T_{max} of 802.22 K. Therefore, the case 26 is better than other 25 cases and it means that this kind of grille-sphere composite packed bed is safer than other 25 design parameter combinations.

5. Conclusions

In the present paper, the grille-sphere composite packed bed design parameters, which would affect the heat transfer in high temperature gas cooled reactor, have been analyzed using Taguchi method. The following conclusions would be derived:

(1) The tube to particle diameter ratio is the most significant design parameter for the maximal fuel element temperature. Besides, the contribution ratios of the other two design parameters, the thickness and thermal conductivity of grille, are 3.59% and 11.97%, respectively, which also play important roles for composite packed bed design.
(2) A relativity optimal design parameter combination is determined. The maximal fuel element temperature is the lowest for the case 26, where the *N* level is 1, δ level is 3 and λ level is 5.

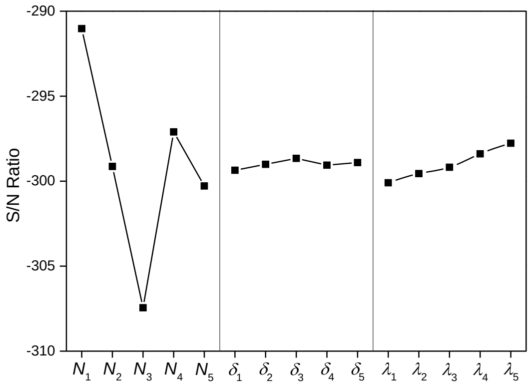

Figure 6: Effects of the design parameters

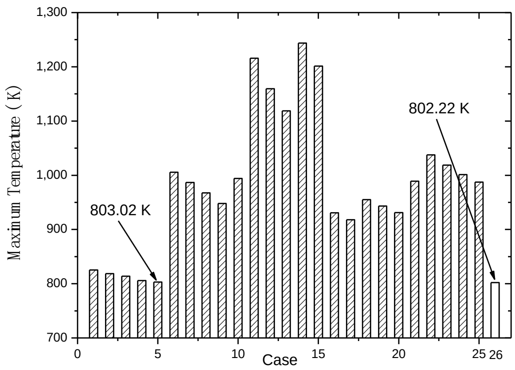

Figure 7: The maximal temperature of all cases

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