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Developing Basic Unit Cell (BUC) Model for Natural Convection Heat Transfer Characteristics in Packed Beds of Proposed Coated Particle Nuclear Fuel Design

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ABSTRACT

Evaluating convective heat transfer performance in packed beds arising in various engineering problems is a complex issue due to the different parameters involved in the media, such as the bed materials, heat transfer mechanisms, packing structure and heat source. Apart from a number of assumptions made in various correlations developed for determining heat transfer performance in packed beds, literature survey also reveals that more experimental researches were conducted with fluid flowing in and out of the medium than heated fluid confined in an enclosed medium. Noted also is that most of the experimental research found in literature were conducted under forced convection compared with the investigation in the present study conducted under natural convection. In a quest to investigate the particle-to-fluid heat transfer characteristics expected in the proposed new fuel design, a basic unit cell (BUC) model is being developed for the theoretical analysis and applied to determine the heat transfer coefficient, *h*, of the medium. The model adopted a concept in which a single unit of the packed bed was analyzed and taken as representative of the entire bed; it related the convective heat transfer effect of the flowing fluid with the conduction and radiative effect at the finite contact spot between adjacent unit cell particles. As a result, the model could account for the thermophysical properties of sphere particles and the heated gas, the interstitial gas effect, gas temperature, contact interface between particles, particle size and particle temperature distribution in the investigated medium. Although the heat transfer phenomenon experienced in the experimental set-up was a reverse case of the proposed fuel design, the study with the achievement in the validation with the Gunn correlation aided in developing the appropriate theoretical relations required for evaluating the heat transfer characteristics in the proposed nuclear fuel design.

Keywords: packed beds, heat transfer coefficient, basic unit cell model, coated particle nuclear fuel

NONMENCLATURE

Symbols

A	Area, m^2
C_p	Specific heat at constant pressure, J/kgK
d	Diameter, m
Gr	Grashof number
g	Gravity, m/s^2
h	Heat transfer coefficient, W/m^2 K
k	Thermal conductivity, W/m K
N_c	Average coordination number
Nu	Nusselt number
Pr	Prandtl number
Q	Heat transfer rate, W
q''	Heat flux, W/m^2
R	Thermal resistance, K/W
Ra	Rayleigh number
T	Temperature, K
t	Time, sec
V	Volume, m^3
v	Specific volume, m^3/kg

Subscript

c	Contact point
cr	Rough contact
eff	Effective
f	Fluid
G	Macrogap
g	Gas
j	Thermal joint
L	Macrocontact
p	Particle
pf	Particle-to-fluid
fp	Fluid-to-particle
R	Radioactive
s	Solid
Bc	Bottom contact
Tc	Top Contact

Superscript

c	Contact Interface between particles
t	Time, sec

Greek

ε	Porosity
ρ	Density, kg/m^3
β	Thermal expansion coefficient, 1/K

1. INTRODUCTION

The Basic Unit Cell (BUC) model adopts the concept of a single unit of the packed bed being analyzed and taken as representing the entire bed; it relates the convective heat effect of the flowing fluid with the conduction and radiation effect between adjacent particles at the finite contact spot. A unit cell is made up of any identified particle in the bed with adjacent contacting particles (see Fig. 1). The model is an application of conservative heat transfer energy balance within any unit cell in the medium. It brings into account every form of heat exchange that occurs in the unit cell. The focus of the present work is the development of a suitable theoretical model for evaluating the natural convection heat transfer characteristics in porous media heated by a hot gas through natural convection and that of heat-generating particles. Heat transfer mechanisms that play an active role in packed beds are as follows (see Fig. 2): (i) the convective heat transfer from the surface of the packing materials (particles) to the fluid, sometimes referred to as particle-to- fluid mode; (ii) the convective heat transfer from the flowing fluid to the particles, sometimes referred to as fluid-to-particle mode; (iii) the conduction heat transfer between the walls of the bed and the particle interface constituting the bed; (iv) the conduction heat transfer between individual particles in the bed, sometimes referred to as particle-to-particle mode; (v) radiant heat transfer between particles and between particles and the container wall; (vi) radiant heat transfer between fluid and particles [1]. However, the modes are not compartmentalized and will naturally influence one another; for instance, conduction between the particles may be affected by the convection between the particles and the fluid. This interaction among the different modes is one of the main reasons for the difficulty in correlating the total heat transfer and analyzing the experimental data obtained. Fundamental heat transfer principles were applied by [2] to characterize the heat transfer mechanism between two contacting rough solid spherical bodies. The model only dealt with conduction through the contact area between spheres while incorporating surface roughness and conduction through the gas phase at lower temperatures. Good results were obtained from the study when the model was compared with other packings though limited to SC and FCC arrangements. It was suggested that the heat transfer trends obtained in regularly packed beds through the model could be used to study the effect of important parameters involved in randomly packed beds. However, the new model developed in this chapter would be based on some of the thermal conduction heat transfer principles used by [2]. While [2] concentrates on conduction across the contact region of rough contacting spherical surfaces, this model is developed based on Hertzian (perfect) contacts between the contacting particles since the particle falls within a Brinell hardness of $1.3 \leq H_B \leq 7.6$GPa [3]. The newly developed basic unit cell model deals with all the aforementioned heat transfer mechanisms, while distinguishing between short-range thermal radiation, defined as radiation to and from spheres in contact with the sphere under consideration, and long-range thermal radiation, defined as radiation to and from spheres not in direct contact with the sphere under consideration (see Fig. 2). One vital form of heat exchange intensely dealt with in the model is conduction mode. To completely resolve the issue of heat transfer by conduction in the unit cell, the model combines both analytical and numerical methods in predicting the conduction mode of heat transfer in packed beds; analytical refers to the use of the concept of thermal contact resistance (TCR) [4] of smooth sphere particles and numerical refers to the use of finite volume method [5] (FVM) to determine the temperature distribution within the particles.

2. CONTACT REGION BETWEEN ADJACENT PARTICLES

The contact region is made up of the nominal contact area found at the contact spot between two adjacent particles and the surrounding gas layer as shown in Fig. 3. The heat transferred in an isolated contact region may be used to determine the thermal heat transfer behaviour of the bed [6]. Thermal energy can be transferred across the joint via radiation, conduction through interstitial gas in the gap and conduction through the finite contact spot [2]. Conduction which is predominant at the contact region [7] occurs in rough spherical surfaces via three main paths [2]: microcontacts, Q_s, the interstitial gas within the microgap, Q_g, and the interstitial gas within the macrogap, Q_G. An expression of the total heat transferred across the region relating to the temperature difference across the region and the joint thermal resistance at the contact region is given in Eq. (1).

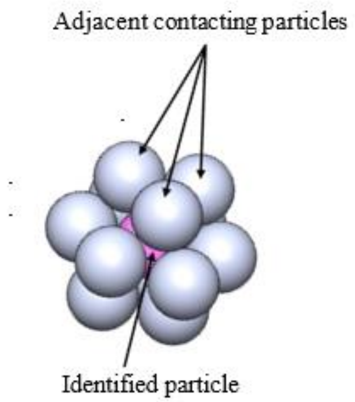

Fig. 1 Single Unit Cell

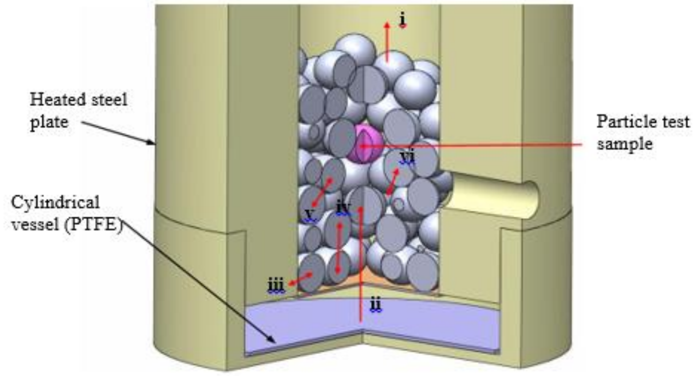

Fig. 2 Section through part of the test facility with a particle test sample highlighted. (i) heat transfer by particle-to-fluid mode, (ii) heat transfer by fluid-to-particle mode, (iii) heat transfer between the bed wall and particles, (iv) heat transfer by particle-to-particle mode, (v) radiant heat transfer between particles, (vi) radiant heat transfer between fluid and particles.
Source: *Noah et al., 2015*

$$Q_{cr} = Q_s + Q_g + Q_G = \frac{\Delta T}{R_j} = \frac{T_1 - T_2}{R_j} \tag{1}$$

Where R_j for the rough contact is given in the equation below:

$$R_j = \left[\frac{1}{\left(\frac{1}{R_S} + \frac{1}{R_g}\right)^{-1} + R_L} + \frac{1}{R_G}\right]^{-1}$$

The total heat by conduction across the region of adjacent particles in perfect contact Q_{cp} can then be expressed by Eq. (2);

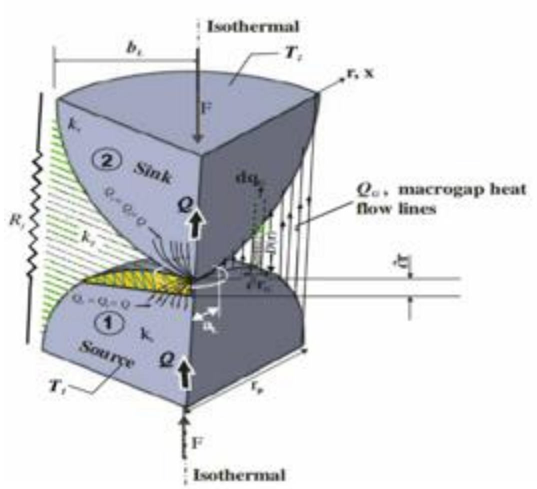

Fig. 3 Heat conduction between two smooth elastic particles in perfect contact (Hertzian contact) [6]

$$Q_{cp} = Q_c + Q_G = k_{eff}^{c} \frac{dT_i}{dz} A_c + \frac{\Delta T_i}{\left[\frac{1}{R_G}\right]^{-1}} \tag{2}$$

The total effective thermal conductivity of the homogeneous section of the packed particle bed is expressed in Eq. (3):

$$k_{eff}^{T} = k_{eff}^{c} + k_{eff}^{r} + k_{eff}^{G} \tag{3}$$

Combining the heat transfer modes mechanism (natural convection, conduction and radiation) acting in the above medium, the fluid-to-particle heat transfer coefficient, h_{fp}, is developed and expressed in Eq. (4).

2.1 The Proposed Medium

Since the coated particle fuel is a heat-generating source by nuclear fission, the temperature distribution on the surface of each coated particle is expected to be uniform. A situation of steady-state heat generation is applicable in this circumstance. Heat is produced by the UO_2 fuel kernel at the constant rate q''' [W/m^3] per unit volume inside the coating layers. The particle-to-fluid heat transfer coefficient, h_{pf} developed for the medium of the proposed design (see Fig. 4), is expressed in Eq. (5).

$$h_{fp} = \frac{(1-\varepsilon)\frac{(\rho C_\rho V_T)}{\Delta t}\left[T^{t+\Delta t} - T^{t}\right] - \sum_{m=1}^{4}\left[\left\{k_{eff}^{c}\frac{dT_i}{dz}A_c + \frac{\Delta T_i}{R_G}\right\}_{Bc} - \left\{A_p q''_R\right\}_{Bc}\right]_m + \sum_{n=1}^{4}\left[\left\{k_{eff}^{c}\frac{dT_i}{dz}A_c + \frac{\Delta T_i}{R_G}\right\}_{Tc} - \left\{A_p q''_R\right\}_{Bc}\right]_n}{\left(A_p - \sum_{e=1}^{8} A_{c_e}\right)\left(T_f - T_p\right)} \tag{4}$$

$$h_{fp} = \frac{(1-\varepsilon)\frac{(\rho c_\rho V_T)}{\Delta t}[T^{t+\Delta t}-T^t]-\sum_{m=1}^{4}\left[\left\{k_{eff}^{c}\frac{dT_i}{dz}A_c+\frac{\Delta T_i}{R_G}\right\}_{Bc}-\{A_p q''_R\}_{Bc}\right]_m+\sum_{n=1}^{4}\left[\left\{k_{eff}^{c}\frac{dT_i}{dz}A_c+\frac{\Delta T_i}{R_G}\right\}_{Tc}-\{A_p q''_R\}_{Bc}\right]_n}{(A_p-\sum_{e=1}^{8}A_{c_e})(T_f-T_p)} \quad (5)$$

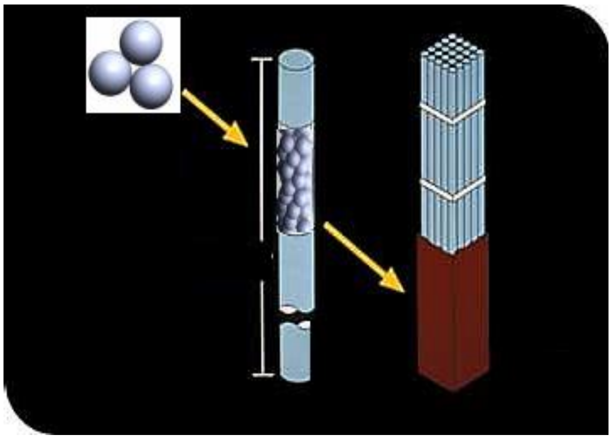

Fig. 4 Proposed new nuclear fuel design

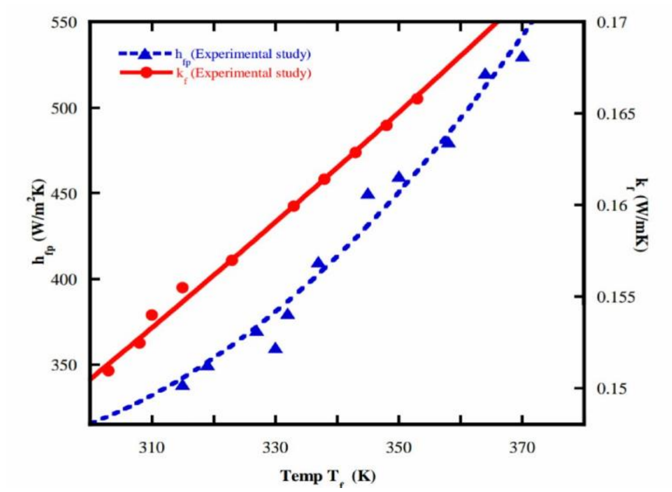

Fig. 5 Effect of gas temperature on convective fluid-to-particle heat transfer coefficient

The heat transfer characteristics in this study for the proposed new fuel design under natural convection are evaluated using the particle-to-fluid heat transfer coefficient, $h$pf, Nusselt number, Grashof number, Prandtl number and the Rayleigh number. These are expressed in Eqs. (6) and (7).

$$Nu = \frac{h_{pf} d_p}{k_f} \quad (6)$$

$$Ra_{d_p} = \frac{g\beta\left|T_s - T_f\right| d_p^3}{v^2} Pr = Gr.Pr \quad (7)$$

2.2 Results

The experimental evaluation of heat transfer in the investigated medium (see Fig. 1) was carried out by applying the first principle heat transfer concept to the heat exchange that occurred in the particle test sample and the results obtained forms a representation of the heat transfer characteristics of the investigated medium. The graphs in Fig. 5 depicted an effect of gas temperature on both fluid-to-particle heat transfer coefficient and thermal conductivity of helium gas. From the figure, it could be seen that the fluid-to-particle heat transfer coefficient increased with a rising gas temperature. Another effect of rising gas temperature in the medium shown in the graph was a slight increase in the gas thermal conductivity.

A more detailed examination of the particle test sample through the BUC model accounted for the transient heat conduction in the particle test sample along with the various sources of heat at the contact points and at the interstice through the application of different methods, which were not considered in the experimental evaluation process. These differences made the results of the BUC model heat transfer characteristics more dependable compared with results obtained from the experimental evaluation. A conclusive action to provide sufficient assurance of the dependability of the theoretical analysis is achieved through close examination of the graph in Fig. 6 depicting the variation of Nusselt number against the Rayleigh number for the experimental and theoretical results.

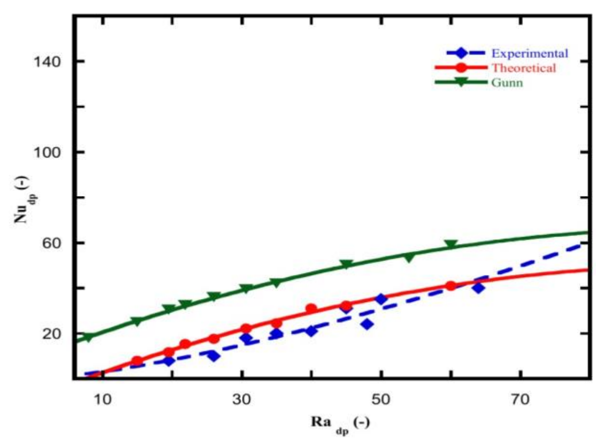

Fig. 6 Variation of Nusselt number with Rayleigh number for fluid-to-particle heat

From the graphs depicted in Fig. 6, the Nusselt number for the experimental and theoretical results is observed to rise gradually but with a different profile. The graph of the theoretical Nusselt number is seen to have a similar profile as that of Gunn's correlation results. The profile of the experimental Nusselt number may be attributed to lumped system application assumptions on the particle test sample and the non-consideration of heat source and heat sink phenomenon associated with contacting particles in the investigated configuration. A further rise in the graph of the experimental results after interception with the graph of theoretical results is observed to approach the graph of validating Gunn's correlation [8] results. This development may be attributed to a phenomenon in which the experimental evaluation approach considers the test sample as a single particle in the investigated configuration gradually but with a different profile.

3. CONCLUSION

The chapter discussed the heat transfer in the traditional nuclear fuel. The aim of the theoretical analysis was to investigate the heat transfer characteristics in packed beds under natural convection and to validate the results with a suitable correlation such as that of Gunn [8]. The investigation carried out in the bed was done in the bulk region of the bed that formed the major part of the medium. The heat transfer coefficient, h_{fp}, Nusselt number, Nu, and the Rayleigh number, Ra, were the parameters used in the evaluation and their values were all determined in the bulk region. The results from the study revealed a rising natural convection heat transfer effect between particle surface and the gas flowing past it at an increasing bed temperature. Slightly differing values are likely to be obtained at the near-wall region because of the high porosity associated with this region. Although the heat transfer phenomenon experienced in the theoretical investigation was a reverse case to the real fuel application but for design purpose, the study leads the way in developing a model suitable for evaluating the heat transfer characteristics within the cladding tube with coated particle fuels. In addition, the study has also established the limitations of experimental evaluation approach in determining the heat transfer characteristics in porous media under natural convection.

REFERENCE

[1] Noah OO, Slabber JF, Meyer JP. Experimental evaluation of natural convection heat transfer in packed beds contained in slender cylindrical geometries. Proceedings of the 5th International Conference on Applications of Porous Media, Romania, 2013; 301-316.

[2] Bahrami M, Yovanovich MM, Culham JR. Effective thermal conductivity of rough spherical packed beds. Int. J. Heat Mass Transfer 2006; 49(20): 3691-3701.

[3] Timoshenko SP, Goodie JN. Theory of Elasticity. Article 140, McGraw-Hill; 1970.

[4] Ridgeway K, Tarbuck KJ. Voidage fluctuations in randomly-packed beds of spheres adjacent to a containing wall. Chemical Engineering Science 1968; 23(9): 1147-1155.

[5] Romkes SJP, Dautzenberg FM, van den Bleek CM, Calis, HPA. CFD modeling and experimental validation of particle-to-fluid mass and heat transfer in a packed bed at very low channel to particle diameter ratio. Chemical Engineering Journal 2003; 96: 3–13.

[6] Balakrishnan AR, Pei DCT. Heat transfer in gas-solid packed bed systems, 2 & 3. The conduction mode. Overall heattransfer rates in adiabatic beds. Ind. Eng. Chem. Process Des. Dev. 1979; 18(1): 40-48.

[7] van Antwerpen W, Rousseau PG, du Toit CG. Multi-sphere unit cell model to calculate the effective thermal conductivity in packed pebble beds of mono-sized spheres, Nuclear Engineering and Design 2012; 247: 83-201.

[8] Gunn DJ. Transfer of heat or mass to particles in fixed and fluidized beds. International Journal for Heat and Mass Transfer 1978; 21(8, 18): 467-476.