Nuclear Engineering and Design 314 (2017) 67–81

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

A methodology to investigate the contribution of conduction and radiation heat transfer to the effective thermal conductivity of packed graphite pebble beds, including the wall effect

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HIGHLIGHTS

- The radiation and conduction components of the effective thermal conductivity are separated.
- Near-wall effects have a notable influence on the effective thermal conductivity.
- Effective thermal conductivity is a function of the macro temperature gradient.
- The effective thermal conductivity profile shows a characteristic trend.
- The trend is a result of the interplay between conduction and radiation.

ARTICLE INFO

Article history:
Received 3 April 2016
Received in revised form 30 November 2016
Accepted 7 January 2017

Keywords:
Effective thermal conductivity
Near-wall effect
Packed pebble bed
Thermal radiation
Thermal conduction
Computational Fluid Dynamics

ABSTRACT

The effective thermal conductivity represents the overall heat transfer characteristics of a packed bed of spheres and must be considered in the analysis and design of pebble bed gas-cooled reactors. During depressurized loss of forced cooling conditions the dominant heat transfer mechanisms for the passive removal of decay heat are radiation and conduction. Predicting the value of the effective thermal conductivity is complex since it inter alia depends on the temperature level and temperature gradient through the bed, as well as the pebble packing structure. The effect of the altered packing structure in the wall region must therefore also be considered. Being able to separate the contributions of radiation and conduction allows a better understanding of the underlying phenomena and the characteristics of the resultant effective thermal conductivity. This paper introduces a purpose-designed test facility and accompanying methodology that combines physical measurements with Computational Fluid Dynamics (CFD) simulations to separate the contributions of radiation and conduction heat transfer, including the wall effects. Preliminary results obtained with the methodology offer important insights into the trends observed in the experimental results and provide a better understanding of the interplay between the underlying heat transfer phenomena.

1. Introduction

Randomly packed beds of spherical particles are used in several thermal-fluid industrial applications that involve energy transfer processes including catalytic reactors, drying processes and pebble bed gas-cooled reactors (PBRs) (Zhou et al., 2007). For the analysis and design of PBRs with inherent safety characteristics a thorough understanding of the heat transfer phenomena in packed pebble beds is essential.

The effective thermal conductivity is an important parameter that is representative of the overall heat transfer through a packed bed of spheres. When considering the safety case of a PBR, during a depressurized loss of forced coolant accident, the effective thermal conductivity consists of three components: (1) thermal radiation between solid surfaces, (2) conduction through the pebble material itself and (3) conduction through physical contact points between the surfaces of the solid materials (Van Antwerpen et al., 2010). According to Rousseau et al. (2014) models for the effective thermal conductivity are typically based on a simple Fourier conduction rate equation as shown in Eq. (1):

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http://dx.doi.org/10.1016/j.nucengdes.2017.01.010
0029-5493/

Nomenclature

A	Area [m^2]
k_{cond}	Conduction component of effective thermal conductivity [W/m-K]
k_{eff}	Effective thermal conductivity [W/m-K]
k_{rad}	Radiation component of effective thermal conductivity [W/m-K]
k_s	Thermal conductivity of solid material [W/m-K]
$\dot{Q}$	Heat transfer rate [W]
Δr	Path length [m]
r_f	Radius of fillet cross-section [m]
r_p	Pebble radius [m]
R_s	Thermal resistance of pebble material aligned with solid-solid interface [K/W]
R_{ss}	Contact resistance at solid-solid interface [K/W]
T	Temperature [K]/[°C]
z	Position in terms of sphere diameters [–]

Abbreviations

CFD	Computational Fluid Dynamics
DEM	Discrete Element Modeling
HTTU	High Temperature Test Unit
MSUC	Multi-sphere Unit Cell
NWTCTF	Near-Wall Thermal Conductivity Test Facility
PBR	Pebble Bed gas-cooled reactor
SC	Simple Cubic

$$\dot{Q} = -k_{eff} A \frac{dT}{dr} \tag{1}$$

with $\dot{Q}$ the heat transfer rate, k_{eff} the effective thermal conductivity, T the temperature, A the applicable area in the pebble bed through which the heat transfer is taking place and r the coordinate perpendicular to the area.

At higher temperatures, above approximately 650 °C, the contribution of the radiation component to the effective thermal conductivity becomes significant (Zhou et al., 2007; Breitbach and Barthels, 1980; Cheng and Yu, 2013; Talukdar et al., 2013). For temperatures around 800 °C and higher radiation becomes the dominant heat transfer mechanism in a packed pebble bed.

The geometry of a randomly packed bed consists of three main regions namely the bulk, wall and near-wall regions (Van Antwerpen, 2009). The porous structure changes significantly in the region near any wall as the packing geometry is disrupted in this area (Van Antwerpen et al., 2010, 2012). This variation in packing structure is known as the wall effect and influences the magnitude of the effective thermal conductivity in the wall region, which includes the pebble to reflector interface. During normal operation the conductive effects in the near-wall region will be negligible compared to convection. However, during a loss of coolant event the near-wall region forms part of the critical path for decay heat removal, thus an accurate prediction of the effective thermal conductivity in this region is important.

2. Background

2.1. Methods to separate conduction and radiation components of the effective thermal conductivity

Existing approaches described in literature to determine the effective thermal conductivity can be divided into three basic types namely experimental, numerical and analytical (Slavin et al., 2002; Tsotsas and Martin, 1987). The experimental approach includes experimental measurements of the temperature distribution and heat flux through the packed pebble bed (Rousseau et al., 2014; Breitbach and Barthels, 1980; Stöcker and Niessen, 1997; Abou-Sena et al., 2003). For the numerical approach the three-dimensional packed bed is subdivided into a large number of cells with the temperatures and heat flows matched at their boundaries (Zhou et al., 2007, 2010; Cheng and Yu, 2013; Asakuma et al., 2014). The analytical approach describes the packed bed as a network of conduction paths and the effective thermal conductivity is described as a combination of the individual conduction paths connected in series, parallel or a combination of both (Van Antwerpen, 2009; Slavin et al., 2002; Wang et al., 2016).

In order to gain better insight into the contribution of the different heat transfer mechanisms to the effective thermal conductivity it is important to separate the conduction and radiation components. This allows a better understanding of the underlying phenomena and the characteristics of the resultant values of the effective thermal conductivity.

The separation of the conduction and radiation contributions by means of an experimental approach only is not possible since both mechanisms naturally occur simultaneously. An experimental method can be coupled with another approach in an attempt to separate the contributing phenomena. None of the experimental studies in current literature attempted to separate the conduction and radiation components (Rousseau et al., 2014; Breitbach and Barthels, 1980; Stöcker and Niessen, 1997; Abou-Sena et al., 2003).

In the studies done by Zhou et al. (2007) and Cheng and Yu (2013) the contribution of the conduction and radiation to the overall effective thermal conductivity was separated by assuming the heat transfer phenomena can be superimposed. The overall effective thermal conductivity, k_{eff}, due to combined conduction-radiation was determined after which the conduction contribution to the effective thermal conductivity, k_{cond}, was calculated using a pure conduction model. Finally, using Eq. (2), the radiation component of the effective thermal conductivity, k_{rad}, was calculated from:

$$k_{eff} = k_{cond} + k_{rad} \tag{2}$$

The effect of radiation heat transfer was isolated and examined in the model of Asakuma et al. (2014) by specifying a constant material thermal conductivity, instead of defining the material property as a function of temperature. Thus the model did not separate the contributing phenomena explicitly, but rather attempted to eliminate the effect of variations in the conduction by keeping the material thermal conductivity constant throughout the analysis. Zhou et al. (2010) did not explicitly separate the conduction and radiation components, but did express the relative contributions of the various contributing heat transfer mechanisms as a percentage of the total heat flux in the packed bed at a certain temperature. This is similar to one of the methods used by Cheng and Yu (2013).

Slavin et al. (2002) modelled the packing structure of the bed by dividing the bed into two regions, (1) the region where spheres are close-packed and (2) the region where deviations from the close-packed structure occur resulting in void regions. Thus the overall unit cell considered in the model was divided into a close-packed cell in parallel with a void cell. The total thermal conductivity of a unit cell was calculated as a summation of the thermal conductivities for the close-packed region and the void region of the unit