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Experimental study of the effective thermal conductivity in the near-wall region of a packed pebble bed

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ABSTRACT

The effective thermal conductivity is an important parameter that represents the overall heat transfer in packed beds, including packed pebble beds. Experimental test facilities have been used to determine the effective thermal conductivity of packed pebble beds; however, the experimental results are often case specific and do not account for wall effects in the near-wall region. Recently the Near-Wall Thermal Conductivity Test Facility (NWTCTF) was developed at the North-West University in Potchefstroom, South Africa to perform detailed investigations of the conduction and radiation heat transfer phenomena in the near-wall region of a packed bed of spheres. The experimental test facility was introduced in a previous paper and some results were presented. This paper provides a short description of the test facility and then presents extensive experimental results obtained for structured and randomly packed beds consisting of 60 mm diameter graphite spheres at temperatures of up to 800 °C, together with associated uncertainties. Results obtained demonstrate the effect of the near-wall region, the packing structure and the presence of the wall on the effective thermal conductivity.

1. Introduction

A thorough understanding and an accurate prediction of the heat transfer through packed pebble beds are essential for the design of various thermal-fluid systems such as catalytic reactors, drying processes, thermal insulation, heat storage systems, packed bed regenerators, hydrogen production and generation IV type nuclear reactors (Asakuma et al., 2016; Ren et al., 2017; Van Antwerpen et al., 2010; Yang et al., 2012; Zhou et al., 2007). Two generation IV type reactors which are favoured for the inherent safety characteristics of their designs are Pebble Bed Gas-cooled Reactors (PBRs) and Fluoride Salt-cooled High-temperature Reactors (FHRs) (Wu et al., 2016; World Nuclear Association, 2017; You et al., 2017).

The overall heat transfer through a packed pebble bed is represented implicitly by a single parameter known as the effective thermal conductivity. When considering upset conditions in a PBR during a depressurized loss of forced coolant incident, conduction and radiation become the dominant heat transfer mechanisms for decay heat removal (Van Antwerpen et al., 2010; You et al., 2017). In order to ensure that an optimal reactor design is achieved it is important to have a thorough understanding of the contributing heat transfer phenomena as well as the interplay between the heat transfer mechanisms for different temperatures and packing structures (Van Antwerpen et al., 2010; You et al., 2017).

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. 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 convective transport. However, during a loss of coolant event the near-wall region forms part of the critical path for decay heat removal.

It is important to consider higher temperatures when investigating the effective thermal conductivity as the contribution of radiation heat transfer to the overall effective thermal conductivity increases significantly at temperatures above 650 °C (Breitbach and Barthels, 1980; Zhou et al., 2007; Cheng and Yu, 2013; Talukdar et al., 2013; Ren et al., 2017). Implicit effective thermal conductivity models are often used in

Abbreviations: BCC, Body Centred Cubic; FHR, Fluoride Salt-cooled High-temperature Reactor; HTGR, High Temperature Gas-cooled REACTOR; HTO, High Temperature Oven; HTR-PM, High Temperature Gas-cooled Reactor Pebble Bed Module; HTTU, High Temperature Test Unit; NWTCTF, Near-Wall Thermal Conductivity Test Facility; PBR, Pebble Bed Gas-cooled Reactor

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Nomenclature

a_0-a_5	polynomial coefficients [–]
a	slope of a first-order line [–]
A	area [m^2]
c_0-c_3	polynomial coefficients [–]
k	solid thermal conductivity [W/m-K]
k_{eff}	effective thermal conductivity [W/m-K]
L	characteristic length scale [m]
$\dot{Q}$	heat transfer rate [W]
Q_{bed}	heat transfer rate through packed bed [W]
$Q_{cooled\ wall}$	heat extracted through cooled wall [W]
Q_{losses}	heat lost through insulation walls [W]
r	path length [m]
T	temperature [K]/[°C]
$u\left(k_{eff}/k\right)$	uncertainty associated with the ratio of effective thermal conductivity to graphite thermal conductivity [–]
$u(Q_{bed})$	uncertainty of heat transfer through packed bed [W]
$u(\Lambda)$	uncertainty of Planck number [–]
y	position in the packed bed measured from the heated wall [m]
ε	emissivity [–]
Λ	Planck number [–]
σ	Stefan-Boltzmann constant [W/m^2-K^4]

practice to predict the heat transfer in full-scale reactors due to the excessive computational resources required by explicit models. For the development and testing of new and existing models it is necessary to have good quality experimental data that can be used to validate the predicted values of the effective thermal conductivity.

Various experimental studies have been done for the investigation of heat transfer in packed pebble beds. Van Antwerpen (2009) concluded that far more experimental work has been done for packed pebble beds at low temperatures with small particle diameters than at higher temperatures with larger particles. When focusing on the safety case for a PBR design, which is the motivation for this study, the experimental test conditions should be similar to what can be expected during actual upset conditions; namely a packed pebble bed consisting of larger particle sizes at higher temperatures, in a stagnant gas environment with limited convective heat transfer.

Researchers that conducted experimental work to predict the effective thermal conductivity in packed pebble beds at higher temperatures for larger sphere diameters include Breitbach and Barthels (1980), Stöcker and Niessen (1997) and Rousseau et al. (2014).

Breitbach and Barthels (1980) conducted experimental work using the High Temperature Oven (HTO) test facility at temperatures of up to 1500 °C. Experimental tests were conducted with zirconium-oxide pebbles and graphite pebbles with a particle diameter of 45 mm and 40 mm respectively. A least-squares regression function was fitted to the temperature distribution to obtain a smooth temperature function. The authors used a transient method to determine the effective thermal conductivity from the temperature distribution.

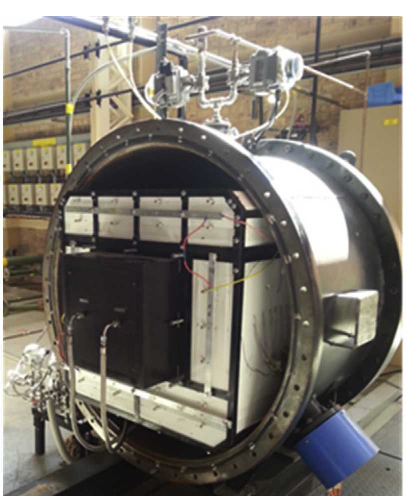
Stöcker and Niessen (1997) used the SANA-I test facility to investigate the heat transfer phenomena inside a High Temperature Gas-cooled Reactor (HTGR) core. Two steady state experimental tests were conducted for a randomly packed pebble bed with graphite pebbles with diameters of 60 mm and 30 mm respectively. Both experimental tests were performed within a helium environment at atmospheric pressure with heater power inputs of 10 kW and 35 kW respectively. The effective thermal conductivity for the packed pebble bed was calculated using the heat transfer and temperature measurements.

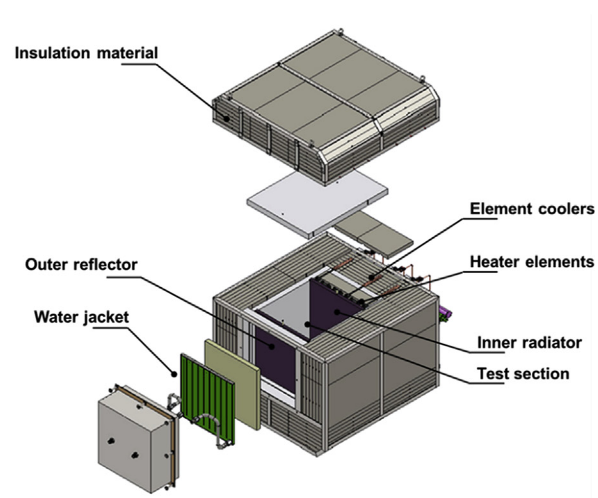
The High Temperature Test Unit (HTTU) test facility was used by Rousseau et al. (2014) to determine the effective thermal conductivity through a randomly packed bed of graphite spheres with a diameter of 60 mm. The experimental tests were conducted at near-vacuum conditions in a nitrogen environment at temperatures of up to 1200 °C. The effective thermal conductivity was determined by using a simple Fourier conduction rate equation, as shown in Eq. (1):

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

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 Δr the path length associated with the relevant area in the pebble bed.

Rousseau et al. (2014) proposed and applied a comprehensive method to the HTTU experimental data to derive the effective thermal conductivity of the pebble bed together with associated uncertainties. Therefore, the HTTU results could be used with confidence in the verification and validation of new models. The HTTU results showed that


(a)



(b)

Fig. 1. (a) Photograph of NWTCTF test unit positioned inside the pressure vessel and (b) exploded view of NWTCTF test unit.